Proceedings of the 1st Nordic Optimization Symposium

10th Nordic MPS meeting

COPENHAGEN 2006

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IMM Technical Report (2006-05) ISSN: 1601-2321

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Welcome

On behalf of the Technical University of Denmark, the Danish Operations Research Society and the Nordic Section of the Mathematical Programming Society we welcome you to Copenhagen and the 1st Nordic Optimization Symposium – the 10th meeting of the Nordic MPS. The meetings of the Nordic MPS have evolved to be more that just a meeting on Mathematical Programming. They are a forum for discussing a wide range of related areas and practical cases. In the organizing committee we wanted the name of the meeting to reflect this. We have therefore in agreement with the board of the Nordic MPS suggested to add a new title, that reflects the much broader field that is our playground at these meetings. Still the odd trustworthy title "Meeting of the Nordic MPS" has been maintained to demonstrate the origin of the symposium. It is our hope that future Nordic MPS meetings will carry on using this "double name".

The program includes 2 plenary lectures by Leo Kroon and Arne Drud and more than 50 contributed presentations. The symposium has this time expanded beyond our Nordic boundaries with participants from eg. the Netherlands, Italy and New Zealand. As a consequence the original 2 parallel streams we had in mind have extended to 3 throughout the symposium.

It is our firm belief that this symposium will – like all the previous Nordic MPS meetings – be a fruitfull ground for collaboration and networking and therebye further tighten the ties between the Nordic countries in relation to optimization, Operations Research and Mathematical Programming.

Finally we would like to thank our sponsors and supporter for their contributions. It has among other things made it possible to give free registration to a number of researchers from the Baltic countries and Ph.D. students in general.

We wish you all an enjoyable 1st Nordic Optimization Symposium (10th Nordic MPS meeting) in Copenhagen.

On behalf of the organizing committee,

Jesper Larsen

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We gratefully acknowledge the generous support by our sponsors and supporters.

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Program

The program of the 1st Nordic Optimization Symposium (10th Nordic MPS meeting) formally starts with the welcome reception Thursday (20. April) at the facilities of DSB (the Danish State Railways) from 19.00.

Registration will be possible from the start of the Ilog workshop and Friday morning from 8.30 to 9.00 before the first session. On Friday evening the symposium dinner will take place at restaurant Nimb in Tivoli starting at 19.00. Finally the business meeting of the Nordic MPS is closing the symposium on Saturday from 15.00 to 15.30.

Due to the overwhelming response 3 parallel sessions throughout the symposium has been necessary to arrange all the interesting presentations. For each of the presentations a page reference to the abstract is included.

Friday (21. April)			
Time	**Plenum**	**Room 1**	**Room 2**
8.30-9.00	*REGISTRATION*		
9.00-10.00	**Plenary talk** *chair: Jesper Larsen* LEO KROON, Robust scheduling of passenger railway timetables (p. 56)		
10.00-10.30	MATTEO FISCHETTI, Solving very-large scale crew scheduling instances at Netherlands railways: how and why? (p. 38)		
10.30-11.00	*COFFEE BREAK*		
11.00-11.30	**Rail Fleet** *chair: Jens Clausen* NIKLAS KOHL, Rolling Stock Scheduling at the Danish State Railways (DSB) (p. 52)	**Integer Programming I** *chair: Kim Allan Andersen* JØRGEN TIND, Column Generation in Integer Programming with Applications in Multicriteria Optimization (p. 103)	**Finance/NLP** *chair: Thomas Stidsen* KOUROSH M. RASMUSSEN, Dynamic diversification strategies of mortgage loans for home owners (p. 78)
11.30-12.00	JESPER HANSEN, Railway Rolling Stock Planning (p. 47)	KENT ANDERSEN, Cutting planes from two rows of a simplex tableau (p. 21)	LENNART FRIMANNSLUND, Separability and sufficient decrease in generating set search methods (p. 40)
12.00-12.30	RICHARD LUSBY, Routing Trains Through Railway Junctions: Dual Formulation of a Set Packing Model (p. 59)	JENS EGEBLAD, A sequence-pair heuristic for the two-dimensional knapsack packing problem (p. 36)	JULIUS ŽILINSKAS, On Minimization Problems in Multidimensional Scaling with City Block Metric (p. 112)
12.30-13.30	*LUNCH*		

Friday (21. April)

Time	Plenum	Room 1	Room 2
13.30-14.00	**Vehicle Routing** *chair: Oli B.G. Madsen* SIMON SPOORENDONK, A non-robust Branch-and-Cut-and-Price algorithm for the Vehicle Routing Problem with Time Windows (p. 97)	**Rail Crew** *chair: Niklas Kohl* LARS KJÆR NIELSEN, Planning work schedules for ticket inspectors in Danish S-trains (p. 62)	**Optimization Software** *chair: Erling Andersen* BO JENSEN, Solving linear optimization problems with MOSEK (p. 51)
14.00-14.30	TROELS MARTIN RANGE, On using a two-level decomposition of the Vehicle Routing Problem with Time Windows (p. 76)	MORTEN NYHAVE NIELSEN, Duty Planning and Design of Experiments (p. 63)	ANDERS SCHACK-NIELSEN, Experiments with different branching schemes in mixed integer optimization using SCIP (p. 89)
14.30-15.00	SANNE WØHLK, Solving the Capacitated Arc Routing Problem with Time Windows to Optimality (p. 110)	MICHAEL FOLKMANN, Estimation of crew demand in S-tog (p. 39)	JOACHIM DAHL, CVXOPT – A Python package for convex optimization (p. 34)
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Friday (21. April)			
Time	**Plenum**	**Room 1**	**Room 2**
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15.50-16.20	DAVID PISINGER, Adaptive Large Neighborhood Search applied to mixed vehicle routing problems (p. 73)	CAMILLA SCHAUMBURG-MÜLLER, A Partial Load Model for a Local Combined Heat and Power Plant (p. 90)	RUNE SANDVIK, Exploiting parallel hardware in optimization (p. 88)
16.20-16.30	*BREAK*		
16.30-17.00	**Routing in practice.** *chair: David Pisinger* MIKAEL RÖNNQVIST, How to solve large scale transportation problem in practice (p. 87)	**Energy.** *chair: Camilla Schaumburg-Müller* TRINE KROGH KRISTOFFERSEN, Stochastic Programming for Optimizing Bidding Strategies of a Hydro-Power Producer (p. 54)	**Applications** *chair: Martin Zachariasen* LARS ROSENBERG RANDLEFF, Optimising Fighter Pilot Survivability (p. 75)
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11.00-11.30	**Routing** *chair: Jens Lysgaard* HANNE L. PETERSEN, Solving a Pickup and Delivery Problem with Sequencing Constraints (p. 70)	**Rail Operations** *chair: Morten Nyhave Nielsen* NATALIA J. REZANOVA, Crew Recovery after Train Cancellations (p. 84)	**Telecommunication II** *chair: Thomas Stidsen* DI YUAN, Resource Allocation of Spatial Time Division Multiple Access in Ad Hoc Networks (p. 111)
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Saturday (22. April)

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Abstracts

All the abstracts of the symposium is printed on the following pages. They are ordered based on the last name of the presenter.

Cutting planes from two rows of a simplex tableau

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Co-authors:

Most cutting planes that are effective in practice are Mixed Integer Gomory (MIG) cuts. MIG cuts can be obtained from a row of the simplex tableau, but also from combinations of these rows. The MIG procedure has two steps. The first step ignores the integrality constraints on non-basic variables, and an inequality is derived based on the integrality of the basic variable only. The second step uses the integrality of non-basic variables to strengthen the inequality.

In this talk, we generalize the MIG procedure to two constraints. We characterize all the facets needed in a first step of a MIG procedure for two constraints, and a polynomial-time separation algorithm is provided. In particular, we describe a new class of general cutting planes, and we prove that none of these cuts are MIG cuts. Each facet can be derived from a subset of no more than four variables. The structure of a facet is intimately related to the geometry of two-dimensional lattice point free polyhedra, and the results are obtained by characterizing these objects.

An algorithm for ranking assignments using reoptimization

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We consider the problem of ranking assignments according to cost in the classical linear assignment problem. An algorithm partitioning the set of possible assignments, as suggested by Murty, is presented where. For each partition, the optimal assignment is calculated using a new reoptimization technique. Encouraging computational results for the new algorithm is presented.

Efficient utilization of resources for public safety

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Resources for public safety include emergency services like fire and rescue services, ambulance services and police services. From a planning perspective, these three services have much in common, although substantial differences exist as well. In this presentation, the similarities and differences between these services are discussed. To provide some background for the discussion, two projects focusing on the construction of decision support tools for public safety decision makers are described; OPAL – Optimized ambulance logistics and OPERA – Optimized and efficient rescue resource allocation.

The majority of the calls for emergency service in Sweden begin with someone dialling the national emergency telephone number, 112. This call is received in an SOS centre, where an SOS operator decides which services that should be contacted. If the police are needed, the SOS operator will transfer the call to a police call centre. The dispatching of all ambulance resources and the majority of the fire and rescue resources are handled at the SOS centres. Therefore calls for these services are often handled by the operator and by an appropriate dispatcher. The operator judges the urgency and the magnitude of the call, and based on this, the dispatcher selects which resources to send.

When comparing ambulance services to fire and rescue services, two major differences can be noticed. The first is that fire and rescue services demand a more diversified range of resources. Since the events triggering the service include fires, traffic accidents and drowning accidents, to name a few, the resources have to include pump vehicles, cutting tools and diving equipment. Even if some ambulance service systems use different kinds of vehicles, e.g. urgency cars and helicopters, most events can be handled by the ordinary ambulance. The second difference is that most fire and rescue resources are busy with emergency events for quite a small portion of their total service time, while ambulance resources might be busy with patients a substantial part of the time. Thus, when planning fire and rescue resources, a common assumption is that they are always available at the station. When planning ambulances, it is important to consider that they may not be available when they are needed.

One thing that sets the planning of police resources apart from the two services discussed above is the patrolling function. The purpose of this function is to prevent crime by deterring the potential criminals who notice the resources. The other objective is to inform the public of the same thing, i.e. that the police resources are available, which contributes to a feeling of safety and security. The latter purpose might be applicable for ambulance resources as well and perhaps even for fire resources. However, this is rarely regarded when the planning of these resources are performed. Apart from this function, a system for police services has much in common with a system for ambulance health care. Calls for service occur stochastically, and should in general be served as quickly as possible.

In Sweden, the municipalities are responsible for the fire and rescue services. The ambulance services are managed by the county councils and the police services by the government. The fact that three different organizations are responsible for the three services reduces the possibility of knowledge transfer between the systems. OPAL and OPERA concern the planning and control of different emergency resources and thus provide an opportunity for the sharing of knowledge between ambulance services and fire and rescue services. So far, OPAL has focused on operational control and tools for dispatching and relocation, while questions of strategic nature have been considered in OPERA. However, it is often possible to transfer knowledge, experience and results gained in one of the projects to the other area.

By simultaneously perform research within different systems for public safety, it is possible to obtain synergy effects as well as increase the interaction between the systems. Therefore, the objective of CERPS – Centre for efficient utilization of resources for public safety – is to perform research concerning all different systems for public safety. This includes police, ambulance, fire and rescue services, coast guard, sea and air rescue, among others.

The centre will be based at Linköping University, but key personnel from relevant organisations involved in public safety will participate as members of the reference group, and as problem owners. In an initial step, three PhD students will begin their education, if possible in January 2007. One student will focus on fire and rescue services, one on ambulance services and the third on police services. However, the education will be built on a common research foundation and the students will collaborate to find new ways of attacking problems within the different systems. This way, they will support each other and at the same time contribute to knowledge transfer between the different systems for public safety.

Finding disjoint spanning trees which minimize the maximum of the two weights

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Co-authors: Christoffer Christensen, Inge Li Gørtz, Daniel Goncalves

The well known NP-hard problem **Partition** is the following. Given a set S of n non-negative integers; partition S into two sets X and Y such that the sum of the elements in X is as close as possible to the sum of the elements in Y (that is, minimize the maximum of the two sums). In this talk we study the following problem: given an edge-weighted graph G containing two edge-disjoint spanning trees. Find a pair of edge-disjoint spanning trees such that the maximum weight of these two trees is as small as possible. In the case when G is precisely the union of two trees this problem may be seen as a generalization of the partition problem in which we have added a graph structure to the numbers (through the edges) and the extra restriction that only sets X and Y which correspond to trees in G are valid partitions. We show how to combine a reduction heuristic (based on an algorithm for weighted matroid partition) for the problem with local search methods to obtain high quality solutions for this problem and compare these to solutions obtained by an approximation algorithm which uses the same reduction heuristic. Finally, we discuss possible implications of these findings.

New Results on the Broadcast Incremental Power (BIP) Algorithm

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Introduction

Many applications of wireless systems require energy-aware networking. Energy efficiency is of particular importance in wireless ad hoc and sensor networks, where the networking units have a limited amount of energy resource. Broadcast is the type of communication process of delivering messages from a source node to all the other nodes in a network. Unlike wired networks, broadcasting is an inherent characteristic of wireless transmission. Signal propagation typically occurs in all directions. In such a networking environment, a certain transmission power corresponds to an area of coverage, and a single transmission delivers a message to all nodes within the area. This property is referred to as the wireless multicast advantage in [2]. As a consequence of this property, the power needed to reach a set of receiving nodes is not the sum, but the maximum of the power for reaching any of them. If d_{ij} denotes the distance between nodes i and j, then the transmission power required by j to be reached by i is equal to κd_{ij}^{α}, where κ is a positive constant and α is an environment-dependent parameter [2, 4].

Minimum energy broadcasting in wireless networks involves routing of messages from a source node to all the other nodes using the minimum amount of energy. The communication paths in minimum energy broadcasting can be characterized by a arborescence rooted at the source. In this work, we refer to the problem of finding this broadcast arborescence as the minimum-energy broadcast routing problem (MEBR). The structure of MEBR is very different from that of the classical minimum spanning tree (MST) problem, as the objective function of the former is node-oriented rather than link-oriented. This has the consequence that MEBR is NP-hard [3, 4].

A number of approximation algorithms have been proposed for solving MEBR. Among them, the most known algorithm is the Broadcast Incremental Power

(BIP) algorithm, presented by Wieselthier et al. at INFOCOM 2000. Another algorithm called Adaptive Broadcast Consumption (ABC) was introduced by Klasing et al. in [5]. An obvious approximation algorithm is to use Prims algorithm. Ambuhl showed in [1], that the approximation ratio of Prims algorithm is no larger than 6. Many other algorithms have been introduced, which are in most cases a variation of the classical BIP.

The contribution of our work consists of four parts: First, we provide a general framework for approximation algorithms for MEBR. This subsumes BIP and several of its extensions, and serves as a tool for general analysis of performance ratio and time complexity. Second, we show that BIP can be implemented to run in $O(n^2 \log n)$ time, contrary to its frequently assumed $O(n^3)$ time complexity. Third, we introduce an improvement of ABC which runs in $O(n^3)$ time. Finally, we provide new results on upper and lower bounds on the approximation ratio of several algorithms subsumed by the framework.

We say that $\mathcal{S}$ and $\mathcal{K}$ are consistent if the new node suggested by the selection step $\mathcal{S}$ is one that minimizes the power increase implied by the construction step $\mathcal{K}$, and correspondingly we say that an approximation algorithm is consistent if these two steps are. This gives an easy hint for improvement of approximation algorithms. For example, BIP is nothing but Prim's algorithm made consistent by replacing its selection function.

Time complexity of BIP

In every iteration of the first phase, BIP adds the node requiring a minimum amount of incremental power to the broadcast arborescence. The corresponding local search, frequently referred to as sweeping, examines all pairs of nodes i and j. If the power assigned to j is large enough for j to reach the critical child node v of i, that is the child node of largest distance from i, then j becomes the new parent of v and the power at i is reduced accordingly. The sweep procedure is applied iteratively until it does not find any more improvements. While it is easy to show that the construction phase of BIP runs in $O(n^2 logn)$ time, a primitive implementation of the sweep procedure will need $O(n^3)$ time. In the full paper, we show that by processing the nodes in the arborescence in a careful order, the time complexity of the sweep procedure can be reduced to $O(n^2)$. Starting with the leaves, we transfer all critical child nodes of their current parents to new parents, if so is possible. By processing one arborescence level at the time and moving in the upward direction, we demonstrate that only $O(n^2)$ operations are needed. Thus, we result in a total complexity of $O(n^2 logn)$ for BIP.

A new approximation algorithm

The main difference between ABC and BIP is that the construction step $\mathcal{K}$ of ABC takes into account possible savings when choosing the parent node for the new node selected by $\mathcal{S}$.But $\mathcal{K}$ is only allowed to consider for every node a power increase that is sufficient to reach the new node selected by the selection function $\mathcal{S}$ of ABC. $\mathcal{S}$ is the same as in Prim's algorithm. Therefore, ABC is not a consistent approximation algorithm. We allow our algorithm greater freedom in two respects: First, our $\mathcal{K}$ may consider a larger power increase than what is sufficient to reach the node selected by $\mathcal{S}$, if that provides additional saving. Second, our $\mathcal{S}$ is not restricted to Prim's order, but consistent with our $\mathcal{K}$, allowing to add to the arborescence one node that is cheapest with respect to all possible savings. Both ABC and our algorithm have time complexity $O(n^3)$, which means that the extension does not imply increased complexity. In the full paper, the algorithm is given in detail, the time complexity proved and numerical results showing its performance and execution time are given.

Bounds

By a straightforward generalization of the result given by Wan et al. in [6], we can now identify a class of approximation algorithms that have an approximation ratio no larger than c, including BIP, ABC and our algorithm. We also obtain a new, stronger lower bound (namely 4.6) on the approximation ratio of ABC, which also holds for several other algorithms subsumed by the framework.

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Modeling the Danish Natural Gas Supply

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As a result of the liberalization of the markets for electricity and natural gas, these energy commodities have become increasingly interdependent. This is evident in Denmark on the market side with in e.g. the proposed DONG Elsam merger, and in the institutional reshuffle which led to a merging of the transmissions systems operators (TSOs) for electricity and natural gas to Energinet.dk. It is recognized that there is interplay, yet it is still being uncovered where this interdependency is most evident e.g. competitive energy consumption, energy transmission, energy storage, prices or security of supply. Recent national and international incidents, such as the power outage in southern Sweden and Eastern Denmark on September 23rd 2003 and the gas controversy between Russia and Ukraine primo 2006, illustrate the importance of targeted research in this area.

As a part of the project, "A Model of and Analyses of an Integrated Electricity and Natural Gas System", supported by the Danish Energy Research Program, we have developed a natural gas emphasized extension to the Balmorel model of regional electricity and district heating (www.Balmorel.com). Using this model we have analyzed the attractiveness of options for market driven gas allocation available to the system as a whole. The analysis focuses on the interplay between different forms of boundary assumptions for the system and thus demonstrates how different results occur using various individually reasonable paradigms.

Specifically the analysis illustrates how boundary assumptions regarding the production of gas in the North Sea, the export of gas, and the technical and economic parameters pertaining to the gas storage facilities. The simulations include an endogenous demand-side where gas is consumed by end-users, fires district heating facilities and/or is transformed by way of electricity generators operating in a competitive Nordic electricity market. The implications of various assumptions is analyzed by comparing levels of production, consumption, transformation, exports and storage and their implication on prices for electricity and natural gas in a number of boundary scenarios. The analysis is but one of several which will be performed using the integrated model, and contains the first public presentation of results from the above mentioned project.

The model is formulated in GAMS as a linear programming model. Since both supply- and demand-side mechanisms are endogenous, the model is a welfare maximizing partial equilibrium model, where welfare is defined as the sum of consumer and producer surplus across the modeled business sectors. The model is solved by CPLEX. The standard Balmorel model handles the electricity and combined heat and power sectors, and the gas module is formulated as an add-on, and is yet completely integrated with respect to input data formats, reporting, etc. The model can be generated to simulate a yearly market solution at a user defined temporal and geographical resolution. It can also be generated to simulate weeks iteratively with an hour-by-hour time resolution.

The present version of the model has around 75,000 equations, 180,000 variables, and 520,000 non-zeroes for an aggregated simulation of a single year. The hour-by-hour model has 48,000 equations, 117,000 variables and 334,000 non-zeros per simulated week.

The key relations in the model, from the point of view of the present paper, relate to the natural gas system, and are as follows:

Gas production

- Annual gas production from the North Sea is at most equal to a predefined value. This annual target value is an assumed optimal level of production at given prices reflecting the gas producer's optimization problem, and is derived from available forecasts. The model thus decides when it is economically efficient to produce towards this annual target value, by considering mainly the demand side and infrastructural capacities.

Gas storage

- Technically, the rate of gas injection, rate of extraction and the total volumetric capacity is limited to reflect facility specifications.
- Economically, storage access is procured by the market by purchasing a linear combination of available packaged deals for injection capacity, extraction capacity and volumetric storage capacity. Additionally a volumetric injection tariff is imposed.

Domestic demand

- Domestic gas consumption is endogenously represented for energy transformation purposes (i.e. generation of electricity and district heating).

- Additionally, an exogenous component containing the residual domestic market (i.e. direct consumption in private homes, industrial applications etc), is based on energy consumption forecasts using historical data.

Import/export

- Import and export is technically constrained by capacities at the border stations.
- The sale and purchase of natural gas across border with Germany (and in some cases Holland) is controlled by a seasonal price-quantity profile.
- Natural gas exports to Sweden are handled similarly to the Danish domestic demand with an exogenous component and an endogenous component.

Gas transmission and distribution

- The market procures access rights to the transmission network in the form of capacity based products. These grant the holder the right of entry or exit to the system on an hourly basis. Available products have duration of a year, a month, a week or a day. The price of the flexible products is higher in time of high demand.
- Capacity procurement is undertaken by the collective market. This reflects the fact that capacity contracts are tradable amongst market players, and are subjected to a "use-it-or-lose-it" clause to prevent hostile buy-up of transmission rights.
- A volumetric tariff is induced in both the transmission and distribution systems.

The presentation will give an account of the mathematical model, show calculation examples, and derive interpretations of the dual variables from the optimal solution.

CVXOPT – A Python package for convex optimization

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CVXOPT is a free software package for convex optimization, written in the high-levelprogramming language Python. Python is an interpreted language that runs on a wide range of platforms, including some embedded devices, and offers an extensive collection of libraries (for example, network and database interfaces, plotting and visualization routines, graphical user interfaces, etc.). CVXOPT includes routines for basic dense and sparse matrix operations, interfaces to free linear algebra packages (BLAS, LAPACK, UMFPACK, CHOLMOD) and convex optimization routines written in Python. Its main purpose is to facilitate the development of embedded applications of convex optimization. In the talk we present the current state of CVXOPT, with practical examples of algorithms and applications implemented in Python.

An overview over model characteristics and practical solvers in Nonlinear Programming

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The field of Nonlinear Programming (NLP) is very complex. The models can be convex or non-convex models, separable or non-separable, with or without discrete variables, with smooth or non-smooth functions, they can have few or many degrees of freedom, and they can be small or large. Difficulty can be caused by combinatorial aspects or by nonlinearities. NLP can be seen from an theoretical point of view (theoretical algorithms and their convergence proofs), from a software point of view (the behavior of actual implementations and the use of various numerical components), and from a users point of view (user interfaces such as libraries or modeling system solvers, either as freeware or as commercially supported software, and with nonlinearities defines through subroutines, in symbolic form, or as lists of instructions). Finally, users can be interested in globally or locally optimal solutions.

Our main interest is existing NLP software, also called solvers. We will describe some solvers and use them as a basis for a discussion of this complex environment and the interactions between model attributes and solvers. The solvers will include interior point solvers such as IPOPT and KNITRO (designed for large smooth models without discrete variables), active set methods such as MINOS, SNOPT, and CONOPT (designed for models with a limited number of degrees of freedom), MINLP solvers such as DICOPT and SBB (for models with discrete variables), and global solvers such as BARON and LINGO (designed for highly nonlinear but fairly small models). We will also see how specialized solvers such as Cplex (for QP) and Mosek (for general convex models) fit into the overall picture.

The aim of the talk is to guide potential users towards the types of solvers that could be useful for their applications.

A sequence-pair heuristic for the two-dimensional knapsack packing problem

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The two-dimensional knapsack problem is to orthogonally pack a subset of some given rectangles into a larger rectangle, such that the profit of the chosen rectangles is maximized. Formally, we have a set $N = \{1, \ldots, n\}$ of rectangular items, each item having width $w(j)$, height $h(j)$ and an associated profit $p(j)$. An enclosing rectangle (the knapsack) of dimensions $W \times H$ is given and the objective is to pack a maximum profit subset of the items such that no two items overlap, and all chosen items are within the boundary of the knapsack.

In the present paper we propose a new heuristic based on the sequence pair representation proposed by Murata et al. (1996). Murata showed that every packing of n rectangles can be represented by a pair of sequences given as permutations of the numbers $\{1, \ldots, n\}$. Tang and Wong (2001) showed that every sequence pair can be transformed to a packing in $O(n \log \log n)$ time. Pisinger (2006) presented a similar transformation with same running time, but where the packing is semi-normalized.

The sequence pair representation makes it easy to construct a local search heuristic for packing problems. The algorithm maintains a pair of sequences given as permutations of the numbers $\{1, \ldots, n\}$. In each step a neighbor solution is generated by making a small permutation in one or both sequences. The new sequence pair is transformed to a packing and the corresponding objective function is evaluated. Based on the local search framework chosen, the new solution can be accepted, or the algorithm tries a new neighbor solution to the previous solution.

The sequence pair representation has been used for solving the placement problem in VLSI-design. In this setting the objective is to minimize the area of the enclosing rectangle of the final packing. In our setting we have modified the approach to a fixed knapsack $W \times H$ as follows: In the objective function, we only add the profit of rectangles which have been fully placed within the knapsack area.

The developed algorithm has been tested on the cgcut, gcut and okp instances available from ORLIB. For the gcut13 instance with 32 rectangles, the best known solution was improved from 8.622.498 (Fekete, Schepers 2006) to 8.720.134.

Solving very-large scale crew scheduling instances at Netherlands railways: how and why?

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Recent advances in the OR technology for solving crew scheduling problems increased dramatically the size (and complexity) of the instances that can be attacked successfully in practical railways applications. Indeed, highly-constrained crew scheduling instances involving about 13,000 trips to be assigned to 1000+ duties in 29 depots are nowadays solved routinely, on a PC, by the main Dutch railway operator, NS Reizigers, using the commercial software TURNI. As a matter of fact, the high scalability of TURNI algorithms suggests that instances of about one order of magnitude larger (i.e., involving up to 100,000 trips) are no longer out of reach. In this talk we address the issue of why this technology is expected to produce important savings at NS Reizigers, and how it can be implemented within the TURNI framework.

Estimation of crew demand in S-tog

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We present a model used for estimating the required manpower in early steps of planning in S-tog. With basis in a profile for the required materiel for the time table and different profiles of a working day for the train drivers we estimate the number of drivers needed to cover the driving. The profiles are divided into separate days due to the different characteristics for the weekdays. The model includes a number of different criteria used internally in planning in S-tog.

We present results for different real life problems and further studies to extend the usability to earlier steps in the tactical planning.

Separability and sufficient decrease in generating set search methods

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Generating set search (GSS) methods [4] are often one of the few applicable alternatives for optimization of functions which are subject to numerical noise. Numerical noise may arise for instance when the function is computed through simulations on a computer, or when the function contains difficult subproblems such as integration or the solution of differential equations, which usually have to be solved approximately. We illustrate these types of functions with a function which arises in the maximum likelihood estimation of fish populations.

It is well known that GSS methods are slow in their most basic form because of what one can call zig-zagging, a phenomenon caused by the angle between search directions and the negative gradient being close to orthogonal. Zig-zagging can be alleviated by having the method choose its search directions adaptively. We have previously developed a GSS method [2] which chooses its search directions as the eigenvectors of what we call a curvature information matrix, which for differentiable function is an approximation to an average Hessian matrix. Let $q_j, j = 1, \ldots, n$ be a set of linearly independent search directions and let Q be the matrix where column j is q_j. The curvature information matrix C satisfies

$$C = QC_QQ^T \tag{1}$$

where element $(i, j), j \leq i$ of C_Q is computed by the formula

$$(C_Q)_{ij} = \frac{f(x + hq_i + kq_j) - f(x + hq_i) - f(x + kq_j) + f(x)}{hk},$$

for some x, which is usually different for each (i, j)-pair. The new search directions in the GSS method are now the eigenvectors of C. By searching along the eigenvectors, which are both conjugate and orthogonal, the method performs significantly better than a method without adaptive search directions.

This method can be enhanced further by taking sparsity into account, which makes the method faster and applicable to a larger number of variables. Usually, GSS methods are not used for large n, $n > 100$ being large in this context. We present a definition of sparsity which is applicable to non-differentiable as well as differentiable functions, and hence is an extension of sparsity relating to mixed partial derivatives as in [3]. Unlike in [5], where it is shown that if the individual element functions that make up the objective function are available, one can solve problems with up to 5000 variables efficiently, we assume that f is available only in its entirety. We show how to utilize sparsity by computing only a small fraction of the elements in the matrix C_Q. If ρ is the number of nonzero elements in the lower triangular part of C the number of computed elements must be larger or equal to ρ. When determining which elements in C_Q are to be computed we encounter the following matrix row selection problem. The equation (1) can be rewritten as

$$C_Q = Q^T C Q \quad \Longleftrightarrow \quad K\mathbf{vec}(C) = \mathbf{vec}(C_Q),$$

where K denotes the Kronecker product $(Q^T \otimes Q^T)$ and $\mathbf{vec}(C)$ are the entries of the matrix C stacked in a vector. If C is assumed to be sparse in addition to symmetric, the number of columns in the coefficient matrix K can be reduced, giving a system, say

$$KP_c c = \mathbf{vec}(C_Q),$$

where c is the vector of nonzero elements in the lower triangle of C and the matrix P_c removes (and adds) the appropriate columns in K. Since, from (1), C_Q is also symmetric, about half of the rows of the coefficient matrix KP_c can be deleted giving a matrix, say $P_{r_1}KP_c$, but we still have an overdetermined equation system. The problem becomes what rows we can eliminate to obtain a square nonsingular equation system, say

$$P_{r_2}P_{r_1}KP_c c = P_{r_2}P_{r_1}\mathbf{vec}(C_Q).$$

While these rows are easily identifiable in theory, for example via QR-factorisation of the matrix $(P_{r_1}KP_c)^T$, this is prohibitively expensive for large problems. The dimension of $P_{r_1}KP_c$ is $n(n+1)/2 \times \rho$, so if for instance $n = 200$ and C is tridiagonal, then the dimension of $P_{r_1}KP_c$ is 20100×399. We discuss the problem and how one can solve it by a greedy algorithm which uses a heuristic ordering of the rows of $P_{r_1}KP_c$.

Numerical results show the method exploiting sparsity to perform significantly better than the method not exploiting sparsity when $\rho < n(n+1)/2$.

Finally we look at the convergence theory of GSS methods, and how making the method enforce sufficient decrease rather than simple decrease is beneficial, and how the sufficient decrease condition can affect the accuracy of the final solution, by acting as an aid to the stopping criterion.

This work is a continuation of the work presented at the ninth meeting of the Nordic MPS in Norrköping in 2004, published in [1].

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Studying robustness by simulation in DSB S-tog. Two case studies.

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Abstract

Two independent studies of robustness in plans of DSB S-tog are presented. They are of a very different level of detail and they differ in their main goals. First a simulation model of low detail is presented. This model concentrates only on train circuits and is ideal for quick inclusion of e.g. various recovery methods. The second model presented is work in progress. This model is very large and not suited for quick adjustments. The purpose of the model is to enable overall robustness evaluations of both crew and timetable plans on future scenarios.

Robustness of timetables

The first case study is the study of the effect on robustness when covering the S-tog network with various timetables with different characteristics. The main characteristic of the model is that rolling stock is simulated as it circulates according to the timetable. Drivers are assumed available for all departures. Delay distributions are constructed from historical data and applied to the simulation on station level. Buffer times in the model are present only on terminals, i.e. lost time can be gained only when trains arrive at their terminals. The test setups are worst case scenarios of driving peak hour demand all day. It is therefore possible to assume that no changes of train composition occur and as a consequence this is not included in the model.

The case study also investigates the effect of a variety of recovery method when employed individually on a disrupted operation. Specifically, the recovery methods implemented in the simulation model are *Insertion of On-time Trains from the Central Depot*, *Early Turn-around* and *Cancelling Train Lines*. These methods were chosen because of their different characteristics w.r.t the direct decrease of delays and the increase of headways.

The timetables tested are mainly timetables used in operation on the S-tog network. However, also timetables that might be interesting for operation in the future were tested. Finally, two timetables were included in the tests that represent entirely new suggestions for covering the S-tog network.

Results show that the necessary size of buffer times on terminals seen with respect to the benefit on robustness is surprisingly small. Tests with different sizes of delays show that small delays have a significant negative effect on robustness when occurring together with large delays as opposed to the small delays contributing with almost no effect on robustness when they occur alone. Results on comparing the different timetables with and without the recovery methods are also presented. The expected results in this case were that a high number of train lines in the network would result in a decreased regularity. This is confirmed in most cases. For a few timetables, inserted time buffers make the number of lines less important to the value of regularity. The recovery methods are compared on their stand-alone efficiency seen with respect to regularity and reliability.

Robustness of Crew plan vs. timetable

The second case study is work in progress on the simulation tool SiMS - Simulation of Crew at S-tog. The simulation tool simulates the trains in circuit according to the timetable where trains are covered by the drivers. The combined effect of simulating over both timetable and crew plan enables a more detailed evaluation of the effect of planning on the robustness of operation. In the simulation model delays occur on both trains and drivers. All delay distributions are based historical data.

SiMS simulates the circuits of trains without marshalling, and the process of covering each departure with drivers. Drivers are available at crew depots only. SiMS is basically run on the tasks given by the crew plan. The trains are running in circuits according to the train sequence file as transporters picking up drivers. In that way the departures given by the timetable is covered.

As a train can only run in operation when a driver is present, simulation of the covering of train-tasks is included. For this purpose, reserve drivers are available in a predefined schedule over the day. Tasks are covered by employing a set of dispatching rules that prioritize the use of vacant scheduled drivers or reserve drivers. One dispatching rule could be the swapping of tasks among drivers to cover more tasks in total. If no possible solution is found, an imaginary driver is used for covering the task. An imaginary driver is equivalent to an extra reserve. In reality, when no vacant scheduled driver or reserve driver can be found, the train is cancelled.

All of the S-tog network is included in SiMS. Hence the amount of data necessary is excessive. First of all, the crew plan with tasks of each single driver must be available. Also, the timetable at the detailed level of all departures during the day is necessary. In the timetable data the minimum driving times must also be included. For connecting the train numbers and the tasks of drivers the train sequences are included. For each station, information is given on the dwell time, minimum dwell time, number of available platforms, the probability of delay and a delay distribution variating across the day. A list of the working hours of reserve drivers is also included.

SiMS will make it possible to quantify robustness of the crew plan when analysing the results on e.g. regularity, employed reserve and imaginary drivers, and violations of work rules. Furthermore, it will make evaluation of future timetable or crew scenarios possible.

Integrated production and distribution planning of the supply chain for Södra Cell AB

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In this paper we consider integrated planning of transportation of raw material, production and distribution of products of the supply chain at Södra Cell AB, a major European pulp mill company. The strategic planning period is one year. Decisions included in the planning are transportation of raw materials from harvest areas to pulp mills, production mix and contents at pulp mills, distribution of pulp products from mills to customer via terminals or directly and selection of potential orders and their levels at customers. Distribution is carried out by three different transportation modes; vessels, trains and trucks. We propose a mathematical model for the entire supply chain which include a large number of continuous variables and a set of binary variables to reflect decisions about product mix and order selection at customers. Five different alternatives in a case study carried out at Södra Cell are analyzed and evaluated.

Railway Rolling Stock Planning

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Carmen Systems is developing a new rolling stock planning system for and in cooporation with the Danish State Railways (DSB). The aim is to develop a system that will fit the needs of any railway operating a fixed timetable for passenger traffic/public transport – from intercity to commuter traffic. The system shall be used for planning any type of vehicle: locomotives, coaches and multiple units.

The output of the system are *train compositions* for all trips in the timetable and vehicle rotations including *local activitites*, which is the name for activities performed in order to carry out the operation, e.g. refuelling and cleaning. For depots with limited track capacity, the parking of units on side tracks and scheduling of these shunting movements is also part of the planning problem. By train composition we mean the exact (ordered) sequence of units in a train.

We propose to decompose the problem into three separate optimization problems: The *Composition Problem*, the *Rotation Problem* and the *Depot Planning Problem*. In this paper the focus is on the Composition Problem.

The main input consists of vehicle data and a timetable. In this context a trip (leg) is defined as a departure/arrival pair where the composition cannot change. A train number consists of one or more trips, where compositions must be assigned such that at least one unit covers all the trips. This is called a *through coach requirement*.

Compositions can change between trips by attaching/detaching units to/from the station depots. At the end of a train number/through coach requirement the units in the composition can either be moved to the depot or be recycled into an outgoing train (called a trip successor) to be decided by the system. The continuation of units that are detached to depots is not decided in the Composition Problem, but will be considered in the Rotation Problem in order to obtain complete vehicle rotations.

The compositions of two incoming trains can be merged into one outgoing train composition. Similarly one incoming composition can be split in two outgoing trains. If splits and merges are mandatory to perform they are given as (overlapping) through coach requirements.

Carmen Rave$^{\mathrm{TM}}$ will be used as rule system - giving a fully customisable application. It evaluates which compositions that are legal on each trip, considering details like electrification, platform lengths, speed restrictions etc. In addition each alternative get a cost based on factors like quality of service (mainly seat capacity compared to passenger estimates), operating costs etc. The rule system is also used for evaluating legality and costs for all composition transitions, based on factors like connection time, shunting effort etc.

The Composition Problem can now be formulated as follows: Assign compositions according to given templates for all trips and decide trip successors in order to minimise the total cost including composition, transition and fleet cost while respecting through coach requirements, limited storage capacity in depots, boundary conditions for units placed in the depots (e.g. requirement of a cyclic solution) and other types of global constraints.

This problem have been studied by several others. Peeters and Kroon [6] describe a Column Generation approach for multiple units where the trip successors are predefined. Fioole et. al. [5] describe a MIP model that also handles split/merge of multiple units, again with trip predefined successors. Cordeau et. al. [1,2,3] describe the simultaneous locomotive and car assignment problem and suggest a Benders decomposition approach. See also Cordeau et. al. [4] for a survey on various Rolling Stock Optimization subjects.

Our suggested solutions approaches are mainly extensions of the first two papers mentioned above. We have developed both a MIP model and a column generation approach for solving the Composition Problem. Both have been extended to support both split/merge, variable trip successors and oher special features. In our presentation we will give comparative results and report on the chosen approach.

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Approximation Algorithms for the Minimum Energy Broadcast Routing Problem

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Multicast sessions in wireless ad hoc networks require messages to be routed from a source node to a set of destination nodes. The message to any destination can either be transmitted directly from the source, or relayed through intermediate nodes. Message forwarding from any node in the route is a power-consuming operation, and since batteries are the only available energy source, this resource is scarce. Since the power consumption increases rapidly with the distance between sender and recipient, relaying may be more power- effective than direct transmission, especially when the distribution of the nodes is close to rectilinear. On the other hand, in wireless networks direct transmission has the advantage that the message reaches all nodes in some neighborhood of the source. Finding the message routes from the source to all destinations, while minimizing the total power consumption, hence becomes a non-trivial and relevant problem.

In this work we consider the special case where all nodes but the source are destinations, and address the problem of minimizing the total power consumption subject to the constraint that the message can be broadcasted from the source to all other network nodes. This problem is frequently referred to as the Minimum Energy Broadcast Routing Problem (MEBR). The problem is known to be NP-hard, and we present and analyze a class of approximation algorithms subsuming the well known Broadcast Incremental Power (BIP) heuristic. Algorithms belonging to the suggested class are compared theoretically with respect to their worst-case performance and time complexity, and numerical experiments are presented.

Solving linear optimization problems with MOSEK

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MOSEK is a software package intended at solution of large-scale linear and convex nonlinear optimization problems. This talk will present the linear optimization capabilities in MOSEK. In particular we will review the recent advances in the linear optimization algorithms implemented. Finally, we will present numerical results that compares the interior-point and simplex algorithms as implemented in MOSEK.

Rolling Stock Scheduling at the Danish State Railways (DSB)

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DSB operates long-distance and regional trains mainly in Denmark. An important cost driver is rolling stock. Therefore optimal scheduling of rolling stock is of major importance. DSB's fleet of rolling stock consist of different types of locomotives, coaches and multiple units. These vary with respect to seating capacity, traction (electric or diesel), level of comfort, speed characteristics etc. A rolling stock schedule consists of an assignment of rolling stock to each train in the time table as well as a specification for how rolling stock is re-cycled from one train to the next. The assignment of rolling stock to a train is denoted the train composition. The train composition may change from geographical segment to segment on a given train by attachment or detachment of units. Further, the sequence of units in a train composition is of significance.

The objective of the rolling stock scheduling problem is to ensure that the seating capacity of all trains is not less than the expected number of passengers while minimizing operational costs and maximizing the operational stability of the schedule. A number of operational constrains must be taken into consideration. Examples of these are given below:

- A train composition will typically consist of more than one unit, but not all combinations of rolling stock types can be operated.
- Attachments and detachments can only take place where the infrastructure (tracks, signals etc) permit this. Furthermore, the timetable must allocate sufficient time for the operation.
- For service and/or speed reasons some rolling stock types are incompatible with some trains.
- Electrical traction can only be used on the electrified parts of the network.
- Re-cyclings must ensure sufficient time for necessary local activities such as cleaning and refuelling. These activities can only take place at certain stations and must not necessarily be done before each train, but rather within certain time or distance intervals.

Mathematically the rolling stock scheduling problem can be modelled as a multicommodity flow problem with a large number of side constraints. This may be a feasible approach for simpler networks, parts of networks, scheduling for locomotives only or for studies where some operational constraints can be ignored. A number of papers have been published along these lines. According to these, rolling stock scheduling optimization software is in use at Green Cargo (Sweden), NS (the Netherlands), SNCF (France) and elsewhere. However, multicommodity flow models are not sufficient for rolling stock scheduling at DSB. This is partly due to the relatively large number of different rolling stock types and quite complex operational patterns.

DSB´s current rolling stock scheduling system does not contain any optimization functionality. A new rolling stock scheduling system is currently being developed in cooperation with Carmen Systems. Some preliminary optimization results have been obtained.

Stochastic Programming for Optimizing Bidding Strategies of a Hydro-Power Producer

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Stimulated by to the tendency to decentralize and deregulate the power sector, new power optimization problems have arisen within the last decades. In particular, with the restructuring of power markets and the introduction of a power auction, bidding procedures of individual power producers have become extremely relevant. We here address the problem of optimizing bidding strategies of a hydro-power producer by means of stochastic programming. Indeed, from the perspective of a price-taking hydro-power producer trading in the so-called day-ahead power market, market prices are highly uncertain, and we provide a framework for determining optimal bidding strategies taking into account this uncertainty. Realistic market price scenarios are generated, and a two-stage stochastic mixed-integer linear programming model that takes in both production and trading aspects is developed. The idea is to explore the effects of including uncertainty into optimization and to compare the stochastic approach to a deterministic one. The model is illustrated with data from a Norwegian hydro-power producer and the Nordic power market at Nord Pool.

Modeling the production side, a simple but illustrative model of a small hydro-power plant is presented. The plant consists of two reservoirs in a cascade, the upper reservoir being a larger reservoir and the lower reservoir being a smaller one, both reservoirs being connected to a power station with a generator. Hydro-power production works as follows. Water reaching the plant flows to the upper reservoir where it is stored until a decision is made to release it for generation. When being released, the water from the upper reservoir flows to the lower reservoir and is likewise stored until it is decided to use it for generation. Water that is not discharged on purpose and used for generation is considered spill. Using mixed-integer terms, modeling production consists of minimizing operating costs including start-up costs as well as opportunity costs of storage, subject to operating limits and storage balances.

On the trading side, the day-ahead market at Nord Pool is the starting point. Here, contracts for physical delivery the following operation day are traded. The contracts are power obligations of a duration of one hour or longer, divided into hourly bids and block bids. All bids consist of a price and a volume. For hourly bids a linear interpolation between the price-volume points is made to construct the piece-wise linear bidding curve that determines the volume dispatched. Block bids are aggregated bids valid for a number of consecutive hours and accepted or rejected as a whole. It should be stressed that no previous studies allow for both piecewise linear bids and block bids. Each day the hydropower submits sales bids to the market for every hour of the following operation day. Trading is modeled by mixed-integer terms, maximizing sales revenues subject to a number of constraints expressing the relation between the volumes bid and the volumes dispatched for hourly bids and block bids, respectively.

Market prices are determined by clearing the market, making these unknown at the time of bidding. In that prices are rather hard to predict, the bidding problem is subjected to uncertainty, this uncertainty being included by formulating the problem as a two-stage stochastic program. This involves a probabilistic foundation in which prices are represented by a stochastic process with a know distribution. The first stage concerns the day-ahead bidding decisions, whereas the second stage takes in the real-time production decisions and the objective is to maximize expected future trading and production profits subject to the constraints being considered. The case study concerns a small Norwegian hydropower plant. Inflows and initial reservoir levels are real data from a typical day, measured in 2005. To model day-ahead market prices in 2005, the Nordic market at Nord Pool has provided real data from 2004. Based on the historical time series, the stochastic process is modeled by a moving average process taking in seasonal variations. To approximate the continuous distribution by a discrete one, we use sampling and end up with a large number of scenarios that are successively reduced until the set of scenarios is, on one hand, sufficient to make the model computationally tractable, but on the other hand, still retains a certain quality of the approximation. The final problem is solved by standard linear programming software. Solving both the stochastic programming problem and the corresponding deterministic problem with expected prices, it is clear that the gain of applying the stochastic approach compared to a deterministic one is rather moderate. It is therefore of some importance to focus on forecasting procedures. However, the structure of the solution depends on whether stochasticity is present or not, in that a deterministic model suggests to use hourly bids only, whereas a stochastic model proposes to combine hourly bids and block bids. As block bids are used more and more frequently, this is an interesting feature of the model.

Robust scheduling of passenger railway timetables

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In this presentation, we describe two models that aim at improving the punctuality of passenger railway services.

The first model is a Stochastic Optimization model for designing cyclic railway timetables. The model can be used to explicitly take into account the existence of small disturbances in the process times (running times, dwell times, transfer times, etc.) in the design of the timetable. The application of the model leads to such an allocation of buffers and time supplements that these can be used effectively. The application of the model to several practical cases has shown that reductions of the average delays of the trains of up to 20% can be achieved by relatively small timetable modifications.

The second model is an extension of a Node Packing model, and aims at improving the robustness of passenger train movements inside railway stations. This is accomplished by minimizing the number of crossing train movements inside the stations. The application of the model allows one to make a trade-off between robustness and several other service aspects, such as the number of cross-platform connections. In general, cross-platform connections tend to increase the number of crossing train movements inside the stations.

How to benefit from co-operation between railway planners and operations researchers

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Railway planners and operation researchers usually come from two different communities. In traditional planning the problems are often solved based on knowledge; experience and intuition. Normally, this way of solving problems provides high-quality solutions. However, the problems are seldom solved to optimality and may therefore be improved if mathematically based optimisation methods are introduced.

Even though the traditional planning seldom solves the problems to optimality it has some advantages. In the traditional planning it is easy to see what can be done to improve the solutions – e.g. removing a bottleneck in the railway infrastructure to improve the timetables on the entire line. In case a mathematical optimization model was used this information may not be found.

Combining traditional and mathematical planning may mean that is it possible to take advantage of the benefits from both planning methods. An example of this can be seen at DSB S-tog (operator of the Copenhagen suburban rail network) where both traditional planning and operations research is used in the timetabling process.

In some situations it is however not possible to use mathematical based methods in the planning process. Assumptions such as that the headway time and/or distance is assumed independent from the speed of the trains may imply that the use of the model can be limited or even provide false results. The assumption of headways being independent from the speed seems to be of minor importance but since both the headway time and distance depends on both the speed and the running characteristics of the train, the assumption can have a major impact on the results.

The presentation will demonstrate the dependence between the speed of the train and the headway time and headway distance. Afterwards, the importance of the optimal speed of the trains will be demonstrated regarding capacity and train regularity. Based on the examples and demonstrations given in the presentation, it will be discussed how it is possible to benefit from co-operation between traditional railway planners and operations researchers.

Routing Trains Through Railway Junctions: Dual Formulation of a Set Packing Model

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The problem of routing trains through railway junctions is an integral part of railway operations. At large busy junctions track capacity is a sparse resource. As a result of this, one can almost guarantee that at certain times of the day many trains, both freight and passenger, will compete for track sections within the junction. It is important to find an assignment of trains to routes that ensures maximum utilization of the junction without compromising the safety requirements.This is a difficult problem.

This scheduling problem arises at a number of levels within the planning process for a railway company. Initially it occurs at the strategic planning level of determining the future capacity of the junction due to infrastructural changes to the track layout or the station. It also occurs at the tactical level of timetable generation. Once a proposed timetable has been generated there is a need to see if in fact it is feasible. Finally, it arises on a day-to-day operational level when train routes need to be adjusted due to unforeseen disruptions such as late train arrival, track maintenance or even accidents, which make the published time table no longer feasible. We are focusing on the second instance of the problem outlined above - timetable feasibility.

The problem we are addressing can be formally defined as follows. Given a proposed timetable (i.e. the respective arrival and departure times for a set of trains) as well as the track configuration of the junction, what is the maximum number of trains that can be assigned a route through the junction ensuring that at most one train is on any given track section at any given time and also ensuring other safety requirements are satisfied. The interconnected nature of a railway junction means that train routes are highly interdependent. Changes to one part of the timetable will inevitably cause conflicts in others. Effective and efficient solution approaches are vital. However, despite its noticeable importance, this problem has received relatively limited attention in the literature.

Previous approaches have been based on node packing formulations. Every node in such a formulation represents a possible route through the junction for a particular train. Any two nodes that are incompatible, that is, any two routes that cannot be assigned simultaneously without conflict, are joined by an edge. A maximal node packing is then one that indicates the maximum number of trains that can be assigned a route through the junction. While this approach is effective in that it can accurately incorporate any level of train route compatibility, the resulting conflict graph usually has many nodes. This results in many constraints and the weakness of the linear programming relaxation explains why this method relies heavily on pre-processing techniques as well as the addition of valid inequalities. The purpose of this presentation is to discuss a different approach of formulating the problem as a set packing problem, and in particular to focus on the corresponding dual formulation which has some nice properties that one can exploit when solving this problem.

Set packing problems typically appear in scheduling applications where one has to assign elements to sets under the strict requirement that no element appears in more than one set. Given the requirement there can be at most one train on any track section at any time, we demonstrate the inherent set packing structure of the problem. The primal set packing formulation has relatively few variables that can be generated via a column generation procedure. However, it does have significantly many constraints making it unattractive from a computational point of view. The corresponding dual formulation on the other hand, has appreciably fewer constraints; the most we could expect would be the number of primal variables. It does have many more variables. However, due to the nature of this problem we would expect the majority of these dual variables to be zero at optimality.

The solution approach that we propose utilizes the inherent advantages of the dual formulation. Essentially it involves the novel idea of implementing primal column generation as dual constraint addition. We show that by adding primal variables we have the ability to dynamically update the dual problem and in essence work with a small dual basis. The solution to the dual problem is obviously the dual variables of the primal set packing linear program. This can easily be used to find the reduced cost of any primal non-basic variable. We present our solution procedure which begins with an initial dual problem having enough constraints to ensure a basic primal feasible solution, and iteratively solve it on adding entering primal variables as dual constraints. We also employ inactive dual constraint removal to maintain a small basis. Inactive constraints in the dual indicate the corresponding primal variable is at vale zero. We believe that significant improvements to solution time and quality can be achieved using our approach.

A Branch-and-Cut Algorithm for the Capacitated Open Vehicle Routing Problem

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In open vehicle routing problems, the vehicles are not required to return to the depot after completing service. In this paper, we present the first exact optimization algorithm for the open version of the well-known capacitated vehicle routing problem (CVRP). The algorithm is based on branch-and-cut. We show that, even though the open CVRP initially looks like a minor variation of the standard CVRP, the integer programming formulation and cutting planes need to be modified in subtle ways.

Computational results are given for several standard test instances, which enables us for the first time to assess the quality of existing heuristic methods, and to compare the relative difficulty of open and closed versions of the same problem.

Planning work schedules for ticket inspectors in Danish S-trains

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DSB S-trains use the S-train network in Greater Copenhagen. The problem is concerned with constructing work schedules and assigning them to a fixed number of ticket inspectors. The ticket inspectors inspect the tickets of passengers on the trains while they are driving. A work schedule for a ticket inspector is a route in the network with a starting time at a starting station and an end time at an end station. The work schedule also states which trains to travel with and when to change trains. The objective is to maximize the number of departures covered with respect to a predefined priority of the departures. The priorities reflect the desire to inspect as many passengers as possible. A Solution approach to this max-covering problem is the following: A dynamic programming algorithm is used to construct single work schedules and a greedy heuristic constructs the set of work schedules one by one. Local search heuristics are then used to improve the greedy solutions. The problem can be modelled as an integer multicommodity flow problem with side constraints. The flow version is not easily solved due the size of instanses, but using Lagrangian relaxation on the multicommodity flow formulation yields good upper bounds on the problem. Solutions found on testinstances from DSB S-train are within 2-6% of upper bounds.

Duty Planning and Design of Experiments

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A duty for a train driver consists of a set of tasks, which typically are passenger train movements and empty stock movements. A feasible duty has to comply with many types of rigid rules, which result in e.g. constraints on maximum working hours and minimum break hours. Furthermore, it is necessary to take into consideration many essential features for the set of duties. These features normally relate to the set of all duties in a plan, e.g. the average working hours for all duties, the average working hours in late duties and the variation of tasks in duties. The duty planning in DSB S-tog is supported by the TURNI system, which uses a mathematical programming technique. To find a (near) optimal solution to a complex duty planning problems several hours of computer time is used. Therefore, in order to evaluate the influence of many features the theory of design of experiments has been applied. A case study with six features has been analysed using a fractional factorial design, in which all main effects and all two-way interactions are taken into considerations.

Scheduling ships with flexible cargo sizes by use of column generation

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We study a ship scheduling problem where the contracts say that the revenues for the cargos increase with their sizes and that the size of a given cargo has to be within a given interval. The problem is solved by a column generation approach. Columns are dynamically generated in a shortest path problem where we use discrete cargo sizes. Before we transfer a column to the master problem, we fix the geographical route and re-optimize the schedule with use of continuous cargo sizes. This approach does not converge in the same way as normal column generation, but we are able to find reasonable bounds for the deviation from the true model optimum.

Transportation of Animals – Combining Routing and Inventory

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We present a problem that deals with collection of animals for slaughter. The problem is taken from the Norwegian meat industry, and may be viewed as a rich Vehicle Routing Problem extended with constraints regarding inventory and planned production at the slaughterhouse.

The Vehicle Routing Problem (VRP) deals with the allocation of transportation tasks to a fleet of vehicles, and the simultaneous routing for each vehicle. In addition to capacity constraints on the vehicles, several constraints may be added to the basic VRP to have a richer model that corresponds more closely to the real world. In our problem, we have to deal with a heterogeneous vehicle fleet, rules for how several different animal categories may be mixed during transport, precedence constraints, and more. Constraints that are usually not present in a vehicle routing setting also have to be added. These are constraints to ensure that the lairage capacity at the slaughterhouse is not exceeded, and that there are always enough animals available to secure a smooth production flow.

This means that we have both a hard VRP and an inventory problem to solve at the same time, which strongly suggests the use of heuristic solution methods. We have developed a tabu search based metaheuristic for the Livestock Collection Problem, and computational results for this method will be presented.

Representative systems for Discrete Bicriterion Optimization Problems

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Introduction

In general, a description of real world applications as single criterion optimization problems is seldom realistic, since they are often by nature imposed with more objectives to be simultaneously optimized. For instance, consider transporting commodities through a network. For this problem it seems relevant to consider two weight criteria to be minimized simultaneously, namely total *transportation time* and total *transportation cost*. Within the last decades, focus on multi objective optimization, and in particular bicriterion optimization, has risen. The *discrete* bicriterion optimization problem (DBOP) can be stated as

$$\min f(x) = (f_1(x), f_2(x))^T \text{s.t.} x \in \mathcal{X} \tag{1}$$

where X is a discrete feasible set, and $f : \mathcal{X} \to Z^2$ is a vector-valued objective or criterion function. $\mathcal{Y} := f(\mathcal{X})$ denotes the set of attainable outcomes or criterion vectors. For a bi criterion optimization problem, the object is to identify either all *efficient solutions*, $\mathcal{X}_E$ or all *nondominated criterion points*, $\mathcal{Y}_N := f(\mathcal{X}_E)$ in which one criterion cannot be improved without worsening the other.

Since the problem of finding $\mathcal{Y}_N$ is, in general (see Ehrgott[2]), intractable for DBOPs, the idea of computing a representation of $\mathcal{Y}_N$ arose. For DBOPs, the literature on exact, i.e., non-heuristic, approaches for computing representations is scarce. Among the few methods for generating representations of $\mathcal{Y}_N$ are Klamroth,Tind, and Wiecek [3], Sayin and Kouvelis [6], and Kouvelis and Sayin[4].

The box algorithm

In this communication we present a new generic method to compute representative systems for discrete bicriterion optimization problems, the *box method*. The representation consists of a collection of nondominated points. Each point is associated with a rectangle (or *box*) and represents all non dominated points within this box. At any stage of the algorithm, $\mathcal{Y}_N$ is contained in the collection of boxes. Hence, the rectangles bound the non dominated set, and thus also show regions containing nonondominated points. Representing points are generated with a modification of the ϵ-constraint method ([1]).

Initially the algorithm finds the two lexicographical optimal solutions yielding the upper left and lower right corner point for the *starting box* in the criterion space. This box contains the complete nondominated set. In each iteration of the algorithm a modified ϵ-constraint problem is solved. Thereby, the representation is refined by discarding, from the starting box, rectangular pieces in which no nondominated points exists. This process continues until a stopping criterion is fulfilled.

We present two versions of the box algorithm. The *a posteriori* algorithm displays an adaptive scheme, in which the biggest of the remaining boxes is processed in each iteration. In the *a priori algorithm* the refinement of the box representation follows a scheme predetermined by the area of a the starting box.

Quality of a representative system

Since in general, the representative system is different from $\mathcal{Y}_N$, the question about the "quality" of such a representation naturally occurs. By stating and discussing the following four quality measures[1], we fill in a gap in literature for representations of discrete bicriterion optimization problems.

Cardinality : The size of the representation – decision makers typically require a small representation.

Accuracy : The representation should mirror $\mathcal{Y}_N$ completely – no large parts should be over looked.

[1]These extend the ideas of Sayin [5] that deals with representations of continuous multi objective problems.

Representation error : The distance between the representation and the nondominated set – the representation should be as close as possible to $\mathcal{Y}_N$.

Cluster density : The density of representing points – although the density might vary, clusters should be avoided.

We emphasize, that the sequality issues are conflicting by nature. For example, the smaller the cardinality of a representation, the larger the "gaps", i.e. the more inaccurate the representation. In the presentation we shall indicate to which extend these quality issues are addressed by the two versions of the box algorithm. The geometrical features of the rectangles are used to measure the quality attributes.

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Label Setting Algorithms for variants of the Shortest Path Problem with Resource Constraints

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The Shortest Path Problem with Resource Constraints is a common subproblem in many Branch-and- Price algorithms, e.g. the Vehicle Routing Problem with Time Windows. Label setting algorithms are the most common solution method for solving Shortest Path Problems (Boland et al. 2006, Irnich 2006, Feillet et al. 2004, Righini et al. 2004) .

Recently the introduction of the *subset row inequalities* in the master problem of a non-robust Branch-and-Cut-and-Price algorithm for solving the Vehicle Routing Problem with Time Windows lead to a modified pricing problem (Jepsen et al. 2006) . The additional *subset penalty constraints* were imposed in the shortest path problem and an extended dominance criteria for solving the Elementary Shortest Path Problem with Resource Constraints was proposed. Given a subset S the *subset penalty constraints* is saying that a penalty must be paid for each k visits to nodes in S.

We will review a general label setting algorithm for solving the Shortest Path Problem with Resource Constraints and k-cycle elimination, the Elementary Shortest Path Problem with Resource Constraints and the S-Elementary Shortest Path Problem with Resource Constraints. The latter demands that all nodes in the subset S are visited at most once. All problems may contain subset penalty constraints which are handled as well.

The label setting algorithm is bi-directional which has previously been proposed for the elementary case (Righini et al. 2004). We extend this to handle k-cycle elimination and a subset of elementary nodes.

Furthermore the performance of the label setting algorithm is improved up by preprocessing lower bounds on the cost of shortest paths from all nodes to the target node. The calculation is done through early termination of a Branch-and-Cut algorithm which actually introduces Branch-and-Cut approach to solve Shortest Path Problem with Resource Constraints. This has shown to have a significant positive impact on the running time of larger instances.

Solving a Pickup and Delivery Problem with Sequencing Constraints

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Motivation and Background

As congestion is an ever-growing problem on the roads of Europe, intermodality plays an increasingly important role in the transportation of goods. Furthermore, the complexity of the planning problems thus induced presents additional requirements to the tools available to planners.

This project was initiated in cooperation with a software company producing computer systems for operation and fleet management in small and medium-sized transportation companies. The software company presented a problem that is intriguing, in that it does not seem to have been previously mentioned in the literature, at the same time as it is conceivingly simple.

Problem description

A number of items must be transported from individual addresses in one region to individual addresses in another region, i.e. a set of orders is given, each one consisting of a pickup address and a delivery address. The two regions are far apart, and thus there is some long-haul container transport involved between the pickup and delivery depots. This long-haul transport is not part of the problem considered here. What remains are the two geographically separated problems of picking up and delivering the items in a feasible and suitable way with regard to container loading and routing.

The pickups are performed by a truck carrying a container, and the items are placed into this container as they are picked up. After visiting the final pickup point the container is returned to the depot where it is locked and sent on unopened to another depot from which the delivery starts, without any opportunities to repack.

Subsequently all items are delivered at their respective delivery points in an order such that each item is accessible from the back of the container when its delivery point is reached, i.e. the items must be delivered in the "opposite" order of that in which they were picked up. The loading/unloading of the container thus follows a (variation of the) last-in, first-out (LIFO) principle. The objective of the problem is to find the combined cheapest possible route for pickup and delivery.

The modification imposed on the LIFO principle in this problem, is that the items can be placed in one of several "rows" in the container that each individually obeys this principle, but with no mutual constraints.

Thus a solution to a given problem consists of a pickup route, a delivery route, and a row assignment, which for each item tells which container row it should be placed into.

The items considered here are identical Euro Pallets, which fit 3 by 11 on the floor area of a 40-foot pallet container, thus providing three individually accessible rows available for loading.

The solution

An obvious feasible solution to the problem can be found by solving the problem with strict LIFO conditions. In this case the pickup and delivery orderings must be exactly eachother's opposites, and the solution can then be obtained by adding the two graphs and solving a regular TSP for the resulting graph. This opens an opportunity to use some existing methods, and in the case at hand this has been done by a savings algorithm, producing an initial solution to the problem.

Subsequently the problem has been solved heuristically using both a tabu search (TS) and a simulated annealing (SA) approach, where a combination of different neighbourhood structures has been applied.

The first neighbourhood structure considered for the heuristics only performs changes to the routing of the two tours, and leaves the row assignments untouched. In this case the neighbourhood consists of all possible swappings of two neighbouring items on a route. During this operation it is additionally necessary to consider whether the two items are placed in the same row, and in that case also swap their positions in the opposite route to maintain a feasible solution.

Furthermore a neighbourhood has been implemented which is based on changes to the row assignment, considering each possible pair of items that are currently assigned to different rows, and swapping their positions (both in the row assignment, and in each of the routes).

The final implementation of the solution algorithm uses a combination of the two neighbourhood structures.

Results

The results obtained so far indicate that the primal bound obtained by letting the problem obey strict LIFO conditions and heuristically solving the regular TSP for the added graphs is quite weak, as the results are typically around 60% above the best known solution.

For further testing and comparison the SA-algorithm has been implemented in such a way that it can take the running time as an input parameter and calculate the temperature reduction factor based on this. Each of the two heuristics has been tested on a set of randomly generated problems with Euclidean distances, with running times of 10 and 180 seconds. The results show that with a running time of 180 seconds the SA-algorithm produces objective values that are around 10-12% above that of the best known solution, while this ratio for the TS-algorithm is 15-20%. For running times of 10 seconds, the corresponding numbers are around 20% and 25-30%.

Adaptive Large Neighborhood Search applied to mixed vehicle routing problems

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Adaptive Large Neighborhood Search (ALNS) – presented in Ropke and Pisinger (2004) – is an extension of Large Neighborhood Search which introduces an adaptive layer to choose among a number of insertion and removal heuristics. The framework has a number of advantages: it provides solutions of very high quality when applied to various VRP problems, it is robust, and to some extent self-calibrating. A general description of the ALNS framework is given, and it is discussed how the various components can be designed in a particular setting.

The ALNS framework is used to solve a mixed vehicle routing problem consisting of: The vehicle routing problem with time windows (VRPTW), the capacitated vehicle routing problem (CVRP), the multi-depot vehicle routing problem (MDVRP), the site dependent vehicle routing problem (SDVRP) and the open vehicle routing problem (OVRP). All problem variants are transformed to a unified model and solved using the ALNS framework.

The talk is concluded with a computational study, in which the five different variants of the vehicle routing problem are evaluated on standard benchmark tests from the literature. The outcome of the tests is promising as the algorithm is able to improve 183 best known solutions out of 486 benchmark tests. We may draw the philosophical conclusion, that a mixture of good and less good heuristics lead to an overall better solution quality than using good heuristics solely: It is however necessary to hierarchically control the search, such that well-performing heuristics are given preference.

An Adaptive Radial Basis Algorithm (ARBF) for Mixed-Integer Expensive Constrained Global Optimization

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An algorithm for solving expensive, black-box, mixed integer nonlinear problems is presented. The costly objective function is approximated with the use of Radial Basis Function interpolation, fitting the surface to n sampled points, which is then used to find a new sampling point. The algorithm relies on good mixed-integer nonlinear sub-solvers in TOMLAB, like OQNLP or the constrained DIRECT implementations. Depending on the initial experimental design, i.e. the n sampled starting points, the original RBF algorithm sometimes fails and make no progress. A method how to detect this problem is presented, along with results from a recent comprehensive test benchmark.

Optimising Fighter Pilot Survivability

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The talk addresses the optimisation of aircraft self protection against ground based Radio Frequency (RF) threats. On modern fighter aircraft more and more systems are implemented in order to improve the pilot's awareness about the current situation of the aircraft and the world surrounding it. As the number and complexity of these systems increase so does the quantity of threats to the aircraft and appropriate countermeasures for the pilot to choose from. To help the pilot decide on proper evasive action when a threat occurs, a decision support system could be implemented aboard the aircraft.

Threats can often be mitigated using onboard countermeasures. Different kinds of threats require different countermeasures and e.g. the angle and distance between the aircraft and the threat influence the efficiency of the countermeasures. Some countermeasures are limited resources, and they should be used when their contributions to the survivability are most needed. Countermeasures are generally in mutually exclusive states (e.g. turned off, warming up, turned on, and turning off), and state changes will take a preset amount of time. This means that a change should preferably be initiated seconds before the new state is needed.

A simple battlefield scenario is defined, and information about positions and specifications of the threats in this scenario are assumed known from intelligence reports before the aircraft mission is commenced. Sensors aboard the aircraft may add to the knowledge of the scenario as the aircraft approaches threats during the mission. Added to the mix, network-centric capabilities may provide information in the cockpit that must be assessed and integrated into the situation awareness of both the pilot and the decision support system.

The work presented tries to predict the best use of a number of onboard countermeasures on a generic fighter aircraft. The use of countermeasures is estimated within a timeframe of a few minutes. The lethality of present threats is defined, and this measure is used to calculate the survivability of the pilot. The better the countermeasures are used, the higher the resulting survivability of the pilot in the given scenario.

On using a two-level decomposition of the Vehicle Routing Problem with Time Windows

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Given an origin, a destination, and a set of customers, then the Vehicle Routing Problem with Time Windows (VRPTW) is the problem of finding a set of cost minimizing elementary paths from the origin to the destination such that each customer is visited exactly once and each customer is visited within a predetermined time interval. VRPTW is a hard problem to solve exactly. A prevalent approach is to decompose VRPTW into a Set Partitioning Problem (SPP) and an Elementary Shortest Path Problem with Time Windows (ESPPTW).The columns of the SPP is generated dynamically by the ESPPTW using the dual information from the SPP. Unfortunately, the ESPPTW is also a hard problem to solve. Therefore, it is relaxed to a non-elementary Shortest Path Problem with Time Windows (SPPTW) for which a pseudo-polynomial algorithm exists. If the underlying network is acyclic then no cyclic path will exist and the SPPTW will yield an elementary path. The underlying network in VRPTW is usually not acyclic and therefore the SPPTW may have a non- elementary path as the optimal solution. The lower bound obtained from the column generation for VRPTW will therefore be weaker when using SPPTW instead of ESPPTW to generate the columns. It is possible to tighten the lower bound by making the SPPTW k-cycle-free. It is possible to construct dynamic programming algorithms for ESPPTW from the k-cycle-free algorithms by selecting k large enough e.q. equal to the number of customers. The problem is, however, the algorithms for k-cycle-free SPPTW have a time complexity which increases exponential with k.

We will discuss two subjects. First we will discuss the two-level decomposition of the VRPTW and afterwards we will discuss a new branching strategy, which can be used at both levels of the decomposition.

Variations of shortest-path problems are often solved by means of dynamic programming. This is also the case for both SPPTW and ESPPTW. Dynamic programming can capture non-linear effects such as time consumption, but the complexity increases exponentially for ESPPTW with the number of customers.

The ESPPTW can, however, be decomposed into a Set Packing Problem with one additional constraint and an SPPTW. Embedding this decomposition of the ESPPTW into the decomposition of the VRPTW will produce a two-level decomposition of the VRPTW. The master problem of the ESPPTW can be viewed as an intermediate adjustment layer which adjusts the dual-prices received from the SPP, such that the columns produced by the SPPTW will tend to have less cycles. The price to pay for this is a larger number of calls to the dynamic programming algorithm for SPPTW. We will discuss the use of this decomposition to generate elementary paths for the VRPTW master problem.

It may be necessary to embed the column generation into a Branch-and- Bound to obtain a feasible integer solution for the VRPTW master problem. A branching strategy is then necessary. Arc branching and vehicle branching is two common branching strategies for VRPTW. We will discuss a new branching strategy, where one branch is enforced in the SPPTW and the other branch is enforced in the VRPTW master problem. It is possible to remove a set of columns from the master problem, when enforcing the branching in the pricing problem. As we are able to remove a set of columns in one of the two branches we can obtain a significant tightening. The other branch will not be subject to the same tightening.

Dynamic diversification strategies of mortgage loans for home owners

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House buyers in several countries today can issue both adjustable rate mortgages (ARMs) as well as fixed rate mortgages (FRMs) to finance the purchase of their properties. An ARM may be issued with interest rate caps and a FRM may have an embedded (Bermudan type) call option. Besides, any mortgage loan can be issued such that the cashflows do not include principal payments for some period of time. These loan products have very different risk profiles, which is why advising the house owner on the proper choice of mortgage loans is a challenging financial problem. Some mortgage banks argue that a single loan product with some embedded option is the right choice for a mortgagor with a given risk attitude. This argument is often accompanied by the fact that trade frictions such as high fixed transaction costs make it unattractive to hold a portfolio of loans as a private house owner. Despite existence of fixed transaction costs, we show that most mortgagors with some degree of risk aversion benefit from holding more than one mortgage loan in order to diversify some of the interest rate as well as the wealth risk away. Using a mean-absolute deviation (MAD) model it is possible to obtain such diversified loan portfolios. However, due to the fact that the mortgage loan cashflows follow some heavy tailed distributions, we also develop a mean-CVaR model to consider the risk at the tails explicitly. Based on these results we devise a set of rules (of thumb) as to which type of mortgagor should use which combination of mortgage loans.

Scheduling a Triple Round Robintournament for the Best Danish Soccer League

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In this paper we face the problem of designing a seasonal schedule for the best Danish soccer league "SAS Ligaen". SAS Ligaen consists of 12 teams which play a triple round robin tournament meaning that all teams meet all other teams three times . The tournament is partitioned into time slots and all teams play one game in each slot leading to 33 time slots. These time slots are partitioned into three parts consisting of the slots 1 - 11, 12 - 22 and 23 - 33 and each part consists of a single round robin tournament i.e. all teams meet all other teams once.

Triple round robin tournaments are very rare and they lead to a number of additional constraints compared to double round robin tournaments since all teams cannot have the same number of home games. The schedule for SAS Ligaen must satisfy that the six best teams of the preceding year have 6 home games in part 1 while the rest of the teams have 5 home games. Furthermore, parts 2 and 3 must constitute a traditional double round robin schedule where all teams play one away game and one home game agains t all othe r teams .

Two teams are categorized as top teams since they normally perform well but also because they have more spectators. This means that a high revenue can be expected if a team meets one of these teams at home. As a consequence the rest of the teams want to meet the top teams at home in Part 1. However, one of the teams cannot meet a top team at home when the two top teams are among the six best teams of the preceding year.

In addition to the above constraints the schedule must satisfy a large number of requirements which are common for sports leagues. The teams want to play away or home in certain slots, the teams want alternating patterns of home and away games, there must be a certain number of slots between two games with the same opponents, all teams must have one home game and one away game in the last two slots, etc. Some of the constraints are considered to be hard constraints which must be satisfied while others are weak constraints which should be satisfied if possible.

We present a logic based Benders approach to find a schedule for SAS Ligaen. The problem is decomposed into a master problem and a subproblem. The master problem is an integer programming problem and it is used to determine when the teams play home and when they play away. The solution is known as a pattern set since it gives a pattern of home and away games for each team.

The master problem contains all the constraints concerning when the teams play home and away. Therefore the pattern set satisfies that the 6 best teams have an extra home game in part 1, all teams have 11 home games and 11 away games in slots 12-33 and half the teams play home in each slot. This is, however, not enough to ensure existence of a corresponding timetable which is at able saying when the teams meet but not where they meet.

The pattern set found in the master problem is said to be feasible if a corresponding timetable exists. We use a number of subproblems to check feasibility of the pattern set. In normal Benders decomposition the subproblem is a linear programming problem and it is possible to use the dual solution to obtain a cut for the master problem when it is infeasible. This is not the case here since the problem of finding a corresponding timetable is an integer programming problem. Instead we use integer programming subproblems and constraint programming subproblems to check feasibility and add a logic-based Benders cut to the master problem if the pattern set is infeasible.

The algorithm iterates between the master problem and the subproblem until a feasible pattern set has been found. When this happens an integer programming problem is used to find a corresponding timetable and we have a feasible schedule. The algorithm then starts searching for a better schedule by enforcing upper bounds on the value of the pattern set and the timetable.

The quality of a schedule is measured by penalizing violated constraints. Each of the weak constraints have a penalty coefficient and since the algorithm minimizes the total value of the schedule the weak constraints are ranked according to these penalties.

The algorithm has been tested by using the constraints for SAS Ligaen 2005/2006 and in 30 seconds it is able to find a schedule which satisfies more constraints than the actual schedule. Furthermore, in 180 seconds it is able to find a schedule where the minimum separation between games with the same opponents is 3 slots compared to 0 slots in the actual schedule. The algorithm has been presented to the Danish Football Association and they expect to use it for scheduling SAS Ligaen 2006/2007.

Modelling and Solving an Imperfect Competition Problem

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The concentration on the Danish as well as other Nordic markets for electricity generation is very high compared to markets for other goods, and at the same time electricity demand in general tends to be rather unresponsive to price changes. In the latest years, the restructuring of the Nordic electricity markets has caused a reduction of the available electricity generation capacity. Furthermore, entry into the market for electricity generation requires large investments over long time horizons, and may often be accompanied by regulations further retarding entry of new firms on the market, which would increase the competitive pressure.

These circumstances make it natural for policy makers to worry about the exercise of market power in the Nordic electricity markets. These worries beg a number of further more practical questions, like: which mergers should be allowed and refused? Should certain transmission lines be upgraded to limit the exercise of market power?

Such questions are, however, not easily answered. The electricity markets are very complex, entailing a number of interconnected decisions and restrictions among numerous decision makers and facilities across the Nordic area and abroad. It is not even clear to which extent market power is actually exercised in the Nordic market today, or whether further reductions in generation capacity will actually increase the use of market power significantly.

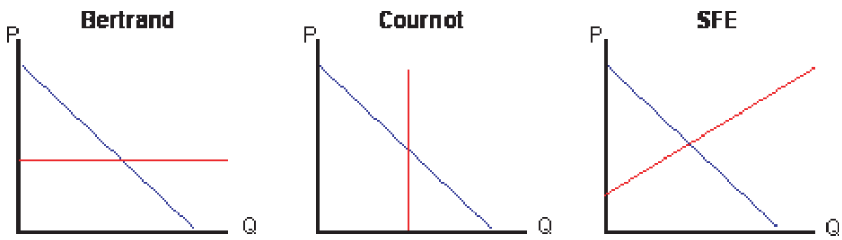
As part of answering the questions, a model for simulating market power has been built. The preset paper describes this model and illustrates the use.

The model is formulated within game theory. In game theory agents chose actions defined by their strategic variables. In an economic model of market behaviour this would either be the price of the product or the quantity that the firm produces. In general, the quality of the product could also be the subject of strategic considerations.

When firms use price as the strategic variable, they must consider how the choice of price will affect the quantity they are able to sell. This is called Bertrand Competition. In a situation where firms do not have to respect any constraints on capacity the products of the firms on the market must be at least slightly differentiated in quality, function or brand in order to allow market power. Otherwise, the consumers would simply shift their demand to the rival charging the lowest price.

The use of quantities as strategic variables is called Cournot Competition. In this situation, the market power derives from the unwillingness of rivals to accommodate all the consumers that wish to shift away from a particular firm. In the Nash equilibrium where all firms have decided exactly how much they want to produce, the equilibrium price is found as the price that assures that the consumers will buy all the output of all firms.

Although Cournot and Bertrand competition are the most commonly used means of modelling market behaviour, other options do exist. Some of these games utilize strategies which are much more complex than the simple price or quantity setting strategies. One such strategy is a combination of price and quantity in an auction-like game, i.e. $s = (q1, p1), (q2, p2), \ldots, (qz, pz)$ for z different combinations of prices and quantities. A firm will therefore supply a sequence of coordinates which specify all the combinations of price and quantity at which it is willing to service the market.



The problem may be formulated as a variational inequalities problem. Such problem contains smooth optimisation problems as a special case. For a smooth optimisation problem the formulation as a variational inequalities problems is close to the statement of the Karush Kuhn Tucker optimality conditions.

The solution methods for variational inequalities problems are not as advanced as for classical optimisation problems. The present problem was solved using the diagonalisation algorithm. In this, the firms take turns in setting strategic parameters by solving an optimisation problem, while the other firs keep their strategic variables fixed at their previous values.

Convergence of the diagonalisation algorithm is not in general assured, and for discrete steps models like the one here, no convergence results exist as far as we know. The lack of convergence results is inherent to the problem's nature.

The paper describes two methods of solving the sub-problem concerning optimisation for one firm in the above iterations. One is based on formulation as an integer problem, the other as a linear programming problem, solved parametrically in the right hand sides. The former is implemented in GAMS, the latter in a tailored linear programming code.

The problem and solution properties are illustrated interactively.

Literature: A background report, "Modelling Imperfect Competition on the Nordic Electricity Markets with Balmorel" may be found at www.Balmorel.com.

Crew Recovery after Train Cancellations

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DSB S-tog A/S is the railway operator on the S-train network in the Copenhagen area. Each segment of the network is covered by at least two train lines, each having a cyclic schedule with twenty minute periods. A line is either a *main line*, running the whole day or an *extra line*, operating during rush hours.

Operations on the S-train network have been suffering from severe delays caused by external and internal disruptions, including new speed limitations, signalling problems, accidents, rolling stock failures, planning problems, etc. One general recover strategy against severe delays is *re-scheduling*, where trains are re-routed or extra lines are cancelled. Line cancellations have an immediate effect on the crew schedule of train drivers. In order to cover working hours of the crew previously assigned to cancelled lines, the duties are re-scheduled. The size of the schedule (approx. 150 drivers and 2,500 tasks during a day) makes it hard for operators to find a good crew recovery solution fast. Currently, there are no predefined crew recovery plans. Drivers are in the worst case assigned to tasks arbitrarily without considering their original duties. Decisions are based on the previous experience, and the quality of each crew recovery schedule depends on the particular operator.

A Decision Support System (DSS) aimed at finding an optimal (or a near-optimal) crew recovery solution would unquestionably help operators in their work. Building a prototype for the DSS is a part of a Ph.D. study at the department of Informatics and Mathematical Modelling of the Technical University of Denmark in a cooperation with DSB S-tog A/S.

Solutions to the *crew scheduling problem* within the railway industry have been successfully implemented by many researchers and practitioners. However, the *crew recovery problem* differs from the crew scheduling by its objectives. Since the drivers are already on contract, the objective of minimizing crew costs is not appropriate for the crew recovery.

Three main crew recovery objectives are defined by DSB S-tog A/S for this project. First, the crew recovery schedule shall contain as few modifications from the original schedule as possible. Second, the schedule shall be robust in order to withstand further disruptions. Third, the *idle time*, when a driver is not engaged in any activity (e.g. waiting at a depot or deadheading) shall be minimized.

Minimizing the idle time of the drivers results in a very tight schedule, contradicting with the robustness requirement. Furthermore, the robustness of the schedule is very difficult to define and measure. The crew recovery is therefore a challenging problem, aimed at finding a trade-off between the objectives.

The crew recovery schedule is based on the original crew schedule for a particular day. The re-scheduling starts at a chosen *time of disruption* and is made either for the rest of the day or for a certain time period. The exact position of each driver at the time of disruption is assumed to be known.

The recovery schedule must satisfy a number of feasibility constraints. All non-cancelled train tasks must be covered. The duty time of each driver shall not be extended by more than a certain time period. All planned breaks shall be held. A minimum required time between tasks for changing trains, walking from/to a depot, shunting, etc. must be satisfied. Reserve drivers are used whenever necessary.

The crew schedule is represented by disjoint paths on a directed graph, where vertices correspond to tasks, i.e. train rides, deadheading, breaks, driver check-ins at the time of disruption and check-outs at the end of the duty, and arcs represent connections between tasks. The number of paths corresponds to the number of drivers. Each path must contain some driver-specific vertices, corresponding to tasks specified for a particular driver (check-ins, breaks, check-outs).

Since time is a crucial factor in recovery situations, the system must provide a solution fast. A heuristic approach is therefore applied. The method consists of a construction heuristic and a number of improvement heuristics. The construction heuristic is aimed at creating feasible paths through the graph, such that all train rides and driver-specific vertices are covered. If the crew of regular and reserve drivers is not sufficient to cover all tasks in the recovery schedule, *ghost* drivers are introduced, representing drivers who are asked to work overtime. It is also allowed to shift times of breaks and check-outs if necessary in order to achieve feasibility. Improvement (meta)heuristics are based on neighbourhood search defined through 2-opt and 3-opt swaps and are aimed at achieving the three main objectives of the crew recovery.

Equity and acceptability measures in urban traffic planning models

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Transport planners today face major challenges in devising future transport plans to meet multiple expectations and objectives. Traditionally, measures of efficiency of the traffic system in terms of travel times and speeds are used for scenario evaluation. To accommodate wider expectations and objectives in the planning process, measures other than the traditional ones may be used. We are looking at two measures: equity and acceptability in the context of urban traffic planning.

We evaluate a measure of equity, or fairness, which is based on analysing the distribution of the consumer surplus after a change in the traffic network model. The consumer surplus is computed based on a discrete choice model for the travel alternatives in the network. We give examples of traffic network equity measures based on the Gini coefficient and the Theil's entropy measure.

The acceptability measure is a bit more complex, since the acceptability of a policy typically is viewed as an outcome of a process in which the population of a society has a chance to support, vote against or be neutral to the proposed policy. The decision on the vote of an individual is here modelled as a discrete choice utility model. The utility measure for an individual includes here both the direct utility for the individual and the utility for the total population.

In the presentation, some examples of the use of the equity and accessibility measures are given for typical planning scenarios on a Norrköping traffic equilibrium network model. The equity and acceptability measures are in the examples computed based on sensitivity information from an optimization problem formulation of the traffic equilibrium problem.

How to solve large scale transportation problem in practice

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The transportation and routing constitute a large proportion of the overall logistic cost in forestry. Transportation and routing are often combined with other operations such as harvesting, road building and production at paper, pulp and saw mills. It often involves several transportation modes such as truck, train and ships. Further, it covers strategic, tactical and operative planning horizons. In this seminar we will discuss a number of problems arising in the Swedish forestry. We will discuss how models, methods and data handling can be combined to industrial decision support system (DSS) in order to assist forest managers.

On a strategic level we will consider how truck, train and ship transportation can be integrated in order to decide for example which terminals to use and which train systems to implement. One DSS that deals with these questions is FlowOpt. It is a system that is developed and tested at the Forest Research Institute in Sweden (Skogforsk) together with a number of larger Swedish forest companies. FlowOpt can also be used on a tactical level to, for example, decide catchment areas for industries, establish efficient back hauling routes and study co-operation between companies. It is based on an LP-model and solved using column generation. The latter due to the huge number of potential back haulage routes.

On an operative level we will discuss RuttOpt which also is a DSS developed at Skogforsk. It is a system that finds daily routes (pick up and delivery) for individual logging trucks. Tests in a number of case studies shows large savings. The model is solved using a two phase approach based on LP and tabu search. In order to develop these DSS we make use of a national road data base with detailed information on all forest roads and standard geographical information system for result generation and analysis. We also discuss experiences from implementations of related/similar systems at companies and the current status in Sweden.

Exploiting parallel hardware in optimization

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Within the next few years computers with several CPU's will become very common. This has increased the interest in methods for solving large scale linear optimization problems on parallel computers. MOSEK implements the well known interior point and simplex algorithms for linear optimization. In this talk a parallel implementation of the interior point algorithm is outlined and computational results are presented. Also the method of "concurrent optimization" where several different algorithms run on the same problem in parallel is examined.

Experiments with different branching schemes in mixed integer optimization using SCIP

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SCIP is a general framework for constraint and integer optimization. SCIP is intended to be easily extendable and customizable and should thereby facilitate focused research in the different parts of mixed integer optimization. In this talk I present my experiences using SCIP to implement and compare various branching schemes. In particular I test heuristics for branching on hyperplanes as opposed to single variables.

A Partial Load Model for a Local Combined Heat and Power Plant

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Local combined heat and power (CHP) production in Denmark has, in recent years, undergone several changes. Perhaps most significant was the transition from unloading production at a feed-in tariff to selling it on the Nordic power exchange, NordPool. In connection herewith, the plants must plan their production and their bids to the power market at a time when the sales prices for electricity are yet unknown.

In previous work [1], a model (1)-(11) was constructed that alleviates planning difficulties for a single local CHP plant, consisting of a combined heat and power generating unit, a heat boiler, and a heat storage facility. The model creates a day-ahead production schedule for the plant, taking into account restrictions regarding production capacity of both the combined heat and power unit (4) and the heat boiler (7); start-up constraints for the CHP unit (5)-(6) and the heat boiler (8)-(9); capacity limitations of the heat storage facility (10); meeting heat demand (2)-(3); while minimising production expenses (1), including starting costs for both production units. In other terms, minimise

$$\sum s,t\phi^s \left\{ c^{kv} \sum_o m_{ot}\delta^s_{ot} + m^s_{kt}c^k + \ c^{kv}_{start}v^s_t + c^k_{start}w^s_t - \pi^s_t c_m \sum_o m_{ot}\delta^s_{ot} \right\} \tag{1}$$

subject to:

$$V_{t+1}^s = V_t^s + \sum_o m_{ot}\delta_{ot}^s + m_{kt}^s - d_t, \quad \forall s, t = 1, \ldots, T-1 \tag{2}$$
$$V_1^s = V_T^s + \sum_o m_{oT}\delta_{oT}^s + m_{kT}^s - d_T, \quad \forall s \tag{3}$$
$$z_t^s m_{\min} \leq \sum_o m_{ot}\delta_{ot}^s \leq z_t^s K_{kv}, \quad \forall s, t \tag{4}$$
$$v_t^s \geq z_t^s - z_{t-1}^s, \quad \forall s, t = 2, \ldots, T \tag{5}$$
$$v_1^s = z_1^s - z_{init}, \quad \forall s \tag{6}$$
$$y_t^s m_{\min}^k \leq m_{kt}^s \leq y_t^s K_k, \quad \forall s, t \tag{7}$$
$$w_t^s \geq y_t^s - y_{t-1}^s, \quad \forall s, t = 2, \ldots, T \tag{8}$$
$$w_1^s = y_1^s - y_{init}, \quad \forall s \tag{9}$$
$$0 \leq V_t^s \leq V_{\max}, \quad \forall s, t \tag{10}$$
$$z_t^s, y_t^s \in \{0, 1\}, m_{ot}, m_{kt}^s, v_t^s, w_t^s \geq 0, \quad \forall o, s, t \tag{11}$$

There are, however, other factors that may influence planning besides the expected sales price of the electricity generated, such as emission of environmental pollutants that are generated during power production, or the fact that production may be more efficient, and thus more economical, at certain load levels.

New constraints

By segmenting the load variable (m_{ot}) and the electricity-to-heat ratio (c_m) as well as the production cost (c^{kv}) of the combined heat and power unit using the index $g \in \{1, \ldots, G\}$, it is possible to take into account that power production is not necessarily linear within the capacity limits of the CHP unit. This leads to the modification of constraints (2)-(6) as well as the addition of a few others regarding the segments. Total production is assumed continuously varying between the minimum of segment 1 and the maximum of segment G (which equals the installed production capacity of the unit). Thus maximum for one segment equals minimum for the next and segment g needs to be fully loaded before there can be any production in segment $g+1$. The maximum load capacity of a segment equals the difference between the upper and lower bounds of the segment. The minimum load capacity of segment 1 is given by $m_{\min}^g, g \in \{1\}$ and is zero for the remaining segments.

Because of the 'sequential additivity' of the segments, a constraint is needed to ensure that if the CHP unit is producing in the segment following the present, then the present segment must be fully loaded, i.e.

$$\sum_o m_{ot}^g \delta_{ot}^s \geq z_t^{s,g+1} \left(K_{kv}^g - m_{\min}^g\right), \quad g \in \{1, \ldots, G-1\} \, \forall s, t. \tag{12}$$

A similar constraint is introduced, linking the segments directly. If the CHP unit is running in the following segment, it must also be running in the present segment. As the binary variable z_t^{sg} indicates whether the CHP unit is running in price scenario s and segment g during hour t, this translates to

$$z_t^{sg} \geq z_t^{s,g+1}, \quad g \in \{1, \dots, G-1\} \, \forall s, t. \tag{13}$$

Finally, a constraint that guarantees connectivity between start-up and production is needed. It ensures that a start-up is not planned in a given hour (i.e. $v_t^s = 1$) unless production is bid in the first segment of the hour in question. Conversely, if there is production, it should be at least minimum production. This results in the constraint

$$m_{\min}^1 v_t^s \leq \sum_o m_{ot}^1 \delta_{ot}^s, \quad \forall s, t. \tag{14}$$

Emission

Emissions from a production unit naturally depends on the load. However, the efficiency of the unit often varies depending on the load as well, i.e. emissions may be relatively low at full load compared to half load. Including an emission cost in the objective function is relatively simple. Letting n^g indicate emission and c_n the associated cost, emission expences may be considered in the model by including the term

$$c_n \sum_{o,g} n^g m_{ot}^g \delta_{ot}^s$$

in the objective function.

Thus, one may consider both environmental and economical consequences of whether production takes place under full or partial load. Numerical examples are given using data from [2], where the emission factor is varied depending on the load, in order to illustrate the functionality of the model and to ensure that the functionality is reasonable compared real life experience.

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An IP model for optimizing container positioning problems

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Abstract

The work presented deals with the problem of positioning containers in storage blocks in marine terminals. The problem consists in finding optimal sequences of positions for each container transported through the terminal. The problem is decomposed such that the positioning problem is solved for each storage block in the terminal yard which reduces the problem size significantly. No previous attempts to solve this specific problem by optimization approaches have been found in the literature. An integer linear programming model for the container positioning problem (CPP) is presented. The model is validated though solution of test cases using the modeling tool Mosel and the Xpress-MP solver and larger problem instances with data from a Scandinavian container terminal are solved using the CPLEX solver.

Container Positioning Problems

In port container terminals several different operations are carried out. For a comprehensive overview of port container terminal operations, equipment, problem areas, and scientific approaches, see [1].

One of the most complex problems occurring in port container terminals is the container positioning problem (CPP), consisting in finding the optimal sequence of positions for containers in a storage block by minimizing the reshuffling time. Arrival and departure times for containers are assumed known and the time it takes to move containers between positions is estimated on the basis of position coordinates. Figure 1 provides an overview of a storage block.

The CPP is formulated as an integer linear programming model with the binary

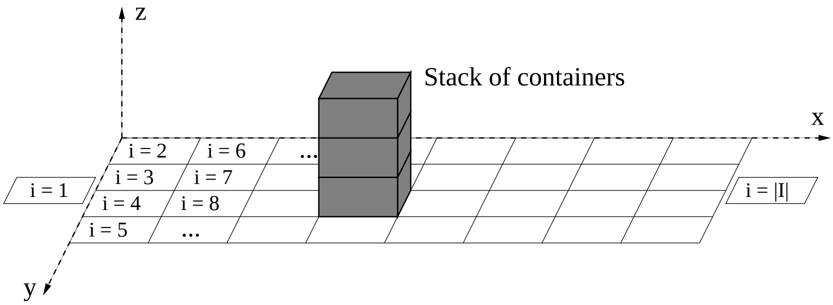

Figure 1: Each storage block consists of a number of positions where containers can be stacked.

decision variables $x_{cti} \in \mathbb{B}^{|\mathcal{C}|\times|\mathcal{T}|\times|\mathcal{I}|}$ (equals 1 if and only if container c is at position i in time slot t) and $y_{ct} \in \mathbb{B}^{|\mathcal{C}|\times|\mathcal{T}|}$ (equals 1 if and only if container c is moving between positions, i.e. carried by a crane, in time slot t). The objective is to minimize the moving time $\sum_{c\in\mathcal{C},t\in\mathcal{T}} y_{ct}$. The constraints concern: 1) Pick-up, drop-off, positions and sequences for each container, 2) Situations where two containers share the same position (including the last-in first-out principle), 3) Moving of containers, and 4) Capacity restrictions.

The first type of restrictions are represented by seven constraints. By equalities $x_{cP_c1} = 1$, $x_{cD_c|\mathcal{I}|} = 1$, $\forall c \in \mathcal{C}$ the containers' pick-up and drop-off times, P_c and D_c, are met, inequalities $\sum_{i\in\mathcal{I}} x_{cti} + y_{ct} = 1$, $\forall c \in \mathcal{C}, t \in \{P_c, ..., D_c\}$ and $x_{cti} = 0$, $\forall c \in \mathcal{C}, t \in \{0, ..., P_c - 1\} \cup \{D_c + 1, ..., |\mathcal{T}|\}$ ensure that each container is at exactly one position ($x_{cti} = 1$) or moving between positions ($y_{ct} = 1$) in each time slot t between it's pick-up and drop-off time and that both decision variables equal 0 outside this time window, and in equalities $x_{ct1} = 0$, $\forall c \in \mathcal{C}, t \in \mathcal{T}\backslash\{P_c\}$ and $x_{ct|\mathcal{I}|} = 0$, $\forall c \in \mathcal{C}, t \in \mathcal{T}\backslash\{D_c\}$ any storage at the pick-up and drop-off points is prevented. Finally the continuity of sequences of positions is insured by the inequality $x_{cti} \le 1 - x_{ct'i} + x_{ct'-1i}$, $\forall c \in \mathcal{C}, t \in \mathcal{T}\backslash\{|\mathcal{T}|\}, t' \in \mathcal{T}\backslash\{1\}, t < t', i \in \mathcal{I}$.

The second type of restrictions, concerning two containers at the same position, are formulated in the following three constraints. The inequalities $x_{cti} + x_{c'ti} \le 1 + x_{ct-1i} + x_{c't-1i}$, $\forall(c, c' \neq c) \in \mathcal{C}^2, t \in \mathcal{T}\backslash\{1\}, i \in \mathcal{I}$ and $x_{cti} + x_{c'ti} \le 1 + x_{ct+1i} + x_{c't+1i}$, $\forall(c, c' \neq c) \in \mathcal{C}^2, t \in \mathcal{T}\backslash\{|\mathcal{T}|\}, i \in \mathcal{I}$ prevent two containers to arrive or depart from a position at the same time, and inequalities $x_{cti} \ge x_{c'ti} - (2 - x_{ct'i} - x_{c't'i} + x_{c't'-1i})$, $\forall(c, c' \neq c) \in \mathcal{C}^2, t \in \mathcal{T}\backslash\{1\}, t' \in \mathcal{T}\backslash\{1, |\mathcal{T}|\}, t > t', i \in \mathcal{I}\backslash\{1, |\mathcal{I}|\}$ ensure the last-in first-out principle concerning removing of upper containers (last arrivals) in a stack before lower ones (first arrivals) can be moved.

The third type of constraints, concerning moving of containers, are modeled in three inequalities. By $y_{ct} \geq x_{ct+1i} - x_{cti}$, $\forall c \in \mathcal{C}, t \in \mathcal{T} \backslash \{|\mathcal{T}|\}, i \in \mathcal{I} \backslash \{|1, \mathcal{I}|\}$ and $y_{ct} \geq x_{ct-1i} - x_{cti}$, $\forall c \in \mathcal{C}, t \in \mathcal{T} \backslash \{1\}, i \in \mathcal{I} \backslash \{|1, \mathcal{I}|\}$ the moving variable y_{ct} is set equal to 1 if container c arrives/departs at/from a position in time slot t, and by inequalities $\sum_{t'<t<t''} y_{ct} \geq T_{ij}(x_{ct'i} + x_{ct''j} - 1)$, $\forall c \in \mathcal{C}, t' \in \mathcal{T} \backslash \{\mathcal{T}-2, ..., \mathcal{T}\}, t'' \in \mathcal{T} \backslash \{1, 2, 3\}, t' < t'', (i, j) \in \mathcal{I}^2$ the last-in first-out principle is conserved.

The fourth type of restrictions are observed by $\sum_{c \in \mathcal{C}} y_{ct} \leq M$, $\forall t \in \mathcal{T}$ and $\sum_{c \in \mathcal{C}} x_{cti} \leq H$, $\forall t \in \mathcal{T}, i \in \mathcal{I}$ ensuring that the crane capacity and maximum stacking level are not exceeded.

The model is implemented in the modeling tool Mosel and validated by the solution of small test cases using the Xpress-MP solver [2]. Furthermore, larger problem instances with data from a Scandinavian container terminal have been solved using the CPLEX solver providing good results.

The proposed integer linear programming model is an improvement of the CPP MIP model developed by Tranberg [3]. Ongoing work include solution of larger test cases and real problem instances from a smaller port container terminal. Furthermore, heuristic approaches for the CPP are investigated.

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A non-robust Branch-and-Cut-and-Price algorithm for the Vehicle Routing Problem with Time Windows

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A non-robust Branch-and-Cut-and-Price algorithm for the Vehicle Routing Problem with Time Windows is presented. The standard Dantzig-Wolfe decomposition leads to a Set Partition Problem as master problem and an Elementary Shortest Path Problem with Resource Constraints as the pricing problem (Desrosiers 1984) . In a *non-robust* algorithm (Fukasawa et al. 2005) some additional constraints must also be satisfied in the pricing problem.

The additional constraints arise with the introduction of the *subset row inequalities* used as cutting planes in the master problem. Given a subset row inequality based on a subset of rows S where $|S| = n$ and a $1 < k \leq n$ then the coefficient of a route in the master problem equals the number of visited customers in S integral divided by k and the right hand side becomes . $\lfloor \frac{n}{k} \rfloor$. Hence the inequality states that no set of overlapping routes can be part of an integral solution. We show that the subset row inequalities are valid for the Set Packing Problem and intersect with the set of clique and odd hole inequalities which are also known to be valid inequalities for the Set Packing Problem, and hence a valid inequality for the Set Partition Problem.

The pricing problem is solved with a label setting algorithm modified to handle the non-robustness. The additional constraints in the pricing problem stemming from the subset row inequalities of the master problem are denoted *subset penalty constraints*, since a penalty must be payed for each k visits to subset of customers S. The penalty equals the negated dual value of the corresponding subset row inequality. This is done by extending the known dominance criteria used in similar label setting algorithms (Feillet et al. 2004, Chabrier 2005) by modifying the cost calculation based on previous and future visits to customers in S.

The introduction of the subset row inequalities has made it possible to solve 11 previously unsolved instances from Solomon's benchmarks (Solomon 1987).

The subset row inequalities are a general cutting plane that can be applied to any

Set Packing like problem, hence appears to be applicable in other Branch-and-Cut-and-Price algorithms. The main concern is how to handle the additional constraints that arises in the pricing problem of these algorithms.

Shortcut Span Protection

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Introduction

Designing resilient networks has been in focus of research and industry for some years now, resulting in a large variety of both well-known and experimental resilience provisioning mechanisms. Many of these studies focus on providing networks with the least amount of capacity possible to fulfil the demanded level of protection.

Mesh Protection Methods

Two well-known methods for providing resilience in mesh networks are span protection and path protection. In span protection, the entire traffic is re-routed locally between the nodes adjacent to the failed span, meaning that the end nodes of a connection are unaware of the failure. This results in a short notification time, but generally also means a longer protection path.

In path protection, the affected connections are re-routed on an end-to-end basis, where an individual backup path can be found for each connection. This approach results in high resource efficiency and does not necessarily result in a backup path of higher cost compared to the original working path. Restoring connections between their end-nodes requires considerably longer notification times than in the local span protection approach. Since each affected connection can be re-routed individually, a large amount of complexity is added to the network.

A more recent method is termed local-to-egress or local backup dynamic protection, described in [1] and [2] respectively, where the traffic is re-routed between the upstream node adjacent to the failure and the egress node of the connection. This combines the advantages of the two aforementioned methods, specifically the short failure notification time and the freedom of finding a backup path that does not need resume the original path locally. The different protection methods are illustrated in Figure 1.

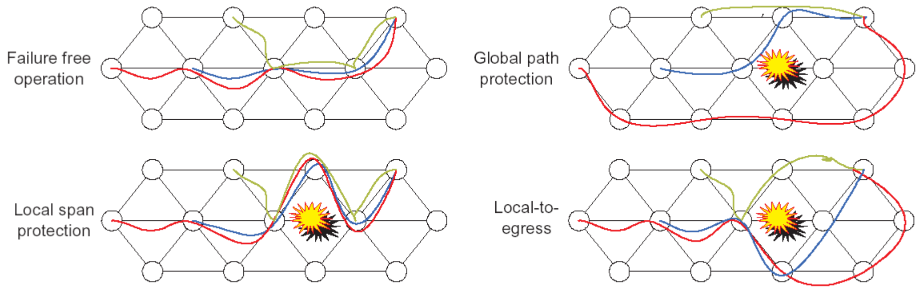

Figure 1: Protection methods for mesh networks

Model

To reduce the complexity of the protection method and the restoration time, we want to investigate a variation of the local-to-egress protection method, which we have termed, Shortcut Span Protection (SSP). In SSP, the traffic is bundled between the failure adjacent node and the egress node if several affected connections have the same destination node. The advantage of the proposed method lies in a less complex (and therefore faster) decision-making and routing process, resulting in less complex core nodes. The SSP is expected to require more capacity than path protection, but less than span protection.

We will now describe a Linear Programming (LP) model for the joint routing and protection problem for the SSP protection scheme. Given a network with N nodes indexed by i, j, k, l, q, r, a number of oriented links L, indexed by (ij) and by (qr), indexing the normal links and the failed links respectively. The cost of the link is given by the constant $c_{(ij)}$. The communication demand, i.e. the number of oriented circuits which should be established between the nodes k and l is given by the constant $D^{(kl)}$. The model is a so called link-path model and it contains 3 types of variables: $x_p^{(kl)} \in R^+$, the non-failure flow paths between node k and node l, $y_p^{(qr),l} \in R^+$, the failure recovery flow from the start node q of the failed link qr to the end node of the flow l, the required **non-oriented** capacity $z_{\{ij\}} \in R^+$. The non-failure paths are defined by the incidence matrix $A_{p,(qr)}^{(kl)} \in \{0,1\}$ and the restoration paths $B_{p,(ij)}^{(qr),l} \in \{0,1\}$.

Shortcut span protection link-path LP model

$$\min \sum_{\{ij\}} c_{\{ij\}} \cdot z_{\{ij\}} \tag{1}$$

$$\sum_p x_p^{(kl)} \quad \geq \quad D^{(kl)} \quad \forall (kl), \tag{2}$$

$$\sum_p y_p^{(qr),l} - \sum_k \sum_p A_{p,(qr)}^{(kl)} \cdot x_p^{(kl)} \quad \geq \quad 0 \quad \forall (qr), l, \tag{3}$$

$$\begin{aligned} z_{\{ij\}} - \sum_{(kl)} \sum_p [A_{p,(ij)}^{(kl)} + A_{p,(ji)}^{(kl)}] \cdot x_p^{(kl)} & \\ - \sum_l \sum_p [B_{p,(ij)}^{(qr),l} + B_{p,(ji)}^{(qr),l}] \cdot y_p^{(qr),l} - & \\ \sum_l \sum_p [B_{p,(ij)}^{(rq),l} + B_{p,(ji)}^{(rq),l}] \cdot y_p^{(rq),l} & \quad \geq \quad 0 \quad \forall \{ij\}, \{qr\}, \end{aligned} \tag{4}$$

$$x_p^{(kl)}, y_p^{(qr),l}, z_{\{ij\}} \in R^+ \tag{5}$$

The SSP LP model consists of an objective function (1), demand constraints (2), protection constraints (3) and capacity constraints (4) and domain definitions (5). The objective function (1) measure the cost of the necessary capacity in the network. The demand constraint (2) ensures that the circuits are established in the non-failure situation. The protection constraint (3) ensures that protection paths are assigned to reroute communication in case of any single link failure. Finally constraint (4) ensure that enough capacity is assigned to the links to cover all single link failure situations. This model can now be solved using column generation. Finally, we can by adding binary variables, limit the choice of paths to one to each egress node.

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Column Generation in Integer Programming with Applications in Multicriteria Optimization

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This paper presents in a unified form a column generation scheme for integer programming. The scheme incorporates the two major algorithmic approaches in integer programming, branch and bound technique and cutting plane technique. With integrality conditions imposed on the variables it is of importance to limit the number of columns introduced in the integer programming problem. This is equally important in the case of multiple criteria where usually multiple alternative efficient solutions are required. The suggested scheme gives additional dual information that limits the work required to move among the alternatives to be generated.

Real-time optimisation and incidence handling in ready-mix dispatching

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Transvision A/S is a Danish software company with more than 25 years of experience providing solutions for transport and distributions planning and optimisation. Transvision A/S has delivered solutions to a wide range of industries in Denmark, Sweden and Norway plus a number of other European countries; each industry having its own special demands and business rules. The purpose of this presentation is to illustrate how real life problems - and how to solve them - deviate from the classic transportation problems described in the literature, taking the transportation of ready-mix concrete as an example.

Planning the delivery of ready-mix concrete to construction sites is a very complex task. Typical concrete only has a lifetime of 2 hours, so after a batch of concrete has been produced at a plant, it must be delivered at the construction site within this time frame. If the product cannot be delivered in due time, it will harden in the truck barrel leading to severe cleaning costs. At the construction site almost continuous deliveries of concrete are needed in order to keep the resources busy and to maintain the workability of the concrete. Compared to traditional route planning, where focus is on assigning the individual orders to the vehicles, an aspect of timing between the vehicles is added. This implies that the plan for an individual vehicle is correlated with the plans for all the other vehicles, which severely impacts the performance of the planning process.

An important competitive parameter in the ready-mix business is the ability to keep a steady delivery flow - and at the same time being able to change the delivery rhythm according to demands at the construction site. Construction sites tend to have many unforeseen incidents leading to order changes. On average an order is changed 5 times before all loads have been delivered. At the same time the vehicles that deliver the loads, send progress reports back to the planning system. Due to the demanded precision of the operation, a vehicle sends an update, on average every 15th minute. The consequence of all these updates from the vehicles is that the plan is updated continuously and in order to keep it close to optimal, loads have to be re-scheduled continuously too.

Transvision A/S has developed a solution for Unicon A/S to handle the above formulated dispatching problem. Unicons operation in Denmark and Norway includes approximately 70 production plants, 350 vehicles and 25 dispatchers. One of the central features of the solution is the incremental improvement of the plan through plan servers working in parallel. Each plan server works with various improvement strategies, and is thus competing on delivering the next improvement of the plan. The challenge of this setup is the highly dynamical environment. If an order or a trip that is part of the planning scenario is altered during the planning process, then the planning result must be rejected since the initial conditions of the plan are no longer valid. In peak production time 50% of the plans will be rejected if a plan server has spent more than 5 seconds on the planning process.

This presentation will give an introduction to the planning problems: The analysis of the non-standard planning problem and the practical approach of how to solve it. The solution gives rise to a discussion of several interesting issues regarding vehicle routing optimisation in general. Some of these are: Multiprocessor optimisation, competing optimisation strategies, handling incidences through incremental re-planning, scalability through partial planning, the cost of having a real-time operation.

Robustness and flexibility in stochastic service network design

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Stochastic integer programs of reasonable size are, from a practical perspective, impossible to solve exactly. Several approaches are tried, such a meta-heuristics, and approximate versions of exact methods. In this work we take another path. We know from Wallace [3] as well as and Higle and Wallace [2] that the solutions to stochastic versions of mathematical program will look very different from their corresponding deterministic counterparts. The reason is that even if we solve a large number of versions of the deterministic problem (based on what-if analysis, sensitivity analysis or scenario analysis) these will all be knife-edge solutions without the ability to accommodate surprises. A large collection of non-robust solutions is still not robust. Robustness normally implies paying some costs up front to achieve lower expected costs later on. Or, in another vocabulary, the union of solutions containing no options will still contain no options. A detailed example is worked out in [2] . So, robust solutions simply look different from their deterministic counterparts. In this work we study a specific multi-commodity network design problem, called service network design, see Crainic [1] for an overview. The goal of the work is to discover in what ways the stochastic solutions differ from the deterministic ones. A later goal is to develop heuristics based on these findings. We shall report on what structures we have found. These are very simple, but such that a deterministic model would never produce them. Development of heuristics is left for later work.

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Quadratic Solver for the Transport Assignment Problem with Inseparable Cost function

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We present a new inseparable cost function and a new solution approach. The cost function can be calibrated to accomodate the extra delay in turning movements caused by right of way traffic and the solver guarantees convergence in quadratic time even for inseparable cost functions.

Although Bar-Gera's Origin Based Approach (OBA) for the Transport Assignemnt Problem (TAP) apply almost the same algorithm, we differ in significant areas. We do not use approach proportions and our projected Quasi Newton Method (QNM) is not restricted to a diagonal Hessian.

We show that without significant performance impact this new solver can solve the same instances. Furthermore the usage of the full Hessian only requires the cost function to be locally smooth and not separable.

We combine a true QNM with generic network algorithms to achieve a much more versatile solver for the TAP. We solve instances from the TAP problem library with both separable and simple inseparable cost functions and compare these to OBA.

An exact algorithm for Aircraft Landing Problem

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This presentation addresses the problem of scheduling aircraft landings at an airport. Given a set of planes and runways, the objective is to minimize the total (weighted) deviation from the target landing time for each plane. There are costs associated with landing either earlier or later than a target landing time for each plane. Each plane has to land on one of the runways within its predetermined time windows such that separation criteria between all pairs of planes are satisfied. This type of problem is a large-scale optimization problem, which occurs at busy airports where making optimal use of the bottleneck resource (the runways) is crucial to keep the airport operating smoothly.

This research is the first attempt to develop a branch-and-price exact algorithm for the Aircraft Landing Problem (ALP), in which the column generation method is applied to solve the linear relaxation problem for each branch node throughout the branch-and-bound procedure. We formulate the ALP as a set partitioning problem with side constraints on the number of available runways. We also present a mixed integer formulation for the subproblem in column generation, which can be used to generate the columns with the minimum negative reduced cost. Then a branch-and-bound method is developed to find the optimal integer solution for the ALP. Finally, the branch-and-price exact algorithm is implemented and tested on the public data from OR_Library involving up to 50 aircraft and 4 runways. The computational results show that the algorithm can solve the problem optimally in acceptable CPU time. Furthermore, the optimal solutions can be achieved with less than 500 columns generated and 12 branch nodes explored.

Solving the Capacitated Arc Routing Problem with Time Windows to Optimality

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The Capacitated Arc Routing Problem (CARP) is the problem of servicing a set of edges in a graph using a number of capacity constrained vehicles. This problem occurs in practice in problems such as street sweeping, refuse collection and winter gritting. We consider a variant of the CARP in which each edges require its service to be performed within a fixed time window. This problem is referred to as the Capacitated Arc Routing Problem with Time Windows (CARP-TW).

Few attempts have been made on solving the CARP-TW to optimality. These are all based on transforming the problem into an equivalent node routing problem. Here we consider different strategies for solving the CARP-TW to optimality without converting the problem to node routing. The first strategy is based directly on an IP model for the CARP-TW, and the second two are based on a column generation approach.

Resource Allocation of Spatial Time Division Multiple Access in Ad Hoc Networks

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An ad hoc network is characterized by a set of wireless networking devices setting up a temporary communication infrastructure. We study resource optimization of Spatial Time Division Multiple Access (STDMA) in ad hoc network. STDMA uses a schedule to organize transmission activities. The schedule consists of a number of time slots and specifies which devices are allowed to transmit in each of the slots. We consider two objectives of STDMA scheduling. The first objective is to find a minimum-length schedule in which every device (or every link) receives at least one slot. The second objective arises in traffic-sensitive scheduling, and amounts to finding a schedule that maximizes the network throughput for a given traffic distribution. We discuss mathematical programming models and methods that can be used to compute sharp bounds for these problems. We also present a simple but effective greedy algorithm. The algorithm is suitable for distributed implementation in ad hoc networks.

On Minimization Problems in Multidimensional Scaling with City Block Metric

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Multidimensional scaling (MDS) is a technique for exploratory analysis of multidimensional data widely usable in different applications [1], [2]; e.g. applications of MDS based visualization of observation points in interactive optimization systems is discussed in [3]. Let us give a short formulation of the problem. The dissimilarity between pairs of n objects is given by the matrix (δ_{ij}), $i, j = 1, \ldots, n$, and it is supposed that $\delta_{ij} = \delta_{ji}$. The points in an m-dimensional embedding space $x_i \in R^m, i = 1, \ldots, n$ should be found whose interpoint distances fit the given dissimilarities. Different measures of accuracy of fit can be chosen defining different images of the considered set of objects. In the case the objects are points in a high dimensional vector space such images can be interpreted as different nonlinear projections of the set of points in high dimensional space to an embedding space of lower dimensionality. The problem of construction of images of the considered objects is reduced to minimization of an accuracy of fit criterion, e.g. of the most frequently used least squares STRESS function

$$S(X) = \sum_{i<j} w_{ij}(d_{ij}(X) - \delta_{ij})^2 \tag{1}$$

where $X = (x_{11}, \ldots, x_{n1}, x_{1m}, \ldots, x_{nm})$; $d_{ij}(X)$ denotes the distance between the points x_i and x_j ; it is supposed that the weights are positive: $w_{ij} > 0, i, j = 1, \ldots, n$. To define a particular criterion a norm in R^m should be chosen implying the particular formula for calculating distances $d_{ij}(X)$. The most frequently used norm is Euclidean. However, MDS with other Minkowski norms in embedding space can be even more informative than MDS with Euclidean norm. Analysis of MDS results corresponding to different norms is recommended since they can highlight different properties of the considered objects similarly as different orthogonal projections of a three dimensional object complement each other.

In the present paper MDS algorithms based on STRESS criterion with city block norm in the embedding space are considered. $S(X)$ normally has many local minima. The non differentiability of $S(X)$ in this case can not be ignored. Therefore MDS with city block distances is a difficult high dimensional ($X \in R^N, N = n \times m$) global optimization problem; in this case STRESS can be non differentiable even at the minimum point. Complexity of such optimization problems is similar to the complexity of the distance geometry problems, e.g. of molecular conformation.

For minimization of STRESS we apply combination of a metaheuristic global search with local minimization. Evolutionary metaheuristics is applied for global search. Since the objective function can be non differentiable at local minimizer, application of local descent methods with high convergence rate, e.g. of different versions of Newton method, seems questionable. Therefore we either apply local search methods, or employ piecewise quadratic structure of the objective function. In the present paper a generalization of the algorithm of [4] from two dimensional scaling to general case is presented. The widening of applications of stereo screens makes such a generalization an urgent problem for stereo visualization of multidimensional data. In the present paper we investigate the efficiency of the proposed algorithm, and compare performance of the algorithm depending on dimensionality of the embedding space. The values of minimum fit against to dimensionality of the embedding space are also presented.

Acknowledgement

The research is supported by the NATO Reintegration grant CBP.EAP.RIG.981300 and Lithuanian State Science and Studies Foundation.

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Presentation of IMM

IMM, department of Informatics and Mathematical Modelling at the Technical University of Denmark, carries out teaching and research within computer science and information processing, with focus on application withins engineering science, often in close co-operation with companies and institutions. Much of IMM's research activities are based on specific, practical problems.

Computerised mathematical models play an increasingly decisive role within engineering science, i.e. within industrial production, within planning and economics, within the hospital sector, etc. IMM's activities are aimed at methodologies enabling one to deal with today's ever increasing quantities of information.

IMM has two divisions, Computer Science and Engineering (CSE) and Mathematical Modelling (MM). CSE has four sections and MM six sections, one of which is Operations Research. The OR-section focuses on manpower planning, routing, telecommunication, financial planning, and railway OR, using both classical exact solution methods such as column generation and Branch-and-Cut, and metaheuristics like Simulated Annealing and Generic Algorithms.

IMM employs 80 faculty, 65 ph.d.-students, and 32 other staff members, with a turnover of 90 million DKK. The department has the equivalent of 900 full time students producing 20 Ph.D-degrees, 150 M.Sc.-degrees and 70 B.Sc.-degrees each year.

More information on IMM can be found at `www.imm.dtu.dk` and additional information on the activities within Operations Research at IMM can be found by visiting the IMM website clicking on **Operations Research** in the **Research** menu.

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Presentation of CTT

CTT – Centre for Traffic and Transport, is one of the 15 departments and centres which form DTU. The goal of CTT is to perform research, teaching and innovation within the area of traffic and transport. The strength of CTT is the ability to combine technical areas, quantitative models and methods, and IT. Furthermore the CTT focus is on applications. In 2004, 68% of CTT's activities were financed by external sources.

The CTT research activities are concentrated within the following areas:

- Logistics and Transport
- Traffic and Transport Models
- Geographical Information Systems
- Decision Models and Evaluation Methods
- Traffic Informatics
- Traffic Engineering
- Traffic Planning

Within the Logistics and Transport subject the areas of special interest are

- Optimization of inter-modal transport systems
- Supply network optimization
- Optimization of container operations in terminals
- Optimal loading of container ships
- Network design
- Distribution planning problems – including Vehicle Routing Problems
- Optimization of Timetable based transport systems
- Revenue management within transport systems

CTT is offering 24 courses on bachelor and mainly on master level.

Additional information can be found on `http://www.ctt.dtu.dk`.

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Presentation of DORS

History

DORS was founded in 1962 and has been the only professional society for operations researcher in academia and industry in Denmark since then. DORS has had its ups and downs just as the OR profession itself. In the early 90es the level of activity was at a minimum culminating with a proposal to dissolve the society. Fortunately this proposal was rejected and since then DORS has experienced slow but steady growth.

Membership and Geography

Today DORS membership total about 175. Membership fees are about 450 EUR for companies, 250 EUR for academic departments, 35 EUR for individuals and 9 EUR for students. Virtually all Danish university departments active in the field of OR are members along with major Danish and international companies including companies with transportation, energy and optimization software. The vast majority of DORS 14.000 EUR annual budget arise from membership fees. The DORS board has 8 members which are elected for a two years term, four each year. The typical board member is a Ph.D. student, younger professor or younger OR professional in industry. Board turn-over is limited with members serving at least for four years typically longer.

DORS activities, and to some extend membership, is concentrated around the Copenhagen area. This is a challenge for DORS as there are significant OR communities outside Copenhagen, in particular around Århus and Odense, which do not benefit from DORS activities to the extend, we would like. Previously the statutes of DORS required at least two board members from outside the Copenhagen area, but this rule was abandoned as it didn't ensure itself ensure any activity outside Copenhagen.

An other challenge for DORS is that the transportation sector has been and still is strongly represented in the board and in our activities. There is a strong interest in transportation research in Denmark, but DORS should offer something to those active or interested in other applications as well. We are actively, and generally successfully, trying to promote other application areas.

Activities

DORS organize 6-8 meetings per year and often co-sponsor more. There are different kinds of meetings. The annual career meeting takes place in the fall and is focused on OR students. Three or four companies hiring OR graduates present their company and typical OR assignments. In 2005 presenters were Cowi (consulting engineers), DONG (Oil and natural gas providers), PA Consulting and Transvision (vehicle routing software). Company visits take place one to two times per year. Every second year DORS and Ilog organize a seminar where Ilog present their optimization software products. Other meetings focus on other software products. A meeting in the fall of 2005 focused on the modeling languages GAMS and Mosel and provided members the opportunity to share their own views and experiences. Recent examples of traditional topic / application field meetings include a meeting on simulation and optimization of timetables in public transportation and a meeting on huge macroeconomic models and solution methods for these.

Virtually all meetings take place in the late afternoons to enable students as well as professionals to participate. Meetings attract 20 to 50 participants. Depending on the topic, some of these are not DORS members, but students and professionals interested in the topic of the meeting. The goal of the board is that all meetings organized by DORS should attract at least 30 participants, but occasionally timing and/or insufficient promotion cause lower participation.

The DORS bulletin is named Orbit and is published 2-3 timer per year. It publishes short papers (often around four pages) on important applications, surveys and occasionally brief popular summaries of dissertations. For example the winner of the biannual DORS OR master thesis price is required to write a short paper for Orbit. Papers are mainly written in Danish, but English and occasionally other Nordic languages are also acceptable for the Danish audience. We think Orbit has a quite high standard in terms of contents as well as layout. Orbit circulation is around 250. With this circulation, it is difficult to provide high quality at reasonable unit costs. We are therefore seeking ways to increase the circulations beyond the group of DORS members.

Electronic Communication

The DORS homepage on `www.dorsnet.dk` provide information on DORS activities as well as information on DORS in Danish. Old issues of Orbit can also be downloaded. Traffic on the site is not very high and we expect it is not frequently used by most members. We have now appointed a dedicated webmaster and expect to improve the contents and use of dorsnet. The major vehicle for communication with the member is e-mail. Most DORS members are on the DORS mailing list and it is typically this way activities are promoted. Other promotion is facilitated by university professor, which we provide with posters and overhead slides promoting meetings.

Practical oriented

Compared to some OR societies DORS is oriented towards practical applications of OR. We virtually never organize meetings on topics within theoretical operations research or pure mathematical programming and Orbit does not publish papers on such issues. We see DORS as bridge between academia and industry and do not try to compete with activities at the university department. We do, however, have a very good cooperation with the university departments, in particular in the Copenhagen area, i.e. the department of mathematical modeling (IMM) and the transportation and traffic center (CTT) at the technical university of Denmark (DTU) and the departments of mathematics and computer science (DIKU) of the University of Copenhagen.

International relations

DORS is a member of EURO as well as of IFORS. There is some Danish participation in the EURO and IFORS conferences, in EURO working groups as well as in the summer institutes. However, there is definitely room for improvement and the DORS board is currently evaluation how DORS members can benefit more from the EURO and IFORS memberships and how DORS can contribute to the promotion of OR internationally. There are a lot of things we, as a professional society in a small country, would like to do, but cannot do alone. For example we would like to offer our members an OR magazine with a contents and quality equivalent to that of ORMS Today. We would also like to provide relevant professional networking possibilities in particular for those in industry. To do this we must strengthen cooperation with other OR societies. Recently the editor of Orbit Jesper Larsen was elected secretary of DORS. The will clearly strengthen the relations between DORS and EURO.

DORS is a well functioning small OR society, but of course we face challenges as discussed above. The board constantly tries to improve the quality of our activities, but for all of us time is a limiting factor.

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