Linköpings Tekniska Högskola
Matematiska institutionen/optimeringslära
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Till CENIITs forskningsprogramråd: SLUTRAPPORT

Projektnamn: Combinatorial optimization models and methods for cyclic sequencing
Projektledare: Maud Göthe Lundgren
Projektnummer: 98.16

1. Scientific Results

Transportation and cost allocation:
In the area of transportation we develop a column generation procedure for the solution of *vehicle routing problems*. Here a sequencing sub-problem has to be solved repeatedly in order to generate possible routes for the vehicles. We have developed a new way of mathematically modeling and solving the *Traveling Salesman Sub-tour Problem* (TSSP*)*, which is a basic version of such a sequencing sub-problem. The approach is based on an earlier work on the so-called Node Weighted Steiner Tree Problem [6], that is, the sub-tour is modeled as a 1-tree with complicating vertex degree restrictions. This approach is classical for the traditional Traveling Salesman Problem, but not for the TSSP. In order to obtain strong relaxations of this model, the vertex degree restrictions have to be modeled properly. The results of this work were earlier documented in [8], [17] and [19].

We have continued the work to develop an efficient column generation procedure for the vehicle routing problem and sub-tour problems. In [9] we present a combined column generation and cutting plane scheme, which is a more robust and efficient version of the procedure presented in [17]. The two approaches presented in [8] (subgradient optimization) and in [9] are combined into a two-phase solution method, see [12]. Here, the subgradient scheme is utilized to generate a set of initial columns for the column generation phase in order to accelerate it. The combination of these schemes is made in order to utilize the advantages of the respective schemes; e.g., the fastness of the subgradient scheme and the finite convergence of the column generation scheme. Concerning solution times the computational experiences have so far showed very promising results. A joint paper with Di Yuan, ITN, concerning the two-phase method presented in [12], and how it is applied on the TSSP and the multi-commodity flow problem is currently prepared.

A work on the Heterogeneous Fleet Vehicle Routing Problem (HFVRP) was initiated during the last year, which concerns the question of how to design a set of routes from one (or many) central depot(s) to a number of demand points (customers) and to determine the fleet size and mix to be used in order to satisfy the demands and such that the total cost of the routing plan is minimized. The HFVRP is a relative to the classical Vehicle Routing Problem (VRP) in which there is an unlimited number of identical vehicles. This problem is known to be *NP*-hard, and therefore, HFVRP is also *NP*-hard. In practice, the HFVRP seems to be much harder than the VRP, and this is one possible explanation for, why few authors have addressed lower bounding procedures for HFVRP. In this work we co-operate with the research division of the company DaimlerChrysler, and aim to solve real life application occurring in their operational planning activites.

Our research work on the TSSP has lead to some theoretical observations concerning generalizations of the Held and Karp 1-tree problem, which is a classical relaxation of the Traveling Salesman Problem. In [11] we present two generalizations, and polynomial procedures for their solution.

In co-operation with the project *Optimal snow removal* (PO Lindberg/Div. of Optimization, VTI, Vägverket), financed by CDU (Centrum för drift och underhåll av infrastruktur) at KTH, we have developed a column generation based procedure for the generation of routes for snow-plowes. This work was documented in [3].

In the area of cost allocation we study the problem of allocating a common transportation cost among the customers in a general vehicle routing problem, arising at Norsk Hydro AB. In order to compute faire cost allocations we use solution concepts from the area of game theory, such as the *core* and the *nucleolus*. Both such concepts require that a large number of sequencing sub-problems is solved. It is, however, possible to reduce the number of sub-problems that must be solved, by instead of formulating and solving the full cost allocation problem directly, using a constraint generation approach. We have studied two different allocation principles: Firstly, by allocating the cost of a given route among the customers served by that route and, secondly, by considering a total customer area and allocate the total cost among all customers. This work was documented in [7], [16], [5] and [14].

Production and transportation:
In Production Scheduling we study the production process at a refinery, Nynäs AB, and how it can be planned and controlled by the use of optimization models and methods. The production planning is performed at three different levels:

- *Production planning*: Which products should be produced where? (5 refineries, planning horizon 1 year)
- *Transportation planning*: How and when should the products be distributed? (planning horizon ~3 months)
- *Production scheduling*: How should the production plant be optimally utilized? Which production modes should be used in the distillation and the hydration units? (planning horizon 2-4 weeks)

The decisions made at one planning level will affect the conditions at the other levels and small changes in the conditions will often result in considerable consequences in the planning process. Initially, we have focused on the production scheduling level, and considered the problem to schedule and coordinate the production at the distillation and the hydration units. We have developed two different optimization techniques for solving this problem, one based on the generation of valid inequalities and the other is a tabu search method. The results are reported in [1], [4], [10], [15] and in [18].

When focusing on the transportation planning problem at the refinery, the planning concerns the scheduling of ships for distribution of bitumen, which is a main type of product. We suggest a shipment planning model that include considerations of production, by representing the production (process scheduling) by a linear programming model. This is done in order to obtain better over all schedules for both shipping and production, than the ones obtained when the two steps are planned separately; Sometimes costly production schedules are required in order to meet the planned shipments. The solution scheme is based on column generation, where columns/ship routes are generated successively as they are needed. This work is documented in [2] and [13].

2. Exams and promotions

1999: Licentiate Jan Persson, Title: Production Planning and Scheduling in Refinery Industry, Theses No. 763
2001: Docent Maud Göthe-Lundgren
2002: Licentiate Andreas Westerlund, Title: Decomposition Schemes for the Traveling Salesman Subtour Problem, Theses No. 939
2002: Ph.D. Jan Persson, Title: Production Scheduling and Shipment Planning at Oil Refineries - Optimization Based Methods, Theses No. 742
2002: Ph.D. Stefan Engevall, Title: Cost Allocation in Some Routing Problems - A Game Theoretic Approach, Theses No. 754
2003: Professor Maud Göthe-Lundgren

In the joint project *Optimal snow removal* (see above):
2001: Licentiate Nima Golbaharan, Title: An Application of Optimization to the Snow Removal Problem - A Column Generation Approach, Theses No. 886

3. Personnel

Maud Göthe-Lundgren, 03/professor, project leader
Andreas Westerlund, 02/Licentiate
Jan Persson, 02/Ph.D.
Stefan Engevall, 02/Ph.D.
Peter Broström, master student
Joakim Isaksson, master student

4. Industrial cooperation related to the CENIIT-project

Within this project we had regular contact with Tomas Montin, systemansvarig, at **Nynäs AB**, Nynäshamns raffinaderi (earlier also with Roland Öster, planeringschef). We also had initial contacts with Lena Zetterström (produktionsplanering) at **Scanraff AB** (se Section 1**)**.

We gave a series of seminars at Nynäs, including personnel from the production and the shipping planning divisions. In 2003 a prototype planning tool for combined production and transportation was installed at Nynäs.

In the related project *Optimal snow removal*, where the aim is to develop optimization based tools for route planning, we co-operation with **Vägverket** and **VTI** (se Section 1**)**.

In the year 2003 contacts with **DaimlerChrysler** (Stefan Gnutzmann, researcher), Germany, were initiated. Here we aim to solve real life application occurring in their operational planning activites(se Section 1**)**.

The work on cost allocation problems was done in co-operation with **Norsk Hydro AB** (se Section 1**)**.

In the forestry projects Generation of back-haulage tours and Extraction of logs in Swedish forestry (se Section 5) we co-operated with **Skogforsk** and **Södra skog**, respectively.

In the co-operation project Design and Control of advanced distribution systems we co-operate with **Nynäs AB** and **Södra Cell** (se Section 5).

5. Cooperation with other Ceniit projects:

In co-operation with the Ceniit-project *Decision Support systems based on optimization in forestry* some work has been performed in developing solution methods for the routing applications*: Generation of back-haulage tours* (Skogforsk) and *Extraction of logs in Swedish forestry* (Södra skog). The first application concerns the problem of generating back-haulage tours by the wood flow of assortments into saw- and pulp-mills in order to reduce the overall transportation cost. We also study the problem of how to allocate the transportation cost among the companies that, as a result of the back-haulage tours, are co-operating. The second application concerns the problem of how to route the vehicles (forwarder) that transport the logs from the harvest areas to the piles in the pick up points. This problem constitutes a special case of the general vehicle routing problem. This work has earlier been documented in [20] and [21].

As a continuation of this co-operation we have initiated the project *Design and Control of advanced distribution systems*, financed by Vinnova (2003-2005). Here, we study the supply chains occurring at Nynäs AB and Södra Cell. We intend to develop decision support systems for planning problems in the forest and the refinery industry and to develop the underlying theory for the necessary optimization models and methods. A common structure of these processing industries is the highly divergent product flow, which imply that models and methods of similar type can be developed and utilized. The problems arise from the supply chain occurring at each forest or refinery company.

6. Publications and Masters

Publications (refereed):

[1] J. Persson, M. Göthe-Lundgren, J. Lundgren, B. Gendron, A Tabu Search Algorithm for a Scheduling Problem in Refinery Production. *International Journal of Production Research* 42/3 (2004) 445-471.
[2] J Persson, M Göthe-Lundgren, Shipment planning at oil refineries using column generation and valid inequalities. Accepted for publication in *European Journal of Operational Research*. (2003)
[3] N Golbaharan, PO Lindberg, M Göthe-Lundgren, Optimal Routing of Snowplows – A Column generation Approach, Operations Research Proceedings 2002, Selected Papers, Eds. Leopold-Wildburger, Rendl, Wäscher, Springer-Verlag (2002) 199-210.
[4] M. Göthe-Lundgren, J. Lundgren, J. Persson, An Optimization Model for Refinery Production Scheduling, *International Journal of Production Economics* 78/3 (2002) 255-270.

[5] S. Engevall, M. Göthe-Lundgren, P. Värbrand, The vehicle routing game: An application of cost allocation, Accepted for publication in *Transportation Science* (2003).
[6] S. Engevall, M. Göthe-Lundgren, P. Värbrand, A strong lower bound for the node weighted Steiner tree problem, *Networks*, 31, (1998) 11-17
[7] S. Engevall, M. Göthe-Lundgren, P. Värbrand, The traveling salesman game: An application of cost allocation in a gas and oil company, *Annals of Operations Research*, 82, (1998) 453-472.
Publications (other):
[8] M Göthe-Lundgren, A. Westerlund (1999),"The traveling salesman subtour problem - A Lagrangean based heuristic, Proceedings of the Nordic Mathematical Programming Society Meeting 1999.
Submitted to refereed journals:
[9] M Göthe-Lundgren, T Larsson, A. Westerlund, A stabilized column generation and cutting plane scheme for the traveling salesman sub-tour problem. Submitted to *Discrete Applied Mathematics* (2003), is currently revised.
[10] M. Göthe-Lundgren, J. Lundgren, J. Persson , Refinery Production Scheduling - A Mixed Integer Linear Programming Model and Valid Inequalities. Submitted to *European Journal of Operational Research* (2002).
[11] M Göthe-Lundgren, T Larsson, A Westerlund, Two generalizations of the Held and Karp 1-tree problem. Submitted to *Computers and Operations Research* (2004).
Theses:
[12] A.Westerlund, Decomposition Schemes for the Traveling Salesman Subtour Problem, Linköping Studies in Science and Technology, Licentiate Thesis No. (2002).
[13] J. Persson, Production Scheduling and Shipment Planning at Oil Refineries, Linköping Studies in Science and Technology, Dissertations No. 742 (2002).
(Dissertations from the International Graduate School of Management and Industrial Engineering)
[14] S. Engevall, Cost Allocation in Some Routing Problems – A Game theoretic Approach, Linköping Studies in Science and Technology, Dissertations No. 754 (2002).
(Dissertations from the International Graduate School of Management and Industrial Engineering)
[15] J. Persson, Production Planning and Scheduling in Refinery Industry, Linköping Studies in Science and Technology, Theses No. 763.
(Dissertations from the International Graduate School of Management and Industrial Engineering, no. 25, Licenciate Thesis)
[16] S. Engevall, Cost Allocation in Distribution Planning, Linköping Studies in Science and Technology, Theses No. 585.
(Dissertations from the International Graduate School of Management and Industrial Engineering, no. 1, Licenciate Thesis)
Other reports:
[17] M Göthe-Lundgren, T Larsson, A. Westerlund, “A column generation and cutting plane scheme for the traveling salesman sub-tour problem”, LiTH-MAT-R-2001-24.
[18] M Göthe-Lundgren, J Lundgren, J Persson, "An optimization model for refinery production scheduling", LiTH-MAT-R-2000-13.
[19] M Göthe-Lundgren, A. Westerlund, "The traveling salesman subtour problem", LiTH-MAT-R-1999-19.
Masters:
[20] Solving the Forwarding Problem using Taburoute, by Peter Broström, LiTH-MAT-EX-2001-03.
[21] Genering av effektiva returflöden och kostnadsdelning i skogsindustrin, by Joakim Isaksson, LiTH-MAT-EX-2001-05.
[22] Klassificering av virkesdefekter med relaxation labeling, by A.Löfwenmark, LiTH-MAT-EX-2000-04.
[23] A combinatorial optimization approach for configuration of test equipment, by M.Sundqvist, LiTH-MAT-EX-2000-03.
[24] Extraction of logs in Swedish forestry, by Andreas Westerlund, LiTH-MAT-EX-98-19.