Technical University of Denmark

ROUTE 2014

International Workshop on Vehicle Routing, Intermodal Transport and Related Areas

June 1-4, 2014

ROUTE 2014

June 2014

CO-SPONSORS

TRANSVISION
Transportation Optimisation

DTU Transport
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WELCOME

I would like to welcome you to ROUTE 2014, an international workshop on vehicle routing, intermodal transportation and related areas. ROUTE 2014 will take place at Comwell Borupgaard, Snekkersten, Denmark, from June 1 to 4, 2014.

ROUTE 2014 aims to provide a forum for scientific exchange and cooperation in the fields of vehicle routing, intermodal transportation and related areas. Previous editions of the workshop were hosted in 2000 and 2003 by the Technical University of Denmark, in 2005 by the University of Bologna, in 2007 by the Georgia Institute of Technology, in 2009 by the Technical University of Denmark, and in 2011 by the Technical University of Barcelona, the University of Valencia and the University of Brescia.

I would not have agreed to organize ROUTE 2014 if it were not for Oli B.G. Madsen. His name is inextricably linked to the ROUTE series, and his advice and overall assistance in the organization of this event were critical. Also I want to thank Michaela Horn Simonsen and Christos A. Kontovas for their support.

This year we have a set of 27 presentations, arranged in a single stream. As I have indicated already, all sessions of ROUTE 2014 are named after Shakespearean themes, in part due to proximity to Kronborg castle which we will visit on Tuesday June 3. The link of each theme to the papers of the corresponding session will be explained in real-time by the session chairs.

Last but not least, I would like to thank TRANSVISIONS and the DTU Department of Transport for being co-sponsors to this event.

I look forward to an excellent workshop.

Harilaos N. Psaraftis
Chairman of ROUTE 2014

SPECIAL ISSUE OF NETWORKS

As already communicated, there will be a special issue of Networks devoted to ROUTE 2014.

The review process will be just as strict as for a usual submission to Networks. The manuscript should follow the guidelines for manuscripts as stated on the Networks homepage.

http://onlinelibrary.wiley.com/journal/10.1002/%28ISSN%291097-0037/homepage/ForAuthors.html

The deadline for submission of manuscripts is September 1, 2014 and the manuscripts should be sent to Harilaos N. Psaraftis (Guest Editor) at hnpsar@transport.dtu.dk

We are looking forward to receiving your submission.

NETWORKS
An International Journal

Networks

Edited By: Dr. B. L. Golden and Dr. D.R. Shier

Impact Factor: 0.645

ISI Journal Citation Reports © Ranking: 2012: 37/50 (Computer Science Hardware & Architecture); 56/79 (Operations Research & Management Science)

Online ISSN: 1097-0037

SCHEDULE AT A GLANCE

	SUNDAY JUNE 1	MONDAY JUNE 2	TUESDAY JUNE 3	WEDNESDAY JUNE 4
0830-0900		P5	P16	P22
0900-0930		P6	P17	P23
0930-1000		P7	P18	P24
1000-1030		coffee	coffee	coffee
1030-1100		P8	P19	P25
1100-1130		P9	P20	P26
1130-1200		P10	P21	P27
1200-1230		lunch	lunch	lunch
1230-1300				
1300-1330				
1330-1400		P11	Excursion to Maritime Museum and Kronborg Castle Helsingør	departure
1400-1430	Arrival, registration and coffee	P12		
1430-1500		P13		
1500-1530		coffee		
1530-1600	opening	P14		
1600-1630	P1	P15		
1630-1700	P2			
1700-1730	P3			
1730-1800	P4			
1800-1830				
1830-1900	dinner	dinner		
1900-1930			banquet	
1930-2000				
2000-2030				
2030-2100				
2130-2200				
2200-2230				

SCHEDULE IN DETAIL

Sunday June 1

14:00 Arrival, registration, coffee

15:45 Workshop opening

Harilaos N. Psaraftis, Allan Larsen, DTU

16:00-18:00 SESSION A. To be or not to be

Chair: Gilbert Laporte

16:00 T. Vidal, P. Jaillet and N. Maculan
A new polynomial algorithm for nested resource allocation, speed optimization, and other related problems (P1)

16:30 B. Bruck and M. Iori
Non-Hamiltonian Formulations for the Single Vehicle Routing Problem with Deliveries and Selective Pickup (P2)

17:00 J. Desrosiers, J. B. Gauthier and M. Lübbecke
Dual-guided pivot rules for linear programming (P3)

17:30 E. Bartolini, A. Mingozzi and R. Roberti
On the Fixed Charge Transportation Problem (P4)

18:30 Dinner

Monday June 2

08:30-10:00 SESSION B1. The merchant of Venice

Chair: Pitu Mirchandani

08:30 B. Brouer, G. Desaulniers, C. Vad Karsten and D. Pisinger
A matheuristic for the liner shipping network design problem considering transit time restrictions (P5)

09:00 M. Christiansen, A. Agra, H. Andersson and L. Wolsey
Discrete time formulations and valid inequalities for a maritime inventory routing problem (P6)

09:30 H.N. Psaraftis and C.A. Kontovas
Slow steaming in maritime transportation: fundamentals, trade-offs, and decision models (P7)

10:00 Coffee Break

10:30-12:00 SESSION B2. The tempest

Chair: Bruce Golden

10:30 G. Pantuso G., K. Fagerholt K. and S.W. Wallace
Modeling challenges in maritime fleet renewal problems (P8)

11:00 N. Gausel, J.G. Rakke, K. Fagerholt and H.N. Psaraftis
Maritime Routing and Speed Optimization with
Emission Control Area Regulations (P9)

11:30 I. Gribkovskaia, E.K. Norlund and Y. Maisiuk
Routing and fleet sizing for offshore supply vessels (P10)

12:00 Lunch

13:30-16:00 SESSION C. The comedy of errors

Chair: Geir Hasle

13:30 S.W Wallace and R. Bai
Stochastic network design with rerouting (P11)

14:00 T. Krogh Boomsma, S. Røpke and M. Schiøtt Eckhausen
Solving the vehicle routing problem with stochastic demands by a branch-and-cut-and-price algorithm (P12)

14:30 F. Semet, S. Binart , P. Dejax and M. Gendreau
Reactive optimization methods for a field service routing problem
with stochastic travel and service times (P13)

15:00 Coffee Break

15:30 R. Eglese
Disruption management in vehicle routing: problems and models (P14)

16:00 J.D. Adler and P.B. Mirchandani
A Routing and Reservation System for battery swaps for
electric vehicles (P15)

18:30 Dinner

Tuesday June 3

08:30-10:00 SESSION D1. The taming of the shrew

Chair: Paolo Toth

08:30 T. G Crainic, P.K. Nguyen and M. Toulouse
Meta-heuristics for Synchronized Multi-zone Multi-trip Pickup and Delivery Problems (P16)

09:00 S. Voß
Some POPMUSIC Applications in Logistics (P17)

09:30 M. Dell'Amico, J. C. Díaz Díaz, G. Hasle and M. Iori
An Adaptive Iterated Local Search for the Mixed Capacitated General Routing Problem (P18)

10:00 Coffee Break

10:30-12:00 SESSION D2. Mighnight summer's dream

Chair: Marielle Christiansen

10:30 C. Archetti, N. Boland and M.G. Speranza
A matheuristic for the multi-vehicle inventory routing problem (P19)

11:00 G. Ghiani and E. Guerriero
A Lower Bound for the Quickest Path Problem (P20)

11:30 E. Uchoa, D. Pecin, A. Pesso, M. Poggi, A. Subramanian and T. Vidal
New Benchmark Instances for the Capacitated Vehicle Routing Problem (P21)

12:00 Lunch

13:30 Excursion to Maritime Museum and Kronborg Castle (Helsingør)

19:00 Banquet

Wednesday June 4

08:30-10:00 SESSION E1. As you like it

Chair: Grazia Speranza

08:30 R. Wolfler Calvo, P. Gianessi and L. Létocart
A New Exact Approach for the Vehicle Routing Problem with Intermediate Replenishment Facilities (P22)

09:00 L. Bertazzi, B. Golden, R. H. Smith and X. Wang
Min-Max vs. Min-Sum Vehicle Routing: A Worst-Case Analysis (P23)

09:30 R.G. van Anholt, L. C. Coelho, G. Laporte and I. Vis
An Inventory-Routing Problem with Pickups and Deliveries Arising in the Replenishment of Automated Teller Machines (P24)

10:00 Coffee Break

10:30-12:00 SESSION E2. All's well that ends well

Chair: Harilaos N. Psaraftis

10:30 D. Pecin, A. Pessoa, M. Poggi and E. Uchoa
Improved Branch-Cut-and-Price for Capacitated Vehicle Routing (P25)

11:00 S. Dabia, E. Demir, N.P. Dellaert, T. van Woensel and M. SteadieSeifi
A Branch-and-Price algorithm for the vehicle routing problem with time windows considering driving and working hour regulations (P26)

11:30 G. Desaulniers, F. Errico, S. Irnich and M. Schneider
Branch-price-and-cut algorithms for electric vehicle routing problems with time windows (P27)

12:00 Lunch

14:00 Departure

VENUE

ROUTE 2014 will take place at Comwell Borupgaard, Snekkersten, Denmark, from June 1 to 4, 2014. Comwell Borupgaard is located in a beautiful old park near the seaside 45 km north of Copenhagen and 3.5 km south of Helsingør (also known as Elsinore) and 350 m from a train station with direct train connection to Copenhagen Airport.

See here for more details: http://www.comwellborupgaard.dk/

Comwell Borupgaard

Nørrevej 80, DK-3070 Snekkersten

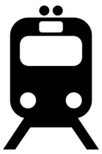
Tel. (+45) 4838 0333

The hotel is surrounded by a well kept park. It houses modern meeting- and conference facilities and offers some of the most luxurious spa facilities in Denmark. The hotel is within a reach of well known tourist attractions such as Kronborg Castle, Louisiana Museum of Modern Art, Fredensborg Palace and Rungstedlund. All these destinations are just a short drive from Borupgaard.

There are several ways to get to Comwell Borupgaard, all quite simple and time-saving.

From Copenhagen to Helsingør, take motorway E47.

The hotel offers free parking.



Trains are leaving directly from Copenhagen Airport Kastrup and Copenhagen Central Station to Snekkersten Station. The hotel is less than 350 metres away from the station.

It takes an hour from Copenhagen Airport and approximately 45 minutes from Copenhagen Central Station.

TRAIN JOURNEY PLANNER

Go to http://www.rejseplanen.dk/

Or see train schedule on next page. Please take the Øresund train, direction Helsingør when you are coming, and direction Copenhagen or Malmø when you are leaving. Note that the airport station is CPH Lufthavn.

Køreplan Timetable

Øresund

Gyldig fra 15.12.2013

DSB Øresund

Dag / Myldretid / Aften og lø-sø morgen	ma-fr 1 4.13-18.53 lø-sø 2 8.33-18.53	ma-fr 1 4.42-19.02 lø-sø 2 8.42-19.02	ma-fr 1 6.22- 8.42* 16.02-17.02	ma-fr 3 6.18- 7.18 15.18-17.58	alle dage 19.13-22.33 lø-sø 2 4.13-8.13	alle dage 22.53-23.33	alle dage 19.22-0.22 lø-sø 2 4.42-8.22	alle nætter 0.33-3.33	nat efter 4 fr og lø 1.22-3.22
Malmö C	13 33 53		22 42 02		13 33 53	53 13 33		33	
Triangeln	16 36 56		25 45 05		16 36 56	56 16 36		36	
Hyllie	21 41 01		30 50 10		21 41 01	01 21 41		41	
CPH Lufthavn ✈	34 54 14	42 02 22	42 02 22		34 54 14	14 34 54	22 42 02	54	22
Tårnby	38 58 18	45 05 25	45 05 25		38 58 18	18 38 58	25 45 05	58	25
Ørestad	40 00 20	48 08 28	48 08 28		40 00 20	20 40 00	28 48 08	00	28
København H ank.	48 08 28	56 16 36	56 16 36		48 08 28	28 48 08	36 56 16	08	36
København H	52 12 32	01 21 41	01 21 41	18 38 58	52 12 32		41 01 21	12	41
Nørreport	55 15 35	04 24 44	04 24 44	21 41 01	55 15 35		44 04 24	15	44
Østerport	59 19 39	08 28 48	08 28 48	25 45 05	59 19 39		48 08 28	19	48
Hellerup	04 24 44	13 33 53	13 33 53				53 13 33		53
Klampenborg		18 38 58	18 38 58				58 18 38		58
Skodsborg		23 43 03	23 43 03				03 23 43		03
Vedbæk		26 46 06	26 46 06				06 26 46		06
Rungsted Kyst		30 50 10	30 50 10	41 01 21			10 30 50		10
Kokkedal	18 38 58	34 54 14	34 54 14	45 05 25			14 34 54		14
Nivå	21 41 01	37 57 17	37 57 17				17 37 57		17
Humlebæk	25 45 05			50 10 30			21 41 01		21
Espergærde	29 49 09			54 14 34			26 46 06		26
Snekkersten	32 52 12		*Ikke	57 17 37			29 49 09		29
Helsingør ank.	36 56 16		30/6-8/8	01 21 41			34 54 14		34

1 Ikke 24/12-26/12, 31/12, 1/1, 18/4, 21/4 og 29/5.
2 Også 24/12-26/12, 31/12, 1/1, 18/4, 21/4 og 29/5.
3 Ikke 24/12-1/1, 17/4, 18/4, 21/4, 16/5, 29/5, 5/6, 9/6 og perioden 30/6-8/8.
4 Også nat efter 24/12, 25/12, 31/12, 16/4, 17/4, 20/4, 15/5, 28/5 og 8/6.

Renoveringen af Nørreport Station betyder, at hverken Øresundstog, Regionaltog eller IC-tog standser her hele døgnet alle dage til og med 21. april 2014. Alle S-tog og Metro standser på Nørreport Station.

DSB Øresund
Kundecenter
tlf. 70 13 13 11
Hele døgnet for billetter, trafikinformation, hittegods og meget mere....

DSB Øresund
Kundehenvendelser
Postboks 320
0900 København C
-modtager kun skriftlige henvendelser på adressen eller på dsboresund@dsb.dk

DSB Øresund
Rejsetidsgaranti
Postboks 320
0900 København C
-modtager kun skriftlige henvendelser på adressen eller på rejsetidsgaranti@dsboresund.dk

Dag / Myldretid / Aften og lø-sø morgen	alle dage 4.30-5.10	alle dage 4.38-5.16	ma-fr 1 5.43-19.43 lø-sø 2 8.43-19.43	ma-fr 1 6.01-20.01 lø-sø 2 9.01-20.01	ma-fr 1 6.01-6.41* 7.21* 14.21-17.21	ma-fr 3 6.36- 8.16 16.16-16.56	lø-sø 2 5.45-8.25 alle dage 20.05-0.05	lø-sø 2 6.21-9.01 alle dage 20.41-23.21	alle dage 23.52-0.32	alle nætter 1.01-4.01	nat efter 4 fr og lø 1.05-3.05
Helsingør		38 58 16	43 03 23		*Ikke	36 56 16	45 05 25				05
Snekkersten		42 02 22	47 07 27		30/6-8/8	39 59 19	49 09 29				09
Espergærde		45 05 25	50 10 30			42 02 22	52 12 32				12
Humlebæk		48 08 28	53 13 33			46 06 26	56 16 36				16
Nivå		52 12 32	57 17 37	01 21 41	01 21 41		01 21 41				21
Kokkedal		55 15 35	00 20 40	04 24 44	04 24 44	51 11 31	04 24 44				24
Rungsted Kyst		58 18 38		07 27 47	07 27 47	55 15 35	07 27 47				27
Vedbæk		02 22 42		11 31 51	11 31 51		11 31 51				31
Skodsborg		06 26 46		15 35 55	15 35 55		15 35 55				35
Klampenborg		10 30 50		19 39 59	19 39 59		19 39 59				39
Hellerup		15 35 55	15 35 55	24 44 04	24 44 04		24 44 04				44
Østerport	30 50 10	21 41 01	21 41 01	30 50 10	30 50 10	13 33 53	30 50 10	21 41 01		01	50
Nørreport	33 53 13	24 44 04	24 44 04	33 53 13	33 53 13	16 36 56	33 53 13	24 44 04		04	53
København H ank.	37 57 17	28 48 08	28 48 08	37 57 17	37 57 17	20 40 00	37 57 17	28 48 08		08	57
København H	40 00 20	32 52 12	32 52 12	40 00 20	40 00 20		40 00 20	32 52 12	52 12 32	12	00
Ørestad	46 06 26	38 58 18	38 58 18	46 06 26	46 06 26		46 06 26	38 58 18	58 18 38	18	06
Tårnby	49 09 29	41 01 21	41 01 21	49 09 29	49 09 29		49 09 29	41 01 21	01 21 41	21	09
CPH Lufthavn ✈	52 12 32	46 06 26	46 06 26	52 12 32	54 14 34		52 12 32	46 06 26	06 26 46	26	12
Hyllie		59 19 39	59 19 39		09 29 49			59 19 39	19 39 59	39	
Triangeln		02 22 42	02 22 42		12 32 52			02 22 42	22 42 02	42	
Malmö C ank.		06 26 46	06 26 46		16 36 56			06 26 46	26 46 06	46	

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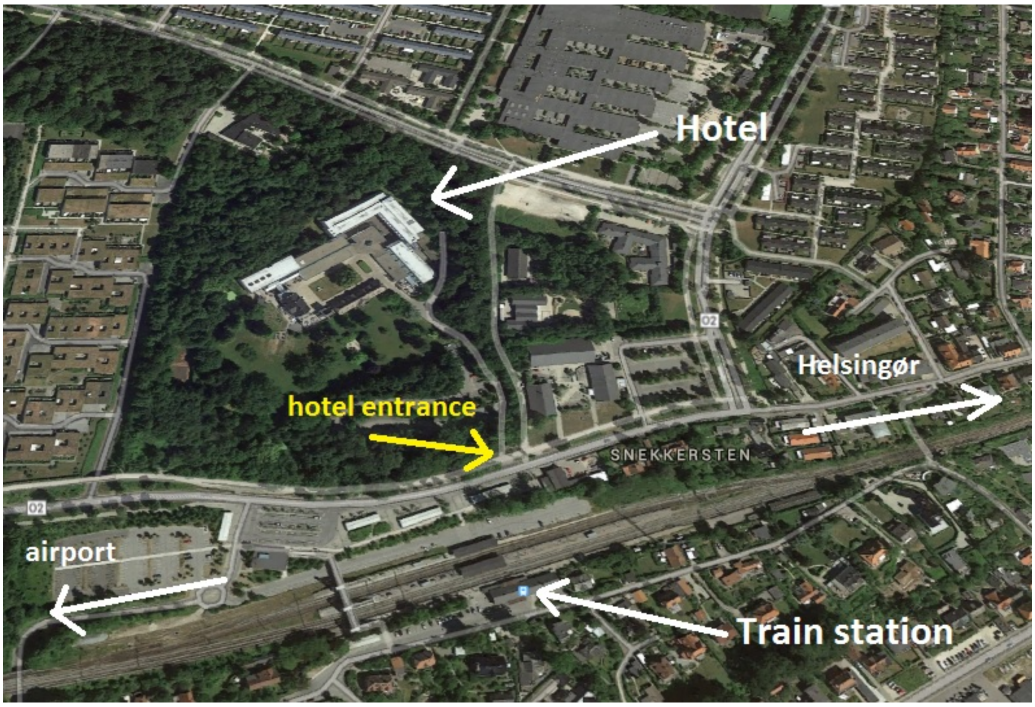
The hotel is just across the street from the Snekkersten train station, see map below.



EXCURSION

On Tuesday (June 3rd) there will be an excursion to the Kronborg Castle and the adjacent Maritime Museum.

Kronborg Castle

Hamlet's Castle in Elsinore

http://www.kronborg.dk/

Photo and Text © http://www.kronborg.dk

Kronborg Castle in Elsinore, is one of northern Europe's most important Renaissance castles. Known all over the world from Shakespeare's Hamlet, it is also the most famous castle in Denmark with about 200,000 visitors each year.

Experience one of Denmark's most important sights

King Frederik II built Kronborg in 1574-1585 at the narrowest neck of the Sound between Denmark and Sweden – the Renaissance counterpart of a modern motorway. Through it sailed trading vessels from all over the world and had to pay a tax, 'the Sound Dues' to the Danish King.

The myth of Hamlet

So how does Hamlet get into the picture? William Shakespeare must have heard or read about the legendary Danish Prince, and since Kronborg was already known all over Europe in the Renaissance, he probably thought 'That is Hamlet's castle'. Since the 17th century, innumerable theatre productions elsewhere in the world and at Kronborg have made sure the myth of Hamlet has been kept alive.

Maritime Museum of Denmark

Hamlets's Castle in Elsinore

http:// mfs.dk/en /

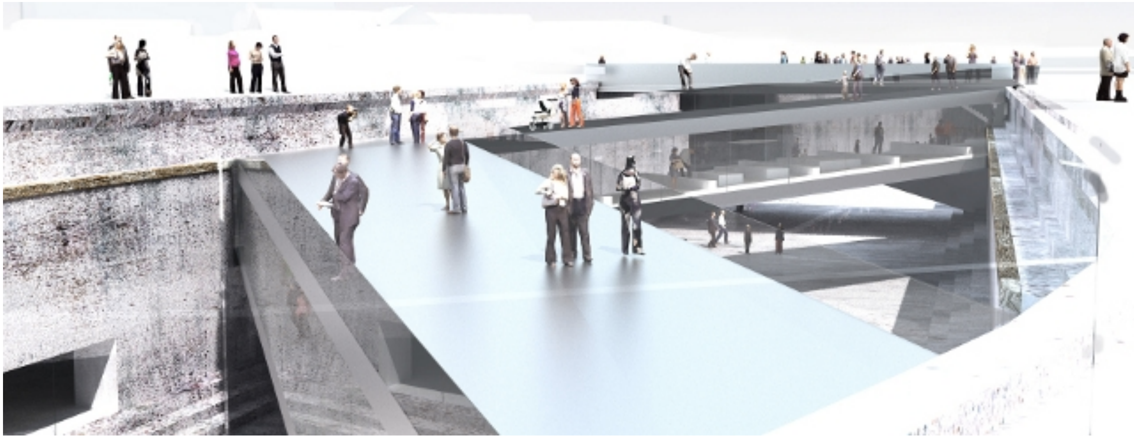


Photo and Text © http://mfs.dk

M/S Maritime Museum of Denmark is the Danish national maritime museum. The museum is a state-approved independent institution, primarily funded by the Danish Ministry of Culture.

The museum's patron is Her Majesty Queen Margrethe II.

Here you'll experience a colourful world with a whole range of exhibitions telling the story of Denmark as one of the world's leading shipping nations - of the past and present. The museum's maritime collections are presented in evocative and dramatic exhibitions, with films projected directly onto the architecture of the building.

Through thematic highlights we're whirled into the challenges of the oceans faced by those at sea, through the temptations of the ports, and back home at the heart of their families. We explore the myths of the life of the sailor, experience the role of the captain at the helm between the Danish colonies of the 1700s, and sit behind the desk of the shipping executive conducting world trade today. We follow the route of the many products in our supermarkets that have travelled thousands of nautical miles to reach us.

LIST OF PARTICIPANTS

Name	University
Allan Larsen	DTU Transport
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Bruce Golden	Robert H. Smith School of Business
Christos Kontovas	DTU Transport
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Thibault Vidal	Massachusetts Institute of Technology
Tom van Woensel	Eindhoven University of Technology

LIST OF ABSTRACTS

PRESENTER	PAPER	TITLE
Crainic	P 16	Meta-heuristics for Synchronized Multi-zone Multi-trip Pickup and Delivery Problems
Voss	P 17	Some POPMUSIC Applications in Logistics
Speranza	P 18	A matheuristic for the multi-vehicle inventory problem
Hasle	P 19	An Adaptive Iterated Local Search for the mixed capacitated general routing problem
Guerriero	P 20	A Lower Bound for the Quickest Path Problem
Uchoa	P 21	New Benchmark Instances for the Capacitated Vehicle Routing Problem
Desrosiers	P 22	Dual-guided pivot rules for linear programming
Golden	P 23	Min-Max vs. Min-Sum Vehicle Routing: A Worst-Case Analysis
Laporte	P 24	An Inventory-Routing Problem with Pickups and Deliveries Arising in the Replenishment of Automated Teller Machines
Poggi	P 25	Improved Branch-Cut-and-Price for Capacitated Vehicle Routing
van Woensel	P 26	A Branch-and-Price algorithm for the vehicle routing problem with time windows considering driving and working hour regulations
Desaulniers	P 27	Branch-price-and-cut algorithms for electric vehicle routing problems with time windows

A new polynomial algorithm for nested resource allocation, speed optimization, and other related problems.

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We propose an exact polynomial algorithm for a nested resource allocation problem with convex costs and constraints on partial sums of resource consumptions, in the presence of either continuous or integer variables. No assumption of strict convexity or differentiability is needed. This resource allocation problem, albeit extremely simple to formulate, appears prominently in a variety of applications related to production and resource planning, lot sizing, speed optimization in vehicle routing, and telecommunications. The fastest current method [D.S. Hochbaum. Lower and upper bounds for the allocation problem and other nonlinear optimization problems. *Mathematics of Operations Research*, 19(2):390-409, 1994] is based on a greedy algorithm and scaling concepts.

In the proposed new hierarchical decomposition method, solutions from sub-problems are used to convert constraints on sums of resources into bounds for separate variables at higher levels. The resulting time complexity for the integer problem is $O(n \log m \log (B/n))$, and the complexity of obtaining an ε-approximate solution for the continuous case is $O(n \log m \log (B/\varepsilon))$, n being the number of variables, m the number of nested constraints, ε a desired precision, and B the total resource. This matches the best-known complexity of Hochbaum (1994) when $m=n$, and improves it when $m = o(n)$.

Extensive experimental analyses are conducted with four recent algorithms on various continuous problems issued from theory and practice, demonstrating the high performance of

the proposed approach. All problems with up to one million variables are solved in less than one minute on a modern computer, and small-size problems of less than 100 variables are solved in a few milliseconds. This method can also significantly contribute to solve a variety of combinatorial optimization problems involving speed optimization sub-problems.

TITLE OF THE TALK

Non-Hamiltonian Formulations for the Single Vehicle Routing Problem with Deliveries and Selective Pickups

AUTHORS' NAMES AND AFFILIATIONS

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Manuel Iori, speaker, DISMI, University of Modena and Reggio Emilia, Italy, manuel.iori@unimore.it.

ABSTRACT

In one-to-many-to-one single vehicle routing problems, a single capacitated vehicle based at a central depot is required to perform some deliveries of a first commodity to a set of customers, and some pickups of a second commodity that has to be brought back to the depot. This class of problems is well studied in the literature because models several issues arising in reverse logistics.

The most representative problem of this class is probably the *single vehicle routing problem with deliveries and selective pickups* (SDSP). In the SDSP, each customer requires a delivery (linehaul customer), a pickup (backhaul customer), or both (combined-demand customer). While all delivery demands must be performed, pickup demands are optional and generate a certain revenue if performed. Moreover, the vehicle is allowed to visit either once or twice any combined-demand customer. The objective is to minimize the total cost, which is given by the total transportation cost minus the revenues generated by performing the pickup demands.

The fist mention to the problem is probably in [1], and since then a good research effort has been devoted to its solution. As far as we know, all mathematical formulations proposed in the literature attempt to produce a Hamiltonian tour by working on a modified network, which is obtained by splitting each combined-demand customer into two single-demand customers, a linehaul one and a backhaul one. This can result in a significant loss in performance, because the size of the network can be even doubled. Consequently, existing algorithms solved to proven optimality only instances with up to 22 combined-demand customers (see [2] and [3]), or 68 single-demand customers (see [4]).

In this work we focus instead on the original SDSP network and present new formulations that can yield non-Hamiltonian tours. Through the use of Benders decomposition and additional valid inequalities separated in a branch-and-cut framework, we are able to outmatch previous results in the literature, obtaining the optimal solution for all instances with up to 110 combined-demand customers.

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Dual-guided pivot rules for linear programming

Column Generation is only the *Primal Simplex* for huge problems. We are now dealing with routing and scheduling applications where master problems reach more than 10,000 rows. Degeneracy is the main issue during the solution process.

We describe a generic primal algorithm guided by dual feasibility considerations. The resolution process moves from one solution to the next according to an exchange mechanism that is defined by a direction and a post-evaluated step size. The core component of this direction is obtained via the smallest reduced cost that can be achieved upon dividing the set of dual variables in two subsets: one being fixed whiles the other being optimized. From a primal perspective, it is the selection of a convex combination of variables entering the basis. The most known special case is the *Primal Simplex* where all dual variables are fixed. Other special cases are, amongst others, the strongly polynomial *Minimum Mean Cycle-Canceling* algorithm for network flow problems for which all dual variables are optimized at every iteration, and the *Improved Primal Simplex* for which one fixes the dual variables associated with the non-degenerate variables, this choice yielding non-degenerate pivots only. Properties of this generic algorithm allow identifying subsets for the fixed dual variables that totally avoid degenerate pivots. Ultimately, we propose an interpretation in terms of a dynamic Dantzig-Wolfe decomposition from which emanates a vector space decomposition algorithm.

On the Fixed Charge Transportation Problem

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The *Fixed Charge Transportation Problem* (FCTP) is a generalization of the well-known *Transportation Problem*, where the cost for sending goods from origins to destinations is composed of a fixed cost and a continuous cost proportional to the amount of goods sent.

The FCTP is a special case of the *Single Commodity Uncapacitated Fixed Charge Network Flow Problem* (see [Ortega and Wolsey 2003]), which itself is a special case of the more general *Fixed Charge Problem* formulated by [Hirsch and Dantzig (1968)].

In practical applications, the fixed costs may represent toll charges on highways, landing fees at airports, setup costs in production systems, or the cost for building roads. Not only does the FCTP arise in distribution, transportation, scheduling, and location systems, but also in allocation of launch vehicles to space missions, solid-waste management, process selection, and teacher assignment.

Most of the exact methods proposed up to 2012 are based on a textbook mixed-integer programming formulation having continuous variables that represent the flow from origins to destinations and binary variables that model the usage the links between origins and destinations. [Agarwal and Anjea (2012)] studied the structure of the projection polyhedron of such a formulation in the space its binary variables. They developed several classes of valid inequalities, which generalize the set covering inequalities, and derived conditions under which such inequalities are facet defining. Their exact method could solve randomly generated instances with up to 15 sources and 15 sinks.

[Roberti, Bartolini and Mingozzi (2014)] introduced an integer programming formulation with exponentially many variables corresponding to all possible flow patterns from origins to destinations. They showed that the linear relaxation of this formulation is tighter than that of the standard mixed integer programming formulation. They also described different classes of valid inequalities and a column generation method to compute a valid lower bound embedded into an exact branch-and-price algorithm. Computational results showed that the proposed algorithm could solve instances with up to 70 sources and 70 sinks and outperformed the previous exact algorithms from the literature.

In this talk, we describe a new formulation of the problem that enhances the formulation proposed in [Roberti, Bartolini and Mingozzi (2014)]. This new formulation has exponentially many variables and a pseudo-polynomial number of constraints. Columns represent either flow patterns from origins to destinations or flow patterns from destinations to origins. Those two types of patterns are matched together through the constraints in order to have a valid formulation of the problem.

We show that strong lower bounds can be achieved by solving the linear relaxation of the new formulation with column generation and by adding a small subset of constraints. This

[1] Speaker

new bounds are, on average, better than the lower bounds provided by the formulation of [Roberti, Bartolini and Mingozzi (2014)]. The new bound is embedded into an exact branch-and-cut-and-price algorithm to achieve an optimal integer solution.

Computational results on benchmark instances from the literature show that the proposed exact algorithm outperforms the previous exact algorithms from the literature as well as the method of [Roberti, Bartolini and Mingozzi (2014)]. It is several time faster and can solve all instances unsolved by [Roberti, Bartolini and Mingozzi (2014)]. Moreover, it can solve much harder FCTP instances with up to 100 origins and 100 destinations in reasonable computing times.

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A matheuristic for the liner shipping network design problem considering transit time restrictions

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Abstract

The liner shipping network design problem (LSNDP) is to construct a set of cyclic services (routes) to form a capacitated network for the transport of containerized cargo. The network design maximizes the revenue of container transport considering the cost of vessels deployed to services, overall fuel consumption, port call costs and cargo handling costs. The liner shipping industry transports about 60% of the value of seaborne trade and inherently the lead time for a container transport incurs an inventory cost to the shipper. Therefore, the transit time of a container transport is an important parameter for a competitive liner shipping network. Literature on the LSNDP is quite scarce [3] compared to related maritime shipping transportation problems, but recent years showed increased interest in the LSNDP (Agarwal and Ergun [1], Alvarez [2], Reinhardt and Pisinger [7], Brouer et al. [3], Plum et al. [6]). Research on the LSNDP has focused on maximizing revenue through efficient capacity utilization and minimization of cost. A reference model for the LSNDP and a benchmark suite of liner shipping network instances was introduced by Brouer et al. [3]. The benchmark instances for the LSNDP without transit time restrictions have been solved by a heuristic column generator using a MIP to construct new routes in Brouer et al. [3] and by a composite matheuristic in Brouer et al. [4]. In the present work we will extend the matheuristic presented in Brouer et al. [4], which combines a greedy construction heuristic with an improvement heuristic fine tuning the current solution by solving an integer program (IP) for each service to identify a set of promising port call insertions and removals for each individual service. The transit time restrictions are not necessarily aligned with the desire to maximize utilization of the vessels in the network, and increases the complexity of the multi-commodity flow problem (MCFP), which needs to be solved repeatedly to evaluate a given network configuration. Solving the MCFP without transit time restrictions has been identified as a bottleneck in local search methods for the LSNDP in [2, 3]. Karsten et al. [5] introduce a time constrained multi-commodity flow problem and computational experiments are performed on liner shipping networks from the matheuristic of Brouer et al. [4] extending the evaluation of the network to consider transit time restrictions on each individual cargo flow. The time constrained multi-commodity flow problem restricts all cargo transports to respect the maximal transit time from *LINER-LIB 2012* for each commodity. The computational experiments of Karsten et al. [5] show that as little as 65% of the cargo, that could potentially be transported in an unconstrained network, can be met, when imposing time limits in the considered instances. In Karsten et al. [5] a reduction of the graph along with an extension to handle groups of commodities in a single pass of a resource constrained shortest path problem result in computationally efficient evaluation of a given network design. In this work we

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will present a reformulation of the reference model from Brouer et al. [3] to consider transit times for each individual commodity in the liner shipping network design problem with transit time restrictions (LSNDP-TT). We will extend the matheuristic of Brouer et al. [4] to consider transit time restrictions in the search. Computational results for the benchmark suite *LINER-LIB 2012* will be presented.

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Discrete time formulations and valid inequalities for a maritime inventory routing problem

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A single-product maritime inventory routing problem (MIRP) is studied in which one actor or cooperating actors in the maritime supply chain have the responsibility for both the transportation of goods and the inventories at the ports. The product is produced at loading (production) ports and consumed at discharge (consumption) ports. It is possible to store the product in inventories with time-dependent capacities at both types of ports. The production and consumption rates are deterministic but may vary over the planning horizon. There are berth capacities at the ports, limiting the number of ships that can load or discharge at the same time. A heterogeneous fleet of ships is used to transport the product. Each ship has a given capacity, speed and loading/discharge rate. The ships can wait outside a port before entering for a loading or discharge operation. In order to fit the short sea shipping segment with long loading and discharge times relative to the sailing times, the time in port depends on the quantity loaded or discharged. A ship can both load and discharge at multiple ports in succession. The initial position and load on board each ship is known at the beginning of the planning horizon. The planning problem is to design routes and schedules for the fleet that minimize the transportation and port costs and determine the load or discharge quantity at each port visited without exceeding the storage capacities.

In the presentation, we give an original discrete time model of the problem. Further, we discuss how this model can be reformulated to a pure fixed charge network flow (FCNF) model with side constraints. We have identified mixed integer sets arising from the decomposition of the formulations. In particular, several lot-sizing relaxations are derived for the formulations and used to establish valid inequalities to strengthen the proposed formulations. Until now, the derivation of models and valid inequalities for MIRPs has mainly been inspired by the developments in the routing community. Here, we will present some of these new valid inequalities obtained for MIRPs by generalizing valid inequalities from the recent lot-sizing literature.

Finally, we will present computational results for a set of instances based on real data, where we compare the original and FCNF formulations and the effectiveness of the valid inequalities.

Slow steaming in maritime transportation: fundamentals, trade-offs, and decision models

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Key words: slow steaming, speed optimization, economic speed, ship emissions

EXTENDED ABSTRACT

In recent times, increasing fuel prices and depressed market conditions have brought a new perspective to ship speed. For a variety of reasons, economic but also environmental, sailing at full speed may not necessarily be the best choice. In that sense, optimizing ship speed is receiving increased emphasis these days and is likely to do so in the years ahead.

Ships travel slower than the other transportation modes, but a basic premise has always been that there is value in ship speed. As long-distance trips may typically last one to two months, the benefits of a higher speed may be significant: they mainly entail the economic added value of faster delivery of goods, lower inventory costs and increased trade throughput per unit time. The need for higher speeds in shipping was mainly spurred by strong growth in world trade and development, and in turn was made possible by significant technological advances in maritime transportation in a broad spectrum of areas, including hull design, hydrodynamic performance of vessels, engine and propulsion efficiency, to name just a few. By extension, developments in cargo handling systems and supply chain management and operation have also contributed significantly to fast door-to-door transportation. However, this basic premise is being challenged whenever shipping markets are not very high and whenever fuel prices are not low. In addition, perhaps the most significant factor that is making a difference in recent years is the environmental one: a ship has to be environmentally friendly as regards air emissions. Because of the non-linear relationship between speed and fuel consumption, it is obvious that a ship that goes slower will emit much less than the same ship going faster.

Even for the simple objective to reduce fuel costs (and by extension emissions) by reducing speed, this can be done at two levels. The first level is technological (strategic), that is, build future ships with reduced installed horsepower so that they cannot sail faster than a prescribed speed. However, the first cellular containerships that went up to 33 knots in the late 1960s when fuel was cheap are gone forever. Maersk's new 18,000 TEU 'Triple-E'[1] containerships have a design speed of 17.8 knots, down from the 22 - 25 knots range that has been the industry's norm, and will emit 20% less CO_2 per container moved as compared to the Emma Maersk, previously the world's largest container vessel, and 50% less than the industry average on the Asia-Europe trade lane (Maersk, 2013).

[1] Triple-E stands for Economy of scale, Energy efficiency and Environmentally improved performance.

The second level is logistics-based (tactical/operational), that is, have an existing ship go slower than its design speed. In shipping parlance this is known as “slow steaming” and may involve just slowing down or even ‘derating’ a ship’s engine, that is, reconfiguring the engine so that a lower power output is achieved, so that even slower speeds can be attained[2]. Depending on engine technology, ‘slow steaming kits’ are provided by engine manufacturers so that ships can smoothly reduce speed at any desired level. In case speed is drastically reduced, the practice is known as “super slow steaming”.

In practice, super slow steaming has been pioneered by Maersk Line after it initiated trials involving 110 vessels beginning in 2007. Maersk Line North Asia Region CEO Tim Smith said that the trials showed it was safe to reduce the engine load to as low as 10%, compared with the traditional policy of reducing the load to no less than 40%-60% (TradeWinds, 2009). Given the non-linear relationship between speed and power, for a containership a 10% engine load means sailing at about half of the design speed. Furthermore, China Ocean Shipping (Group) and its partners in the CKYH alliance (K Line, Yang Ming Marine and Hanjin Shipping) were also reported to introduce super-slow steaming on certain routes (Lloyd’s List, 2009).

Slow steaming is not only practiced in the container market, although it may seem to make more sense there due to the higher speeds of containerships. Slow steaming is reported in every market. In December 2010, Maersk Tankers was reported to have their Very Large Crude Carriers (VLCCs) sailing at half their speed. The design speed of 16 knots was reduced to speeds less than 10 knots on almost one third of its ballast legs and between 11 and 13 knots on over one third of its operating days. For example, a typical voyage from the Persian Gulf to Asia normally takes 42 days (at 15 knots laden and 16 knots in ballast). Maersk Tankers decreased speed to 8.5 knots on the ballast leg, thus increasing roundtrip time to 55 days and saving nearly $400,000 off the voyage’s bunker bill (TradeWinds, 2010).

Slow steaming has also an important role on absorbing fleet overcapacity. Since early 2009, the total containership capacity absorbed due to the longer duration of total roundtrip time for long haul services has reached 1.27 MTEU in October 2013 (taking early 2009 as a starting point), based on Alphaliner’s latest estimates (Alphaliner, 2013). The average duration of Far East-North Europe strings had increased from 8 weeks in 2006 to 9 weeks in 2009 when slow steaming was first adopted. The application of even lower speeds has pushed the figure to 11 weeks currently as carriers continue to seek further cost reductions by adopting slower sailing speeds. The same phenomenon has been observed on Far East-Med strings, where the average duration has risen to 10 weeks, compared to only 7 weeks in 2006. As a record number of deliveries of new vessels is continuing to hamper the supply and demand momentum, analysts expect that slow steaming is here to stay. As a record number of vessels were scrapped in 2013; the idle fleet averaged 595,000 TEUs in 2013 compared to 651,000 TEUs in 2012. The lay-up of surplus box ships has been the worst and has lasted for the longest period since early 2009. The twin impact of extra slow steaming and longer port stays has helped to absorb much of capacity but it seems that

[2] Such a reconfiguration may involve dropping a cylinder from the main engine or other measures.

sailing at even slower speeds is not an option. A similar situation pertains to bulk carriers and tankers. Thus, slow steaming is here to stay for the foreseeable future.

The purpose of this paper is to examine the practice of slow steaming from various angles. In that context, some fundamentals are outlined, the main trade-offs are analysed, and some decision models are presented. Some examples are finally presented so as to highlight the main issues that are at play. Material in this paper is mainly taken from various papers and other documents by the authors and their colleagues, including Gkonis and Psaraftis (2012), and Psaraftis and Kontovas (2013, 2014).

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Modeling challenges in maritime fleet renewal problems

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The task of renewing the fleet of a shipping company is one of the most important strategic decisions in maritime transportation. Fluctuations in demand, ageing of vessels, and the development of new and more efficient technologies force shipping companies to decide whether, when and how to renew its vessel fleet. We refer to this as the *maritime fleet renewal problem* (MFRP). Basically, the MFRP is that of deciding how many and what types of ships to operate in each time period, as well as when and how to provide (or dispose of) ships in order to efficiently meet the future (uncertain) demand. The main emphasis is on fleet modification decisions that must be made here-and-now decisions taking into account the future evolution of the market (and consequently of the fleet). Since the problem is faced each time strategic planning is performed, future decisions are only meant as supporting information for the here-and-now fleet modification decisions.

Several alternatives are available when ships are to be provided. Ships can be built or can be bought in the second-hand market. Ships can also be chartered in on time or voyage charters. A number of disposal alternatives are also available. Ships can be sold in the second-hand market or scrapped. Furthermore, ships may be chartered out or be set on lay-up time, which consists of stopping the ship at a port with crew and engine activity reduced to safety levels.

To meet demand, the shipping company has to deploy its ships in order to transport the appropriate amount of cargo from origin to destination. The routing or deployment depends much on the transportation mode of the company, i.e. industrial, tramp or liner. We will refer to the Roll on – Roll off (RoRo) shipping case, which can be categorized as liner shipping, without much loss of generality. When solving the MFRP, we are not really interested in the routing or fleet deployment decisions in themselves. However, in order to find good estimations of the amount of transport work a fleet is able to perform, one also needs to model the deployment of the ships, at least at some high level.

The costs shipping companies meet are due to both providing and operating the fleet of ships. When ships are added to the fleet, costs for buying new or second-hand ships or chartering in ships are met. The value of ships depends on many factors including the state of the freight market. Similarly, also building prices and charter rates depend highly on the market. Fixed operating costs are paid for all the owned ships and consist mainly of manning, insurance, stores, maintenance and repairs, and administrative costs. These costs typically increase with age and are met even if the ship does not sail. When ships are set on lay-up time, fixed operating costs are reduced due to reduced crew and stores and the engine kept on a low regime. Fixed operating costs are paid also for the ships chartered out but not for those chartered in. Finally, variable operating costs are met when a ship sails, and consist of fuel costs, port and canal fees. Revenues are generated by the remuneration for the transportation services provided, coming either from long-term contracts or from spot cargoes. Additional revenues come from selling, scrapping or chartering out ships.

When shipping companies are to renew their fleets, only the current values of demand, new building and second-hand prices, and charter rates are known for sure. The future values of these elements are likely to be uncertain. Similarly, the future travel costs and scrapping values are also uncertain, being mainly dependent on bunker and steel prices, respectively. As far as fixed operating costs are concerned, their main driver is the crew cost whose value is still uncertain but somewhat more easily predictable and under the shipping company's control.

In order to explicitly handle the uncertainty regarding prices and market development, we have proposed a multi-stage stochastic programming model for the MFRP. The model's objective is to minimize the expected cost, while satisfying the shipping company's (uncertain) demand on each trade. The main decision variables represent how to renew the fleet. However, as mentioned above, we must also include variables for how to deploy the ships in the fleet.

We investigate whether uncertainty matters and what problem characteristics that strengthen or weaken the role of uncertainty. Results show that the benefits of using stochastic programming are tangible compared to solving a deterministic model using expected values of the uncertain parameters. We also analyze and discuss the trade-offs between the levels of detail in the modeling of the fleet deployment and the quality of the fleet renewal decisions obtained.

Maritime Routing and Speed Optimization with Emission Control Area Regulations

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1 Abstract

Shipping is the single most important mode of transportation when it comes to global trade, and around 80 percent of the total trade volumes and 70 percent of the total trade values are transported by vessels (UNCTAD, 2012). Although shipping is the most environmentally friendly mode of global cargo transportation it is still responsible for significant emissions of both traditional air pollutants (e.g. SO_x and NO_x) and greenhouse gases due to the size of the shipping operations. As a measure to reduce these emissions the International Maritime Organization (IMO) has introduced restrictions on emissions to air in certain areas of the world seas. These areas are called Emission Control Areas (ECA), see Figure 1.

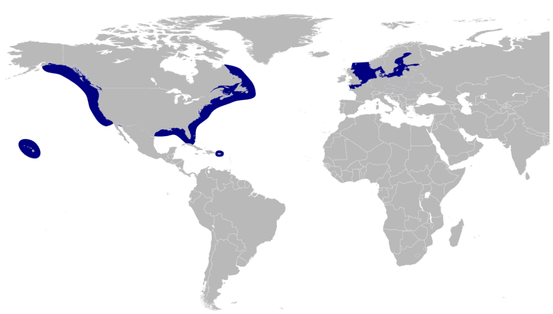

Figure 1: Emission control areas.

In the ECAs the restrictions on emission are primarily achieved by limiting the maximum content of different substances in the fuel oils loaded, bunkered, and subsequently used onboard. As a result the vessels equipped with dual fuel engines will use cheap and "dirty" fuel oils outside, and more expensive and cleaner fuel oils inside the ECAs. For shipping companies this may lead to choosing different sailing paths and speeds than it would have done without the ECAs in order to minimize the total fuels costs. These new sailing paths and speeds might actually lead to higher global emissions of certain gases, and less effective shipping. Abatement technologies are available to allow vessels to use the same fuel both inside and outside ECAs,

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but they include major modifications of the vessels and they demand investments of both money and time. Some vessels may also be deemed unfitted for such modifications. As a result of this it is unlikely that all vessels operating in the ECAs will have abatement technologies installed in the near future. In the the remainder of this work the focus will be on the case where vessels switch fuel types when entering/leaving EACs.

The problem studied consists of finding the optimal route between a set of customers ports that may or may not have time windows for start of service, decide the optimal sailing legs, and the speeds along these legs under the objective of minimizing fuel costs. A sailing leg is defined as a connection between two ports and optimizing the speed used when sailing this is becoming an increasingly important problem in shipping due to high bunker prices and emission reduction, see for instance Fagerholt et al. (2010) and Psaraftis and Kontovas (2013). However, because of ECAs, a shipping company might decide to increase the total length of a sailing leg in order to reduce the distance traveled within the ECA(s), or the speed may differ on the stretch inside and outside the ECA. In the literature, a sailing leg is usually considered a fixed distance or duration between two ports and there is only one possible connection between two ports. Due to the need to select different sailing legs and speeds between ports based on cost and speed choices, a sailing leg is in this work considered to be a sequence of one or more stretches, or parts, with fixed distances. This is to separate the distance sailed within ECAs from other. The rationale for this is that you might want to increase speed when using heavy fuel oils in order to slow down when switching to more expensive fuel oils. Speed optimization under ECA regulations was also studied in Doudnikoff and Lacoste (2014), but there the authors assumed a fixed route with given sailing legs. We present mathematical models for number of scenarios where routes and speed for a single vessel must be decided. The models have been solved using a commercial solver, and the results and their implications are discussed.

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Routing and fleet sizing for offshore supply vessels

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In this talk we address the supply vessel planning problems arising in the servicing of oil and gas offshore installations on the Norwegian continental shelf. Supply vessels provide offshore installations with necessary supplies on periodic basis from an onshore supply base according to the weekly sailing schedules. A schedule is usually valid for a finite number of weeks before another schedule is developed due to the changes in installations' locations or their activities. We present four speed optimization strategies for the generation of green vessel schedules, and the simulation-based tool for the evaluation of strategies under the weather uncertainty. The second study is related to the annual supply vessel fleet sizing with discrete-event simulation. Rerouting and other operational strategies improving robustness of schedule are also studied.

Supply vessel planning on a weekly basis is a fleet mix and periodic vehicle routing and scheduling problem. Each installation requires one or more visits per week, and vessels sail one or more voyages during a week. Vessels departures from the supply base are planned at a fixed times and should be evenly spread throughout the week. Some of the installations are closed at night, yielding multiple time windows. To generate a minimal cost and green weekly schedules, a two stage optimization procedure is applied. In the first stage, a multi-period TSP with multiple time windows is solved with a constant speed to generate a shortest duration voyage for each vessel and each set of installations. Then, we apply speed optimization strategies to find optimized speed on each voyage leg by utilizing waiting time within the voyage. The speed optimized voyages are then used as an input to a set covering model that determines the vessels' voyages to use in the weekly schedules by assigning voyages to start days. A cost minimization objective including vessel charter and voyage fuel costs is used to achieve a weekly schedule with low emissions and a minimal number of vessels. The tests of applying speed strategies during weekly schedule generation show up to 25% less emissions on Statoil instances with 5 to 10 installations. Speed optimization applied a posteriori only on voyages from the optimal weekly schedule yield similar or slightly worse results. One of the strategies currently implemented by the largest Norwegian oil and gas operator Statoil yields around 10% fuel consumption reduction, resulting in 900 tons less CO_2 emissions for a single vessel per year.

Weather conditions are a main uncertainty factor in supply vessel planning since sailing time and service duration at offshore installations are weather dependent. To evaluate the performance of the speed optimization strategies, each speed optimized voyage is simulated accounting for sailing speed reduction and increase in service duration based on the generated weather data. The output of simulation yields a discrete distribution of voyage duration and corresponding average fuel consumption. The optimization model is then solved for a number of runs with different input sets of voyages randomly selected with respect to voyage duration distributions. Test results demonstrate that by taking weather uncertainty into account in speed optimization it is possible to achieve up to 22% less emissions. Application of some speed optimization strategies with weather simulation show even larger emissions reduction compared with the deterministic green schedule planning. Output analysis from schedule simulation under stochastic weather conditions allows for schedule local improvement by voyage rerouting and reassignment of voyages.

The number of vessels operating from a supply base varies during the year according to summer and winter schedules. The company hires two types of vessels to perform supplies to installations; time-charter vessels are hired in advance and have a long-term commitment period, while spot vessels are hired on an ad hoc basis. The daily rates for spot vessels may be significantly higher than for time-charter vessels. The optimal number of time-charter vessels to be hired for a year has a strong economic effect on the total annual vessel costs as supply vessels are rather expensive. The dependence of supply vessels' operations on weather conditions makes the fleet sizing problem highly stochastic. Due to impossibility to describe and model the stochastic phenomena analytically, a discrete-event simulation model is developed to evaluate alternative fleet size configurations for an annual time horizon taking into consideration uncertainty in weather conditions and future spot rates. The model simulates a sequence of voyages planned in the annual vessel schedule. The execution of the voyages depends on weather conditions which influence voyage duration. Because of the bad weather duration of a voyage scheduled for a vessel may be longer than allowed, so that this vessel cannot return to the base in time to start its next planned voyage. The voyage is then performed by another vessel, either an available time-charter vessel or a spot vessel. The system state of the model is characterized by the number of vessels being used offshore. Events changing the state of the system are considered to be voyage start events and voyage end events. By experimenting with various numbers of time-charter vessels and examining total annual vessel costs, the optimal number of time-charter vessels minimizing total annual vessel costs is determined. Significant wave height is used as a measure to quantify stochastic weather conditions influencing on possibility and duration of vessel's service at installations, and significant wave height and mean wave direction represent measures to quantify vessel's sailing speed reduction. The model is validated and tested on a real instance with 22 installations provided by the company. The simulation results confirmed the cost-efficient number of time-charter vessels employed by the company in reality.

The weekly vessel schedule is robust if all installations on planned voyages are visited. Adverse weather conditions decrease the robustness of the schedule. In practice, for each voyage a sequence of visits to the installations is adjusted according to the operational weather forecast. The problem is then to evaluate the robustness of the schedules with the simulation model and to analyze how operational rerouting against bad weather conditions restores the schedule robustness. The model simulates voyages as sequences of visits to installations as stated in the schedule. Rerouting is used to generate for each scheduled voyage a sequence with maximum possible number of installations visits within planned voyage duration. The system state of the model is characterized by the number of unperformed visits to installations. Events changing the state of the system are considered to be visits not performed in voyages. The performance measure is the percentage of completed visits, the experimental design factor is the fixed number of time-charter vessels. The simulation model is validated and tested on real summer and winter vessel schedules. The application of the rerouting module increases the number of completed visits by at least 56%.

Some installations visits may not be performed as planned due to bad weather conditions. Several operational strategies (insertion of visits into next planned voyage, scheduling ad hoc voyages to visit several installations with not performed visits, scheduling ad hoc single installation voyages) are developed in order to maximize the number of these visits to be performed later within a lead time at minimal cost. The discrete-event simulation models are developed to implement the strategies. The experimental design factor is the number of time-charter vessels hired for a year, the performance measures are the percentage of visits completed and the total annual vessel costs. A comparative analysis of the simulation outputs is conducted on a real instance.

Stochastic network design with rerouting

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Service network design under uncertainty is fundamentally crucial for all freight transportation companies. The main challenge is to strike a balance between two conflicting objectives: low network setup costs and low expected operational costs. Together these have a significant impact on the quality of freight services. Increasing redundancy at crucial network links is a common way to improve network flexibility. However, in a highly uncertain environment, a single predefined network is unlikely to suit all possible future scenarios, unless it is prohibitively costly. Hence, rescheduling is often an effective alternative.

The main contribution of this paper is two-fold: primarily, we propose a stochastic programming model for stochastic service network design with options of both vehicle rerouting and service outsourcing to address demand stochasticity more efficiently. Secondly, some interesting observations and insights drawn from our experimental studies could have important implications for stochastic service network design practices. Application of the proposed model could potentially substantially reduce network setup costs and expensive outsourcing, but maintain a similar level of flexibility to those that can be offered by other related models in the literature.

We set the model in the framework of stochastic programming. The main result is a model that provides a design with operational flexibility that can handle varying demand scenarios. This operational flexibility can be useful also if the stochastics is mis-specified, i.e. is different from what we assume. However, in this paper the focus is not on ambiguity (interesting as that is), but rather on understanding the role of rerouting and its effect on operational flexibility. It is also worth noting that for many applications that fit into this modelling scheme, particularly trucking, but also air airfreight transportation, data is normally available in large amounts, and estimating distributions is not unreasonable.

As for earlier papers, we have formulated our model in a two-stage setting. This is not primarily for simplicity, but because we see this as the most appropriate framework. The problem we are discussing in this paper is what has been called an ``inherently two-stage problem'', see Chapter 1 of King and Wallace (2012). These are problems where the first stage is structurally different from all the others. In our case, the first stage is to set up the service network, the rest amount to using/operating the network from Stage 1 in an uncertain environment. Typically, the first stage decisions are either expensive or irreversible (or both). For such models, the focus is on Stage 1, all the other stages are there only for creating a correct understanding of how the network will be operated, so as to get the network set up correctly. The clue of such models is the flow of information from the operational phase to the design phase. It is important to realize that the later stages are not interesting in their own rights; it is quite clear that once the service network is established, a much more detailed model will be developed for operational decisions. So the quality of how we model the operational phase should be based on its ability to feed back to the Stage 1 decisions, and not on its ''accuracy''. In this regard we are also following earlier work, such as Lium et al. (2009). So although the use of the service network in principle is an infinite horizon problem (or maybe just one with a very large but finite number of stages) representing the life of the design, we represent it with weekly snap-shots (scenarios) of demand patterns. For each scenario we model the transportation, including rerouting (and route recovery) of vessels and outsourcing of goods. This is of course an approximation (like all models are), but describes well the setting in which the service network must operate. So for this kind of models, it is actually a goal to avoid the multi-stage aspect of the real problem. That contains many details which are not needed for setting up the network. Only when we reach the operational phase itself do we need to care about the small details related to the fact that the operations take place in a dynamic environment.

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Solving the vehicle routing problem with stochastic demands by a branch-and-cut-and-price algorithm

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The vehicle routing problem with stochastic demands (VRPSD) is defined on a graph $G = (V, E)$. The nodes V of the graph consist of a depot node (node 0) and n customer nodes $V_c = \{1, \dots, n\}$. The demand of each customer $i \in V_c$ is given by a stochastic variable ξ_i with known distribution. It is assumed that the stochastic variables are independent and follow the same distribution, but that the parameters describing the distributions may be different. In the following we will think of the customer demand as an amount of goods that we need to pick up. The customers are served by a homogeneous fleet of vehicles with capacity Q. It is typically assumed that all routes must satisfy that the total expected demand of the customers on the route is less than Q. The VRPSD is formulated as a two-stage stochastic recourse problem. In the first stage we plan routes for the vehicles without knowing the actual demands. In the second stage we carry out the plan and the actual demands are revealed. During stage two we may encounter routes where we reach a customer and are unable to pick up his full demand because the capacity of the vehicle is reached. In that case we will resort to a simple recourse action which consists of filling up the vehicle at the customer, driving back to the depot to empty the vehicle, returning to the customer to pick up the remaining load and then continue on the route. The objective of the VRPSD is to design the routes in stage 1 such as to minimize the expected cost (e.g. distance driven) of the stage 2 solution.

The VRPSD has received considerable attention in the literature, but far less than its deterministic sibling, the capacitated vehicle routing problem (CVRP). State of the art exact methods for solving the VRPSD are proposed in Laporte et al. [2002], Christiansen and Lysgaard [2007] and Jabali et al. [2012]. The methods proposed by Laporte et al. [2002] and Jabali et al. [2012] use branch-and-cut algorithms based on the integer L-shaped algorithm while the method proposed by Christiansen and Lysgaard [2007] use branch-and-price. In this talk we follow the branch-and-price approach. The VRPSD is formulated as a set partitioning problem:

$$\min \sum_{p \in \Omega} c_p x_p$$

subject to

$$\sum_{p \in \Omega} a_{ip} x_p = 1 \qquad \forall i \in V_c$$

$$x_p \in \{0, 1\} \quad \forall p \in \Omega$$

where Ω is the set of all feasible routes, x_p is a binary decision variable that indicates if route $p \in \Omega$ should be included in the solution, c_p is the expected cost of route p and a_{ip} is a parameter that indicates if customer $i \in V_c$ is served on route $p \in \Omega$. Since the model quickly grows very large its linear programming relaxation is solved by column generation and the resulting lower is used in a branch-and-price algorithm. In the column generation algorithm we need to generate routes that have negative reduced cost given a current set of dual variables. Note that the computation of the reduced cost of a route also includes the computation of the expected cost of the route. Christiansen and Lysgaard [2007] proposed to solve a relaxed version this problem using an ordinary shortest path algorithm in a expanded network. We show how this approach can be translated into an ordinary labeling algorithm for a resource constrained shortest path problem. We show that the resulting dominance criterion can be significantly improved for stochastic demands that follow a Poisson distribution (the case considered in Christiansen and Lysgaard [2007]). Furthermore we improve the LP relaxation by using the concept of ng-routes proposed by Baldacci et al. [2011] that imply that the routes returned by the pricing sub-problem are close to being elementary. On top of this we add valid inequalities known for the CVRP to further improve the LP relaxation of the set partitioning formulation. We use the CVRPSEP package by Lysgaard [2003] for this purpose.

Christiansen and Lysgaard [2007] tested their algorithm on 40 instances derived from standard CVRP instances and were able to solve 19 of these. The algorithm presented in this talk solves 39 of the 40 instances (albeit on a more modern computer and allowing more computing time). These results and results on a wider set of instances are presented in the talk.

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Reactive optimization methods for a field service routing problem with stochastic travel and service times

Frédéric SEMET, Sixtine BINART, Pierre DEJAX , Michel GENDREAU

1. The problem

In this talk, we consider a single period problem in which a service company must design tours for its field technicians in order to provide specific services to its customers in the most cost-effective fashion. Each tour (or route) corresponds to the sequence of customers that a given field service technician is scheduled to visit during that period.

A key feature of the problem is that both travel times between locations and service times of customers are stochastic. Furthermore, customers are divided into two types: mandatory and optional. Optional customers can be served at anytime during the planning horizon and may be postponed at any time to a future period. Mandatory customers have an associated hard time window during which they must be served.

We associate with each technician a vehicle and we suppose that this vehicle has unlimited capacity, its own origin and destination depots, and must return to its destination depot by the end of the period (hard time window). The objective is to visit as many optional customers as possible while minimizing the total travel time and visiting all mandatory customers.

To deal with the stochastic travel and service times, we consider reactive optimization approaches in which planned routes are adjusted in real-time. In particular, we allow technicians to drop optional customers from their route, in order to meet time windows at the mandatory customers and at the destination depots.

This problem is closely related to the deterministic multi-period technician routing problem with time windows problem dealt by Tricoire [3] and Bostel et al. [1]. Indeed, the problem that we are addressing is a single period variant of their problem with stochastic travel and service times.

2. Solution approaches

To solve this problem, we propose two different solution approaches consisting in a planning stage followed by an execution stage. In the planning stage, we assume that minimal, modal and maximal values for travel and service times are known a priori and we use these values to build routes (ensuring that, in the worst case, we can serve all the mandatory customers that have been planned without any delay). In the execution stage, we use a dynamic programming algorithm to determine the optimal policy, given the realization of the stochastic values for travel and service times.

In the first method, we first build a set of good quality routes containing optional and mandatory customers, using a dynamic programming based heuristic (inspired from Righini and Salani [2]). Then, we select among them one route for each vehicle by solving exactly an integer program. In the second one, we use a column generation based method to build routes. In this method, the subproblem consists, for each vehicle, in building feasible routes containing both optional and mandatory customers, whereas the master problem consists in assigning a feasible route to each vehicle, while ensuring that each mandatory customer is served at least once and that each optional customer is served at most once.

3. Experimental results

The proposed solution approaches have been tested and validated on instances based on realistic data. Simulations were also run to assess the effectiveness of these approaches with stochastic travel and service times. Results from the computational experiments and the simulations will be reported and discussed. The comparison with a previously implemented two-stage method will be made.

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Disruption management in vehicle routing: problems and models

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Abstract

When distributing goods from a depot to a set of customers, a route and schedule for each delivery vehicle is normally planned that will take into account the customer requirements and constraints such as the capacities of the vehicles and time windows for deliveries. However, after that plan has started to be executed, there may be different types of disruption that mean that the original plan is no longer feasible. Disruption management refers to the process of revising the original plan to reflect the new situation which minimizes the negative impact of the disruption.

In vehicle routing problems, disruptions may occur due to several different types of situations such as vehicle breakdowns, traffic congestion due to accidents, delays in receiving supplies at the depot and other unexpected events. In each case, the best response to the disruption will depend on further details of the distribution problem that is being considered and the relevant objectives for managing the disruption that may include additional costs to customers or the distributor due to deviating from the original plan.

The paper will consider examples of disruption management in vehicle routing, showing how the characteristics of the problem can affect the structure of the resulting optimization model.

In Mu et al. (2011) disruption management is considered when a single vehicle breaks down before it has completed all its deliveries. The case is considered where the delivery is of a single commodity (such as gas containers or oil) that is the same for all customers. This means that any vehicle can be diverted to serve any customer after leaving the depot. Taking the objective to be proportional to the total distance travelled by the vehicles, it is shown that the structure of the disruption management problem is equivalent to an Open Vehicle Routing Problem where each vehicle has a fixed starting point and finishing point at the depot. Two heuristic algorithms are devised and tested based on Tabu Search approaches and compared with results from an exact algorithm.

Mu and Eglese (2013) considers disruption management when there is a delay in orders being released at the depot which means that some, but not all vehicles can leave at the planned time. The objectives considered in the disruption management

problem include minimizing the delays to expected delivery times and minimizing the overtime required for drivers, as well as minimizing costs proportional to the total distance travelled. The structure of the disruption management problem has distinctive features that involve multiple trips for vehicles and the need to consider waiting times.

Zambirinis and Eglese (2014) consider disruption management for the case of a single vehicle breakdown, where the items carried by each vehicle from the depot are for specific customers on the vehicle route (for example in a home delivery operation). This means that to deal with the disruption, the broken down vehicle must be visited by any other vehicle that will take over the delivery of any of its undelivered items and the undelivered items will be transferred to the other vehicle before being transported to the appropriate customer. Minis et al. (2012) have considered this problem and devised a heuristic that has been tested in a real-time fleet management system. Zambirinis and Eglese (2014) provide a mixed integer linear programming formulation for this problem. Features of the formulation and the structure of the problem will be discussed.

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A ROUTING AND RESERVATION SYSTEM FOR BATTERY SWAPS FOR ELECTRIC VEHICLES

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EXTENDED ABSTRACT

The environmental, geopolitical, and financial implications of the world's dependence on oil are well known and documented, and much has been done to lessen our dependence on gasoline. One thrust on this issue has been the embracing of the electric vehicles as an alternative to gasoline powered automobiles. These vehicles have an electric motor rather than a gasoline engine, and a battery to store the energy required to move the vehicle. For many electric vehicles, such as the Nissan LEAF or Chevrolet VOLT, the method of recharging the vehicle battery is to plug the battery into the power grid at places like the home or office [1]. Because the battery requires multiple hours to fully recharge, this method has the implicit assumption that vehicle will be used only for driving short distances. Electric vehicle companies are trying to overcome this limited range requirement with *battery-exchange stations*. These stations will remove a battery that is nearly depleted from a vehicle and replace the battery with one that has already been charged [2]. Once the depleted battery is dropped off at the station it is charged until full so that a different vehicle can use it in the future. This method of refueling electric vehicles has the advantage that it is very quick for each vehicle since the driver only has to wait for the battery to be swapped and not for the battery to be charged. The electric vehicle company Tesla Motors Inc., which currently sells plug-in electric vehicles, has recently shown a prototype vehicle with battery-exchange technology [3].

In this research we devise an algorithm for real-time routing of electric vehicles with swappable batteries that balances the desire for drivers to have quick trips with the need for the operating company to balance the battery swap loads across the stations. Further, the algorithm will make reservations for each vehicle at all of the battery-exchange stations on the desired route. Making reservations will remove the possibility that the batteries the vehicle expected to receive are unavailable due to other vehicles taking them. The objective of the routing and reservation algorithm is to minimize the total expected travel times of not only the vehicle being routed, but of future vehicles as well. Because of this objective, part of the routing and reservation process is to understand how a set of battery reservations could affect future arrivals into the system. This objective also creates situations where drivers may be routed in ways that cause them to go slightly out of their way, leaving batteries available at stations for other vehicles to use.

The routing and reservation system would make the route suggestion based on the current battery charge levels at each station along with the pre-existing reservations made by earlier vehicles, which would be stored in the central server. The model in this research assumes that when the vehicle turns on it will be provided with a single route from the routing and reservation system, and that the driver will take the given route exactly. The steps in this routing and reservation process for each vehicle would be:

1. When the electric vehicle is turned on, the driver would input a destination into the vehicle's system unit. This, combined with the origin of the trip determined by the GPS location of the vehicle, would be sent to the central server.
2. The central server receives this origin and destination (OD) pair and, using the current battery levels at the stations and the reservations already made, determines which route the vehicle should take and when and where the vehicle should stop to swap its battery.
3. The central server makes reservations for the batteries at each of the stations for the most convenient times the vehicle would require it, subject to availability.
4. The central server sends the selected route and reservation times to the unit onboard the vehicle, and the driver begins to travel the route.

We model the system as a *Markov Chance-Decision Process* (MCDP) where the states describe the current reservations at the stations and the actions are routing the vehicles that arrive. In the case of routing electric vehicles through a network with reservations, during each interval of time it is unknown whether or not a vehicle will arrive needing to be routed, and if it does arrive what its OD pair will be. When a vehicle does arrive, its OD pair becomes known and the algorithm routes it precisely, and given the routing and reservations made the new state of the system is then exactly known. Then one time step occurs and a new vehicle may arrive; this process is repeated until the end of the day.

While value iteration and other standard Markov decision process techniques can be used on MCDPs, in both cases the algorithms that find the optimal policy become intractable for a large number of states. The problem of routing and reserving batteries for electric vehicles has an immense number of states due to the possible reservations times at each station. Thus, we turn to Approximate Dynamic Programming (ADP) [4] to find a policy for the MCDP that routes the vehicles effectively without being optimal. Here we still attempt to find the value of each state of the MCDP, only now we accept approximate solutions for the values. In the case of the network routing and reservation problem the value of a state represents the estimated delay penalties of all of the future arrivals.

We use the ADP technique of temporal differencing with a linear model. Dynamic programming requires the calculation of the value of the system in each possible state, and each state can have a unique and independently calculated value. If the values of the states are approximated in such a way that we utilize the similarities of the states, the calculation for all of the state values becomes tractable. Thus, by approximating the values of each state future by using a linear combination of basic functions the problem becomes feasible to solve. The temporal differencing allows us to effectively update the values of each state using information generated from simulating the current best policy. For our basis functions we used, for each station and number of batteries up to the total at the station, the amount of time between the current time and the end of the day that the station has at least that number of batteries unavailable.

We tested the algorithm to determine the amount of savings the algorithm would provide compared to the greedy policy and the run time of the algorithm. The test data was the Arizona state highway network from Upchurch et al. [5]. In that paper Upchurch, Kuby, and Lim had a charging station located in each of the 25 cities in the network plus an addition 25 stations located on longer roads between cities. They also used a gravity based demand model to determine the amount of vehicles wanting to traverse each OD pair between cities. The gravity was a function of the population of the OD cities and the length of the shortest path between them. They assumed that the electric vehicles would have a battery that allows them to travel 100 miles before recharging.

Figure 1 shows a comparison of the amount of delay incurred due to detours and waiting in the policy generated by the algorithm versus having each driver take the shortest path available to them. The different arrival probabilities indicate the probability of a vehicle arriving at each time step. For arrival probabilities between 0.05 and 0.1 the algorithm substantially lowered the amount of delays. When the arrival probability was 0.025 there were no delays at all (and thus the greedy policy was optimal). When the arrival probability was greater than 0.1 there were too many cars so all of the vehicles had to wait until the end of the day before a battery was ready, and so the algorithm was ineffective.

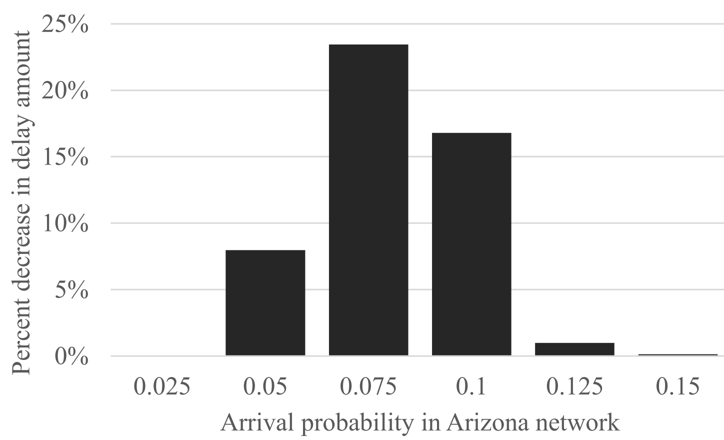

Figure 1: a comparison of the algorithm vs. the greedy policy runs on different random networks

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Meta-heuristics for Synchronized Multi-zone Multi-trip Pickup and Delivery Problems

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We study the *Multi-zone Multi-trip Pickup and Delivery Problem with Time Windows and Synchronization* (*MZT-PDTWS*). In this setting, a homogeneous fleet of vehicles operates out of a single garage to perform multiple sequences of delivery and pickup of customer-specific loads. Loads to be delivered are available at particular facilities during particular operating time intervals, and service at the corresponding customers must be performed within their specified hard time windows. Similarly, loads available at (the same or different) customers within their particular hard time windows, must be collected and brought to one of the available facilities during its particular operating time interval. Vehicles must synchronize their arrivals at facilities with the respective operating time periods, that is, time windows at facilities are hard and vehicles are not permitted to arrive in advance and wait. A number of waiting stations may be used by the vehicles to wait for the next visit at a facility. We assume a *pseudo-backhaul* operating policy (Crainic et al., 2012a) in this paper, i.e., all loads collected at a facility must be delivered before a pickup sequence may be initiated. The goal of the MZT-PDTWS is to determine when and where to deliver the loads present at customers, as well as construct the set of routes and assign them to particular vehicles, providing timely customer service and synchronized arrival at facilities, minimizing the total cost made up of the (variable) costs of operating vehicles and the (fixed) costs of using them.

The time-dependency characterizing demand in the MZT-PDTWS translates into two phenomena. The first concerns facilities, which become available for work at particular time periods only, with a set of loads destined to specific customers and ready to receive collected loads. A given facility may be available at several periods during the planning period considered, with a different operating time and set of loads at each occurrence. To model this time dependency, we define *supply points* as particular combinations of facilities and availability time periods. A supply point is characterized by a set of loads to be delivered to particular customers, and by a no-wait hard time window, meaning that vehicles cannot arrive before the beginning of the time window and wait for the opening of the facility, nor after the end of the time window by paying a penalty. This synchronization requires that vehicles that would arrive earlier than the appointed time go to a *waiting station* (e.g., a parking lot) and wait for the appointed time. When this waiting is deemed uneconomical or no waiting station is available, the vehicle returns to the garage to finish its route.

The second phenomenon concerns customers, which may receive several loads, at different time periods from different facilities, or ship loads at various points in time through a facility to be chosen within a given set, or perform both activities during their operations. We model the type of activity and time dependency associated to each particular load by identifying it as either a *delivery-customer demand* or a *pickup-customer demand*. A delivery-customer demand is characterized by the supply point where it is available for delivery, the customer it must be delivered to, and the time window when the delivery must be performed. A pickup-customer demand is characterized by the customer shipping it and the time window within which the pickup must be performed, as well as by a set of facilities to which the load can be delivered, the choice of a particular one being part of the decisions characterizing the MZT-PDTWS.

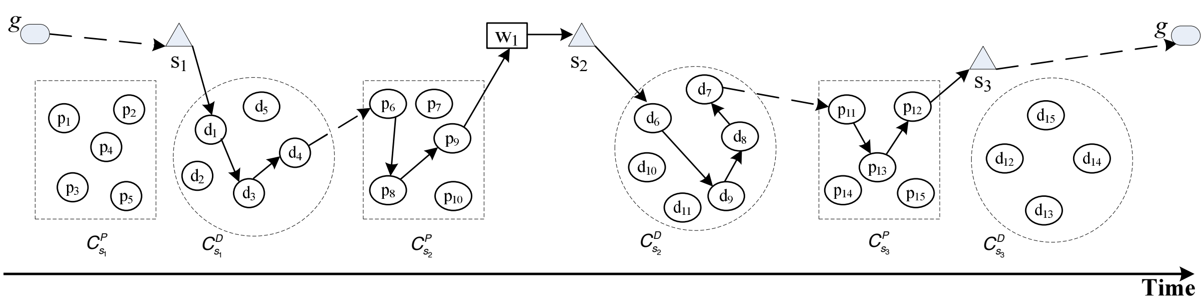

Figure 1: A four-trip route illustration

A vehicle route, illustrated in Figure 1 thus leaves the garage to visit a first facility (S_1 in the figure) within its operating time period (from the garage to the facility, the vehicle could have picked up loads destined to that particular facility) and load (and unload, possibly) freight, proceeds to deliver it to customers within their time windows (Set $\mathcal{C}^D_{s_1}$ of delivery-customer demands), then either moves directly to its next appointment to a facility (S_2), possibly stopping to wait for the appropriate time at a waiting station (w_1), or first moves to a pickup-demand customer and starts a pickup sequence (Set $\mathcal{C}^P_{s_2}$) before going to the facility. The route continues until either there are no more loads to deliver or its cost becomes noncompetitive compared to other routes. The vehicle returns to the garage in both cases. The MZT-PDTWS generalizes the Synchronized Multi-zone Multi-trip VRPTW (Crainic et al., 2009; Nguyen et al., 2013) and the VRP with Backhauls (e.g., Berbeglia et al., 2007). It is encountered in several settings, in particular when planning the operations of two-tiered City Logistics systems (Crainic et al., 2009) accounting for both the inbound and outbound traffic (Crainic et al., 2012a).

We propose a tabu search meta-heuristic for the MZT-PDTWS integrating multiple neighborhoods grouped into two classes. A first set of neighborhoods targets the construction of multiple-trip routes by modifying the supply points a vehicle visits. A second set focuses on improving the routing within sequences of delivery- and pickup-demand customers through intra- and inter-route neighborhoods dedicated to each type of sequence. The neighborhood selection rule is dynamically modified during the search, and a diversification strategy guided by an elite set of solutions and a frequency-based memory is called upon when the search begins to stagnate.

Extensive computational experiments (on instances with up to 72 supply points and 7200 customer demands) will be reported to qualify the impact of a number of major problem characteristics, parameters and search strategies on the behaviour of the solutions and to underline the good performance of the proposed algorithm. As no previous results are available in the literature for the MZT-PDTWS, we also evaluate the performance of the method through comparisons with currently published results on the VRP with Backhauls.

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Some POPMUSIC Applications in Logistics

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Abstract

In this paper we report on recent success stories in solving some logistics problems by means of matheuristics, like the Berth Allocation Problem as it is found in maritime shipping and the operations of container terminals. As an example we propose two POPMUSIC (Partial Optimization Metaheuristic Under Special Intensification Conditions) approaches that incorporate an existing mathematical programming formulation for solving it. POPMUSIC is an efficient metaheuristic that may serve as blueprint for matheuristics approaches once hybridized with mathematical programming. In this regard, the use of exact methods for solving the sub-problems defined in the POPMUSIC template highlight an interoperation between metaheuristics and mathematical programming techniques, which provide a new type of Approach for this problem. Computational experiments reveal excellent results outperforming best approaches known to date.

Keywords: Matheuristic, Popmusic, Metaheuristics, Corridor Method, Logistics

A natural way to solve large optimization problems is to decompose them into independent sub-problems that are solved with an appropriate procedure. However, such approaches may lead to solutions of moderate quality since the sub-problems might have been created in a somewhat arbitrary fashion. Of course, it is not easy to find an appropriate way to decompose a problem *a priori*. The basic idea of POPMUSIC is to locally optimize sub-parts of a solution, *a posteriori*, once a solution to the problem is available. These local optimizations are repeated until a local optimum is found. Therefore, POPMUSIC may be viewed as a local search working with a special, large neighborhood. While POPMUSIC has been acronymed by [10] other metaheuristics may be incorporated into the same framework, too (e.g. [8]). Similarly, in the *variable neighborhood search* (VNS) [4] the neighborhood is altered during the search in such a way that different, e.g. increasingly distant, neighborhoods of a given solution are explored. Such method can be enhanced via *decomposition*, as in the *variable neighborhood decomposition search* (VNDS) (see, e.g., [5]).

For large optimization problems, it is often possible to see the solutions as composed of parts (or chunks [11], cf. the term vocabulary building). Considering the vehicle routing problem, a part may be a tour (or even a customer). Suppose that a solution can be represented as a set of parts. Moreover, some parts are more in relation with some other parts so that a corresponding heuristic measure can be defined between two parts. The central idea of POPMUSIC is to select something that we call *seed part* and a set P of parts that are mostly related with the seed part to form a sub-problem.

Then it is possible to state a local search optimization frame that consists of trying to improve all sub-problems that can be defined, until the solution does not contain a sub-problem that can be improved. In the frame of [10], the set of parts P corresponds precisely to seed parts that have been used to define sub-problems that have been unsuccessfully optimized. Once P contains all the parts of the complete solution, then all sub-problems have been examined without success and the process stops. Basically, the technique is a gradient method starting from a given initial solution and stoping in a local optimum relative to a large neighborhood structure.

POPMUSIC may serve as a general frame encompassing various other approaches like Large Neighbourhood Search, Adaptive Randomized Decomposition etc. An older research which may serve as motivation relates to solving the job shop problem by means of the shifting bottleneck heuristic [1]. The idea of developing heuristics identifying a small/moderate size subset of variables in order to intensify the search in a promising region of the solution space has been used in other contexts. In the knapsack problem family, e.g., [3] propose the idea of selecting a small subset of items (called the core) and solving exactly a restricted problem on that subset. The use of an expanding method to modify the size of the core during the algorithm execution is proposed by [7]. In the same spirit we may consider the *corridor method* (CM) [9]. The basic idea of the CM relies on the use of an exact method over restricted portions of the solution space of a given problem. The concept of a *corridor* is introduced to delimit a portion of the solution space around an incumbent solution. Consequently, the CM defines method-based neighborhoods, in which a neighborhood is build taking into account the method M used to explore it. Kernel Search [2] is also based on the idea of exhaustively exploring promising portions of the solution space.

In this paper we report on some successful matheuristics applications for some logistics problems. As an example consider the Berth Allocation Problem which aims at assigning and scheduling incoming vessels to berthing positions along the quay of a container terminal. This problem is a well-known optimization problem within maritime shipping. We propose two POPMUSIC approaches that incorporate an existing mathematical programming formulation for solving it (see [6]).

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An Adaptive Iterated Local Search for the Mixed Capacitated General Routing Problem

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Abstract

In the literature, there has been a tendency to categorize applications as being either a case of node routing, or a case of arc routing. There are, however, important real-world problems whose essential characteristics cannot be captured neither by the CVRP nor by the CARP, as there is a mixture of requests located on nodes and requests located on links. [8] argue that in certain cases of urban-waste collection, most requests may be adequately modeled as located on streets, but some large point-based demands, located for example at schools or hospitals, are better modeled by the use of vertices. In subscription newspaper delivery, requests are basically located in points, but in dense urban or suburban residential areas a CARP model based on the street network may be a good abstraction. In general, qualified abstraction and problem reduction for a CVRP instance through aggregation, for instance with heuristics based on the road network, will create an

instance with requests located on nodes, edges, and arcs, see, e.g., [5, 4].

To answer the challenges that are induced by these complex problems, several researchers have recently focused their attention on the so-called Mixed Capacitated General Routing Problem (MCGRP). In the MCGRP, requests are located on a subset of vertices, edges, and arcs of a given weighted mixed graph, and a fleet of identical capacitated vehicles based at a central depot is used to satisfy requests with minimum routing cost while adhering to capacity constraints. The MCGRP is able to model a continuum of mixed node and arc routing problems, and hence removes the sharp boundary that is often seen in the literature. As alluded to above, the problem has large practical interest, particularly for so-called street routing applications, see [2]. The MCGRP is also of interest in combinatorial optimization, because it generalizes both the CVRP, the CARP and many other routing problems. Its resulting combinatorial complexity is, however, very high, and solving it to optimality is a difficult task even for moderate-size instances, see [1] and [3].

In this paper, we propose a novel, hybrid metaheuristic, called Adaptive Iterated Local Search (AILS) to solve large-size instances of the MCGRP. It utilizes vital mechanisms from two classical trajectory-based metaheuristics: Iterated Local Search (ILS), see [6], and Adaptive Large Neighborhood Search (ALNS), see [7]. We have combined these mechanisms in a new way, and introduced several new elements. Novel local search and large neighborhood search operators have been designed, and well-known operators have been tailored to the problem at hand. When ALNS finds solutions with a certain quality, they are further intensified by local search (LS). We have designed a new, aggressive LS strategy. In each iteration we explore the union of neighborhoods resulting from five operators, and try to execute all moves with positive savings. In effect, we execute all independent moves before generating a new neighborhood.

Our experimental study shows that the resulting algorithm is highly effective. For five MCGRP benchmarks consisting of 409 instances in total, AILS produces 402 best known solutions, 128 of which are new. 180 of the 402 solutions are proven optimal. One instance was closed for the first time by AILS. Notably, the AILS also achieves high quality computational results for heavily investigated special cases of the MCGRP, viz. four standard benchmarks for the CVRP, and seven standard benchmarks for the CARP.

Keywords

Vehicle Routing; Arc Routing; Mixed Capacitated General Routing Problem; Node, Edge, and Arc Routing Problem; Metaheuristics

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A matheuristic for the multi-vehicle inventory routing problem

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1 Abstract

The interest in the integration of different problems traditionally treated independently is growing in logistics practice and research. Inventory routing problems aim at integrating inventory and transportation planning. Tutorials, with the body of literature available in the area, are available in [3] and [4].

We consider the Inventory Routing Problem (IRP) where customers have to be served over a discrete time horizon by a fleet of capacitated vehicles starting and ending their routes at a depot. The problem is to decide in each time period how much to deliver to each customer and the routes of the vehicles in such a way that the sum of inventory and transportation costs is minimized.

The IRP is related to other classes of vehicle routing problems. Most of these problems, however, assume that the period of service of each customer has been decided, and the task is to optimize the assignment of customers to vehicles and the sequence of customers in each route. The decision on the period of service is considered in the Periodic Vehicle Routing Problem (PVRP), where alternative sequences of periods of visit are given, and the daily demand of each customer is known and must be satisfied in only one visit by exactly one vehicle. The IRP and the PVRP have a different focus and are inspired by different real-world situations. With respect to the

PVRP, the IRP considers a broader decision space, in terms of sequences of visiting periods and in terms of demand served in a visit. Even if in the PVRP all sequences of periods of visits are given as possible, still the two problems are different: In the IRP the demand of a period is not requested to be served in that period but can be served during a previous visit.

The single vehicle version of the IRP was introduced in [2]. The multi-vehicle version of the problem was modeled and solved heuristically in [5]. An in-depth analysis of alternative formulations was carried out in [1].

In this paper we consider the multi-vehicle version of the IRP under the maximum level policy, which means that we are allowed to deliver to any customer any quantity as long as a stock-out situation does not occur and a maximum capacity constraint at the customer is not violated. We present a matheuristic for the solution of the problem based on a tabu search combined with different mathematical programming models. The matheuristic was tested on a large set of benchmark instances and the results prove its effectiveness.

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"A Lower Bound for the Quickest Path Problem"
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The point-to-point quickest path problem is a classical network optimization problem with numerous applications, including that of computing driving directions. In this paper, we define a lower bound on the time-to-target which is both accurate and fast to compute. We show the potential of this bound by embedding it into an A algorithm. Computational results on three large European metropolitan road networks, taken from the OpenStreetMap database, show that the new lower bound allows to achieve an average reduction of 14.36%. This speed-up is valuable for a typical web application setting, where a server needs to answer a multitude of quickest path queries at the same time. Even greater computing time reductions (up to 28:06%) are obtained when computing paths in areas with moderate speeds, e.g. historical city centers.*

New Benchmark Instances for the Capacitated Vehicle Routing Problem

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Abstract

The recent research on the CVRP is being slowed down by the lack of a good set of benchmark instances. The existing sets suffer from at least one of the following drawbacks: (i) became too easy for current algorithms; (ii) are too artificial; (iii) are too homogeneous, not covering the wide range of characteristics found in real applications. We propose a new set of instances, designed in order to provide a more comprehensive and balanced experimental setting. Beyond having a greater discriminating power to tell "which algorithm is better", this benchmark should also allow a deeper statistical analysis of the performance of an algorithm, investigating how the characteristics of an instance affect its performance. We report such an analysis on state-of-the-art exact and heuristic methods.

Keywords: Vehicle Routing Problem, Algorithm Experimentation

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A New Exact Approach for the Vehicle Routing Problem with Intermediate Replenishment Facilities

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Keywords: *Multi-Depot Vehicle Routing Problems, Exact Methods, Multi-Trip Vehicle Routing Problems*

1 Introduction

We present a new exact approach to the problem known as the Vehicle Routing Problem with Intermediate Replenishment Facilities (VRPIRF). VRPIRF is defined on an oriented graph $G = (V, A)$ where the node set $V = \{0, 1 \ldots n, n + 1 \ldots n + p\}$ consists of a *depot* 0, n *clients* and p *facilities*. As in the Capacitated VRP (CVRP), the aim is to find the least cost set of *routes* that visit each client exactly once, the cost of a route being the sum of the costs of the visited arcs. Each client has a *demand* and can be served by one of the homogeneous, fixed capacity *vehicles* based at the depot. The additional feature of VRPIRF is that vehicles are not compelled to go back to the depot after a route but can replenish at facilities and therefore perform a sequence of routes called a *rotation*. However, the rotation of a vehicle must start and end at the depot and its total duration (the sum of the travel times, the service times, and the replenishment times associated with the visited arcs, clients, and facilities, respectively) must not exceed a given *shift duration*.

2 Positioning in the Literature

VRPIRF is a special case of the Multiple Depot VRP with Inter-depot routes (MDVRPI), which generalizes the well-known Multi-Depot VRP problem (MDVRP). MDVRPI presents several depots, each one acting both as the base of its own fleet of vehicles, and as a replenishment facility for vehicles based at other depots. A reference work on MDVRPI is [1]. The authors, which proposed a tabu-search based heuristic, focused on the case with one central depot and p facilities – which we studied. The name of VRPIRF for such variant has been introduced by the authors of [2] : they proposed a local- and tabu-search-based meta-heuristic algorithm. The authors of [3] studied a variant of VRPIRF with additional constraints on replenishment operations, proposing a Branch&Cut algorithm. Another problem closely related to the VRPIRF is the Multi-Trip VRP, in which there are no facilities and the central depot act also as a replenishment facility. Recently, [4] has proposed a memetic algorithm, while [5] designed an exact algorithm.

3 The proposed Algorithm

We propose a new Branch&Cut algorithm for solving the VRPIRF, a problem for which –to the best of our knowledge– not much has been explored for what concerns exact methods. The

B&C method is based on a MILP two-index compact formulation, which makes use of *replenishment arcs* to model the stop to replenish at a facility between two clients. Replenishment arcs are a powerful modeling concept which has been used, as far as we know, by few works in the literature. The paper we refer to is [7], which makes use of such concept in a generalization of the Shortest Path Problem with Resource Constraint (SPPRC) called the Weight Constrained Shortest Path Problem with Replenishment (WCSPP-R) to model activities that reset a cumulated amount of a given resource. The respect of capacity constraints is ensured by separating Capacity Cuts on a first transformation of the graph. Such separation is performed by means of Lysgaard's CVRPSEP routines (see [6]). To impose that a solution is connected, i.e. that the routes of a vehicles actually form a non-discontinuous rotation, we take advantage of replenishment arcs, which allow to represent a rotation as an elementary closed path with both its endpoints on the depot. Connectivity is thus ensured by separation of SECs on a second transformation of the graph. Finally, to impose the shift duration constraint, we exploit a method inspired by the recent literature on *Asymmetric Distance-Constrained VRP* that allows to keep track, given any partial path from the depot to a customer i, of the distance travelled so far. A good reference for understanding such technique is [8].
Tests have been conducted on the benchmark instances proposed in [1] and [2], leading to very promising results.

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Min-Max vs. Min-Sum Vehicle Routing: A Worst-Case Analysis

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Abstract for Route 2014

Both minimizing the sum of lengths of all routes and minimizing the length of the longest route are important objectives for Vehicle Routing Problems. We perform a worst-case study to show that the optimal solution with respect to one objective can be very poor in terms of the other one.

Keywords: Vehicle Routing Problem, Min-Sum, Min-Max, Worst-case Analysis.

An Inventory-Routing Problem with Pickups and Deliveries Arising in the Replenishment of Automated Teller Machines

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The purpose of this presentation is to introduce, model and solve a rich multi-period inventory-routing problem with simultaneous pickups and deliveries. Commodities can brought from and to the depot, as well as being exchanged among customers to efficiently manage their inventory shortages and surpluses. A single customer can both provide and receive commodities at different periods, since its demand changes dynamically throughout the planning horizon and can be either positive or negative. This problem arises, for instance, in the replenishment operations of automated teller machines. New technology provides these machines with the additional functionality of receiving deposits and reissuing these to subsequent customers. Motivated by a real case in the Netherlands, we formulate the problem as a mixed-integer linear programing model and we propose an exact branch-and-cut algorithm for its resolution. Given the complexity of the problem, we also propose a flexible clustering heuristic to decompose it. Through extensive computational experiments using real data, we assess the performance of the solution algorithm and of the clustering procedure. The results show that we are able to obtain good lower and upper bounds for this new and challenging practical problem.

Key words: inventory-routing, inventory management, pickup and delivery, branch-and-cut, clustering, exact algorithm, recirculation automated teller machines.

Improved Branch-Cut-and-Price for Capacitated Vehicle Routing

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Abstract

The best performing exact algorithms for the Capacitated Vehicle Routing Problem developed in the last 10 years are based in the combination of cut and column generation. Some authors only used cuts expressed over the variables of the original formulation, in order to keep the pricing subproblem relatively easy. Other authors could reduce the duality gaps by also using a restricted number of cuts over the Master LP variables, stopping when the pricing becomes prohibitively hard. A particularly effective family of such cuts are the Subset Row Cuts. This work introduces a technique for greatly reducing this impact on the pricing of these cuts, thus allowing much more cuts to be added. The newly proposed Branch-Cut-and-Price algorithm also incorporates and combines for the first time (often in an improved way) several elements found in previous works, like route enumeration and strong branching. All the instances used for benchmarking exact algorithms, with up to 199 customers, were solved to optimality. Moreover, some larger instances with up to 360 customers, only considered before by heuristic methods, were solved too. Below we graphically present two new optimal solutions.

Keywords: Column Generation, Cut Separation, Algorithmic Engineering

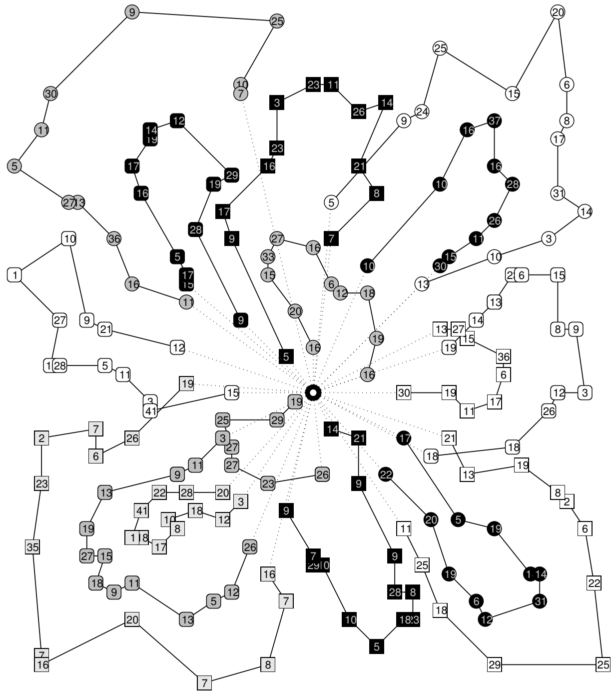

Fig. 1. Optimal solution of M-n200-k16, value 1274

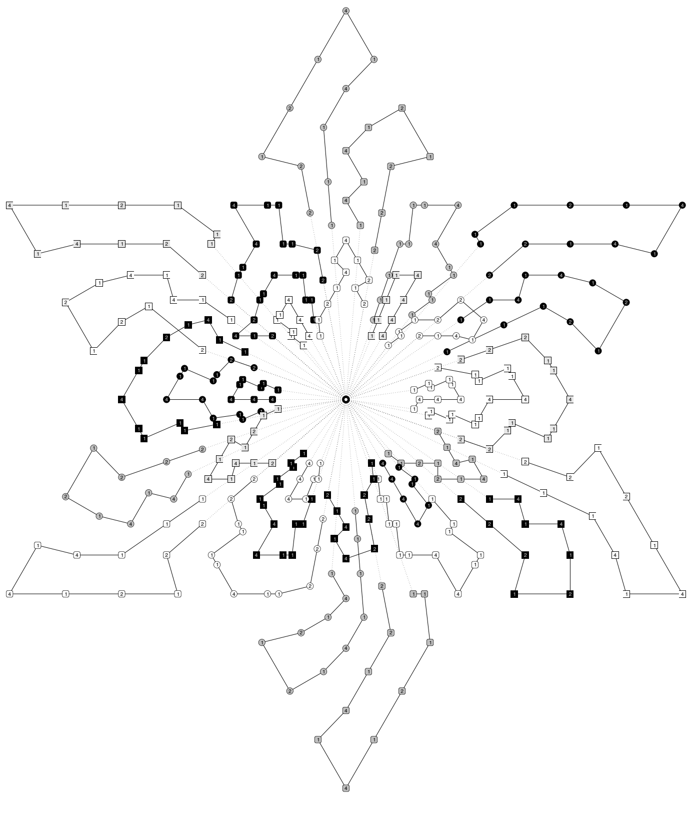

Fig. 2. Optimal solution of G19, value 1365.60

A BRANCH-AND-PRICE ALGORITHM FOR THE VEHICLE ROUTING PROBLEM WITH TIME WINDOWS CONSIDERING DRIVING AND WORKING HOUR REGULATIONS

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1. Introduction

VRPTW have been widely studied, applied in practice, and further developed to include more realistic constraints. Gendreau and Taratilis [4] and Baldacci *et al.* [1] are two of the most recent surveys on the VRPTW. One of the recent series of constraints is the series of restrictions on the amount of driving and working hours of truck drivers. During the last decade, many legislation bodies around the world have passed particular bills concerning driving and working hours of drivers, which both drivers and liable companies are compelled to follow. The European Union Regulation (EC) No. 561/2006 and Directive 2002/15/EC are examples of these rules which have been enforced since 2007. Prescott-Gagnon *et al.* [14] and Drexl and Prescott-Gagnon [3] have cearly explained these regulations. In real-life, solutions derived from VRPTW problems excluding breaks and rests could be infeasible and result in driver's exhaustion and probably accidents. On the other hand, if these breaks and rest are applied to the solution of the classic VRPTW in a post-processing step, drivers could arrive at the customers after inevitable delays. As a result, in order to guarantee the feasibility, these restrictions should be included in the VRPTW modelling. To the best of our knowledge, this new problem which now on in this paper is called *VRPTW-DWR*, has recently attracted the attention of researchers but no exact solution method has been proposed to solve VRPTW-DWR. This paper provides a mathematical programming formulation and optimally solves this model using a tailored Branch-and-Price (B&P) algorithm. In a branch-and-price algorithm, the linear relaxation in each branch-and-bound node is solved using column generation and the pricing problem is an elementary shortest path problem with resource constraints (ESPPRC). This pricing problem is then solved by means of a labeling algorithm which generates columns with negative reduced cost. To improve the performance of the labeling algorithm, new dominance criteria are introduced to eliminate labels that are not leading the routes in the optimal solution. To speed up the branch-and-price algorithm, two heuristics are designed to find the columns with negative reduced cost. Although the shortest path problem here results in worse lower bounds, it is easier to solve and the integrality of the master problem is still guaranteed by branch-and-bound.

2. Driving and Working Hour Regulations in Routing

The VRPTW-DWR has mainly attracted the attention of researchers during the last a few years. The work of Savelsbergh and Sol [15] seems to be the first paper to consider lunch breaks and night rests in the vehicle routing and scheduling problem with pickup and delivery in a fixed time interval, and to propose a branch-and-price algorithm. Zäpfel and Bögl [18] proposed a two-phased heuristic algorithm for a VRPTW where in the first phase it solves a vehicle routing problem with daily breaks and maximum time interval, and in the second phase it tackles driver's rests and weekly time intervals as a personnel assignment problem.

Xu *et al.* [17] have been the first to include driving regulations and night rests enforced by the government (in the US). The authors considered these regulations in a rich pickup and delivery problem with multiple time windows, and argued that its complexity is NP-hard. They also proposed a column generation heuristic algorithm to solve their routing problem.

Goel [5] and [6] applied the EU regulations into a VRPTW and designed a large neighborhood search heuristic in which a labeling algorithm was used to check the feasibility of a solution at each removal and insertion. Another example of using labeling concept in a large neighborhood search is the work of Prescott-Gagnon *et al.* [14] in which a tabu search column generator was used to construct new solutions.

Kok *et al.* [10] used a restricted dynamic programming heuristic for the VRPTW-DWR. This work was the first paper to include all of the EU driving and working regulations including standard and extended. Moreover, the authors showed that their algorithm works for longer time horizons and even rolling horizon frameworks. Kok *et al.* [9], in a post-processing departure time optimization of VRPTW problems, included break and rest scheduling, modeled it as an ILP problem and solved it to optimality.

Meyer *et al.* [13] and Meyer [12] also applied this restricted dynamic programming algorithm for the case of distributed decision making where companies make only routing decisions and leave the break scheduling decisions to the drivers.

Goel and Kok [8] studied vehicle scheduling problems with time windows and team drivers where one driver can drive and the other can rest for 4.5 hours. They proposed a depth-first-breath-second search algorithm with dominance.

Derigs *et al.* [2] introduced EU regulations in a multi-trip VRP, in a air cargo road feeder service business, and presented a neighborhood search algorithm with a decomposition approach where the neighborhood search generates the trips, then a packing heuristic aggregates them to multi-trips.

Finally, the recent work of Goel *et al.* [7] is a study of similar laws valid in Australia for drivers' fatigue, in which they have designed a dynamic programming heuristic algorithm as their solution method.

3. Modeling framework

The research of Kopfer and Meyer [11] seems to be the first paper to model European Union driving regulations as an integer linear programming (ILP) in the form of Traveling Salesman Problem with Time Windows (TSPTW). Zäpfel and Bögl [18] proposed an ILP formulation for their multi-period vehicle routing and scheduling problem where breaks are considered and driving jobs can be outsourced. The work of Wen *et al.* [16] is another example of modeling a vehicle routing and scheduling problem with time windows and standard breaks for both internal and external drivers of vehicles. Goel *et al.* [7] designed a state-space scheduling model for their VRPTW including Australian laws. Meyer M2011 also modeled VRPTW with the EU regulations as a state-space scheduling model. Goel and Kok [8] is another example which applied state-space scheduling modeling for the case of team drivers.

4. Solution methodology

The VRPTW-DWR is reformulated as a set-partitioning problem (the master problem), where in the set P of all feasible paths, the goal is to find the path with minimum travel cost. A feasible path p is defined by the sequence of customers visited along it, while respecting the capacity constraints, time windows, and break scheduling constraints. For each path $p \in P$, c_p is defined as the cost of the path, the constant σ_{ip} measures the number of times customer i is visited by the path p, and y_p is the binary variable that gets value 1 if and only if the path p is included in the solution.

For the pricing problem, column generation algorithm is embedded in a branch-and-bound framework to guarantee integrality. First, it branches on the aggregated variables x_{ij}. Among the fractional variables, it searches for pairs $(i, j), i, j \in V_c$ such that $x^*_{ij} + x^*_{ji}$ is close to 0.5 and puts the branch on the that aggregated variable. If the aggregated variables for all pairs $(i, j), i, j \in V_c$ are integer, it searches for fractional arcs in the current solution and branches on that variable. Then, for each branch candidate, the lower bound in the two offsprings are estimated by solving a LP relaxation using a quick heuristic. Finally, the algorithm applies branch where the lower bound of the child nodes are maximized. However, there is a limit on the breath and depth for the branching. In this paper, the pricing problem is solved by means of a labeling algorithm. This labeling algorithm generates columns with negative reduced cost and the best break schedule. A bi-directional search is performed where the labels are extended in both forward direction (from v_0 to its successors) and backward direction (from v_{n+1} to its predecessors). These forward and backward label extensions are bounded to a specific time t_m in the middle of planning horizon, and later they are merged to construct the complete path. This strategy avoids generating long labels. New dominance criteria are composed in order to eliminate labels that are not going to lead to the optimal solution.

Numerical results and benchmarks against the proposed heuristics in the literature will be presented on the conference.

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Branch-price-and-cut algorithms for electric vehicle routing problems with time windows

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In this paper we consider different variants of the electric vehicle routing problem with time windows (EVRPTW). All variants considered involve a homogeneous fleet of electric vehicles housed in a single depot, a set of customers, and a set of battery recharging stations. Each vehicle has a limited capacity, a limited battery autonomy, and a battery that is fully charged at the beginning of the day. Each customer has a known demand, s service time, and a time window in which its service must start. All recharging stations offer the same service (same recharging rate and no recharging costs) and differ only by their location. For each pair of locations (depot, customers, and stations), the input provides a traveling cost, a traveling time, and an energy consumption. The EVRPTW consists of determining least-cost feasible vehicle routes such that each customer is visited exactly once. Starting and ending at the depot, a route is composed of a sequence of customer visits interspersed by stops at recharging stations if needed. A route is feasible if the total demand of the visited customers does not exceed vehicle capacity, the service at each customer starts within its time window, and the battery charge is positive when traveling.

We consider four EVRPTW variants: at most one recharge per route/full recharges only; any number of recharges per route/full recharges only; at most one recharge per route/variable recharges; any number of recharges per route/variable recharges. For each problem variant, we propose a state-of-the-art branch-price-and-cut algorithm in which the subproblem is solved by a labeling algorithm. A full recharge incurs a recharging time that depends on the energy consumption since the last recharge. This can be handled relatively easily in the labeling algorithm. However, variable recharges require a more complex labeling algorithm where the time component is a function of the quantity of energy recharged. Surprisingly, the variants with full recharges only are not directly suited for bidirectional labeling while the variable recharge cases are suitable. We show how we can combine the algorithm for the variable recharging cases with that for the full recharging cases to yield a bidirectional labeling algorithm for the latter cases. Finally, we also develop an efficient local search heuristic column generator to speed up the overall solution process. Computational results on benchmark instances will be presented.

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