Edition KWV

Silke Jütte

Large-Scale Crew Scheduling

Models, Methods, and Applications in the Railway Industry



Edition KWV

Die "Edition KWV" beinhaltet hochwertige Werke aus dem Bereich der Wirtschaftswissenschaften. Alle Werke in der Reihe erschienen ursprünglich im Kölner Wissenschaftsverlag, dessen Programm Springer Gabler 2018 übernommen hat.

Weitere Bände in der Reihe http://www.springer.com/series/16033

Silke Jütte

Large-Scale Crew Scheduling

Models, Methods, and Applications in the Railway Industry



Silke Jütte IUBH University of Applied Sciences Bad Honnef, Germany

Bis 2018 erschien der Titel im Kölner Wissenschaftsverlag, Köln Dissertation Universität zu Köln, 2012

Edition KWV ISBN 978-3-658-24359-3 ISBN 978-3-658-24360-9 (eBook) https://doi.org/10.1007/978-3-658-24360-9

Library of Congress Control Number: 2019931811

Springer Gabler

© Springer Fachmedien Wiesbaden GmbH, part of Springer Nature 2012, Reprint 2019 Originally published by Kölner Wissenschaftsverlag, Köln, 2012

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the

and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer Gabler imprint is published by the registered company Springer Fachmedien Wiesbaden GmbH part of Springer Nature

The registered company address is: Abraham-Lincoln-Str. 46, 65189 Wiesbaden, Germany

To my father Walter Baumgartner 1942 - 1986

Acknowledgements

"How long until you've finally finished writing that book, Mommy?", my four-year-old son urged some time ago. It took me six years to finish this thesis. Both professionally and personally, these were the most eventful years of my life.

Thinking back at my time as a research assistant at the University of Cologne, I first would like to thank Professor Ulrich Thonemann for supporting my PhD studies and for helping me reconcile profession and family. His way of always thinking forward and of questioning everything inspired my work in many ways. Thank you to Professor Knut Haase for his feedback and suggestions on the algorithms of this thesis, to Professor Ulrich Derigs for co-supervising the thesis, and to Professor Ludwig Kuntz for heading the thesis defense.

This PhD thesis would not have been possible without practical insights into crew scheduling. I am grateful to Marcus Eymer, Tim Krasowka, Jan Reuter, and Stefan Wunderlich for sharing their knowledge with me and for letting me experience the heartbeat of a large railway freight carrier.

The past six years have been a long way to go, and I am glad that I have been accompanied by many people at the university. Thank you to Marc Albers, Michael Becker-Peth, Andreas Brinkhoff, Michael Decker, Nicola Decking, Marcus Dettenbach, André Fuetterer, Torsten Gully, Tanja Haeger, Moritz Heininger, Dominik Heinz, Katja Henne, Kai Hoberg, Simon Höller, Nadine Holtvogt, Christina Jakobs, Sebastian Jucken, Kerstin Kubik, Anna Küpper, Philipp Laufenberg, Katharina Nachtsheim, Philipp Naujoks, Ulf Merschmann, Karin Möllering, Signe Oepen, Henning Olbert, Raik Özsen, Felix Papier, Lukas Pönsgen, Vladislav Richter, Kathrin Rieger, Johanna Rosenbusch, Lisa Scheele, Stefanie Schiefer, Frank Schneider, Monika Scholz, Jeanette Seifert, Marcel Sieke, Analena Stern, Andreas Thalmann, Carina von Weyhe, Alexander Weyers, and Jingnan Zhu for being my colleagues and friends. Especially, I would like to thank Marc Albers and Johanna Rosenbusch. I very much enjoyed working with you and love to look

back to many discussions and distractions in our shared office.

At last, I am deeply grateful to my family: To my mother – for countless hours of babysitting, for all your text messages that cheered me up every morning, and for being an example to me in so many ways. To Sonja, Ute, and Jose – for listening to me and believing in me. I am proud to be your sister and sister-in-law. Finally, to Thomas, Fabian, and Manuel – for keeping my life in balance and never getting tired of showing me what really matters. Thomas: Thank you so much for your love and support. Fabian and Manuel: Thank you for turning my world upside down.

Cologne, 2012 Silke Jütte

Contents

Li	st of	igures	хii
Li	st of	ables	xiv
Li	st of	Algorithms	χv
Li	st of	Abbreviations	x v i
Li	st of	ymbols xv	viii
1	Intr	duction	1
	1.1	Motivation	1
	1.2	Example	2
	1.3	Outline	5
	1.4	Contributions	10
2	Fun	amentals of Large-Scale Crew Scheduling	11
	2.1	Crew Scheduling	11
		2.1.1 Definition of Terms	11
		2.1.2 Fields of Application	12
		2.1.3 Operational Planning Context	13
	2.2	Large-Scale Optimization Techniques	14
		2.2.1 Dantzig-Wolfe Decomposition	14
		2.2.2 Column Generation	16
		2.2.3 Master Problem Solution	19
		2.2.4 Subproblem Solution	22
		2.2.5 Integrality Techniques	25
3	Solv	ng Crew Scheduling Problems in the Railway Industry	32
	3.1	Problem Description	32

Contents

	3.2	Litera	ture Review	38		
	3.3	Railw	ay Crew Scheduling Model	41		
	3.4	Soluti	on Method	43		
	3.5	Organ	nizational Implementation	47		
	3.6	Mana	gerial Implications	48		
		3.6.1	Improving the Job Satisfaction of Crew Members	48		
		3.6.2	Assuring Robustness of a Crew Schedule	51		
		3.6.3	Effect of Business Unit Structure on Crew Scheduling	53		
	3.7	Benef	its	55		
4	The	Divide	e-and-Price Decomposition Algorithm	57		
	4.1	Proble	em Description	58		
	4.2	Litera	ture Review	60		
	4.3	Mathe	ematical Model and Solution Approach	62		
		4.3.1	Mathematical Formulation	64		
		4.3.2	Solution Approach	66		
		4.3.3	Optimization Progress	78		
	4.4	Comp	outational Results	81		
		4.4.1	Planning of Weekly Schedules	82		
		4.4.2	Planning of Daily Schedules	87		
5	Decomposition Strategies for Large-Scale Crew Scheduling Problems					
	5.1	Decon	nposing Crew Scheduling Problem Instances	90		
	5.2	Litera	ture Review	94		
	5.3	Mode	ling and Solution Approach	96		
		5.3.1	Edge Weights	97		
		5.3.2	Subset Sizes	101		
		5.3.3	The GPP Solution Algorithm for Decomposing CSP	102		
	5.4	Comp	outational Results	107		
		5.4.1	Correlation Analysis	109		
		5.4.2	Effects of Edge Weight Definition and Range	111		
		5.4.3	Combination with Divide-and-Price	120		
6	Con	clusion	and Outlook	127		
	6.1	Concl	usion	127		

Contents

References		
6.3	Directions for Further Research	131
6.2	Critical Review	129

List of Figures

1.1	Development of Transportation Volumes inside Germany	2
1.2	Example Railway Network	3
1.3	Chronological Decomposition	8
1.4	Overlapping Partial Problems	8
1.5	Uniform Decomposition	8
2.1	Binary Enumeration Tree	26
3.1	Operational Planning Process at a Railway Freight Carrier	33
3.2	Network of a Major European Railway Freight Carrier	34
3.3	Simultaneous Trips at a Major European Railway Freight Carrier	35
3.4	Activities within a Duty	37
3.5	TEO Solution Process	43
3.6	Visualization of Duties Generated by TEO	49
3.7	Crew Scheduling Scenarios with Hotel Break Penalty Costs	52
4.1	Divide-and-Price Concept	58
4.2	Short-Term Planned Trains at a Railway Freight Carrier	59
4.3	Constraint Aggregation Approach	60
4.4	Constraint Decomposition Approach	60
4.5	Solution Times of a Railway Crew Scheduling Application	63
4.6	Primary Assignment of Trips	64
4.7	Secondary Assignment of Trips	64
4.8	Divide-and-Price Process	67
4.9	Updating of Global and Local Pricing Values	72
4.10	Secondary Assignment of Trip \hat{t} to Region r	73
4.11		73
4.12	Three-Phase-Concept	77

List of Figures

4.13	Optimization Progress, DP7869	79
4.14	Progress in Comparison to Non-Pricing Strategies, DP7869	80
4.15	Decomposition and Pricing Solutions (Weekly Scheduling)	84
4.16	Decomposition and Pricing Solutions (Daily Scheduling) $\ \ \ldots \ \ \ldots$	88
5.1	Feasible Trip Combinations for a 121 Trips Example	91
5.2	Typical Distribution of Number of Connections per Trip	92
5.3	Typical Distribution of Waiting Time per Trip Connection $\ \ldots \ \ldots$	93
5.4	Uniform Edge Cut	98
5.5	Alternatives Edge Cut	98
5.6	Productivity Edge Cut	99
5.7	Productivity Alternatives Edge Cut	99
5.8	GPP Solution Algorithm	103
5.9	Problem Decomposition Phase	108
5.10	Correlation Analysis	110
5.11	Solution Quality, GP14872	113
5.12	Algorithm Runtime and Solution Quality, GP14872	119
5.13	Solution Quality Pure Decomposition and Pricing, GP14872 $$	121
5.14	Performance of Chronological and ProdAlt Decompositions	125

List of Tables

1.1	Sample Timetable	4
1.2	Feasible Duties	4
3.1	Sample Requirements for Crew Scheduling	36
3.2	TEO Optimization Results for Large-Scale Problem Instances $$	46
3.3	Detailed Activities of a Sample Duty	50
3.4	Crew Scheduling Scenarios with Varying Work Time Limit	53
3.5	Crew Schedule Properties for Separation into Business Units $\ . \ . \ .$	54
4.1	Decomposition Settings	83
4.2	Problem Size Settings	86
4.3	Performance of Decomposition and Pricing Solutions	86
5.1	Test Instances	111
5.2	Graph Partitioning Solutions, GP7701	114
5.3	Graph Partitioning Solutions, GP11338	115
5.4	Graph Partitioning Solutions, GP14872	116
5.5	Graph Partitioning Solutions, GP16225	117
5.6	Combined Graph Partitioning and Divide-and-Price	122
5.7	Details of Chronological and ProdAlt Decompositions	126

List of Algorithms

2.1	Column Generation	19
2.2	Dynamic Programming Algorithm for SPPRC	24
2.3	Branch-and-Price	28
2.4	Variable Fixing	31
4.1	Pricing Master Problem Initialization	69
4.2	Pricing Update	71
4.3	Assignment Update Secondary Trips	75
4.4	Assignment Update Primary Trips	76
5.1	GGGP-Range	105
5.2	KLRef-Range	106

List of Abbreviations

a.m. ante meridiem

B&P branch-and-price

CPU central processing unit
CSP crew scheduling problem

DPMP dual pricing master problem

e.g. exempli gratia, for example

etc. et cetera

 ${\rm GGGP} \quad {\rm greedy\ graph\ growing\ partitioning\ heuristic}$

 ${\rm GPP} \qquad {\rm graph \ partitioning \ problem}$

i.e. id est, that is

 ${\rm KL}$ Kernighan-Lin algorithm

LP linear program(ming)

MIP mixed integer linear program(ming)

MLGP multi-level graph partitioning