

Contents

| | |
|--------------------------------------------------------------------------------|------------|
| Acknowledgments | i |
| Abstract | iii |
| Zusammenfassung | vii |
| 1 Introduction | 3 |
| 1.1 Motivation | 3 |
| 1.2 Focus and contribution of this thesis | 4 |
| 1.3 Outline of the thesis | 6 |
| 2 Embedding of the algorithms in the railway planning process | 9 |
| 2.1 Introduction | 9 |
| 2.2 The railway timetabling process | 10 |
| 2.2.1 Liberalization of the European railway market | 10 |
| 2.2.2 Stakeholders involved in the timetabling process | 11 |
| 2.2.3 Main steps of the timetabling process | 12 |
| 2.3 Basics of timetabling | 15 |
| 2.3.1 Characteristics of the infrastructure | 15 |
| 2.3.2 Functional requirements | 16 |
| 2.3.3 Degrees of systematization | 18 |
| 2.4 Computer supported timetable construction | 21 |
| 2.4.1 Visualization of timetables | 22 |
| 2.4.2 Macroscopic timetable evaluation | 25 |
| 2.4.3 Support for automatic timetable construction | 26 |
| 2.5 Embedding of the algorithms for automatic timetable construction | 30 |
| 2.5.1 Mid-Term planning | 30 |
| 2.5.2 Further use cases in short-term and long-term planning | 32 |
| 2.5.3 Integration into planning software | 32 |
| 3 Modelling cyclic railway timetables | 35 |
| 3.1 Introduction | 35 |
| 3.2 The periodic event scheduling problem (PESP) | 35 |
| 3.2.1 General idea | 35 |
| 3.2.2 Types of Constraints | 36 |
| 3.2.3 Visualization of a PESP graph | 41 |
| 3.2.4 Model granularity | 43 |
| 3.3 Optimization Criteria | 44 |
| 3.3.1 Minimization of passenger travel time | 44 |

| | | |
|----------|-----------------------------------------------------------------------------|------------|
| 3.3.2 | Minimization of operational costs | 44 |
| 3.3.3 | Maximizing timetable stability and flexibility | 45 |
| 3.3.4 | Advantages and limits for optimization | 45 |
| 3.4 | Implementation and verification for this thesis | 46 |
| 3.4.1 | Data sources | 46 |
| 3.4.2 | Chosen model granularity | 47 |
| 3.4.3 | Event and constraint definition | 48 |
| 3.4.4 | Choice of objective function | 51 |
| 3.4.5 | Definition and description of test instances | 52 |
| 3.4.6 | Model evaluation with OnTime | 52 |
| 4 | Solving the periodic event scheduling problem | 59 |
| 4.1 | Introduction | 59 |
| 4.2 | Algorithms solving the PESP decision problem | 60 |
| 4.2.1 | A constraint programming method | 60 |
| 4.2.2 | A polynomial reduction from PESP to SAT | 61 |
| 4.3 | Optimizing the PESP using a MILP solver | 63 |
| 4.3.1 | The classical MILP | 63 |
| 4.3.2 | The cyclic MILP | 63 |
| 4.3.3 | Cyclic MILP with non-collision cycles | 66 |
| 4.4 | Choice of solution approach for this thesis | 67 |
| 4.4.1 | Solver and its parameter settings | 68 |
| 4.4.2 | Performance of the cyclic and classical MILP | 70 |
| 4.4.3 | Comparison of different cycle bases | 72 |
| 5 | Decomposition methods | 77 |
| 5.1 | Introduction | 77 |
| 5.2 | Decomposition in optimization theory | 77 |
| 5.3 | Geographical decomposition of the PESP | 79 |
| 5.3.1 | Definition of the decomposition | 80 |
| 5.3.2 | Cuts through track sections | 84 |
| 5.3.3 | Heuristics for the coordination of the master and two subproblems | 90 |
| 5.4 | Computational results | 94 |
| 5.4.1 | Hyperplane heuristic | 96 |
| 5.4.2 | Heuristic space search | 97 |
| 5.4.3 | Expected computation time to find a solution of a certain quality | 98 |
| 5.4.4 | Decomposition method to find a starting solution | 99 |
| 5.4.5 | Summary of the results | 101 |
| 6 | Sequential decomposition | 103 |
| 6.1 | Introduction | 103 |
| 6.2 | Decomposition in the manual planning process | 103 |
| 6.3 | Sequential decomposition for the PESP | 104 |
| 6.3.1 | Algorithmic approach | 105 |
| 6.3.2 | Mathematical properties of the decomposition | 107 |

| | | |
|----------|--------------------------------------------------------------------|------------|
| 6.4 | Implementation and computational results | 111 |
| 6.4.1 | Choice of train line partitions | 112 |
| 6.4.2 | Variation of fixation constraints | 116 |
| 6.4.3 | Influence of the fixation margin on computation time and quality . | 118 |
| 6.4.4 | Experience with Infeasibility | 127 |
| 6.4.5 | Comparison to the global solution method | 129 |
| 7 | Synthesis | 133 |
| 7.1 | Summary of results | 133 |
| 7.2 | Conclusion, discussion | 134 |
| 7.3 | Further research | 135 |
| 7.4 | Recommendations for application | 136 |
| | Glossary | 137 |
| | Bibliography | 141 |
| | CV | 147 |