Part I.

Decomposition Algorithms for Multi-Period Network Design
Multi-period network design has many practical applications. It is suitable for cases where not only the desired target state of the network has to be planned, but also the evolution of the network over time. The first part of this thesis elaborates on an example of this problem setting which arises in the context of planning railway infrastructure. It contains the results achieved in a joint project with GSV, a division of DB Mobility Logistics AG which is concerned with the forecast and simulation of traffic flows. Demands in rail freight transportation are expected to grow significantly over the next two decades, and therefore they presented us with the question how they could plan the expansion of the network capacities to accommodate these future demands using mathematical optimization. A multi-period approach is mandatory here, as limited infrastructure budgets and the implementation times of the infrastructure improvements require the provision of a detailed expansion schedule. To find an optimal evolution of the railway network with respect to the profitability of the transportation of the demand was our objective. The given task was all the more interesting as planners at GSV itself were concerned with this problem during the conduction of our research. This enables us to compare our own solutions to those from experts in the field. We will see that in this respect, our models and algorithms lead to realistic assessments of network capacities and allow for viable proposals for their extension.

Part I is structured as follows. In Chapter 1, we begin with a broader motivation of the topic, giving more information about the recent and the predicted development of rail freight traffic in Germany. Chapter 2 introduces some basic terminology and conveys fundamental knowledge of railway network planning as needed for the understanding of our work. It continues with a classification of the considered problem into a hierarchy of network design problems investigated in the literature, which is accompanied by a presentation of the most common solution approaches. At the end, we distinguish our approach to railway network design from previous approaches to the problem. With this background, we are ready to derive mathematical models for the optimal expansion of railway networks in Chapter 3. We first develop a simplified planning model over a single time period, denoted by (NEP), which can already be of high significance to a planner as such. Even more important is that this single-period model will be a basic ingredient in our algorithm for the solution of the multi-period case. We derive two possible mixed-integer programming formulations for this problem, named (FMNEP) and (BMNEP), for which we show that (FMNEP) is the better one from a theoretical point of view. This is done in Chapter 4. Furthermore, we derive a more compact reformulation of (FMNEP), which gives rise to our final model, denoted by (CFMNEP). For this model, we devise effective preprocessing techniques which allow for a tremendous reduction in problem size by exploiting the special structure of the objective function. Then we are ready to derive an efficient decomposition method for (CFMNEP). It is based on dividing the solution of the problem into a multi-step process named multiple-knapsack decomposition, in which each of the intermediate results provides interesting information to a network planner. In the following, we show how to extend this heuristic procedure to an exact method, by a suitable embedding into a Benders decomposition scheme. The resulting algorithm allows to improve the solutions of a slightly modified multiple-knapsack decomposition iteratively with guaranteed convergence to the optimal solution. These procedures are derived using the example of railway network expansion, but the basic considerations are general enough to allow the transfer
to other multi-period planning contexts as well. Finally, we demonstrate the efficiency of our methods in Chapter 5 by using them to solve the problem originally posed by GSV. We conduct experiments on subnetworks of the German rail freight network to confirm the superiority of Model (FMNEP) to (BMNEP) computationally and to show the significant impact of our model reduction to (CFMNEP) as well as our preprocessing techniques. Then we use our multiple-knapsack decomposition to solve the railway network expansion problem on the Germany-wide instance provided by GSV. Our Germany case study ends with a detailed discussion of the proposed infrastructure development plan and a comparison to the planning considerations of GSV itself. We will see that we are able to provide high-quality results which are convincing to experienced planners.