**Operations Research Proceedings** 

Stefan Helber · Michael Breitner Daniel Rösch · Cornelia Schön Johann-Matthias Graf von der Schulenburg Philipp Sibbertsen · Marc Steinbach Stefan Weber · Anja Wolter *Editors* 

# Operations Research Proceedings 2012

Selected Papers of the International Annual Conference of the German Operations Research Society (GOR), Leibniz Universität Hannover, Germany, September 5–7, 2012





# **Operations Research Proceedings**

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# Preface

This volume contains a selection of short refereed papers related to the presentations given at OR 2012, the International Annual Conference of the German Operations Research Society. The conference was held from September 4–7, 2012, at Leibniz Universität Hannover. More than 500 participants from about 40 countries attended more than 300 contributed talks in 18 different streams, ranging from "Applied Probability" to "Traffic and Transportation".

Special attention was given to those OR-problems that are related to the numerous aspects and interactions of "Energy, Markets and Mobility". The choice of this main topic reflected not only current challenges of society at large, but also important strengths of the hosting institutions, Leibniz Universität Hannover, as well as its business environment in the German state of Lower Saxony. A large number of presentations, both invited and contributed, addressed this field. However, the conference also provided ample opportunity to present and learn about the newest developments in operations research in general.

As in previous years, the presentations of the prize winners were one of the highlights of the conference. The excellent works submitted mainly by junior researchers again confirmed how attractive and vivid operations research is as a field of both theory development and application.

The editors of this book served as the local organizing committee. We are deeply indebted to the many institutions, firms, and individuals who worked hard and often invisibly or donated generously to make the conference a success. To all of them this volume is dedicated.

Stefan Helber Michael Breitner Daniel Rösch Cornelia Schön Johann-Matthias Graf von der Schulenburg Philipp Sibbertsen Marc Steinbach Stefan Weber Anja Wolter

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# Part I Award Winners

# **Product Line Design with Pricing Kits**

#### **Pascal Lutter**

#### **1** Introduction

Product design and pricing are important business decisions. On the one hand, product characteristics induced by product design should match different customer preferences. On the other hand, product pricing should utilize customers' willingnessto-pay (WTP) as much as possible to enhance profit. The resulting conflicts should be anticipated as well as possible to find a compromise between both clients' and corporate interests. Such approaches are being pursued in the literature and there are many specific mathematical programming models. All models support the design and pricing of only complete products. Following the increasing use of modularization and mass customization, it is possible to offer customized products at lower costs. Besides solely offering a variety of different product variants, it is also possible to allow customers to configure the product according to their own preferences. Pricing kits are innovative modular pricing systems in the form of list prices for modular product components and help to determine a corresponding pricing system for individual product components. Applications can be found in the configuration of personal computers or in the automotive sector. Previous descriptions in literature left the crucial aspect of pricing unanswered.

With this contribution, a mathematical optimization model is developed in order to determine a profit maximizing pricing kit. After a brief presentation of current methods for measuring customer preferences, product configuration and pricing, the new concept of pricing kits will be defined and a mathematical formulation will be provided. Then different forms of integration are discussed and compared with pure product line design models in a simulation study. The paper concludes with a brief outlook.

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#### 2 Product Line Design and Pricing

Hereinafter a product will be defined as a pool of characteristics. The characteristics of products are determined by their attributes *m* and corresponding attribute levels *a*. One attribute illustrates one component that is observable or at least conceptually ascertainable. For example, the internal memory of a PC is an attribute whose levels are given by its memory size. The combination of particular levels of a given set of attributes to a complete product is called product design, e.g. a PC is described by the attributes processor, operating system, memory, hard drive, optical drive, video card and monitor. Choosing all attributes at their lowest levels one gets a simple office PC. Another product variant emerges by varying attribute levels.

#### 2.1 Modeling Customer Choice

The anticipation of customer choice requires knowledge of the corresponding preferences in terms of utility for each attribute and level  $u_{kma}$ . In practice, Conjoint Analysis is a common method for investigating customer utility. With these observed utility values, a corresponding WTP can be calculated in order to predict customer decisions for any specific combination of product and price. To anticipate decisions of customers, a deterministic approach, the so-called First-Choice (FC) Rule, also known as the Maximum Utility Rule [6], is applied. This rule assumes perfectly rational customer choices and the exact knowledge of customer utility as well as all other factors that might affect customer choice. Even though these assumptions seem to be very restrictive, the resulting predictions have the same quality as other rules of choice [4].

#### 2.2 Pure Product Line Design and Pricing

Since heterogeneity of demand is increasing and globalization of markets is rising, the pressure on businesses to shape their products in line with the market conditions is growing. In a wider sense product line design contains both determination of quantity of product configurations and price setting. Existing mathematical models can be subdivided into single-stage and two-stage approaches. Single-stage models, also known as product line design (PLD) models, generate a predetermined quantity of different product variants as well as their corresponding prices [5]. It is important to mention that these models assume that product attributes cannot be customized afterwards. Hence, it is not possible to change some product attribute levels due to customer requests. If components are exchanged ex post, all product prices have to be recalculated in order to prevent cannibalization effects. The basis for PLD approaches forms the attribute level, so that product configuration and price setting takes place simultaneously, whereas two-stage models, also known as product line selection (PLS) models, address the level of complete products. In the first step the overall set of possible products is reduced to a smaller amount, so that in a second step the

final choice of products and their prices can be found in a subset of all possibilities of products [3]. It remains unclear how product preselection of the first stage has to take place, since PLS approaches only provide models for the second stage. In a comparison of these two approaches, the PLS approaches can only approximate PLD solutions [6].

#### **3 Pricing Kits**

A pricing kit is a pricing system in terms of list prices for standardized, combinable, complementary as well as substitutive and individually alienable components that can be provided as a complete product at the market. In contrast to product line design where customers are offered fixed products, customers can customize their own product. Precondition for pricing kits are the so-called product kits. A product kit consists of standardized and combinable performance based components [2]. Therefore, it shows the close link to the principle of modularization [1, 7]. Essential for this concept is the transition from the idea of impersonal mass production to a new approach of an individual product design. This concept still differs from complete made-to-measure production because of the use of standardized components. Pricing kits provide the opportunity to set individual prices for all attribute levels. Thus, prices for individual products can easily be calculated. A popular example for the successful usage of this pricing system is the well-known computer company Dell.

#### 3.1 Pricing Kit Model

In the following it is assumed that all relevant customers are allocated in *K* homogenous customer segments, each consisting of  $S_k$  customers. A product consists of *M* attributes with each  $A_m$  levels per attribute *m*. For each customer segment *k* the WTP for all attribute levels  $R_{kma}$  is known. Furthermore, the variable costs  $C_{ma}$  for all attribute levels are given. The binary variables  $x_{kma}$  represent the customer choice with  $x_{kma} = 1$  if the chosen product consists of attribute *m* with level *a* and otherwise  $x_{kma} = 0$ . The realized net benefit per segment *k* for attribute *m* is represented by  $s_{km}$ . The price for all attributes and corresponding levels is given by  $p_{ma}$ . It is assumed that a product necessarily consists of all attributes. In cases of optional attributes a further attribute level can be implemented with  $C_{ma} = 0$ . Finally, it is assumed that the company acts as a monopolist and all customers purchase one product at most. To determine a pricing system in terms of a pricing kit maximizing the contribution margin, the following model is proposed:

$$\max \sum_{k=1}^{K} S_k \sum_{m=1}^{M} \sum_{a=1}^{A_m} x_{kma} \left( p_{ma} - C_{ma} \right)$$
(1)

s.d. 
$$s_{km} = \sum_{a=1}^{A_m} x_{kma} (R_{kma} - p_{ma})$$
  $\forall k, m$  (2)

$$s_{km} \ge R_{kma} \sum_{a'=1}^{A_m} x_{kma'} - p_{ma} \qquad \forall k, m, a \qquad (3)$$

$$\sum_{m=1}^{M} s_{km} \ge 0 \qquad \qquad \forall k \qquad (4)$$

$$\sum_{a=1}^{A_m} x_{kma} = \sum_{a=1}^{A_{m'}} x_{km'a} \qquad \forall k, m, m'$$
(5)

$$\sum_{a=1}^{A_m} x_{kma} \le 1 \qquad \qquad \forall k, m \qquad (6)$$

$$\begin{aligned} x_{kma} &\in \{0, 1\} \\ s_{km}, p_{ma} &\in \mathbb{R} \end{aligned} \qquad \qquad \forall k, m, a \qquad (7) \\ \forall k, m, a \qquad (8) \end{aligned}$$

The objective function (1) maximizes the contribution margin, which is the sum of products of the segment-related contribution margins with the corresponding segment size. Segment-specific contribution margins can be calculated as the difference between the costs and the price of the individual product. Customers' behavior is forecasted using the First Choice Rule: For each attribute customers choose the level which generates the highest net benefit. If the sum of all net benefits is non-negative the product is bought. This behavior is implemented in (2)–(4). (2) calculates the net benefit for all attributes, (3) assures rationality of customer choice and (4) guarantees non-negativity of net benefit of purchased products. The complete specification from the acquired product is ensured with (5), whereas (6) guarantees that each attribute contains not more than one attribute level. Altogether, these restrictions assure that all customized products consist of exactly M attributes each with one level. Finally, the domain of the decision variables is given in (7) and (8). The model can be linearized introducing customer individual prices  $p_{kma}$  which are equal to  $p_{ma}$  if customer k buys attribute m in level a and 0 otherwise. The resulting formulation can be solved using standard solvers like Xpress.

#### 3.2 Integration of Pricing Kits

Offering pure pricing kits (PK) is a straightforward way of using pricing kits. In such cases, the entire product line only consists of a single pricing kit. For many products, this seems to be an inadequate consideration of consumers behavior. One cannot assume that each customer segment consists of willingness and necessary knowledge to choose the right product components. Although there may exist many

consumers who are familiar with the product in general and take pleasure in a full customization of the product, there are also customers showing lower interest in product customization. In particular, those customers could be deterred by a pure PK. A combination of pricing kits and pre-configured products could overcome this drawback. Promising extensions are combined pricing kits (CPK) and upgrade pricing kits (UPK). CPK consist of one or more product variants as well as a pricing kit, while UPK consist of basic product variants that can be customized exchanging certain components. This causes several advantages compared to PK. First, customers with low product involvement can easily afford a fully functional basic version. Second, customers with high product involvement are able to customize the product according to their preferences. The main advantage from a corporate perspective is the use of several basic types and different pricing kits which lead to a better price discrimination.

#### **4** Computational Results

In the evaluation of the proposed pricing kit as well as with its extensions a broad simulation study was conducted, which examines the decision situation under certainty as well as under uncertainty. The performance of proposed models is tested against pure PLD strategies using random instances with 4–6 different customer segments of the same size.

All models are solved in their linear formulation using Xpress. The instances differ with respect to variable costs and the structure of willingness-to-pay. The observed products have 6–8 attributes with 2–4 levels. In contrast to the new models it turns



Fig. 1 Purchase probability of test segments

out that competitive margins are only achieved offering every customer segment its own product variant. Almost equal margins are generated using the new models with two or less pre-configured product variants.

To take account of uncertainties, the influence of another customer segment that has not been considered in the optimization is analyzed. For this purpose, all models were optimized using 4 basic segments. Then the purchase probability of a different test segment is estimated. Three different types of WTP structure are considered. The results are illustrated in Fig. 1. One can draw the conclusion that the pure PLD strategy performs significantly worse than the new pricing strategies. This results from the fact that pricing kits and its extensions provide much more flexibility in the product configuration. Hence, the possibility to change some attribute levels leads to significantly higher purchase probabilities.

#### **5** Outlook

In this paper a mathematical model to determine a pricing kit that maximizes contribution margin was presented and compared with traditional strategies of pure product line design. Further enhancements of pricing kits were discussed and analyzed. It turns out that the proposed pricing strategies are not inferior to the traditional strategies in deterministic situations and show a clear advantage in cases of uncertainty.

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## **Sparsity of Lift-and-Project Cutting Planes**

**Matthias Walter** 

#### **1** Introduction

This work is an extended abstract of the author's diploma thesis and contains the most important concepts and results. It is about a numerical property of a certain cutting plane method in mixed-integer (linear) programming. Many practical problems can be modeled as MIPs. Examples are settings where decisions are modeled with binary variables which are then connected via linear constraints.

Solving MIPs is NP-hard in general, nevertheless large problems can be solved using the combination of many different techniques which evolved during the past decades. Typically, a so-called *branch & cut* method is used which utilizes the linear relaxation to bound the quality of subproblems. The relaxation is created by omitting the integrality constraints and is a *linear program* (LP). The set of feasible solutions of such an LP is a *polyhedron*, the intersection of finitely many halfspaces. Without loss of generality we assume that it is a rational polyhedron of the following form:

$$P = \{x \in \mathbb{Q}^n : Ax \le b\}$$

where  $A \in \mathbb{Q}^{m \times n}$  and  $b \in \mathbb{Q}^m$  associated to a linear objective function  $c^{\intercal}x$  which is to be minimized.

A solution  $x \in \mathbb{Q}^n$  is feasible for the MIP if  $x_i \in \mathbb{Z}$  for all  $i \in I$  where I is a specified subset of the variables. One of the most important observations in mixed-integer programming is that the convex hull

$$P_I := \operatorname{conv} \{ x \in P : x_i \in \mathbb{Z} \; \forall i \in I \}$$

of all feasible points is again a polyhedron.

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Applying a bounding procedure based on the LP-relaxation improves the running time dramatically compared to pure enumeration techniques when solving a mixed-integer program. This effect is stronger if the relaxation P approximates  $P_I$  more tightly. Hence a fundamental way of improving solver software is by adding more valid inequalities, so-called *cutting planes* (see [1, 6]).

One method to generate valid cutting planes is *lift-and-project* and was introduced in [3]. Here the polyhedron P is split into two polyhedra  $P_1$  and  $P_2$  via a disjunction  $\pi^{\mathsf{T}}x \in (-\infty, \pi_0] \cup [\pi_0 + 1, +\infty)$  where  $\pi \in \mathbb{Z}^n$  and  $\pi_0 \in \mathbb{Z}$ . Then the convex hull of the union  $P_1 \cup P_2$  is a stronger relaxation. All inequalities valid for this relaxation which cut off a given point  $\hat{x} \in P$  can be found efficiently via the so-called *cut generating LP* (CGLP). The point  $\hat{x}$  shall be separated via the cut  $\alpha^{\mathsf{T}}x \leq \beta$ .

$$\min \beta - \alpha^{\mathsf{T}} \hat{x} \qquad (CGLP)$$
  
s.t.  $\alpha^{\mathsf{T}} = w^{\mathsf{T}} A + w_0 \pi^{\mathsf{T}}$   
 $\alpha^{\mathsf{T}} = v^{\mathsf{T}} A - v_0 \pi^{\mathsf{T}}$   
 $\beta \ge w^{\mathsf{T}} b + w_0 \pi_0$   
 $\beta \ge v^{\mathsf{T}} b - v_0 (\pi_0 + 1)$   
 $w, v \in \mathbb{Q}^m_+$   
 $w_0, v_0 \in \mathbb{Q}_+$ 

We call a cutting plane *sparse* if only a few of its coefficients  $\alpha_i$  are non-zero. This property is especially relevant from a practical point of view since modern LP-solvers only work with the non-zeros in memory and hence their number influences the running time. In experiments we mostly measure *density* which is the converse concept.

#### **2** Normalization Constraints

Since (CGLP) is a polyhedral cone it must be truncated in order to be able to optimize over it. This is done by so-called *normalization constraints*. The choice of a good normalization is very important because there is a large number of possible liftand-project cutting planes. We now shortly present the most important ones that are studied in literature and also suggest another one that attempts to generate sparser cuts.

There are three "primal" normalizations which try to bound the  $\alpha_i$  or  $\beta$ .

$$\sum_{i=1}^{n} |\alpha_i| = 1 \qquad (\alpha_1 \text{-NC})$$

$$|\alpha_i| \le 1 \quad (\forall i \in [n]) \tag{$\alpha_{\infty}$-NC}$$

$$|\beta| = 1 \qquad (\beta-NC)$$

The other category of normalization constraints is based on the idea of bounding the multipliers  $w, w_0, v$ , and  $v_0$ . All of the following truncations have a very attractive property: There is a correspondence between the bases of (CGLP) and the bases of the original LP (see [4]).

$$w_0 + v_0 = 1 \tag{TNC}$$

$$\sum_{i=1}^{m} w_i + w_0 + \sum_{i=1}^{m} v_i + v_0 = 1$$
 (SNC)

The second normalization highly depends on the representation of a certain inequality  $A_{i,*}x \leq b_i$  in that a scaled version of a row (scaled by some  $\lambda > 1$ ) is preferred over the original row. This happens because it needs a smaller multiplier to get the same result.

If we interpret the values of the multipliers as a resource with capacity equal to 1 we will (on average) use approximately half of it for w and half of it for v. This means that the resulting cut is almost a convex combination of some inequalities of  $Ax \le b$  scaled by 1/2. The scaling factor in turn means that incorporating a generated lift-and-project cut into another lift-and-project cut is penalized. This fact is considered as a reason that with the SNC the rank of the lift-and-project inequalities remains small even after several rounds of cut generation. Because typical MIPs usually have sparse rows rank 1 cuts with a small dual support (a small number of positive multipliers) are sparse as well. A scaled variant was developed by Fischetti, Lodi and Tramontani in [5].

$$\sum_{i=1}^{m} ||A_{i,*}||_2 (w_i + v_i) + ||\pi||_2 (w_0 + v_0) = 1$$
 (ENC)

It makes the choice of all constraints fair by rescaling the weights. Now we want to additionally penalize dense constraints.

$$\sum_{i=1}^{m} |\operatorname{supp}(A_{i,*})| \cdot ||A_{i,*}||_2(w_i + v_i) + ||\pi||_2(w_0 + v_0) = 1$$
(DNC)

Note that by |supp(x)| we denote the number of non-zeros of vector x.

The interpretation in terms of resources is simple. The CGLP is allowed to incorporate two sparser inequalities instead of a single dense inequality with the same average of multipliers.



Fig. 1 Simplex speed for densified rows

#### **3 Results**

This section is divided into three parts. In the first, the impact of sparsity on the running time of the simplex method is measured. The second summarizes the measurements for the lift-and-project cutting planes and the third describes the main result of the thesis.

#### 3.1 Effects of Sparsity

Before testing the normalization constraints in practice we devised the following experiment in order to quantify the effects of using dense rows. For each instance of the MIPLIB 2003 [2] we created a valid very dense equation  $\alpha^{T}x = \beta$  as a linear combination of other equations. We then ran CPLEX in order to solve the instance, except that we hooked Algorithm 1 into the branching decision callback of CPLEX.

Algorithm 1 Pseudocode for Densification Experiment

- 1. Get the current optimal basis B from the node LP.
- 2. For d = 0, ..., 9, carry out Steps 3.1,...,3.2.
- 3. Copy LP to LP' and apply the CPLEX branching steps (bound tightening) to LP'.
- 4. Add  $\alpha^{\intercal} x = \beta$  to the first *d* rows of LP'.
- 5. Feed B as a warm-start basis into LP'.
- 6. Solve LP' with the dual simplex method. Measure the number of simplex iterations (pivot steps) and the solving time.

Туре	Rank	$\alpha_{\infty}$ -NC	$\alpha_1$ -NC	$\beta$ -NC	TNC	SNC	ENC	DNC
Primal density	= 1	82.2	1.9	6.6	8.6	5.4	5.5	5.2
Primal density	$\leq 10$	86.9	3.5	11.6	23.3	11.5	14.0	10.7
Dual density	= 1	23.2	1.8	1.8	2.8	1.2	1.2	1.2
Dual density	$\leq 10$	23.3	3.3	4.6	5.7	1.9	2.2	1.8

Table 1 Relative densities of cuts for the MIPLIB 2003 instances in % (geometric mean).

This procedure does not change the remaining behavior of CPLEX and hence the LPs to be solved in Step 3.1 are essentially the same except that *d* inequalities were "densified" with help of  $\alpha^{T}x = \beta$ . So from the polyhedral point of view the LPs were the same, but nevertheless, the solving times were different as Fig. 1 shows.

#### 3.2 Actual and Possible Sparsity

The goal of this part of the work was to compare the different normalizations with respect to sparsity. First we observed that ( $\alpha_{\infty}$ -NC) leads to horribly dense cuts and approve former results stating that ( $\beta$ -NC) is instable. Interestingly, the cuts obtained from ( $\alpha_1$ -NC) are the best when we are interested only in sparsity but, as shown in [3], they are provably not as strong as other cuts.

Via a big-*M*-based MIP model we were able to force cut coefficients to zero. Since the (CGLP) has the cut violation as an objective value we measured the cut violation that can be obtained for a given maximal number of non-zero coefficients. The result is that if we strive for a sparsest cut for it helps to allow cut violations of 20% below. On the other hand, allowing weaker cut violations does not help much for sparsity.

Another known result is that cuts of higher *cut rank* are typically denser than rank-1 cuts. This effect is present especially for the multiplier-based normalizations. Table 1 provides some details although many more can be found in the thesis.

#### 3.3 Dual Sparsity

We also measured the *dual density* which is defined as the average number of nonzero coefficients in the multiplier vectors w and v. Our experiments indicate a strong correlation between the primal and dual density (see Fig. 2). From that we derived our suggested improvement of the Euclidean normalization constraint introduced in [5].

Among the four related multiplier-based normalizations this normalization (DNC) performs best. It is ongoing work to evaluate the normalization in a realistic branch & cut solving process.



Fig. 2 Correlation between primal and dual density for instance pp08aCUTS

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### **Railway Track Allocation**

**Thomas Schlechte** 

#### 1 Micro-Macro Transformation of Railway Networks

A major challenge is modeling railway systems to allow for resource and capacity analysis. Railway capacity has basically two dimensions, a space dimension which are the physical infrastructure elements as well as a time dimension that refers to the train movements, i.e., occupation or blocking times, on the physical infrastructure. Railway safety systems operate on the same principle all over the world. A train has to reserve infrastructure blocks for some time to pass through. Two trains reserving the same block of the infrastructure within the same point in time is called *block conflict*. Therefore, models for railway capacity involve the definition and calculation of reasonable running and associated reservation and blocking times to allow for a conflict free allocation.

There are *microscopic* models that describe the railway system extremely detailed and thorough. Microscopic models have the advantage that the calculation of the running times and the energy consumption of the trains is very accurate. A major strength of microscopic models is that almost all technical details and local peculiarities are adjustable and are taken into account. Railway system on a microscopic scale covers the behavior of trains and the safety system completely and correctly. Those models of the railway infrastructure are already very large even for very small parts of the network. The reason is that all signals, incline changes, and switches around a railway station have to be modeled to allow for precise running time calculations of trains. In general microscopic models are used in simulation tools which are nowadays present at almost all railway companies all over the world. The most important field of application is to validate a single timetable and to decide whether a timetable is operable and realizable in practice. However, microscopic models are inappropriate for mathematical optimization because of the size and the high level of detail. Hence,

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most optimization approaches consider simplified, so called *macroscopic*, models. The challenging part is to construct a reliable macroscopic model for the associated microscopic model and to facilitate the transition between both models of different scale.

In order to allocate railway capacity significant parts of the microscopic model can be transformed into aggregated resource consumption in space and time. We develop a general macroscopic representation of railway systems which is based on minimal headway times for entering tracks of train routes and which is able to cope with all relevant railway safety systems. We introduce a novel bottom-up approach to generate a macroscopic model by an automatic aggregation of simulation data produced by any microscopic model. The transformation aggregates and shrinks the infrastructure network to a smaller representation, i.e., it conserves all resource and capacity aspects of the results of the microscopic simulation by conservative rounding of all times. The main advantage of our approach is that we can guarantee that our macroscopic results, i.e., train routes, are feasible after re-transformation for the original microscopic model. Because of the conservative rounding macroscopic models tend to underestimate the capacity. Furthermore, we can control the accuracy of our macroscopic model by changing the used fixed time discretization. Finally, we provide a priori error estimations of our transformation algorithm, i.e., in terms of exceeding of running and headway times. We implemented our new transformation algorithm in a tool called NETCAST. The technical details can be found in [9].

#### **2** Optimal Railway Track Allocation

The main application of railway track allocation is to determine the best operational implementable realization of a requested timetable, which is the main focus of our work. But, we want to mention that in a segregated railway system the track allocation process directly gives information about the infrastructure capacity. Imaging the case that two trains of a certain type, i.e., two train slots, are only in conflict in one station. A potential upgrade of the capacity of that station allows for allocating both trains. This kind of feedback to the department concerning network design is very important. Even more long-term infrastructure decisions could be evaluated by applying automatically the track allocation process, i.e., without full details only on a coarse macroscopic level but with different demand expectations. Hence, suitable extensions or simplifications of our models could support infrastructure decisions in a quantifiable way. For example major upgrades of the German railway system like the high-speed route from Erfurt to Nürnberg or the extension of the main station of Stuttgart can be evaluated from a reliable resource perspective. The billions of euros for such large projects can then be justified or ranked by reasonable quantifications of the real capacity benefit with respect to the given expected demand.

The optimal track allocation problem for macroscopic railway models can be formulated with a graph-theoretic model. In that model optimal track allocations correspond to conflict-free paths in special time-expanded graphs.