The Roles of Modelling, Simulation, Heuristic and Exact Optimization in Public Transport

13th Conference on Advanced Systems in Public Transport (CASPT 2015)
Rotterdam, July 19 to July 23, 2015.

Martin Grötschel
Zuse Institute, Technische Universität and MATHEON Berlin, Germany

These are the slides of the presentation I have shown in Rotterdam on July 22.

However, I have deleted all slides, pictures and diagrams where I am not sure about the copyright. This is due to the fact that I have distributed slides before, which were put on the internet by someone else and which contained a piece of a map. A lawyer discovered that map (there are law firms specializing in this “business”), and I had to pay a fine of more than 600 Euros. That is why I have become somewhat cautious.

These slides are for your personal information only.

Martin Grötschel

Thanks to the organizers!

Where do I come from?

What drives me?

Where are the problems?

TU Berlin, Mathematisches Institut

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Institut für Mathematik

Mathematikgebäude der TU Berlin

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Gehe zu: 9003

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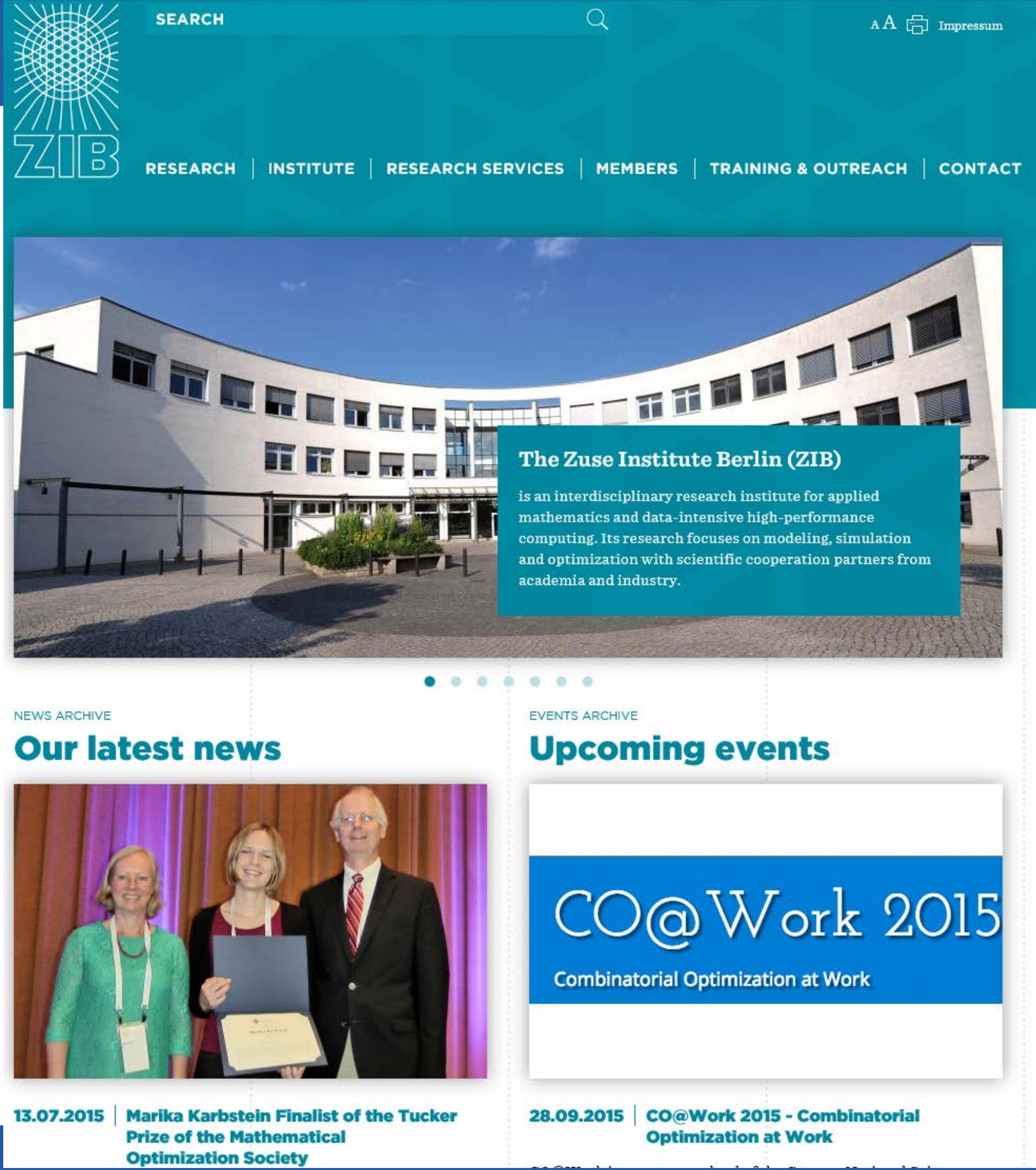
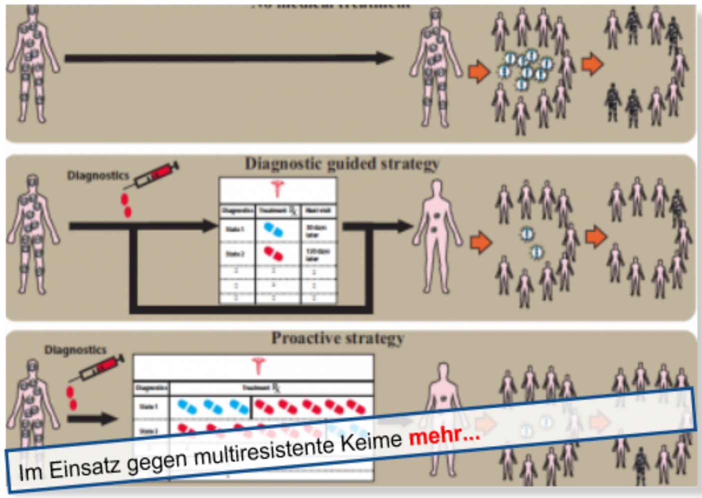


Forschungszentrum MATHEON
Mathematik für Schlüsseltechnologien

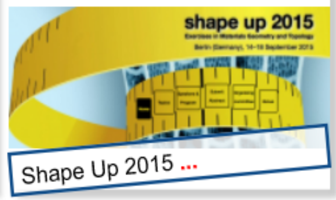
Anmeld

Startseite | Forschung | Transfer | Schule | Presse | Über uns | Neuigkeiten | Veranstaltungen



Im Einsatz gegen multiresistente Keime mehr...

Matheathlon Ergebnisse ...



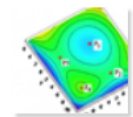
Shape Up 2015 ...

Neuausrichtung des Copernicus-Preises : Mit dem Copernicus-Preis zeichnen die Deutsche Forschungsgemeinschaft (DFG) und die Stiftung für die polnische Wissenschaft (FNP) zusammen ...

2. International MATHEON Conference on Compressed Sensing and its Applications: Welcome to the 2. International MATHEON Conference on Compressed Sensing and its Applications 2015. ...

Das Forschungszentrum MATHEON

entwickelt Mathematik für Schlüsseltechnologien und unterstützt Partner in Industrie, Wirtschaft und Wissenschaft. Schule und Öffentlichkeit bilden einen weiteren Fokus unserer Aktivitäten. MATHEON wird von den drei Berliner Universitäten (FU, HU and TU) und den Forschungsinstituten (WIAS und ZIB) gemeinsam getragen.



Sommerschule : In diesem Jahr findet die Sommerschule "Lust auf Mathematik" vom 5. Juli bis 10. Juli 2015 im Jugendbildungszentrum Blossin e.V. statt. ...

conform! Der Film: Als man noch dachte, dass die Erde eine Scheibe sei, hatten es die Kartographen leicht: ...

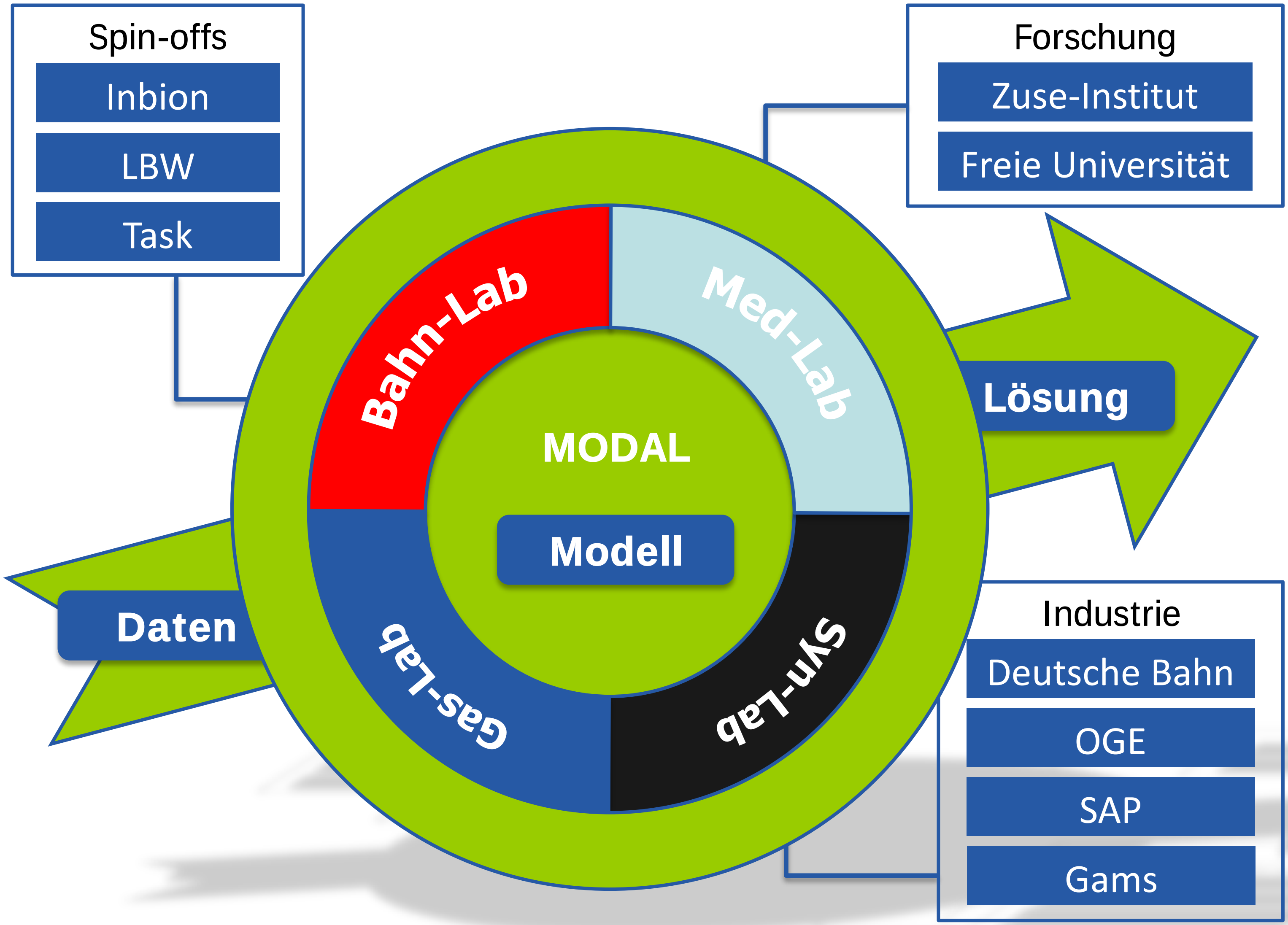
BIMoS

3. BIMoS-Day: The Berlin International Graduate School in Model and Simulation based Research (BIMoS) devotes each BIMoS Day to introducing a broad scientific audience to a novel methodology with a wide range of ...

Aufgelesen

- Mathe ist "männlich", gute Schulleistungen "weiblich" (Tagesspiegel)
- Spätbabylonische Liebe zur Mathematik (Spiegel online)
- Die Mathematik des Riechens (Bild der Wissenschaft)
- Mathematikerin Hélène Esnault (Tagesspiegel)
- Zahlenplattform Imaginary.org (Spiegel online)
- Rechenschwäche. (Berliner Zeitung)
- Die neue „Miss Germany" ist gekürt (Berliner Zeitung)
- Neue Methoden im Mathe-Unterricht (Arte TV)
- Die Optimierung der Welt (Tagesspiegel)
- Mathe-Prof als YouTube-Star (Spiegel Online)

Forschungscampus MODAL: BMBF and industry supported



Why am I interested in public transport?

My fields of mathematical interest are:

- optimization, discrete mathematics and operations research

Public transport and traffic planning are among the application areas offering the biggest challenges from any perspective:

- data acquisition (getting all data, keeping them up-to-date, processing the data,...)
- modelling the concepts, questions and tasks mathematically
- developing reasonable simulation environments
- creating and using appropriate theory
- employing the right/fitting solution methodology
- large scale online and real-time problems
- really huge instance sizes (big data before this became fashion)
- impact for the public and for industry

Why am I interested in public transport?

Problems of the field are:

- Many public transport companies do not know exactly what they want: moving target problem
- Politicians interfere: How should the subsidies be used?
- Customers have different/varying objectives
- Software companies providing “solutions” often make gigantic claims and promises
  - We optimize the resources of the world
  - We have the most powerful solution engines
  - ...can make your solution even more optimal

Marketing

The claims and buzzwords

XYZ's technology is based on sophisticated novel advanced mathematical algorithms combined with artificial intelligence and operations research techniques, developed together by mathematicians, computer scientists and transportation planning experts.
XYZ's unique technology is able to create fully optimal solutions within seconds taking the full set of constraints and preferences into account. Our most powerful solution engine is modular and integrated, robust and easily customizable providing the greatest possible flexibility... There is no planning problem we can't solve, no business operation we can't optimize.

That is what, in some way or the other, some vendors state. How can a customer react to such overblown marketing buzz words?

What do you mean by optimized? What methodology do you really use? Which algorithms do you employ? What optimality guarantee can you provide? Have you ever heard of *NP*-completeness?

We should be happy

- to really understand the problems in public transport
- to formulate (model) the desires/wishes/goals in a way such that everyone involved understands them
- to be able to acquire the necessary data
- to standardize/automatize the solution approach
- to solve the problems addressed a little better than before and
- that the solutions are accepted by the customers.

These are the honest statements of a mathematician, but, of course, this is not marketing language.

Modelling?

Modelling: What is that?

Picasso: „Art is a lie that makes us realize truth“

Olga Chochlowa
Picasso‘s first wife

The model of the mathematician

The model of the artist

A mathematical model is a lie that helps us see the truth.

Picasso and his women

Olga

Francesca

Marie-Thérèse

Jacqueline

Francoise

Confusion: There are many other ways of modelling

- computer models
- business model
- architectural models
- chemical models
- medical models
- …

`model car`

`car model`

Elvis' gold-leafed Cadillac (a gift from Priscilla).

1960 Series 75 Fleetwood Limousine

This vehicle is the ultimate in luxury and opulence. Costing $100,000, it was customised by George Barris with gold plated interior gadgets such as a phone, shoe buffer, refrigerator, entertainment console with a ten record automatic changer RCA record player, swivel TV and tape deck. Forty coats of exterior paint made with pearl, diamond dust and oriental fish scales were used on the outside. Hubcaps, wheel covers, headlight rims and the front grille are gold plated in 24kt gold. Gold lame drapes were used to cover the back windows and to separate the front and back seats. Truly a vehicle fit for a King!

Massenmodell

Model Railway/Modelleisenbahn

Mathematical Modelling: What is that?

Beginning with observations

- of our environment
- a problem in practice of particular interest
- a physical, chemical or biological phenomenon
- an organizational/planning task

possibly with guiding/tailored experiments and including data acquisition:

the attempt of a formal representation via „mathematical concepts“ (variables, equations, inequalities, objective functions , etc.), aiming at the utilization of mathematical theories and tools.

Optimization problems that model reality (occasionally)

$$\begin{aligned} &\max\ f(x) \quad or \quad \min\ f(x) \\ &g_i(x) = 0, \quad i = 1,2,\dots,k \\ &h_j(x) \le 0, \quad j = 1,2,\dots,m \\ &x \in \mathbb{R}^n \ (and \ \ x \in S) \end{aligned}$$

„general“ (nonlinear) program NLP

$$\begin{aligned} &\min c^T x \\ &Ax = a \\ &Bx \le b \\ &\ \ x \ge 0 \end{aligned}$$

linear program LP

$$\begin{aligned} &\min c^T x \\ &Ax = a \\ &Bx \le b \\ &\ \ x \ge 0 \\ &x \in \mathbb{Z}^n \\ &(x \in \{0,1\}^n) \end{aligned}$$

(linear) integer program IP, MIP

program = optimization problem

Simulation, Simulator or simulate are derived from the latin words ***simulare*** and ***similis*** *.*

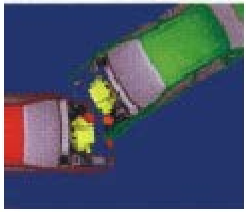
They mean: pretend to be or the same sort.

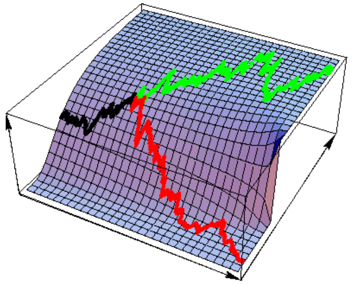
„Computation“ of several (close to reality) variants of a mathematical modell aimimg at:

- „validation“of the correctness of a model
- investigation of typical instances in the model framework, e.g., to avoid experiments or to test some functionality (crash-test)
- good predictions (weather)
- computation of reasonable solutions for the control of a system in practice (control of transport and logistics-systems)

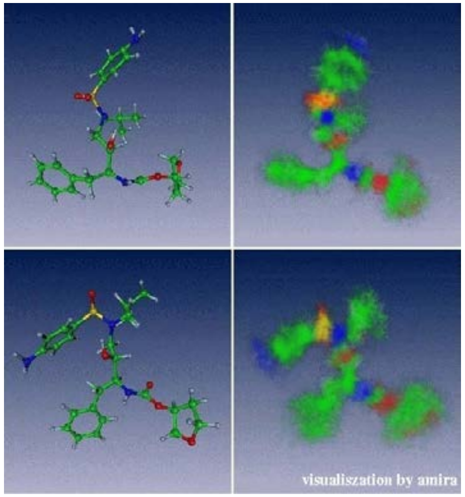
Computation of instances varying several parameters

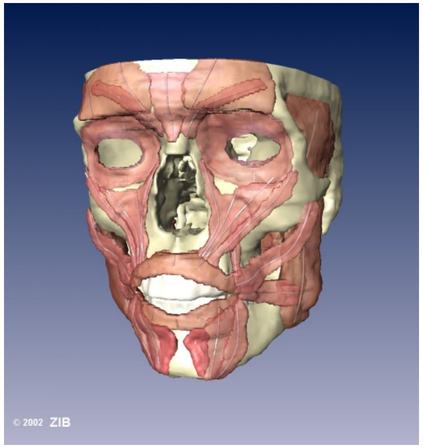
Parameters of a car crash test, e.g.:
speed, material stiffness, various angles





Dynamik eines 'Δ'-hedge gegen einen Garantiefonds in verschiedenen Szenarien.





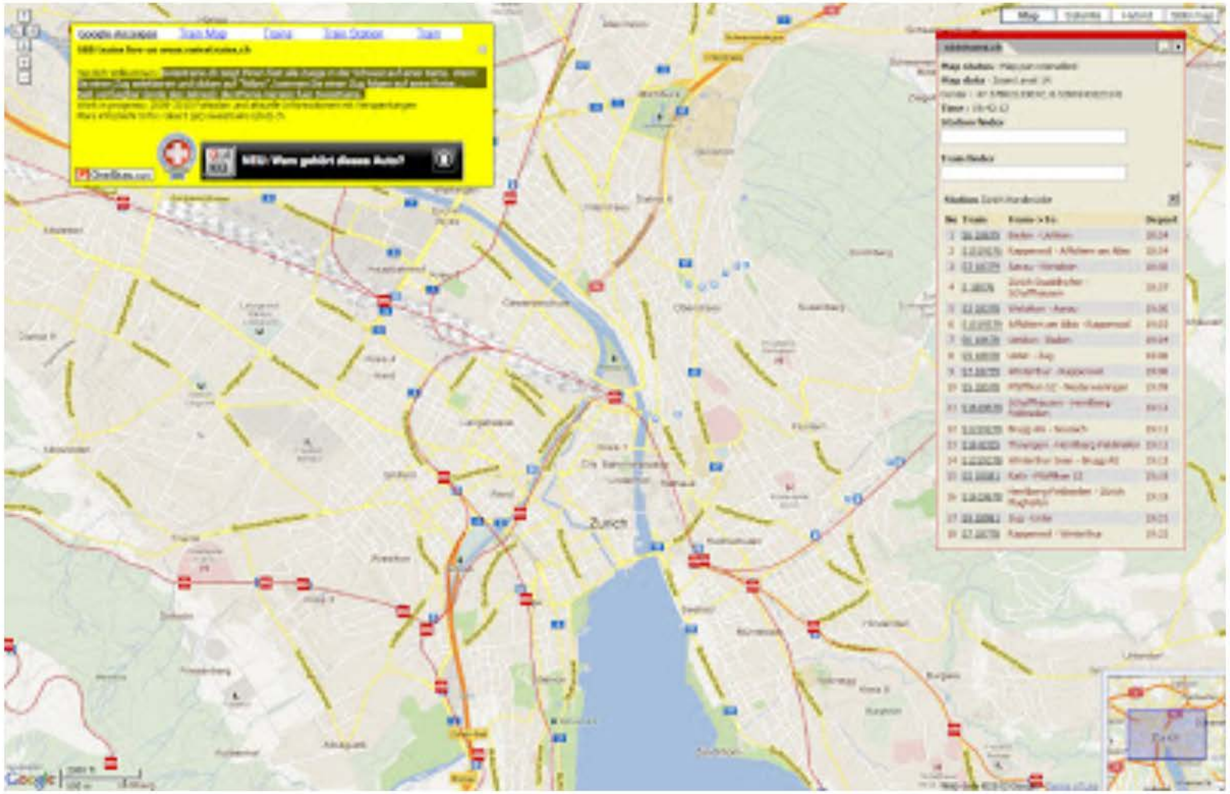
3D-reconstruction of a scull from a magneto-resonance tomografic investigation

Tsunami Model Simulation

The **Nagel–Schreckenberg model** is a theoretical model for the simulation of freeway traffic. The model was developed in the early 1990s by the physicists Kai Nagel and Michael Schreckenberg. It is essentially a simple cellular automaton model for road traffic flow that can reproduce traffic jams, i.e., show a slow down in average car speed when the road is crowded (high density of cars).

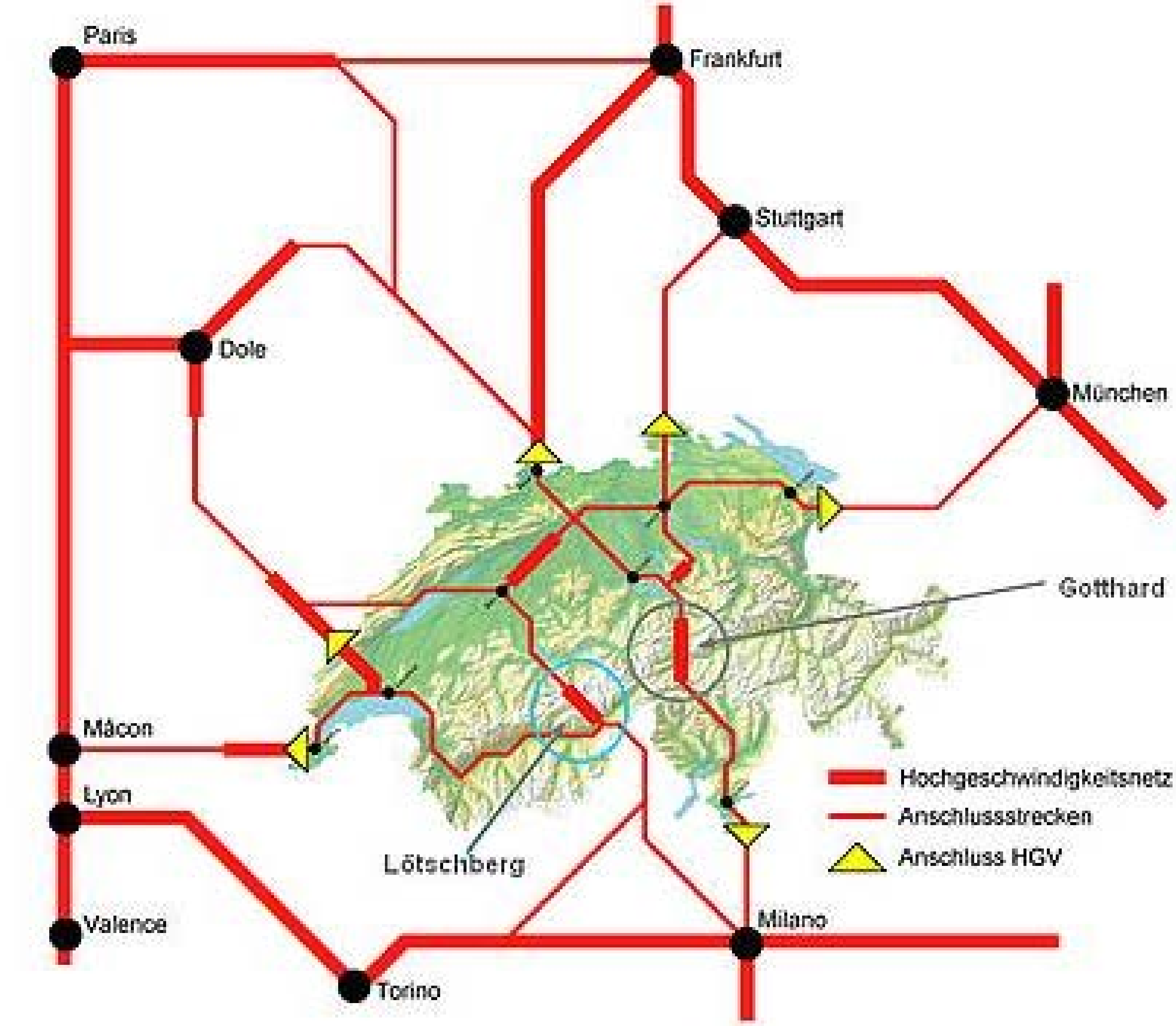
SBB trains live – Die Schweizer Bahn als Simulation

Swisstrains.ch zeigt Ihnen fast alle Zuege in der Schweiz auf einer Karte. Wenn Sie einen Zug selektieren und clicken auf “follow”, koennen Sie einen Zug folgen auf seine Reise… Bald verfuegbar (ende des Jahres): die iPhone-Version fuer Swisstrains.

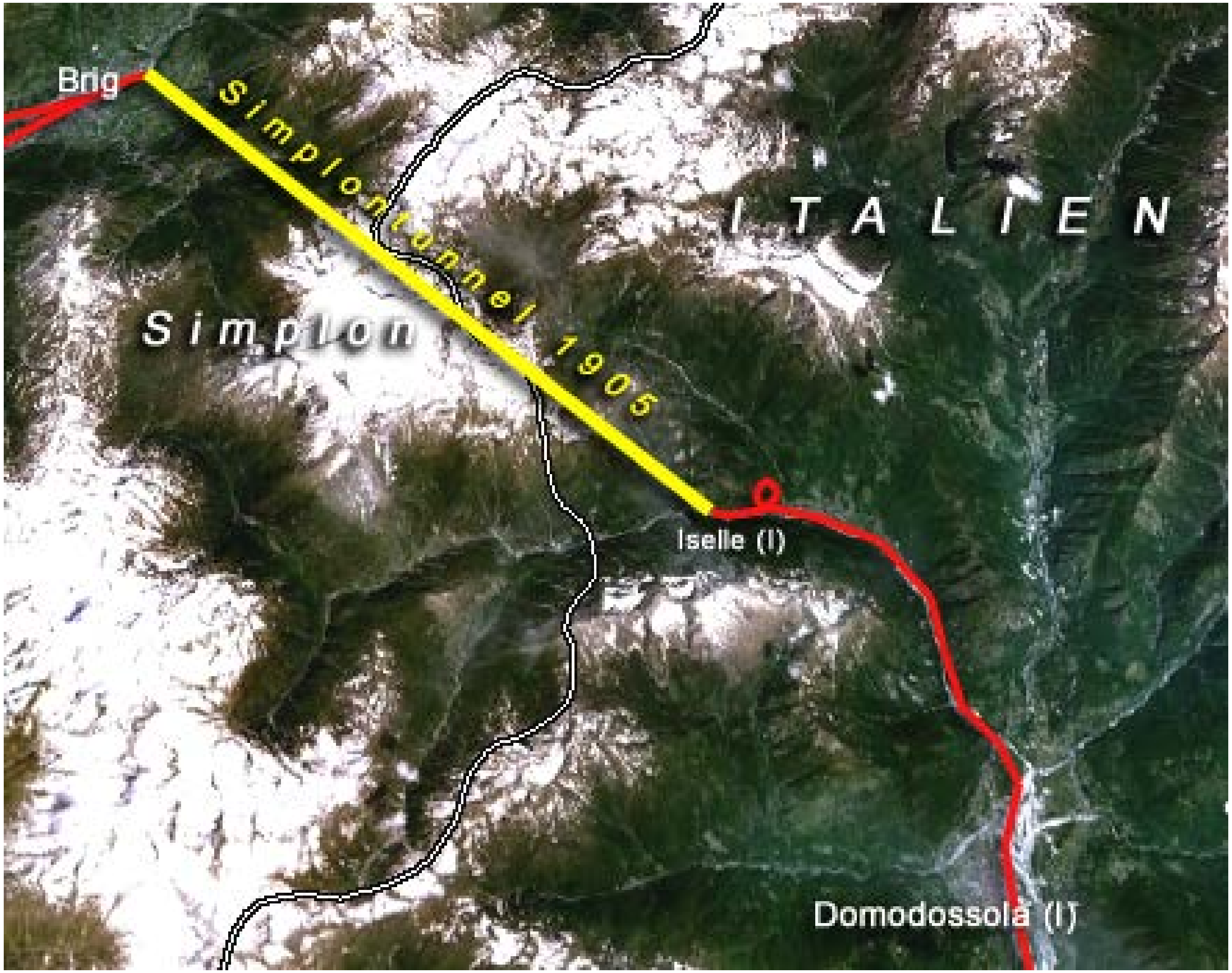


Link: http://www.swisstrains.ch/

European „Bottleneck“



MTO Simplon

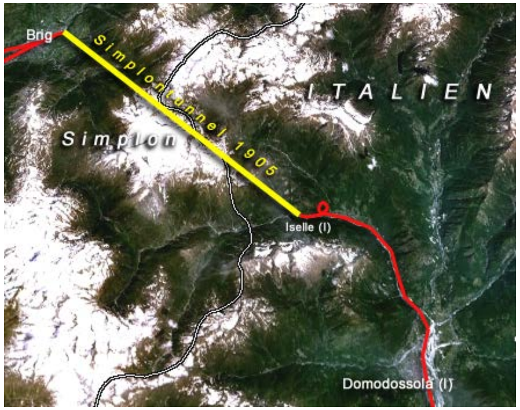


www.swisstrains.ch

MTO Simplon Netzdaten

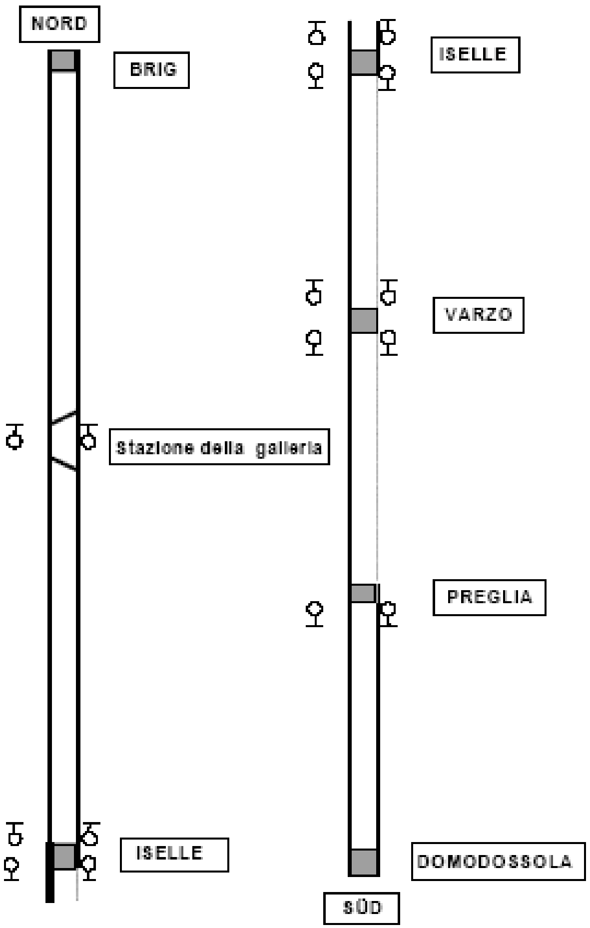
- ca. 45.3 km Strecke (Brig-Domodossola II
- 12 Bahnhöfe
- 560 (2*577=1154) OpenTrack Mikroknoten
- 1831 OpenTrack Mikrokanten
- 223 Signale
- 8 Überleitstellen
- 100 Weichen
- 6 Zuggattungen
- 40 Laufwege
- 230 Fahrstrassen (Blöcke)

- makrotisiert zu 18 Stations und 40 Tracks



Infrastrukturdaten

Complex Traffic at the Simplon



Source: Wikipedia

Slalom route

- ROLA trains traverse the tunnel on the “wrong“ side

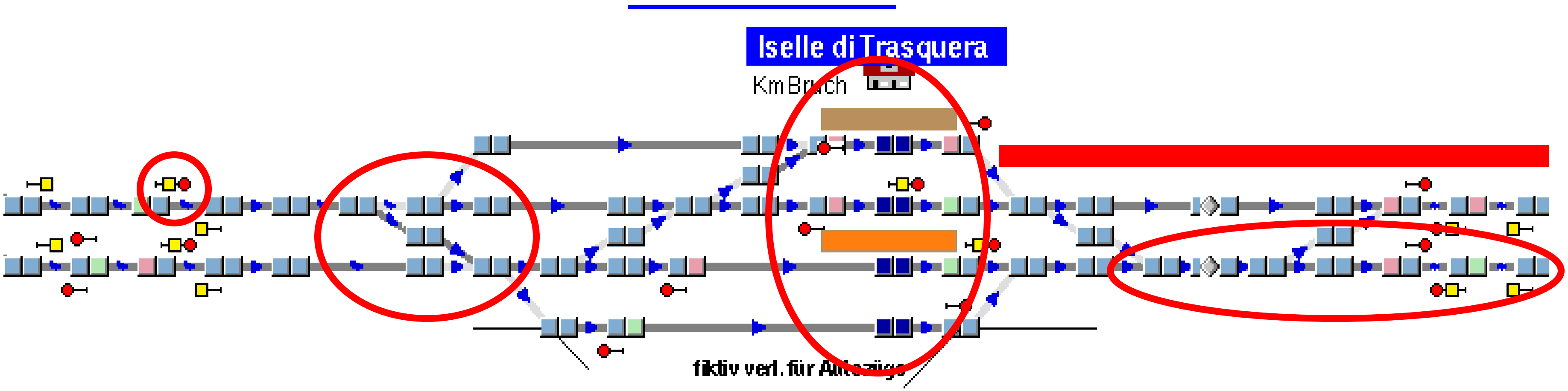
Crossing of trains

- complex crossings of AUTO trains in Iselle

Conflicting routes

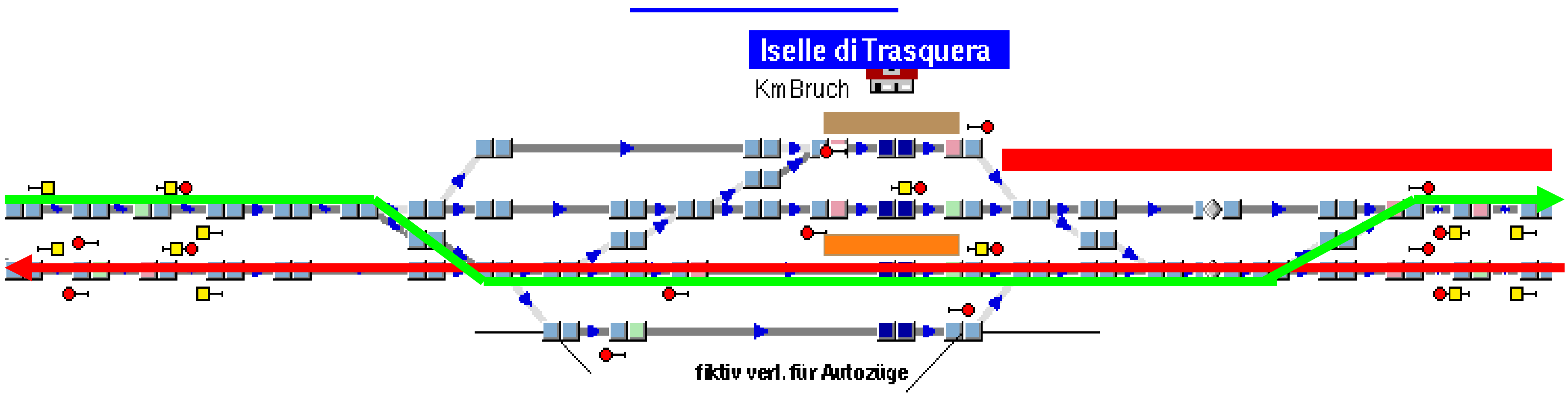
- complex routings in station area Domodossola and Brig

- Detailed railway infrastucture data (OpenTrack)

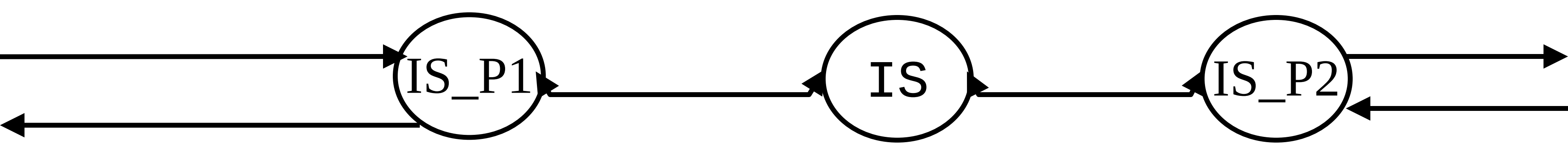


  - Signals
  - Switches
  - Tracks (with max. speed, acceleration, gradient)
  - Stations and Platforms

- Generation of artifical nodes – pseudo stations



- Crossing of train routes



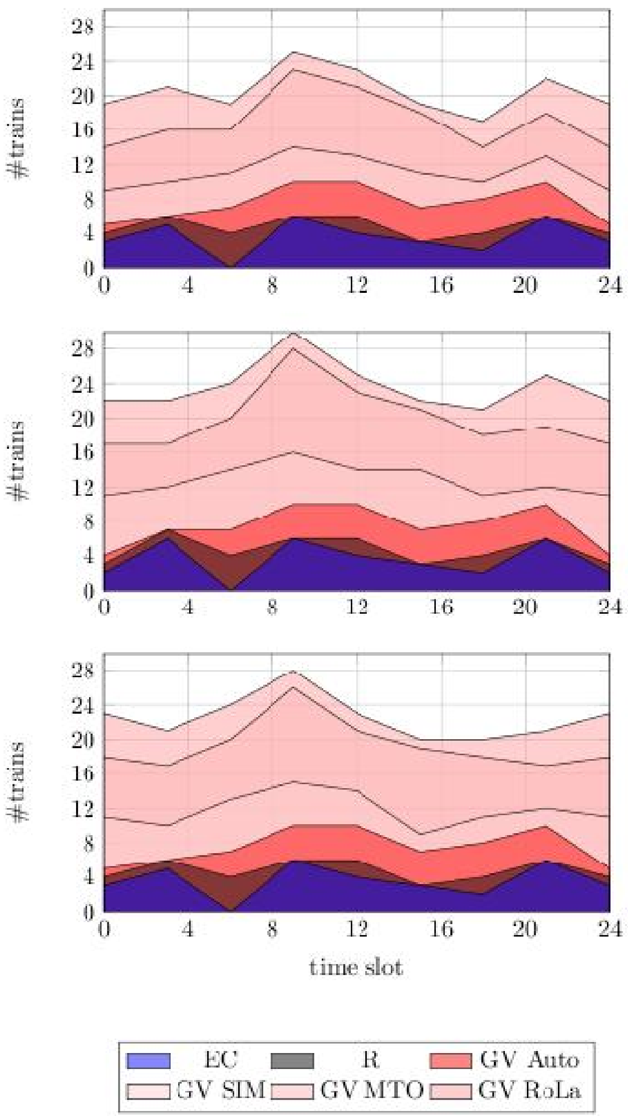
- Two pseudo stations were generated

Time discretization dt/s	6	10	30	60
Number of trains	196	187	166	146
Cols in IP	504314	318303	114934	61966
Rows in IP	222096	142723	53311	29523
Solution time in Sek.	72774.55	12409.19	110.34	10.30

- Adaptive discretization needed

Theoretical Network Capacity

(B., Schlechte, Swarat [2010])



- 180 trains for network small (without station routing and buffer times)
- 196 trains for network big with precise routing through stations (without buffer times)
- 175 trains for network big with precise routing through stations and buffer times

Optimization in the weak sense: To make things better!

This is the world of heuristics, intuition, trial and error, improvement efforts, etc.

We “optimized” in talks and publications usually does not mean that an optimal solution was found. It is often just an euphemism or advertisement.

Optimization in the weak sense: To make things better!

The general standard example of mathematical optimization:

Given a set S and a function f from S to an ordered set T. Find a point x in S such that f(x) is as large or as small as possible (according to the ordering of T).

$$\max \text{ or } \min \left\{ f(x) \middle| x \in S \right\}$$

Usually, S is a subset of the n-dimensional vector space over the reals (in theory); in practice we can only compute with rational numbers, though.

And also usually, the ordered set T is the set of real or rational numbers.

Typical optimization problems

$$\max\ f(x) \ \ or\ \ \min\ f(x)$$
$$g_i(x) = 0, \quad i = 1, 2, \ldots, k$$
$$h_j(x) \le 0, \quad j = 1, 2, \ldots, m$$
$$x \in \mathbb{R}^n \ (and\ \ x \in S)$$

„general“
(nonlinear)
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Complexity Theory

Polynomial time solvability (fast): E.g., Dijkstra‘s algorithm for shortest paths

NP-completeness (difficult): E.g., integer programs

Practical efficiency: experimental mathematics

Kalyanmoy Deb: The great confusion

From his book: „Multi-objective optimization using evolutionary algorithms“ (Wiley, 2001)

Preface

Optimization is a procedure of finding and comparing feasible solutions until no better solution can be found. (Really?)

Classical optimization methods can at best find one solution in one simulation run, thereby making those methods inconvenient to solve multi-objective optimization problems. (???)

Evolutionary algorithms (EAs), on the other hand, can find multiple optimal solutions in one single simulation run due to their population-approach. (True?) Thus, EAs are ideal candidates for solving multi-objective optimization problems. (Very convincing!)

- Such uninformed and misleading statements are really a pity.
- They confuse everyone and just show that the persons making such statements have not really understood what they are doing.

- It is important to understand the roles of modelling, simulation and optimization, the differences between theses and what each of them contributes to the process of solving real problems. See the Simplon tunnel example.

- Each tool is indispensable, “best practice” requires the employment of all three techniques and a concept of managing the interplay.

Integer/combinatorial optimization models

1. travelling salesman problem (the prototype problem)
2. Chinese postman problem
3. shortest path and related graph problems
4. max-flow and min-cost flow problem
5. multicommodity-flow problem
6. set-packing, -partitioning, -covering
7. general integer and mixed-integer programs

- general routing
- location
- cut problems (max and min)
- scheduling
- further variants of flow problems
- dynamic programming
- etc.

Complicating side constraints

- capacities, time windows, maintenance and resource constraints, regularity, periodicity, orientation, robustness, laws, labor rules...

Typical optimization problems

$$\max\ f(x)\ \ or\ \ \min\ f(x)$$
$$g_i(x) = 0,\quad i = 1, 2, \ldots, k$$
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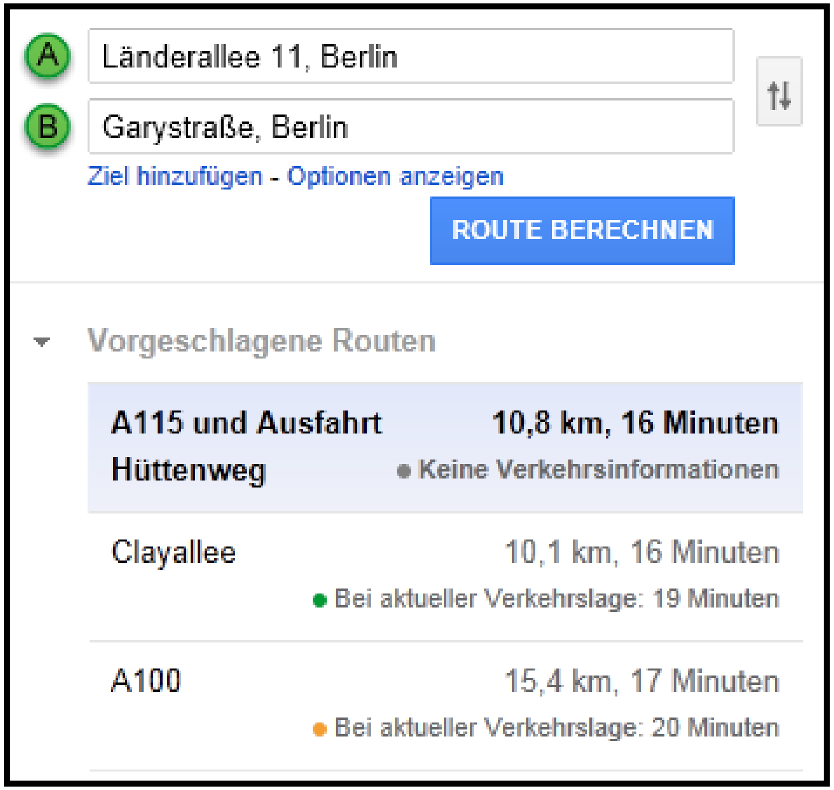
Berlin: Länderallee 11 to Garystr.35



- Shortest path
- Fastest path
- Most ecological path
- Cheapest path
- Compromise path

Multicriteria optimization is difficult

Three good paths: Which is best?

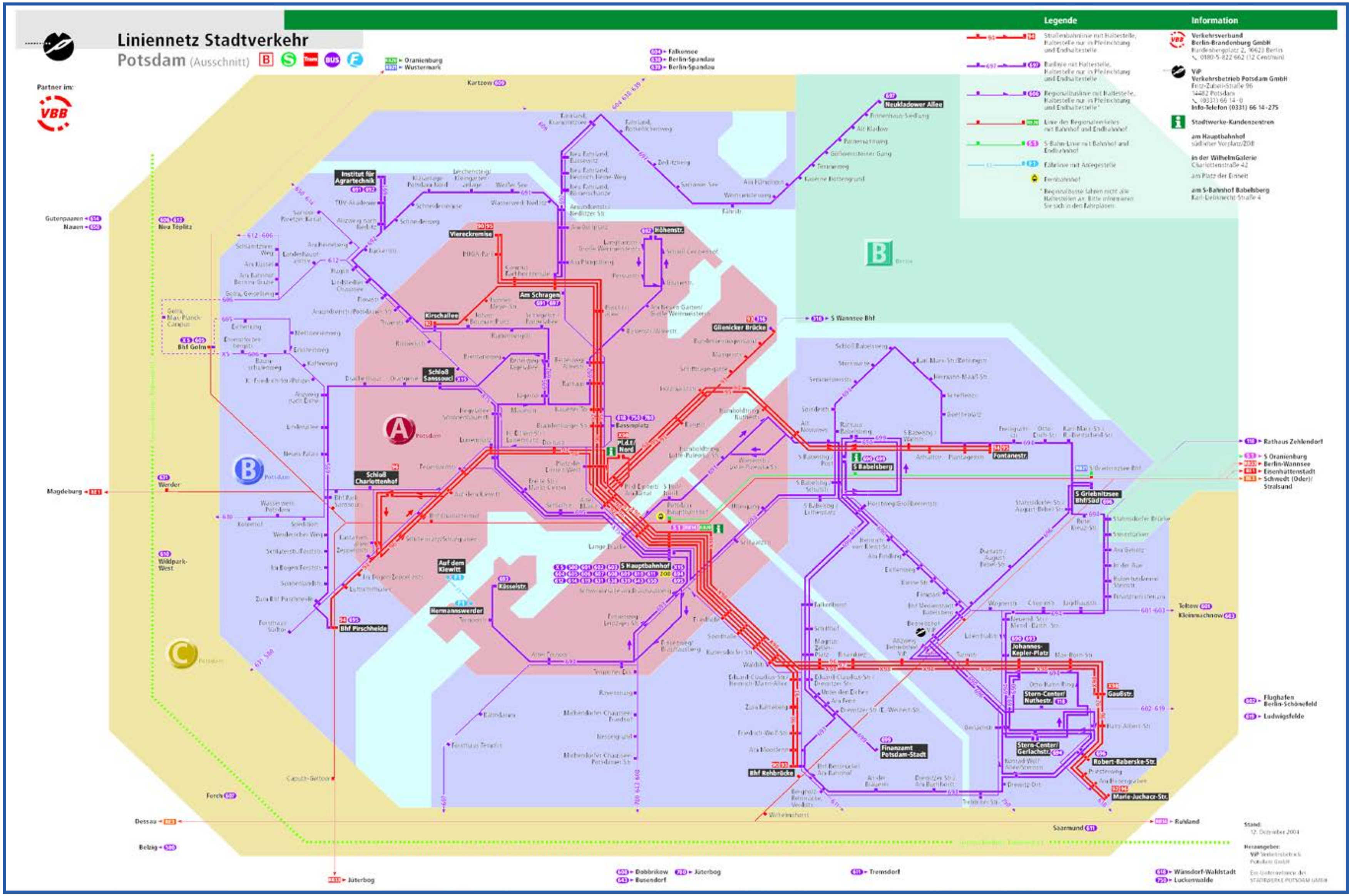
How do I drive?

7,7 km
18 min

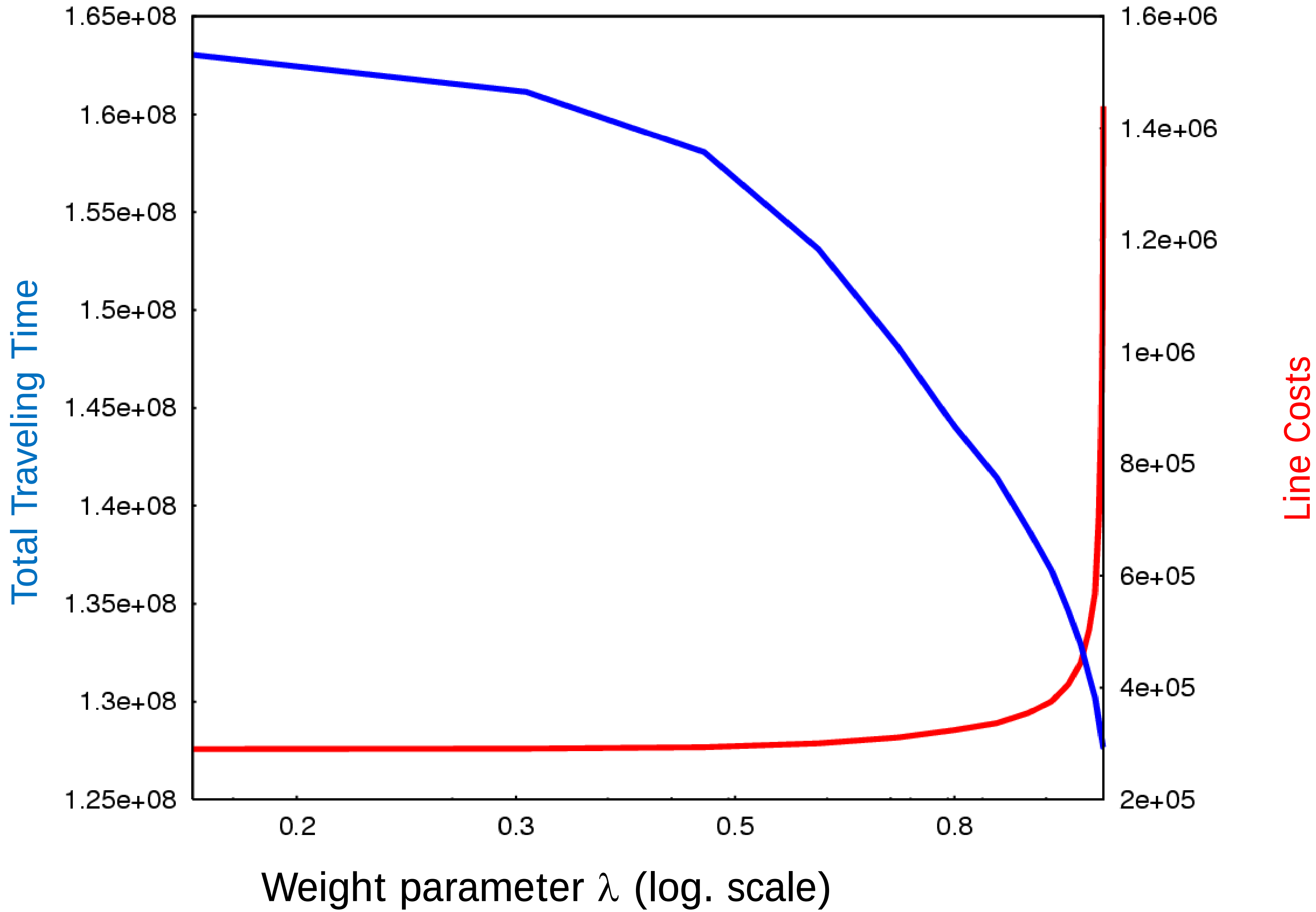
9,7 km
15 min

10 km
16 min

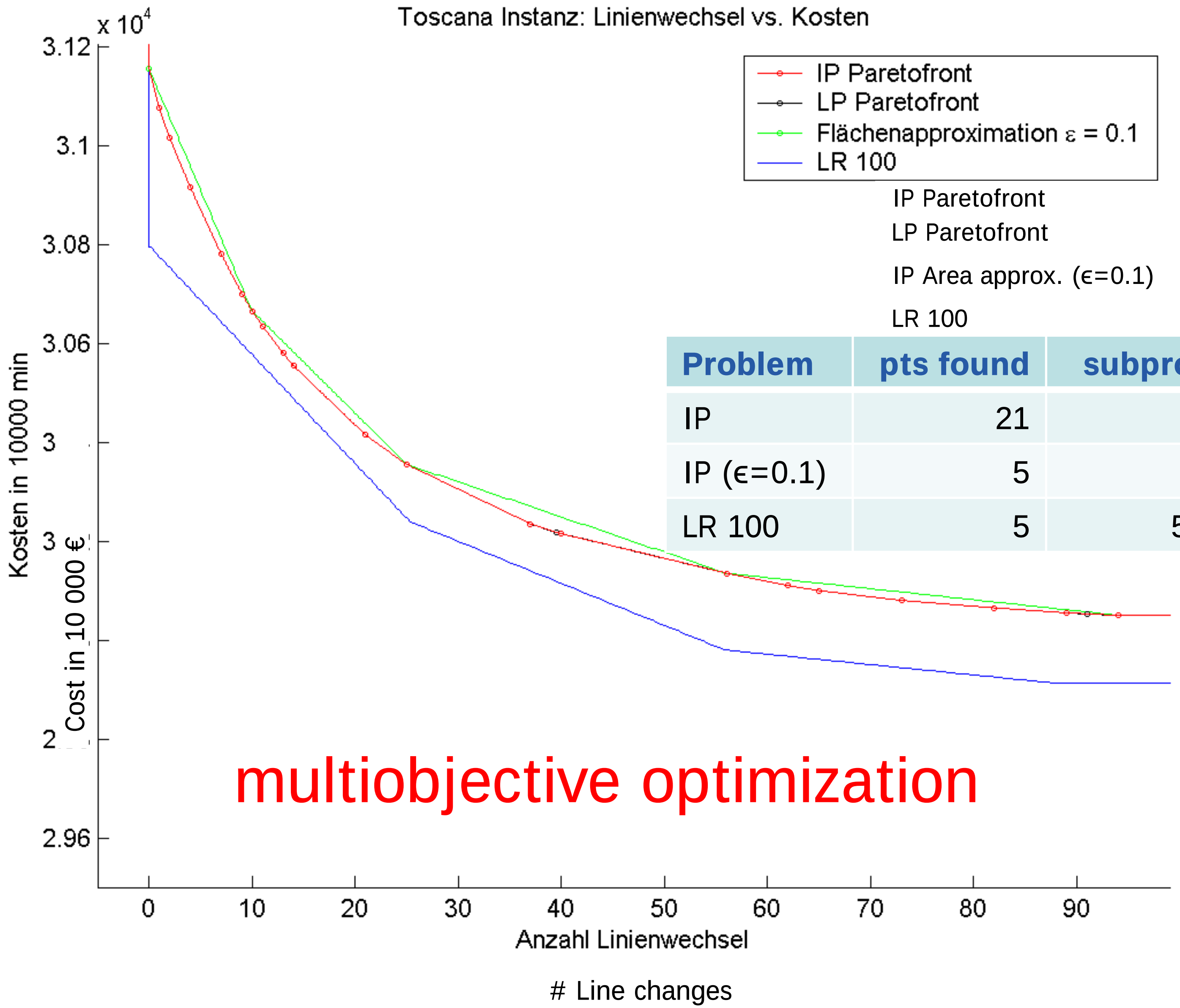
Network, Line and Fare Planning (Potsdam)



Multiobjective optimization Potsdam: Travel Time vs. Line Costs



Scenario Toscana: Cost vs. Line Changes (VS-OPT)
(35 lines, 585 trips, 233 462 arcs)



Problem	pts found	subprob.	CPU sec
IP	21	36	7 101
IP (ϵ=0.1)	5	5	1 508
LR 100	5	500	511

multiobjective optimization

Monday
Optimizing Transit Route Design for Equity
Kelly Bartolaccini, Nicholas Lownes and Travis Waller

"...This paper explore the effects of designing transit routes for eight possible objective function formulations,..."

Example: Routing automated guided vehicles in a container terminal in Hamburg Harbor

Cooperation with

HHLA

Rolf Möhring‘s group

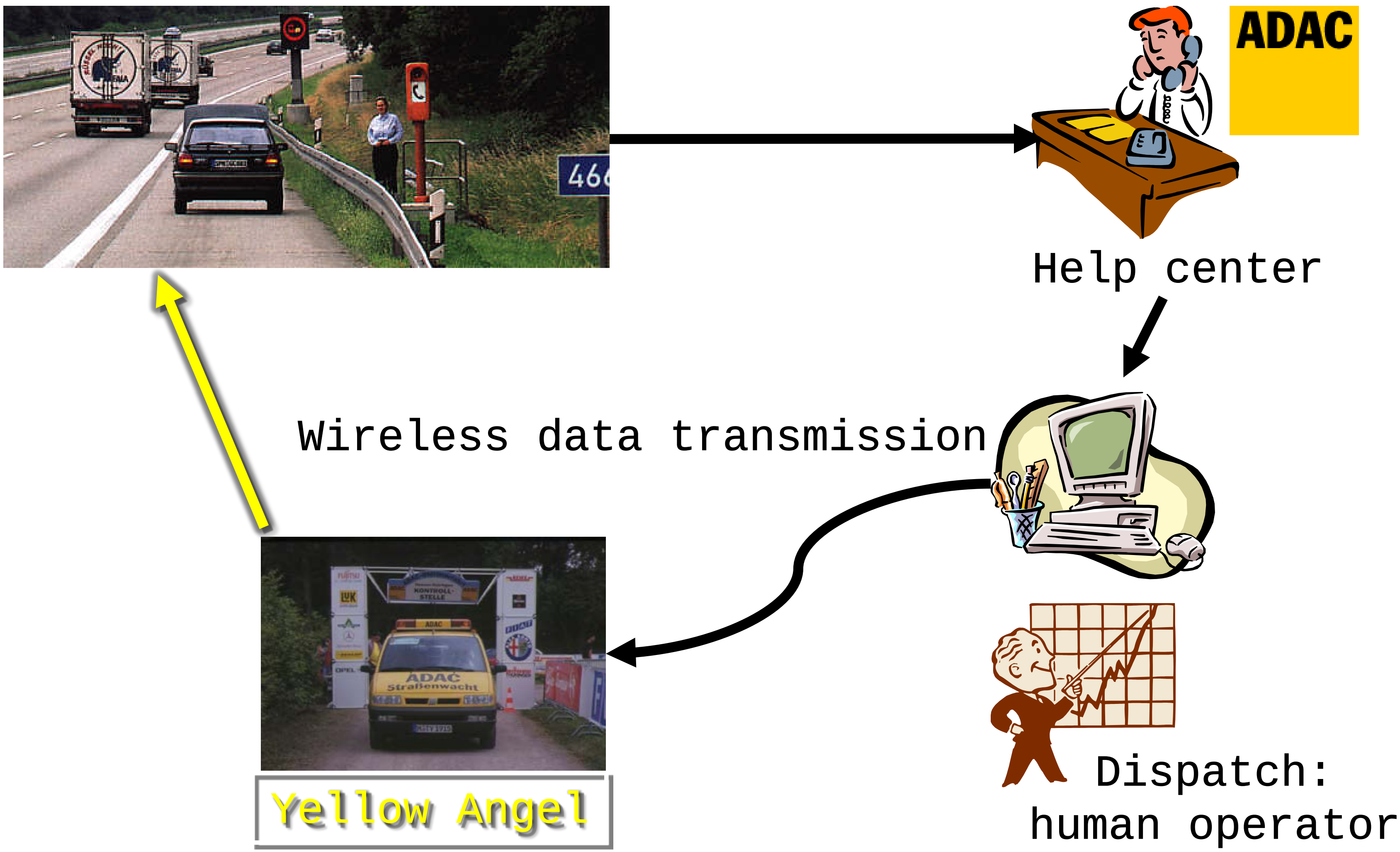
Unit“ of the service fleet:

Yellow Angel

gelber Engel

Supereinsatz. In Berlin und Brandenburg mussten die Gelben Engel letztes Jahr mehr als 240 000 Mal ausrücken, um Havaristen in der Hauptstadt und auf 1700 Autobahnkilometern wieder flottzumachen – ein Rekordeinsatz. Einen Rückgang von zehn Prozent bei den Pannen registrierten dagegen die Gelben Engel in Mecklenburg-Vorpommern. Bei insgesamt 72 389 Einsätzen schafften sie jedoch auch einen Rekord: In 84 Prozent der Fälle konnten die Autofahrer mit dem Wagen weiterfahren.

Service vehicle planning at ADAC



ITCS: Intermodal Transport Control System

CAD/AVL: Computer Aided Dispatch/Automatic Vehicle Location

AVLS: Automatic Vehicle Location System

Traffic Control Center/Betriebsleitstelle

Online and real-time optimization

Ist mein Zug pünktlich?

Ist mein Zug pünktlich oder hat er Verspätung? bahn.de und die mobilen Services der Deutschen Bahn informieren Sie aktuell und zuverlässig.

Suchen Sie einfach nach einem Bahnhof, nach den Zügen Ihrer Reisestrecke oder direkt nach der gebuchten Reiseverbindung auf Ihrer Fahrkarte.

Selbstverständlich finden Sie die aktuellen Informationen auch in der normalen Reiseauskunft ab zwei Stunden vor Abfahrt.

Aktuelle Meldungen

Hier informieren wir Sie über kurzfristige Behinderungen im Zugverkehr.

→ Zu den Verkehrsmeldungen

Aktuelle Infos auf bahn.de, m.bahn.de oder in der DB Navigator App

A big unsolved issue in public transport:

Almost everywhere, experienced dispatchers, following given rules, reschedule in case of sudden accidents, breakdowns, emergencies.

Adjustment of timetables after catastrophes (landslides, floods, power breakdown, IT system failures,...) is necessary, but a big challenge with respect to data acquisitions and optimization methodology.

Not really real-time

Definition?

Several talks at this conference with intuitively similar but mathematically not identical definitions of robustness.

Robust optimization (has become a somewhat standardized term in the optimization community)

Observations and Conclusions from a Business Perspective

Stochastic model and simulation make it possible to judge robustness KPIs:

- Simulation shows that robustness of plans used in practice is non-optimal.
- KPI-based approaches can in principle yield satisfactory results in creating robust plans.
- But: Stochastic robustness measures can still improve on this and avoid issues in defining the trade-off between virtual cost for robustness KPIs and other optimization objectives (in particular: real cost).

Lufthansa Systems

Robustness must consider both resources aircraft and crew:

- Aircraft- and crew-propagated delay have to be considered and optimized together to achieve practically meaningful results.
- In practical applications, transfer passengers may need to be considered as well.

Robustness should be included in the plan way before the tail assignment phase:

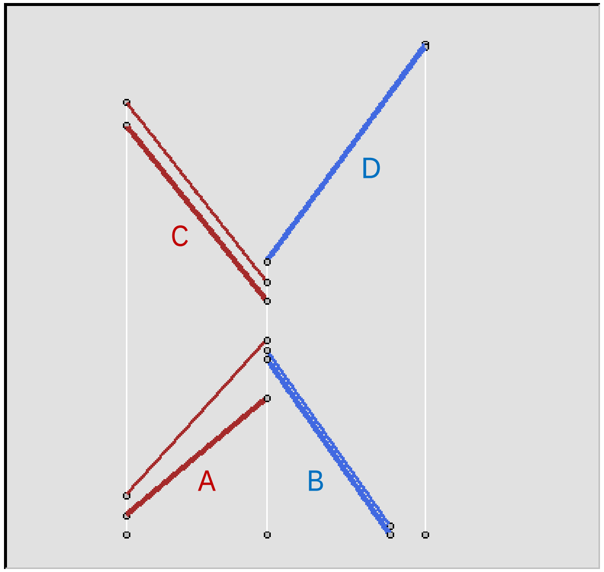
- Minimization of propagated delay in aircraft rotations and following preplanned rotations seem to be partially contradictory objectives ⇨ Crew-rotations should already be based on robust aircraft rotations.
- Retiming can yield considerable improvements in robustness.

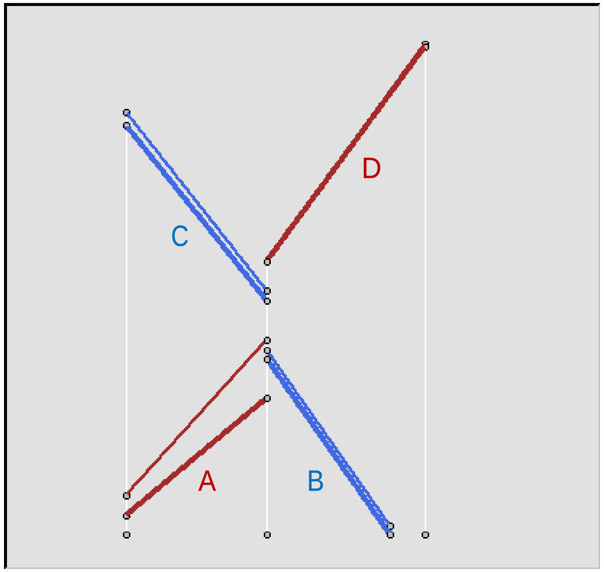
- Tail Assignment = construction of rotations for individual aircraft.
- Constraints
  - Airport curfews
  - Minimal turn time
  - Preassigned activities
  - Maintenance constraints
- Stability
  - Small changes in input data can significantly increase the cost of the schedule, or even make it infeasible.

- Robustness = insensitivity of a solution to changes in input data
- Aim: Find a compromise between price and stability.
- For discrete problems it is a priori not clear what robustness is, because changes in the input data can change the structure of the problem.
- Possible robustness criteria for tail assignment
  - Decrease the number of propagated delays
  - Increase punctuality of flights
  - Increase stability of the solution with respect to disturbances
  - Decrease costs needed to repair disturbed plan
  - ...

Tail Assignment

- Goal: Decrease impact of delays.
- Primary disruptions: genuine disruptions, unavoidable.
- Secondary disruptions: propagated disruptions.





- Additional buffer flight between flights can prevent propagation of delay to the consecutive flight.
- 30% of all delays are secondary.

Flight Duration and Delay Propagation

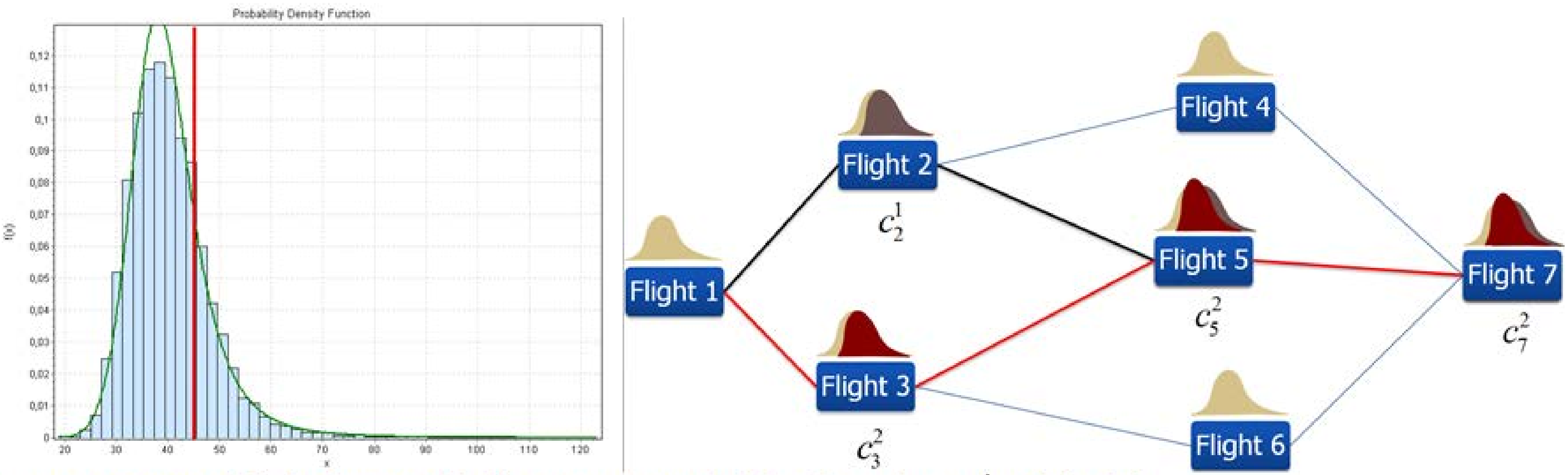


Figure 10: Expected flight duration (left). Propagation of delay through a network (right)

Gate phase

Represents ground delay at departure.

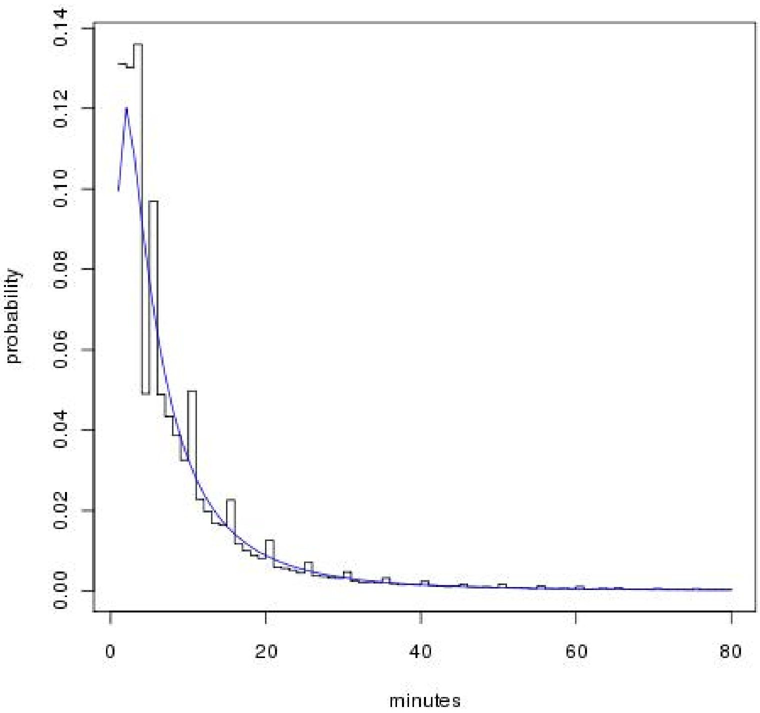
Model: aircraft waits until scheduled departure (but at least minimum ground time), then we decide, if flight is delayed and how long.

Random variables:

Probability of gate delay.

- Specified for every airport and day hour.

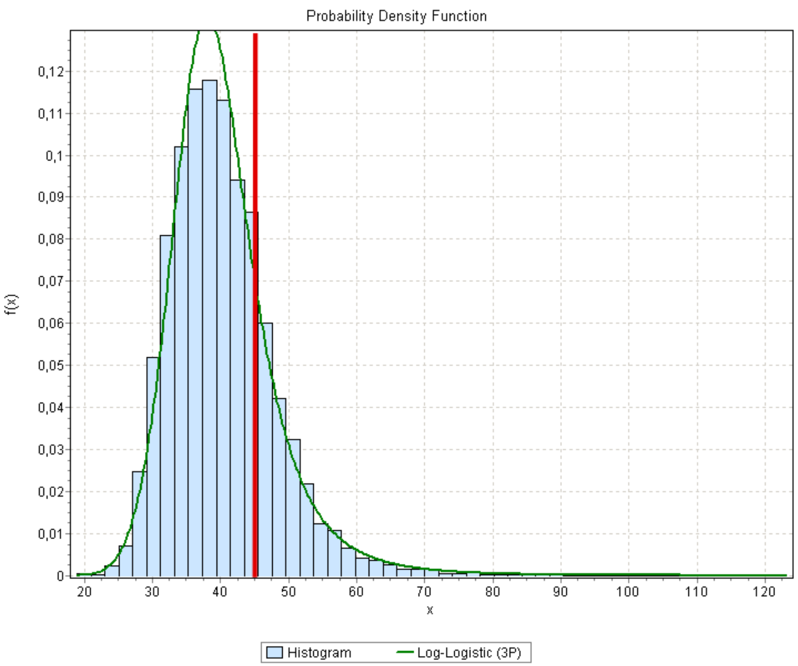
- Length of gate delay.
  - Log-normal distribution, tail follows Power-law distribution.
  - Parameters of distributions are same for all airports.



Random variable represents gate-to-gate time.

Follows Log-Logistic distribution.

- Parameters are estimated for every flight based on scheduled flight duration.



Bicriteria Optimization Model - Profit versus Robustness

$$
\begin{array}{llrll}
(BI-PCP) & \text{(i)} & \max \sum_{p\in P} w_p x_p & & \\
& \text{(ii)} & \max \sum_{q\in Q} r_q y_q & & \\
& \text{(iii)} & \sum_{p\in P_i} x_p & \leq 1, & \forall i \in I \\
& \text{(iv)} & \sum_{q\in Q_j} y_q & \leq 1, & \forall j \in J \\
& \text{(v)} & \sum_{a\in p\in P} x_p - \sum_{a\in q\in Q} y_q & \leq 0, & \forall a \in A_{LR} \\
& \text{(vi)} & x_p, y_q & \in \{0,1\} & \forall p \in P,\ q \in Q
\end{array}
$$

Variables

Path und config usage (request i uses path p, track j uses config q)

Constraints

Path and config choice

Path-config-coupling (track capacity)

Objective Function

Maximize proceedings and robustness

Computational Results

Scenarios for one day, single fleet, no maintenance rules. (18-24 aircraft, 100-170 legs)

- KPI: Bonus for every ground time buffer minute.
  Threshold for maximal ground time buffer bonus minutes (15 minutes).
- EPD: Minimize expected aircraft delay propagation.

Scenario	KPI	EPD	improvement (%)
SC1	35,11	33,56	4,42
SC2	34,28	33,98	0,89
SC3	19,11	18,56	2,87
SC4	39,10	37,26	4,71
SC5	26,12	25,63	1,89
SC6	41,81	41,07	1,77
SC7	20,26	19,74	2,57
SC8	19,80	19,02	3,98

Industry requirements grow

$$
\begin{aligned}
&\max f(x) \quad or \quad \min f(x) \\
&g_i(x) = 0, \quad i = 1, 2, \ldots, \mathrm{p} \\
&h_j(x) \le 0, \quad j = 1, 2, \ldots, \mathrm{q} \\
&x_i \in \mathbb{Z} \qquad for \ some \ i \\
&x_j \in \{0,1\} \quad for \ some \ j \\
&x_k \in \mathbb{R}^n \qquad for \ some \ k
\end{aligned}
$$

More general:
mixed-integer nonlinear program
MINLP

Plus:
Stochastic aspects
Robust optimization
Real time/online optimization
Several objectives

Theoretical vs. practical efficiency

There is no really hard evidence:

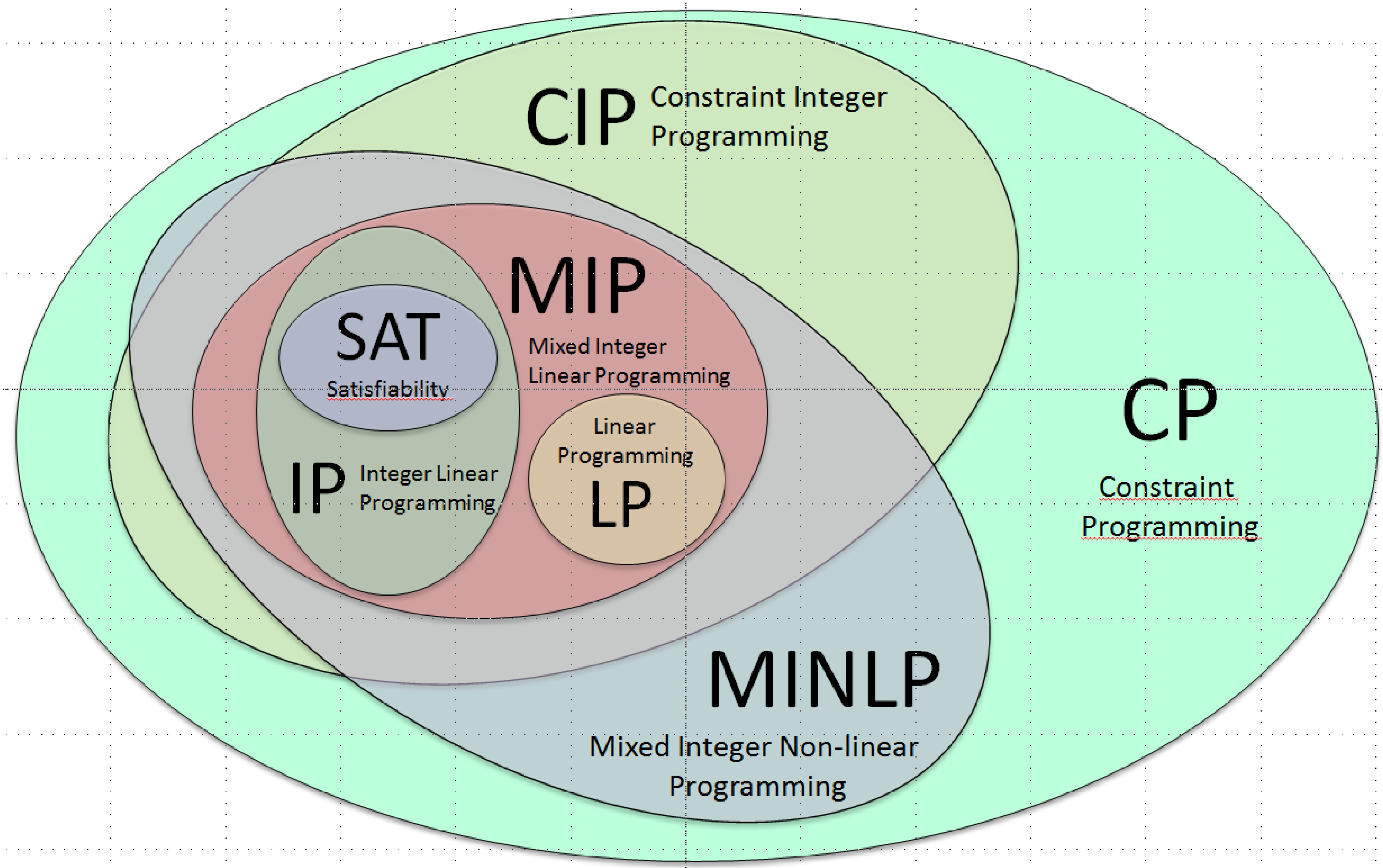
NP-hard problems seem to be hard in practice,
- but: many practical instances can be solved in reasonable time, even if they are large scale
- but: a small variation of a well-solved hard problem may make it very hard in practice (e.g., time windows)
- This particularly applies to public transport.

Problems solvable in polynomial time may be difficult or even unsolvable in practice.

How can you know?
- Testing, experiments, testing,...

Modelling is not easy!
Modelling and solution approach can‘t be separated,
in general

What is an appropriate model?
What is the „right“ LP relaxation?
How exact need answers to be?


CIP Constraint Integer Programming
MIP
Mixed Integer Linear Programming
SAT
Satisfiability
IP Integer Linear Programming
Linear Programming
LP
CP
Constraint Programming
MINLP
Mixed Integer Non-linear Programming

$$
\begin{aligned}
&\min c^T x \\
&Ax = a \\
&Bx \leq b \\
&\quad x \geq 0 \\
&\text{some } x_j \in \mathbb{Z} \\
&\text{some } x_k \in \{0,1\}
\end{aligned}
$$

(linear) 0/1- or
mixed-integer
program
IP, MIP
the „key problem“
in traffic and
transport

Modelling and solution technologies interact

Issues such as:

- multiperiod planning
- coarse to fine modelling
- multi-scale aspects (e.g. planning in seconds and months within one problem instance)

have a significant impact on the solution methodology.

Techniques, e.g.:

- decomposition (Dantzig-Wolfe, Benders,...)
- hierarchical (master-slave) approaches
- Lagrangian relaxations
- dynamic programming

Heuristics: A Survey

- Greedy Algorithms
- Exchange & Insertion Algorithms
- Neighborhood/Local Search
- Variable Neighborhood Search, Iterated Local Search
- Random sampling
- Simulated Annealing
- Taboo search
- Great Deluge Algorithms
- Simulated Tunneling
- Neural Networks
- Scatter Search
- Greedy Randomized Adaptive Search Procedures

Heuristics: A Survey

- Genetic, Evolutionary, and similar Methods
- DNA-Technology
- Ant and Swarm Systems
- (Multi-) Agents
- Population Heuristics
- Memetic Algorithms (Meme are the “missing links” gens and mind)
- Fuzzy Genetics-Based Machine Learning
- Fast and Frugal Method (Psychology)
- Method of Devine Intuition (Psychologist Thorndike)
- .....
- We have great researchers who implemented a unique superfast solution technology

An Unfortunate Development

There is (sometimes) a marketing battle going on with unrealistic, or even ideological, claims about the quality of heuristics – just to catch attention

Linguistic Overkill:

Simulated hybrid meta GA-based neural evolutionary fuzzy variable adaptive search parallel DNA-driven multi-ant-agent method with devine swarm taboo intuition

An Unfortunate Development

There is (sometimes) a marketing battle going on with unrealistic, or even ideological, claims about the quality of heuristics – just to catch attention

Linguistic Overkill:

Vodoo Approach

Heuristics are very important, of course.
It would be good to make honest statements about them.

Algorithms for the Solution of LPs

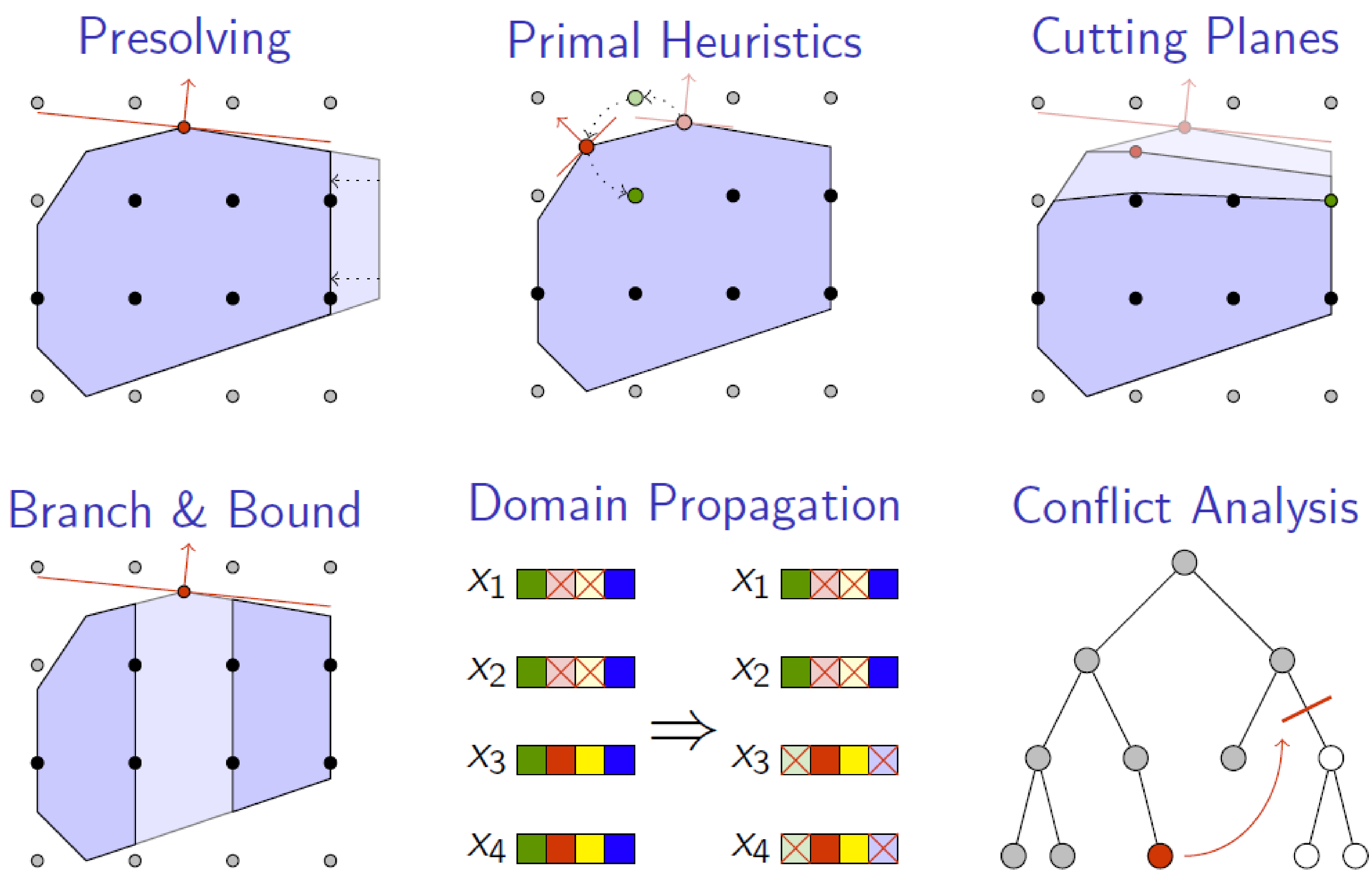
1. Fourier-Motzkin Elimination
2. The Primal Simplex Method
3. The Dual Simplex Method
4. The Ellipsoid Method
5. Interior-Point/Barrier Methods
6. Double Description, Over Relaxation
7. Lagrangian Relaxation,
   Coordinate Ascent/Gradient/Subgradient/Bundle Methods
8. Decomposition Techniques

1. Fourier-Motzkin Elimination
2. The Primal Simplex Method
3. The Dual Simplex Method
4. The Ellipsoid Method
5. Interior-Point/Barrier Methods
6. Double Description, Over Relaxation
7. Lagrangian Relaxation, Coordinate Ascent/Gradient/Subgradient/Bundle Methods
8. Decomposition Techniques

Algorithms for the Solution of MIPs

1. Heuristics
2. Branch&Bound
3. Cutting Planes
4. Flow Techniques
5. Column Generation
6. Benders Decomposition
7. Constraint Programming
8. Domain Decomposition
9. Conflict Analysis
10. Other Methods

MIP Solver Techniques



A Branching Tree

Applegate

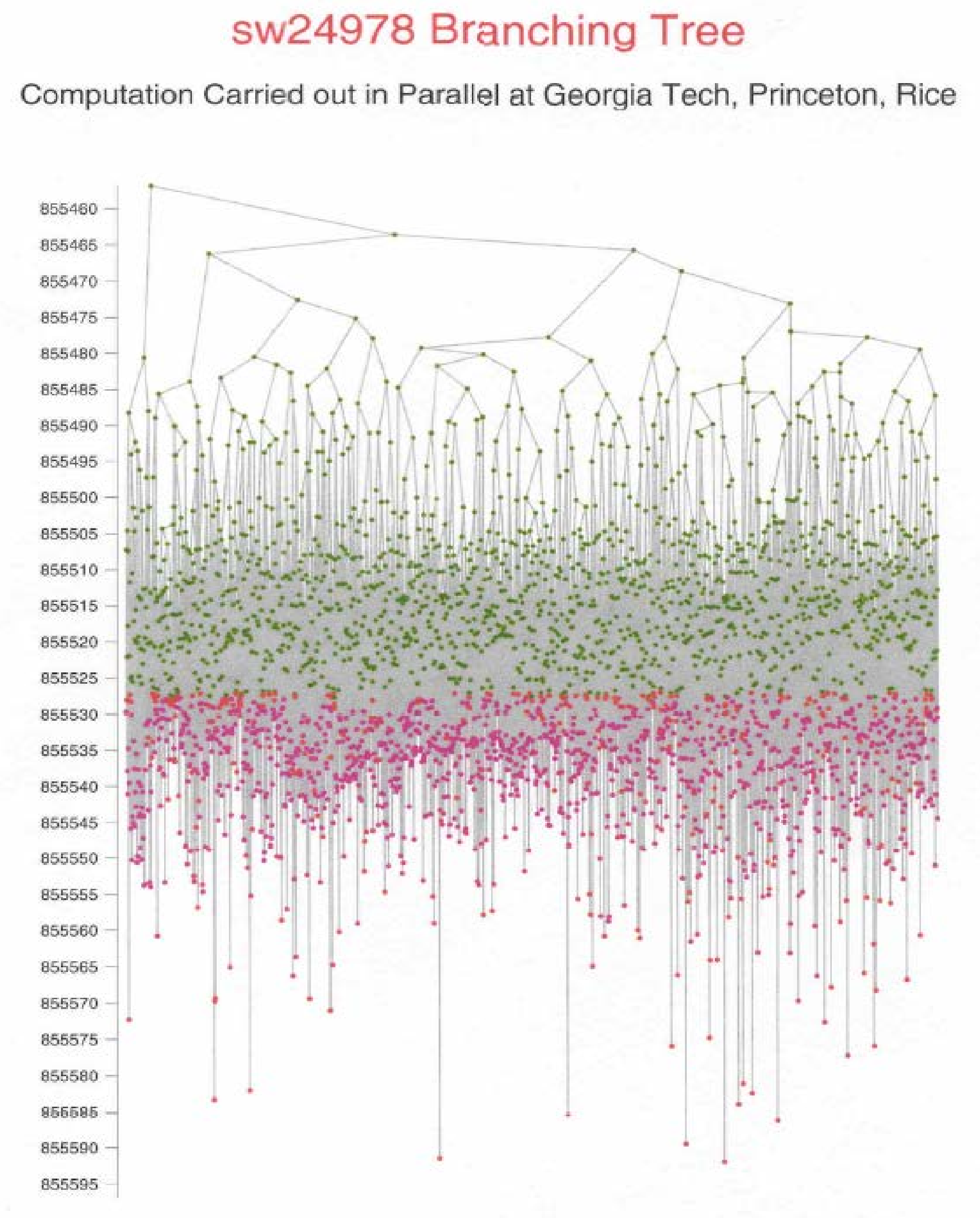
Bixby

Chvátal

Cook

tree copied from

www1.ctt.dtu.dk/ROUTE2003/presentations/cook.pdf



Cutting plane technique for IP and MIP

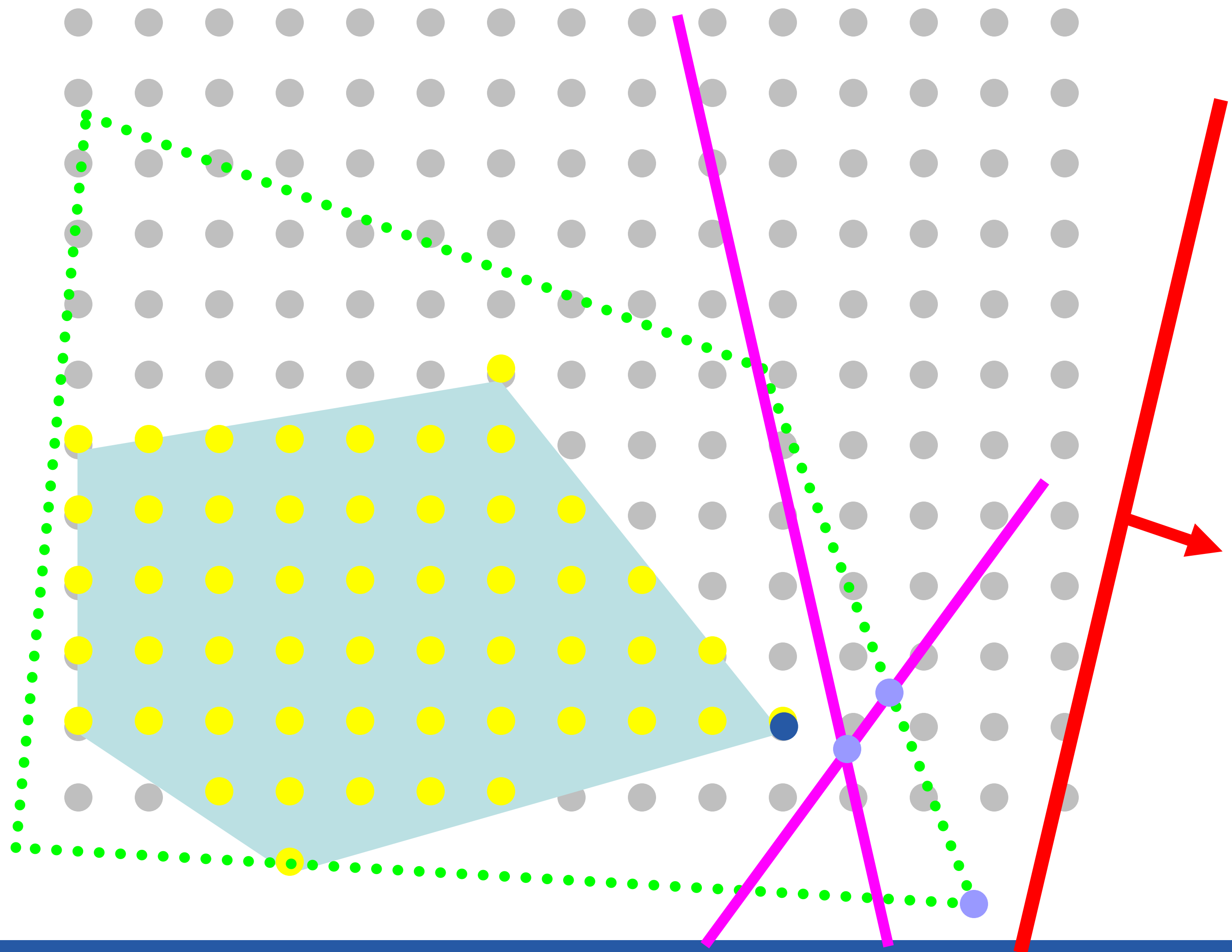
Feasible integer solutions

Objective function

Convex hull

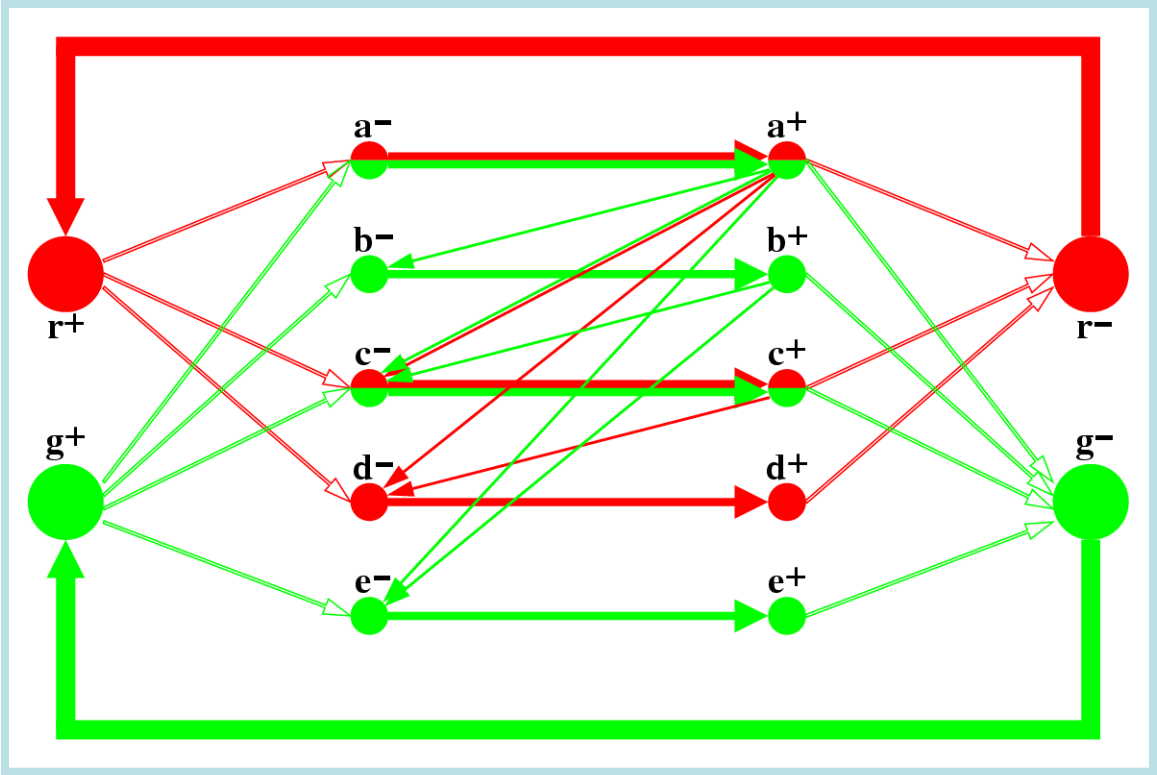
LP-based relaxation

Cutting planes



Bus circulation:Flow through a bus line network

Multicommodity flow with minimum cost




Berlin
BERLIN ZOOLOGISCHER GARTEN
BAHNHOF ZOOLOGISCHER GARTEN
DUNLOP
REIFEN
DUNLOP
TERRASSEN AM ZOO
Fernsehen, Telefonieren und Surfen - alles über eine Verbindung.
T-Com

	BVG	*HHA*	*VHH*
depots	10	14	10
vehicle types	44	40	19
timetabled trips	25 000	16 000	5 500
number of variables	70 000 000	15 100 000	10 000 000
cpu mins	200	50	28

Column Generation can be viewed as a procedure dual to the cutting plane method. The basic principle:

1. Select a small number of variables and solve the linear program (or LP relaxation) using only these.
2. Find an unused variable (or several) which, if included, would (most) improve the objective value, or determine that there is none, i.e., the linear program has been solved: stop.

   Solve the **column generation subproblem (Pricing).**

   Model this as an optimization problem, works best if this is an easy IP (shortest path, dynamic program, etc.)
3. Include the variable(s) in the linear program, re-solve it, and go to step 2.

Successful Applications: Examples

Cutting stock problems (Gilmore, Gomory) **1960**

Air crew scheduling

Aircraft fleeting and routing

Crew rostering

Vehicle routing

Driver assignment

Global shipping

Multi-item lot-sizing

Telecommunications network design

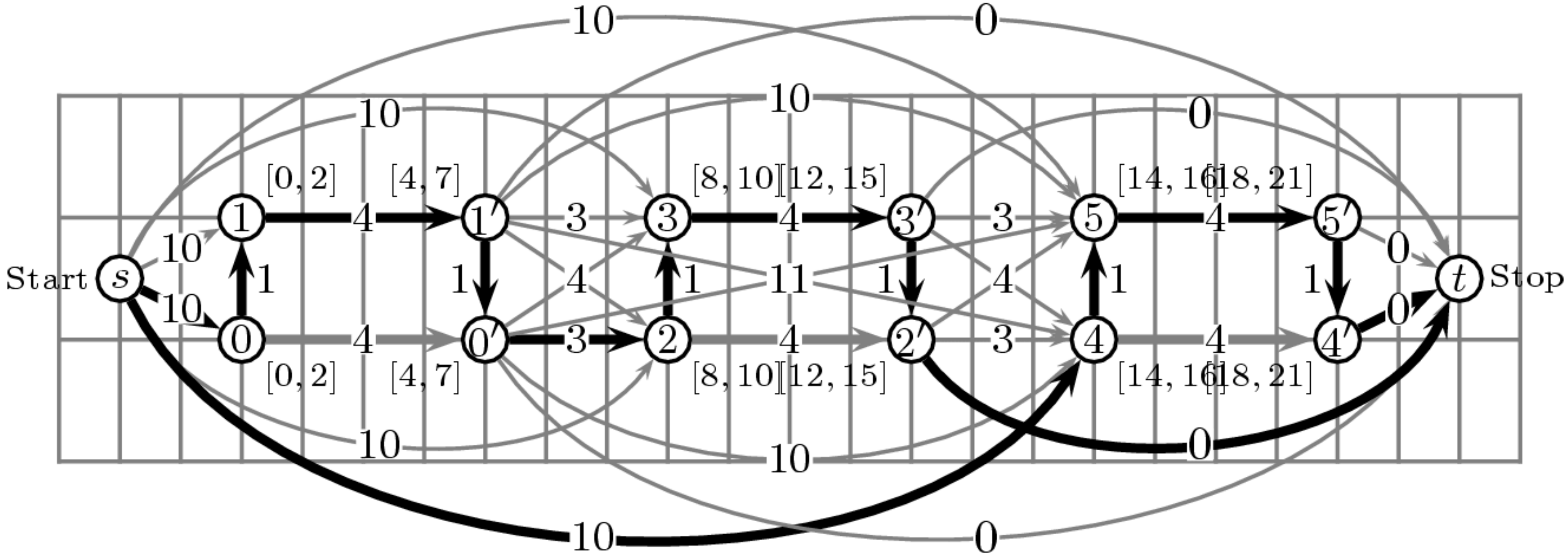
Cancer radiation treatment using IMRT

This method is particularly important if lots of rules have to be satisfied that are not easy to model, blow up the IP enormously and are subject to frequent changes, such as the work rules for drivers in public transport or pilots and crew in the airline business.
(I can give a full hour lecture on “break rules”.)

The “difficult side constraints” are treated in the column generation subroutine(s).

Telebus (transportation of disabled persons)

Graph Theoretical Model, IP: Set Partitioning Model



	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	c_{16}	c_{17}	c_{18}	c_{19}	c_{20}	c_{21}	c_{22}	c_{23}	c_{24}
	14	14	14	14	14	14	16	21	22	28	29	22	21	29	28	16	21	22	22	21	16	23	23	30	30
i	$a_{.0}$	$a_{.1}$	$a_{.2}$	$a_{.3}$	$a_{.4}$	$a_{.5}$	$a_{.6}$	$a_{.7}$	$a_{.8}$	$a_{.9}$	$a_{.10}$	$a_{.11}$	$a_{.12}$	$a_{.13}$	$a_{.14}$	$a_{.15}$	$a_{.16}$	$a_{.17}$	$a_{.18}$	$a_{.19}$	$a_{.20}$	$a_{.21}$	$a_{.22}$	$a_{.23}$	$a_{.24}$
0	1	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	1	1	1	1
1	.	1	.	.	.	.	1	.	.	.	.	1	1	1	1	.	.	.	.	.	.	1	1	1	1
2	.	.	1	.	.	.	.	1	.	.	.	1	.	.	.	1	1	1	.	.	.	1	.	.	.
3	.	.	.	1	.	.	.	.	1	.	.	.	1	.	.	1	.	.	1	1	.	.	1	.	.
4	.	.	.	.	1	.	.	.	.	1	.	.	.	1	.	.	1	.	1	.	1	.	.	1	.
5	.	.	.	.	.	1	.	.	.	.	1	.	.	.	1	.	.	1	.	1	1	.	.	.	1
	x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}

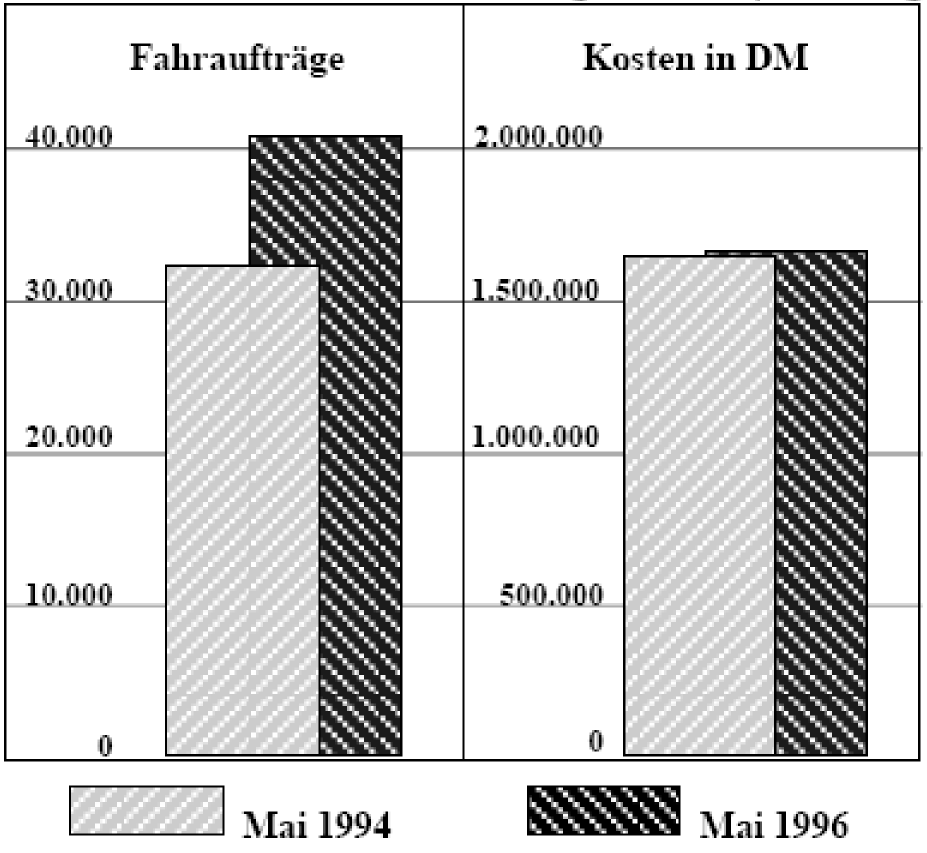
	c_{25}	c_{26}	c_{27}	c_{28}	c_{29}	c_{30}	c_{31}	c_{32}	c_{33}	c_{34}	c_{35}	c_{36}	c_{37}	c_{38}	c_{39}	c_{40}	c_{41}	c_{42}	c_{43}	c_{44}	c_{45}	c_{46}	c_{47}	c_{48}
	23	28	29	30	29	30	23	29	30	29	28	30	23	23	25	30	31	31	30	32	30	31	31	30
i	$a_{.25}$	$a_{.26}$	$a_{.27}$	$a_{.28}$	$a_{.29}$	$a_{.30}$	$a_{.31}$	$a_{.32}$	$a_{.33}$	$a_{.34}$	$a_{.35}$	$a_{.36}$	$a_{.37}$	$a_{.38}$	$a_{.39}$	$a_{.40}$	$a_{.41}$	$a_{.42}$	$a_{.43}$	$a_{.44}$	$a_{.45}$	$a_{.46}$	$a_{.47}$	$a_{.48}$
0	1	1	1	1	1	1	.	.	.	.	.	.	.	.	1	1	1	1	1	1	1	1	.	.
1	.	.	.	.	.	.	1	1	1	1	1	1	.	.	1	1	1	1	1	1	.	.	1	1
2	1	1	1	.	.	.	1	1	1	.	.	.	1	.	1	1	1	.	.	.	1	.	1	.
3	1	.	.	1	1	.	1	.	.	1	1	.	.	1	1	.	.	1	1	.	.	1	.	1
4	.	1	.	1	.	1	.	1	.	1	.	1	1	1	.	1	.	1	.	1	1	1	1	1
5	.	.	1	.	1	1	.	.	1	.	1	1	1	1	.	.	1	.	1	1	1	1	1	1
	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{30}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}	x_{38}	x_{39}	x_{40}	x_{41}	x_{42}	x_{43}	x_{44}	x_{45}	x_{46}	x_{47}	x_{48}

Savings May 94 – May 96

Historie: Telebus-Projekt

Ziele

- Organisatorische Verbesserungen
- Mathematische Fahrzeugeinsatzplanung



Ergebnisse

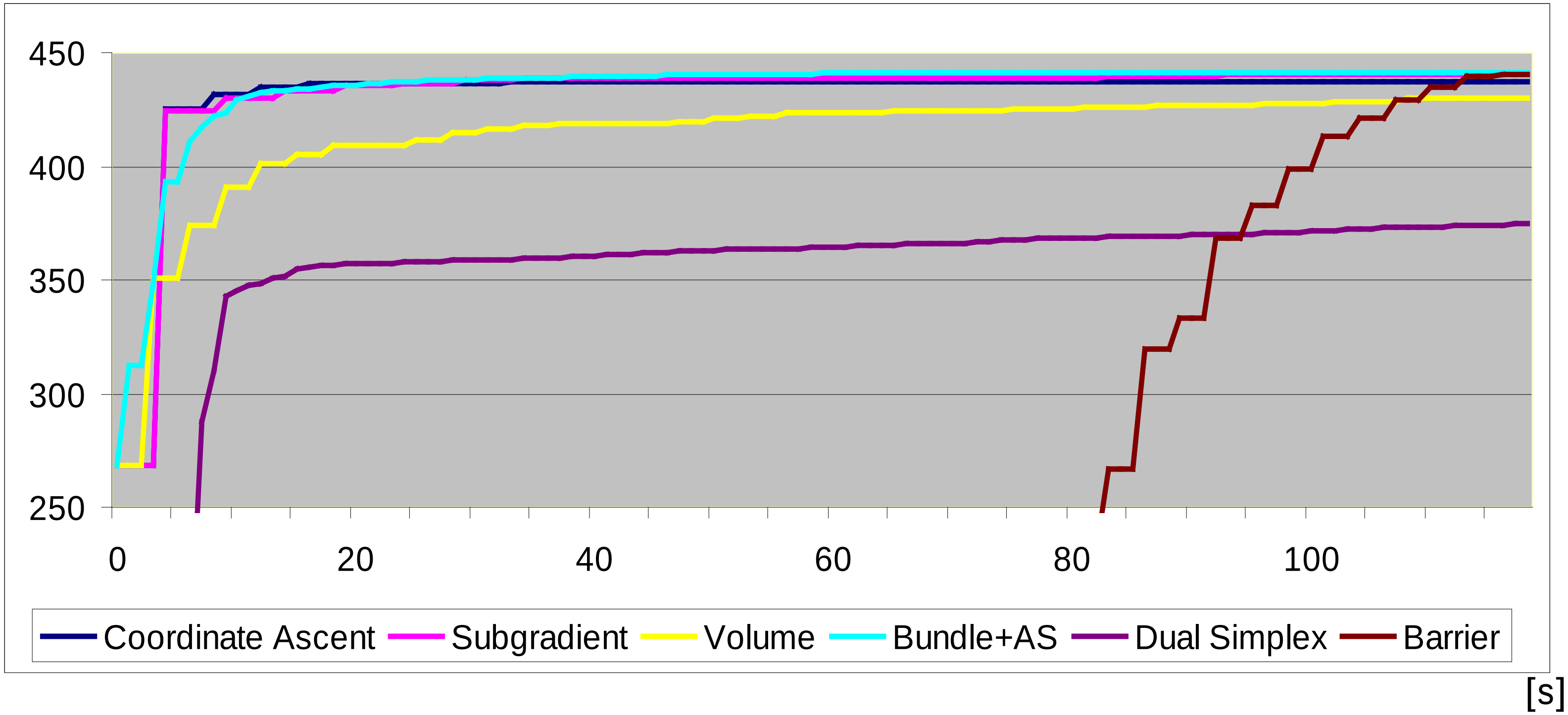
- Serviceverbesserung
- Kostenreduktion
- Vereinfachung der Arbeitsabläufe
- Telebus-Computersystem

Computational Results for a Duty Scheduling Set Partitioning Model

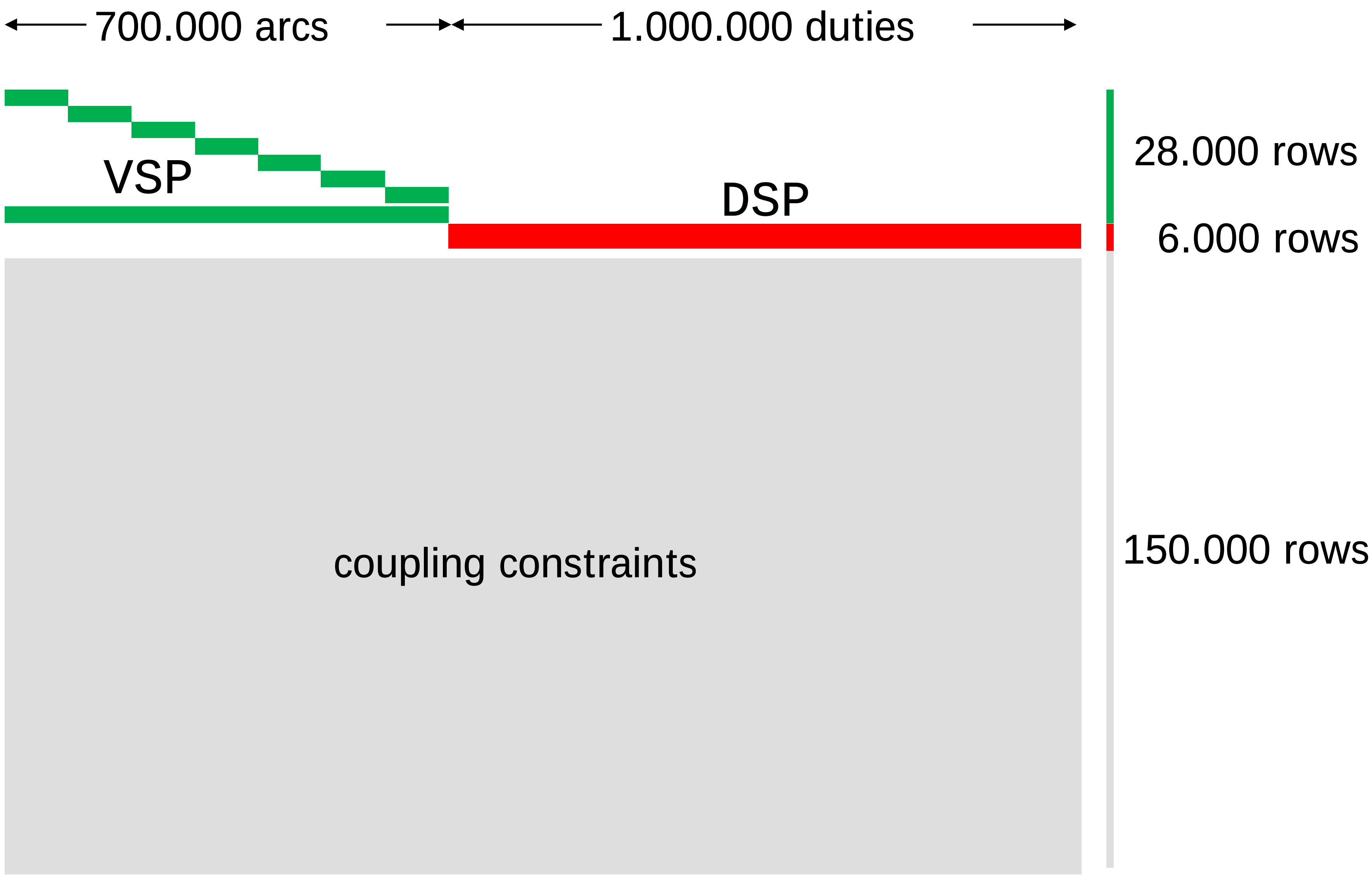
Duty Scheduling Problem Ivu41:

- 870 500 col
- 3 570 rows
- 10.5 non-zeroes per col

Coordinate Ascent:	Fast, low quality
Subgradient:	(Theoretical) Convergence
Volume:	Primal approximation
Bundle+AS:	Conv. + primal approx.
Dual Simplex:	Primal+dual optimal
Barrier:	Primal+dual optimal



Integrated Bus and Driver Scheduling: Model Structure

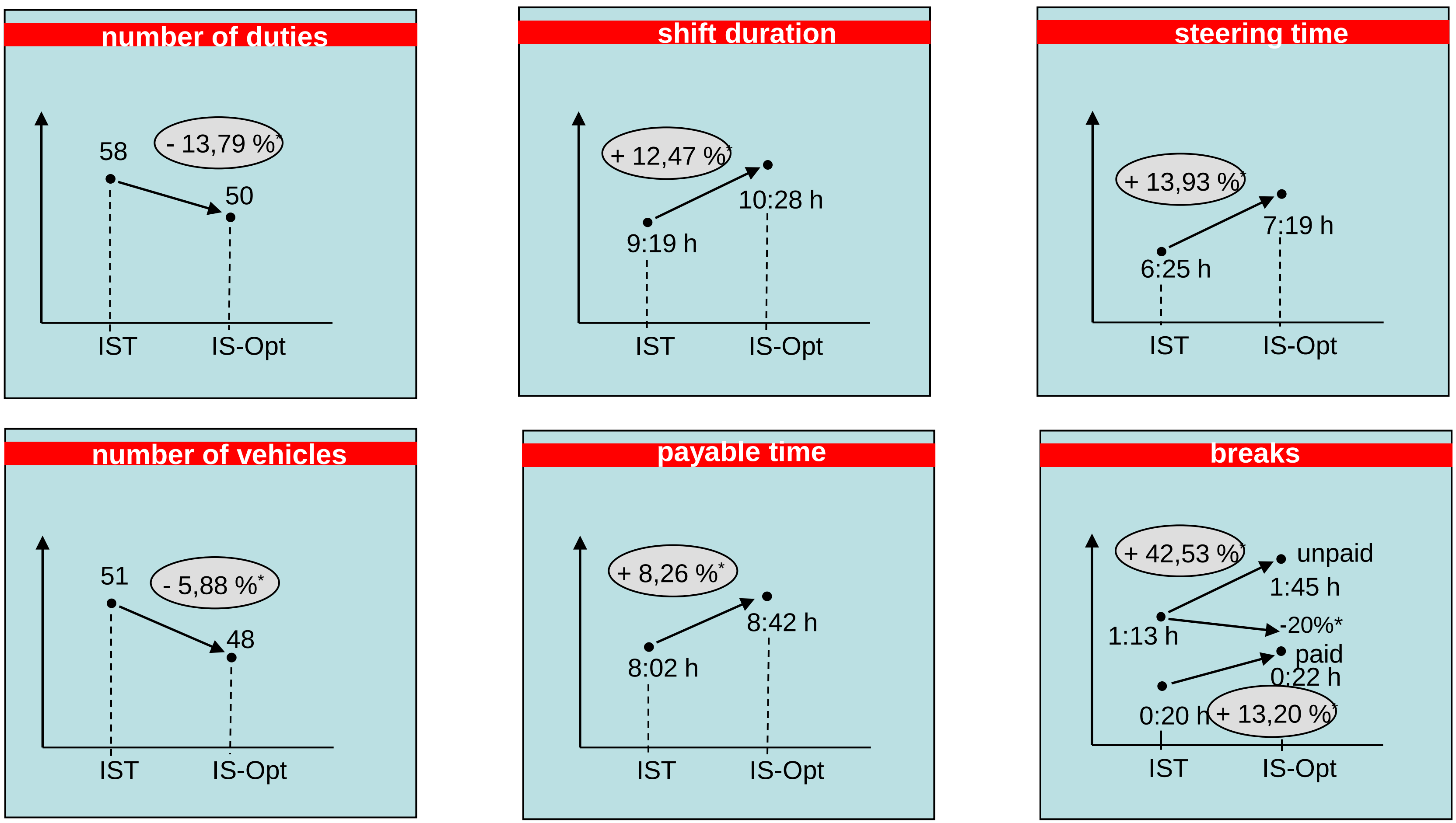


Integrated vehicle and driver optimization

Despite of the high productivity the automated planning, the integrated optimization brings further improvements

Slide of DB

Example optimization



Primal MIP heuristics, examples:

- Rounding Heuristics
- Diving Heuristics
- Large Neighborhood Search
- Local Branching
- RINS
- Crossover
- DINS
- RENS (Relaxation Enforced Neighborhood Search)
- Feasibility Pump(s)
- Undercover

special „simple“ combinatorial optimization problems

Finding a

- minimum spanning tree
- shortest path
- maximum matching
- Chinese Postman tour
- maximal flow through a network
- cost-minimal flow
- ...

solvable in polynomial time by special purpose algorithms

Special “hard” combinatorial optimization problems

- travelling salesman problem
- location und routing
- set-packing, partitioning, -covering
- max-cut
- linear ordering
- scheduling (with a few exceptions)
- node and edge colouring
- ...

NP-hard (in the sense of complexity theory)

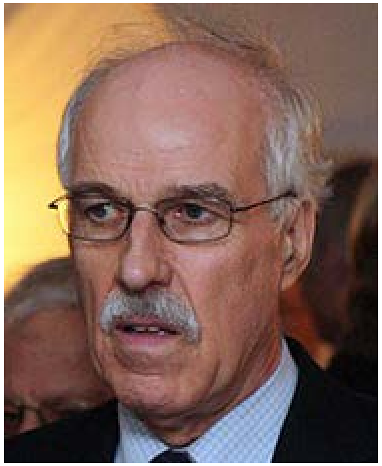
The most successful solution techniques employ linear programming.

Lessons learned from these have now entered the general tools developed for general MIP solving.

All modern efficient LP and MIP solvers are, in addition to implementing the mathematics of the codes correctly, a huge conglomerate of heuristics aiming at speeding up evry step of the methods to achieve best performance in practice.

This is tested on large collections of instances from customers.

Independent Testing: http://plato.la.asu.edu/



Benchmarks for Optimization Software

by Hans Mittelmann (mittelmann at asu.edu)

Note that on top of the benchmarks a link to logfiles is given!

COMBINATORIAL OPTIMIZATION

- Concorde-TSP with different LP solvers (7-2-2015)

LINEAR PROGRAMMING

- Benchmark of Simplex LP solvers (7-3-2015)
- Benchmark of parallel LP solvers (7-9-2015)
- Parallel Barrier Solvers on Large LP/QP problems (6-29-2015)
- Large Network-LP Benchmark (commercial vs free) (6-28-2015)

MIXED INTEGER LINEAR PROGRAMMING

- MILP Benchmark - MIPLIB2010 (7-7-2015)
- The EASY MIPLIB Instances (7-8-2015) **(MIPLIB2010)**
- MILP cases that are slightly pathological (7-6-2015)
- Feasibility Benchmark (6-29-2015) **(MIPLIB2010)**
- Infeasibility Detection for MILP (7-5-2015) **(MIPLIB2010)**

SEMIDEFINITE/SQL PROGRAMMING

- SQL problems from the 7th DIMACS Challenge (8-8-2002)
- Several SDP codes on sparse and other SDP problems (12-14-2014)
- MISOCP and large SOCP Benchmark (7-11-2015)

NONLINEAR PROGRAMMING

- AMPL-NLP Benchmark, IPOPT, KNITRO, LOQO, PENNLP, SNOPT, WORHP, XPRESS & CONOPT (6-29-2015)

MIXED INTEGER QPs and QCPs

- MIQ(C)P Benchmark (7-2-2015)

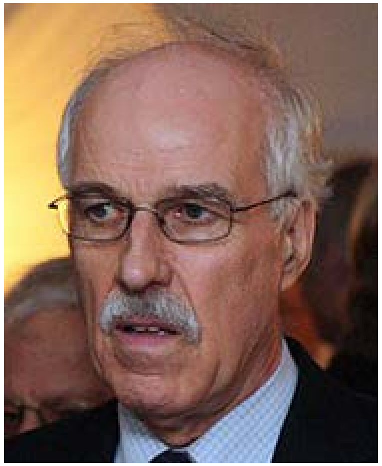
MIXED INTEGER NONLINEAR PROGRAMMING

- MINLP Benchmark (1-9-2014)

PROBLEMS WITH EQUILIBRIUM CONSTRAINTS

- MPEC Benchmark (6-1-2015)

Independent Testing: http://plato.la.asu.edu/



Benchmarks for
Softwa

by Hans Mittelmann (mitt

Note that on top of the benchm... ...ink to logfiles is given!

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MIXED INTEGER LINEAR PROGRAMMING

- MILP Benchmark - MIPLIB20... ...015)
- The EASY... ...(MIPLIB2010)
- ...(7-6-2015)
- ...PLIB2010)
- ...5) (MIPLIB2010)

...NG

- ...nge (8-8-2002)
- ...P problems (12-14-2014)
- ...2015)

- ...NLP Benchmark, IPOPT, KNITRO, LOQO, PENNLP, SNOPT, WORHP, XPRESS & CONOPT (6-29-2015)

MIXED INTEGER QPs and QCPs

- MIQ(C)P Benchmark (7-2-2015)

MIXED INTEGER NONLINEAR PROGRAMMING

- MINLP Benchmark (1-9-2014)

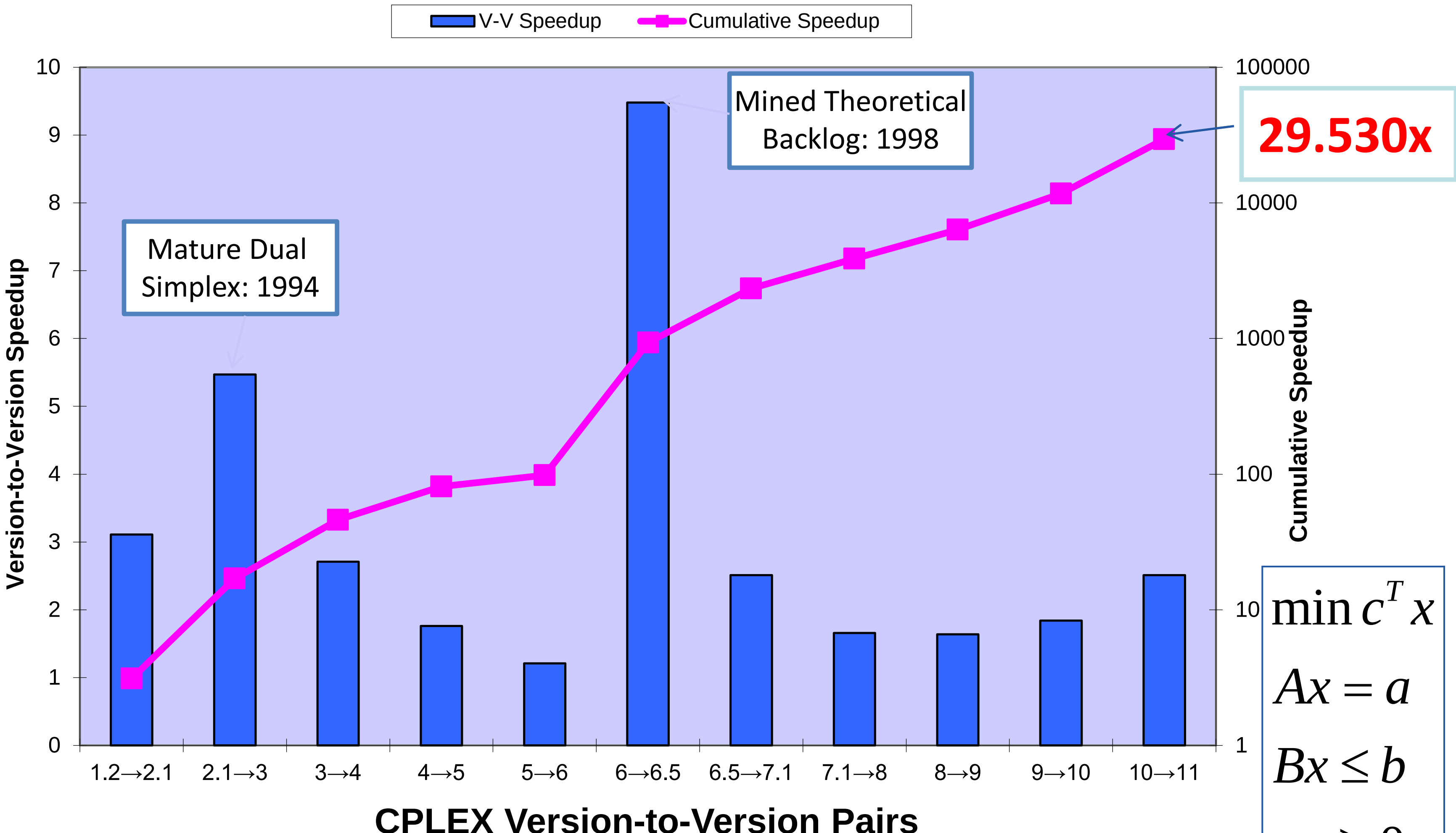
PROBLEMS WITH EQUILIBRIUM CONSTRAINTS

- MPEC Benchmark (6-1-2015)

Independent test sets and independent testing are desperately needed in the public transport community.

Courtesy Bob Bixby

MIP Speedups 1991 – 2008



1½ years in 1991 ~ 1 second in 2008

$$\min c^T x$$
$$Ax = a$$
$$Bx \leq b$$
$$x \geq 0$$
$$x \in \mathbb{Z}^n$$

Gurobi MIP Speedups 2009-2014

- Gurobi 1.0 and CPLEX 11.0 roughly equivalent
- Gurobi version-to-version improvements
  - Gurobi 1.0 -> 6.0: 29.4X

Courtesy Bob Bixby

- **Overall improvement:** 1990 to 2014
  - **Algorithms:** 870,000x
  - **Machines:** 6,500x
  - NET: Algorithm x Machine 5,600,000,000x

    (180 years / 5.6B ~= 1 second)

What is the SCIP Optimization Suite?

The SCIP Optimization Suite is a toolbox for generating and solving mixed integer programs. It consists of the following parts:

SCIP	mixed integer (linear and nonlinear) programming solver and constraint programming framework
SoPlex	linear programming solver
ZIMPL	mathematical programming language
UG	parallel framework for mixed integer (linear and nonlinear) programs
GCG	generic branch-cut-and-price solver

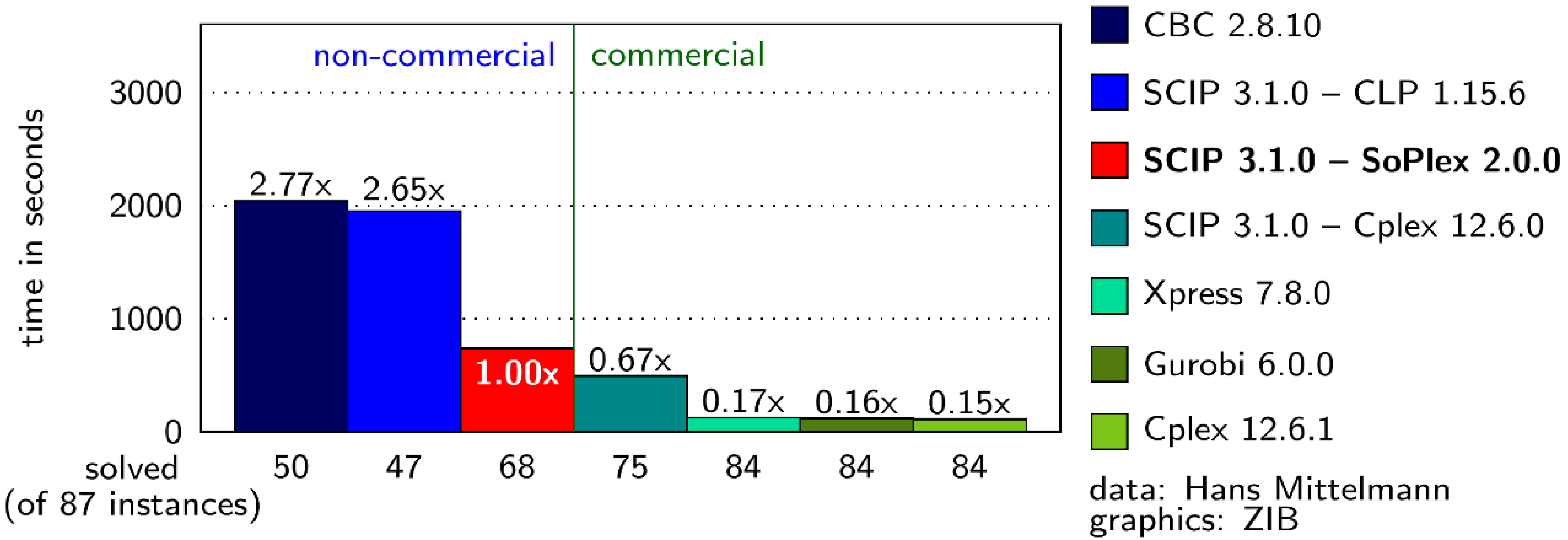
The user can easily generate linear programs and mixed integer programs with the modeling language ZIMPL. The resulting model can directly be loaded into SCIP and solved. In the solution process SCIP may use SoPlex as underlying LP solver.

Since all five components are available in source code and free for academic use, they are an ideal tool for academic research purposes and for teaching mixed integer programming.

Download the SCIP Optimization Suite (Linux). Previous releases and versions for different platforms are available here.

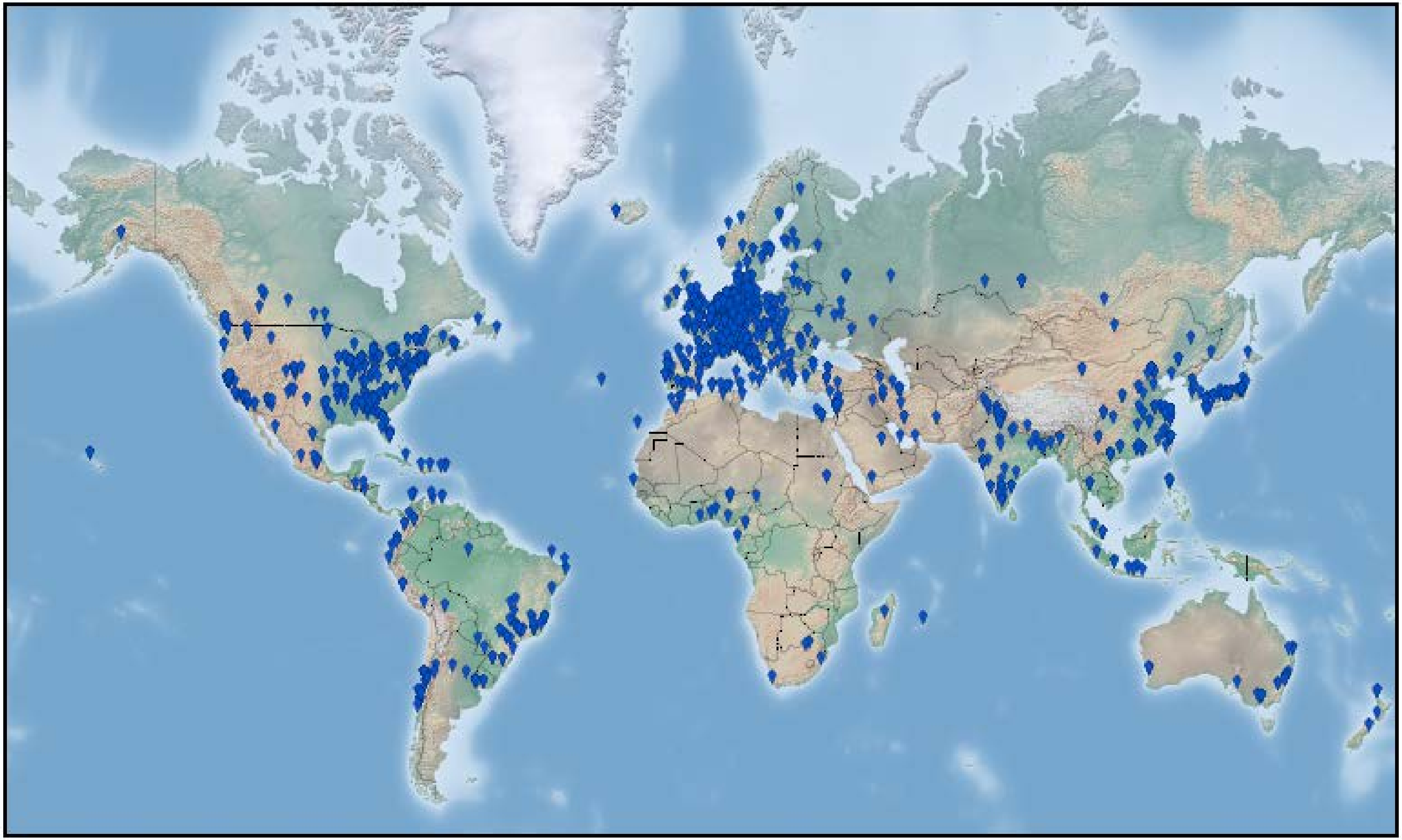
About

SCIP is currently one of the fastest non-commercial solvers for mixed integer programming (MIP) and mixed integer nonlinear programming (MINLP). It is also a framework for constraint integer programming and branch-cut-and-price. It allows for total control of the solution process and the access of detailed information down to the guts of the solver.



MIP solver benchmark (1 thread): Shifted geometric mean of results taken from the homepage of Hans Mittelmann (16/Jan/2015). Unsolved or failed instances are accounted for with the time limit of 2 hours.

SCIP users worldwide



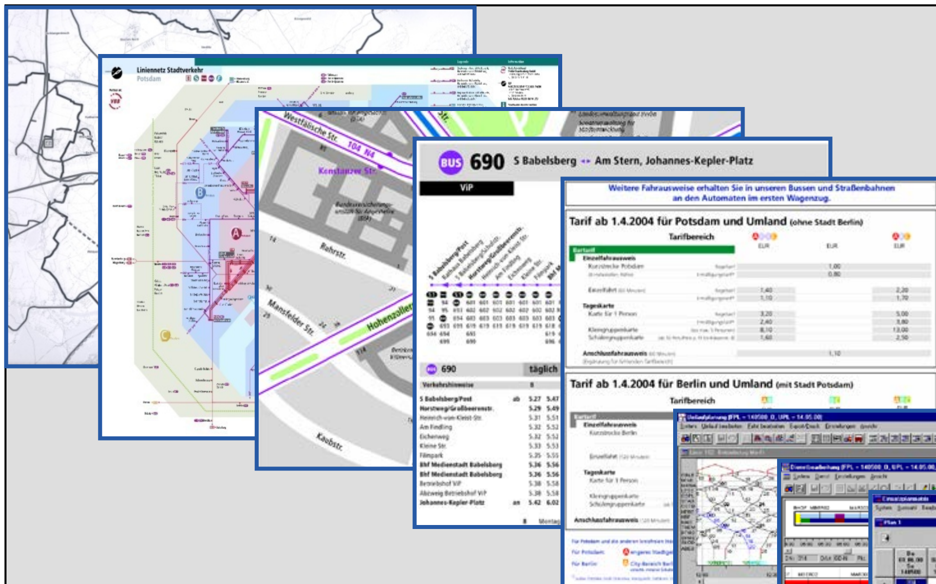
We have all data, of course!

Big data:

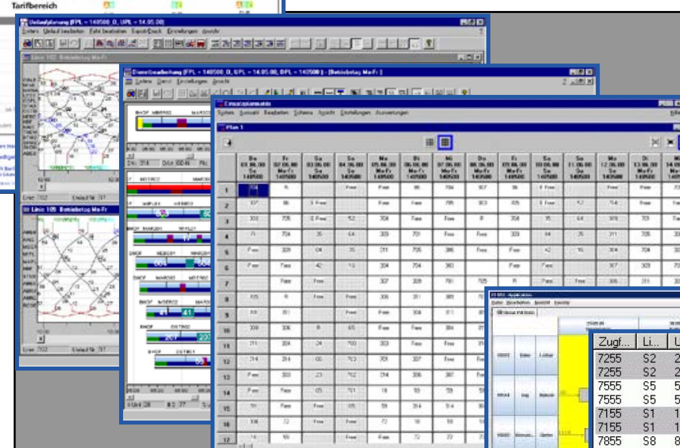
a huge problem, a huge challenge and a huge chance!

Planning Process in Public Transport

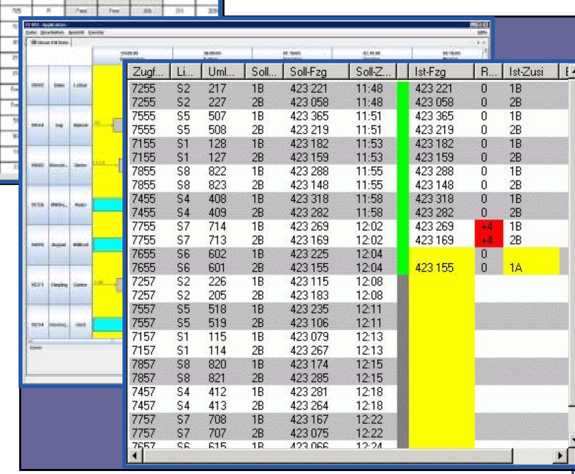
Service Planning



Operational Planning



Operations Control



Phase:	**Planning**	**Scheduling**	**Dispatching**
Horizon:	Long Term	Medium term Timetable Period	(very) Short term Day of Operation online planning
Objective:	Service Level	Cost Reduction	Get it done
Steps:	Network Design Line Planning Timetabling	Vehicle Scheduling Duty Scheduling Duty Rostering	Crew Assignment Delay Management Failure Management

politically difficult

done well

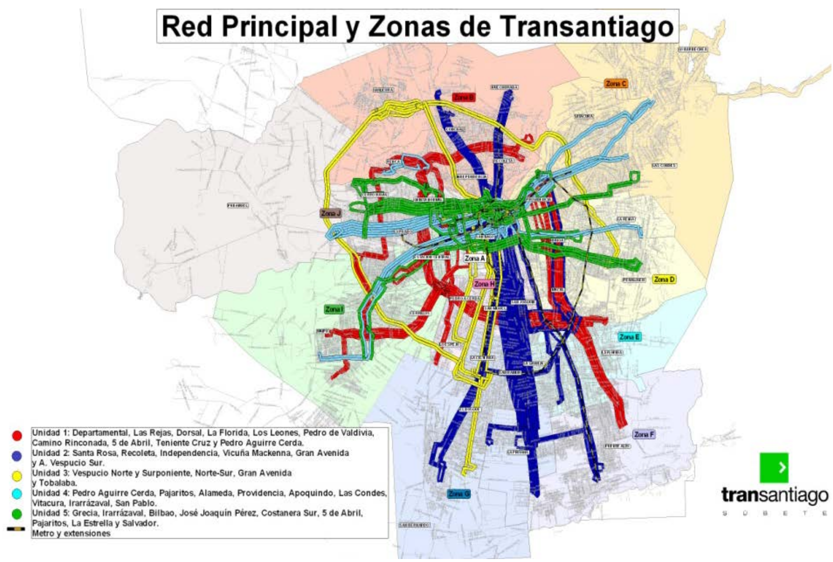
industry in general not ready

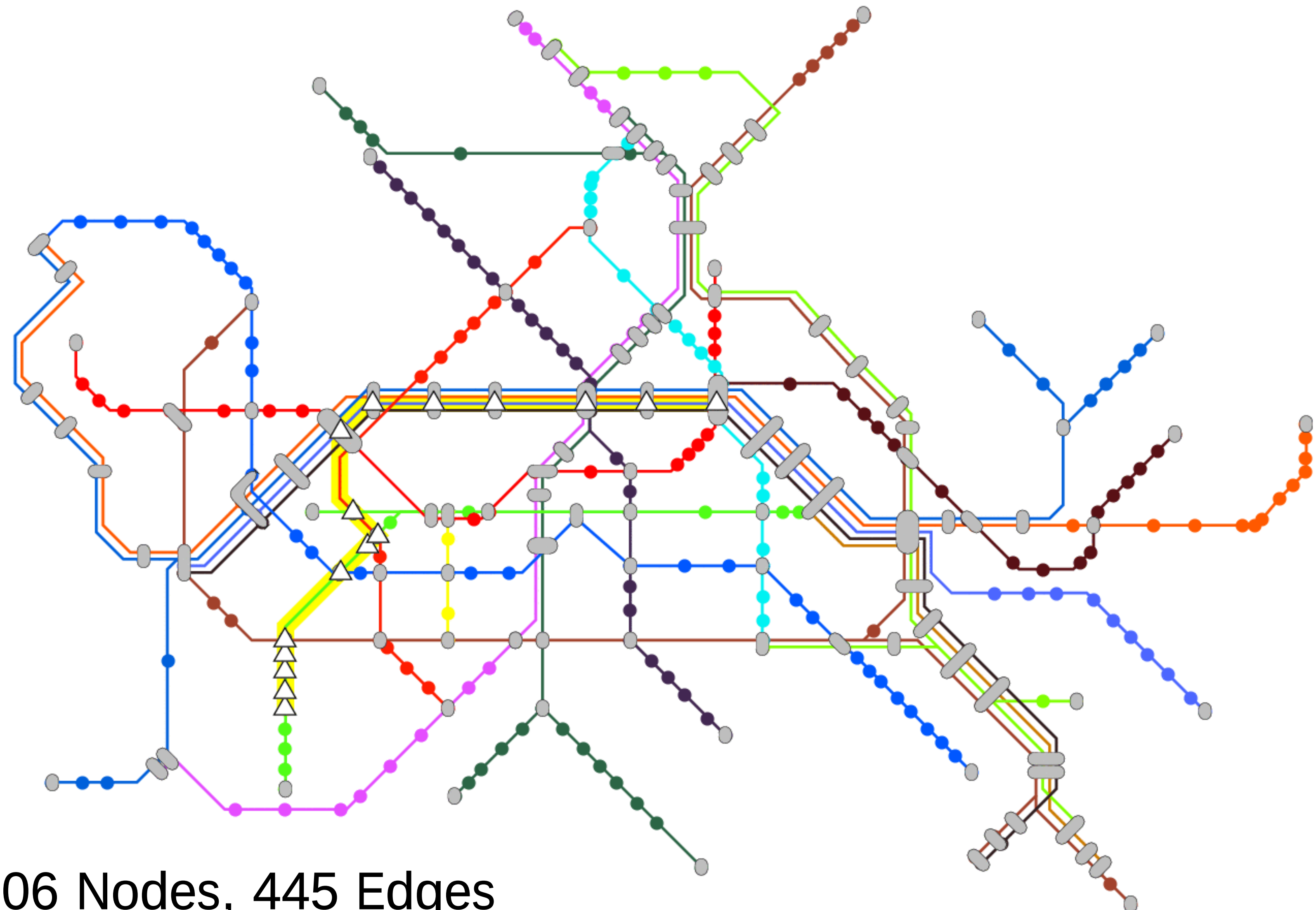

Berlin
Fernsehen, Telefonieren und Surfen - alles über eine Verbindung.
BAHNHOF ZOOLOGISCHER GARTEN
DB BERLIN ZOOLOGISCHER GARTEN
DUNLOP
REIFEN
DUNLOP
TERRASSEN AM ZOO
Billig- und Linienflüge im Vergleich

Santiago
de Chile
2007

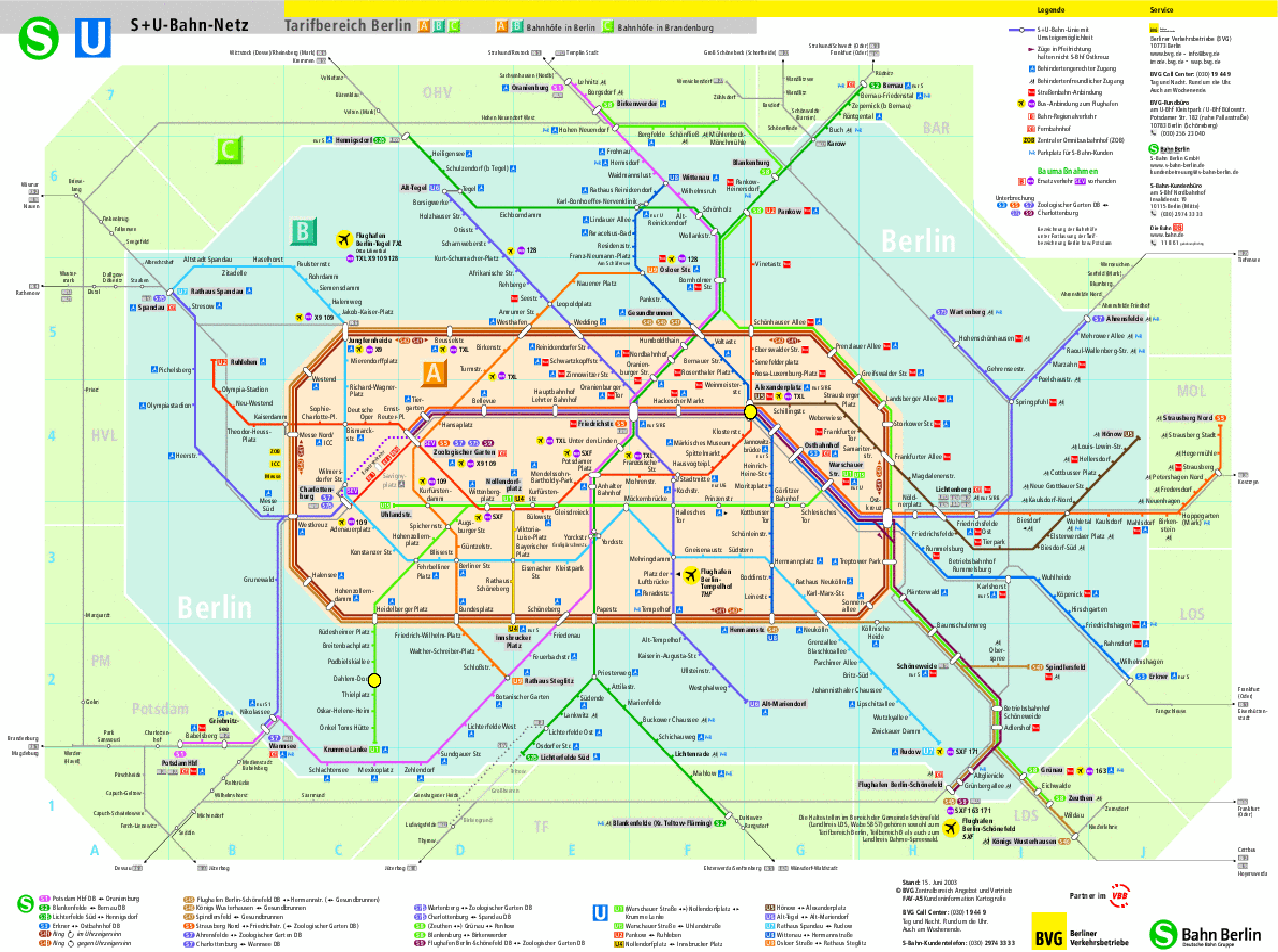
What is a good public transit network?

	Santiago	*Berlin*
Area	1 400 km²	900 km²
Population	5.8 Mio.	3.4 Mio.
commuter train		164 stations 329 km tracks 15 lines
metro	52 stations 45 km tracks 3 (+3) lines since 1975	170 stations 144 km tracks 9 lines
tram		377 stations 188 km tracks 21 lines
bus	7 000 buses 3 000 companies	1 300 buses



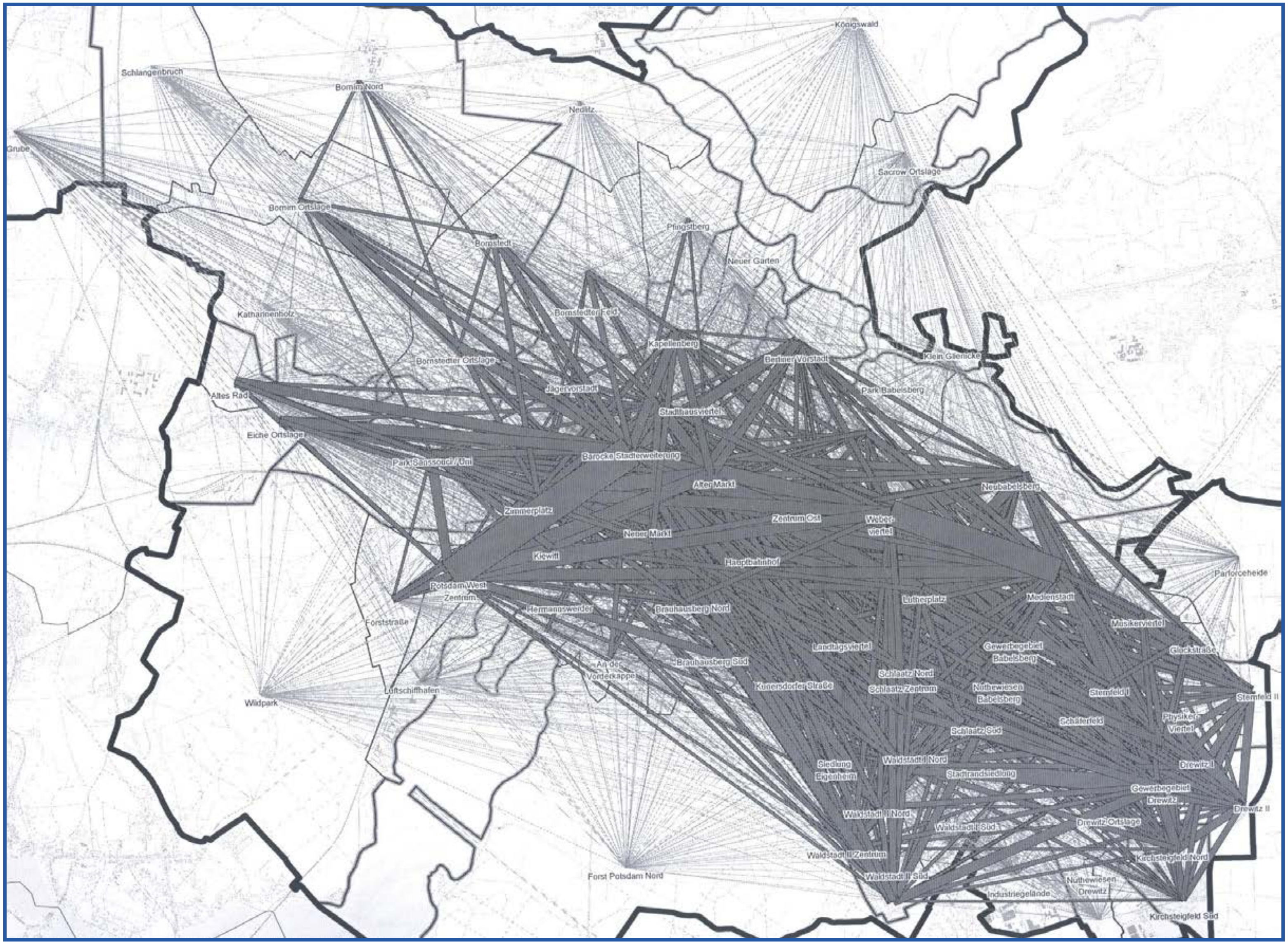


306 Nodes, 445 Edges



S+U-Bahn-Netz
Tarifbereich Berlin
Bahnhöfe in Berlin
Bahnhöfe in Brandenburg
Legende
Service
OHV
BAR
MOL
LOS
LDS
TF
PM
HVL
Berlin
Potsdam
A
B
C
Alexanderplatz
Friedrichstr.
Zoologischer Garten
Ostbahnhof
Gesundbrunnen
Westend
Südkreuz
Schönhauser Allee
Potsdam Hbf
Wannsee
Spandau
Oranienburg
Bernau
Erkner
Flughafen Berlin-Schönefeld
Flughafen Berlin-Tegel TXL
Flughafen Berlin-Tempelhof THF
Stand: 15. Juni 2003
Partner im VBB
BVG
Berliner Verkehrsbetriebe
S-Bahn Berlin

Potsdam Origin-Destination Matrix



Line Planning and Path Connectivity

Line Planning

Find a cost minimal set of lines and associated frequencies, s.t. a given set of travel demands can be transported in minimal time.

Prototype problem for line planning:

Path Connectivity

Find a set of paths to connect a (sub)set of nodes in a graph.

▷ Steiner connectivity problem

Line Planning: Model Comparison

	(CG)[1]	(DC)[2]	(BD)[3]
capacity constr.	$\mathcal{O}(\lvert\mathcal{L}\rvert\lvert A\rvert)$	$\mathcal{O}(\lvert D\rvert\lvert A\rvert)$	$\lvert A\rvert$
pass. vars	assoc. with lines	independent of lines	
optimality gap[4]	inf[5]	0.161%	0.068%
Δ direct traveler[4,6]	0.0%	0.006%	19.26%

1 (CG) Change-and-go model of Schöbel and Scholl [SS2005]
(complete and detailed treatment of transfers)

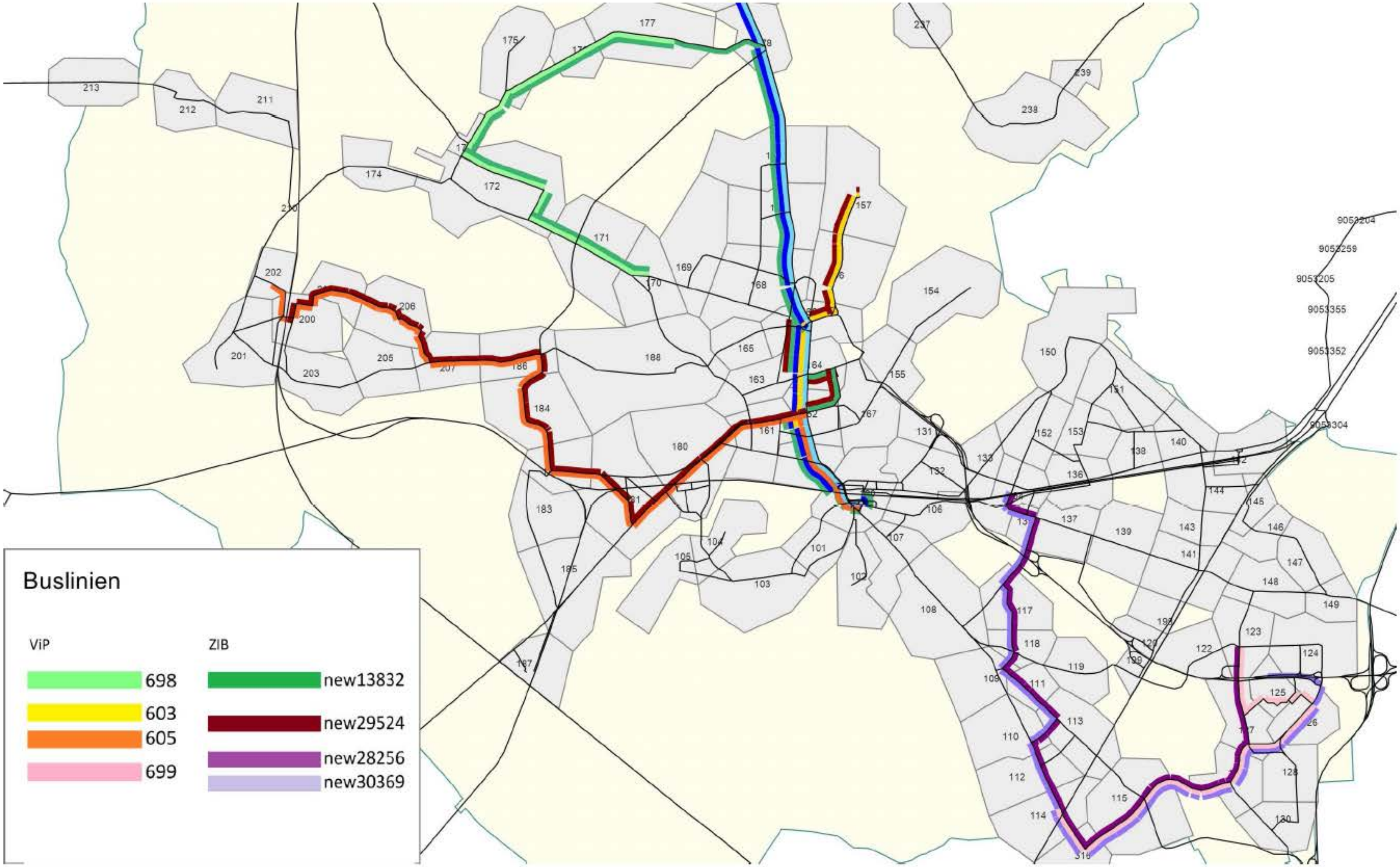
2 (DC) Direct connection model of Borndörfer and Karbstein [BK2012,2013]
(distinguish 0 and at least 1 transfer; dcmetric inequalities)

3 (BD) basic dynamic model of Borndörfer, Grötschel, Pfetsch [BGP2005]
(tractable line planning model, rudimental treatment of transfers)

4 geometric mean on 13 instances after 10 hours of computation

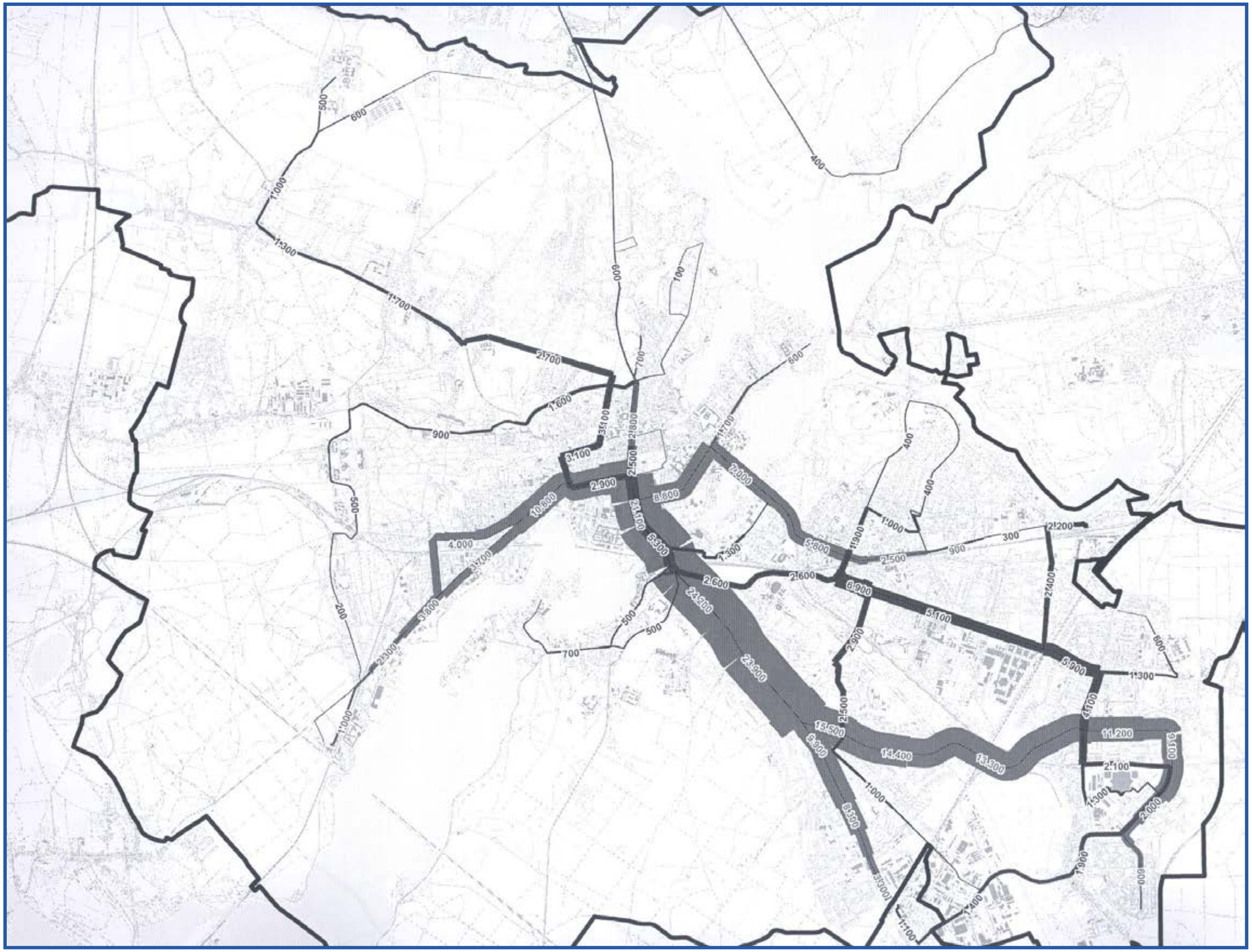
5 root LP for 7 of 13 instances could not be solved within 10 hours

6 difference of direct travelers predicted by model with exact direct travelers in system optimum

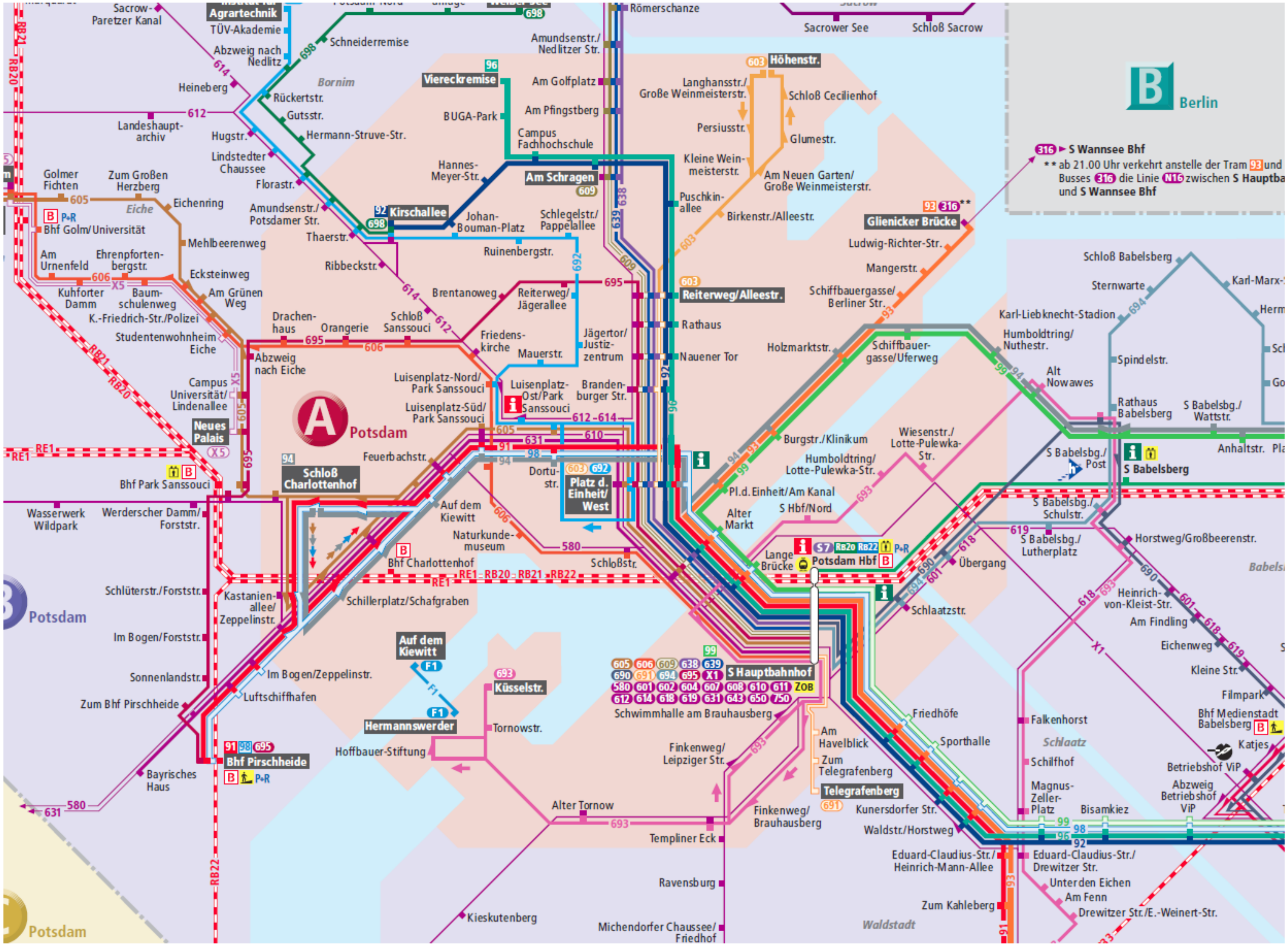


Graphic: VISUM, ptv AG

Passenger Flow



Potsdam – Lineplan 2010



Optimize everything in an integrated fashion, examples:

- Network design
- Line (and frequency) planning
- Timetable construction
- Vehicle circulation
- Crew assignment
- Crew rostering
- Crew dispatching
- Fare planning

Dream not to become true in my lifetime

And find quality guarantees, i.e., upper and lower bounds on the optimum value of the problem instance considered.

Some Traffic and Transport Projects

Supereinsatz. In Berlin und Brandenburg mussten die Gelben Engel letztes Jahr mehr als 240 000 Mal ausrücken, um Havaristen in der Hauptstadt und auf 1700 Autobahnkilometern wieder flottzumachen – ein Rekordeinsatz. Einen Rückgang von zehn Prozent bei den Pannen registrierten dagegen die Gelben Engel in Mecklenburg-Vorpommern. Bei insgesamt 72 389 Einsätzen schafften sie jedoch auch einen Rekord: In 84 Prozent der Fälle konnten die Autofahrer mit dem Wagen weiterfahren.

Public Transport Projects (ZIB and MATHEON)

Busses (Berlin and elsewhere)

Telebus (Transportation of disabled persons)

Bus Circulation

Bus Driver Scheduling

Integrated Vehicle and Driver Scheduling

Timetable Exchange

Subways and Light Railways

Subway Time Tabling

Vehicle Scheduling

Infrastructure Planning

Line Planing

Network Planning (Potsdam)

Fare Planing

Airlines

Airline Crew Scheduling/Rostering

Tail Assignment: Robustness

Free Flight Planning

Railways

Railway Track Allocation

ICE Circulation

Spin-Offs : LBW, Intranetz

13. Further examples

a. Bus circulation
b. Train/ICE circulation
c. Driver scheduling
d. Crew scheduling
e. Tail assignment
f. Planning the public transport system of a city
g. Generating competition, Trassenbörse
h. Tail assignment
i. Free flight

What can go wrong?

- Data
- Old habits, very conservative environment
- Rule based versus objective/goal oriented decision making
- Psychology of decision making
- Users do not understand the mathematics used.
- Users are reluctant to employ mathematics because interfacing with optimization software needs knowledge and education.
- Large number of failed projects
- Big skepticism or overly ambitious projects
- But things have significantly improved in the last years

The Roles of Modelling, Simulation, Heuristic and Exact Optimization in Public Transport

13th Conference on Advanced Systems in Public Transport (CASPT 2015)
Rotterdam, July 19 to July 23, 2015.

The END
Thanks for your patience