Or on OR

Martin Grötschel

20th European Conference on Operational Research

EURO XX, Rhodes, Greece

July 7, 2004

Martin Grötschel

- Institute of Mathematics, Technische Universität Berlin (TUB)
- DFG-Research Center “Mathematics for key technologies” (FZT 86)
- Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)

groetschel@zib.de http://www.zib.de/groetschel

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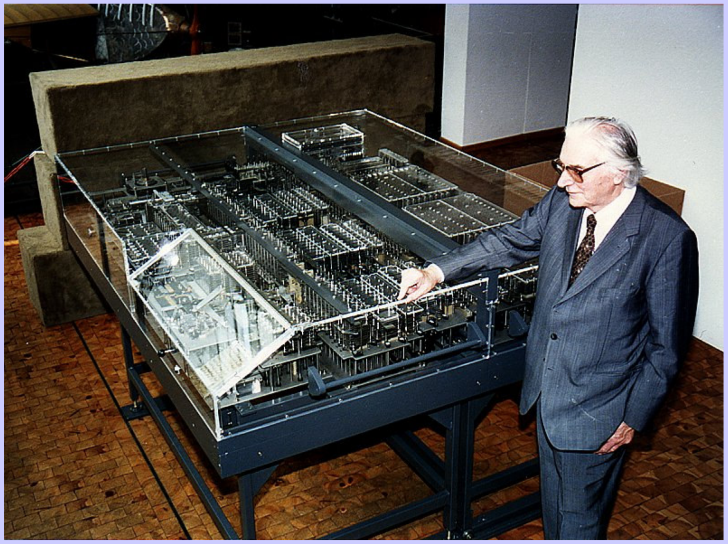
Konrad-Zuse-Zentrum für Informationstechnik
Zuse-Institute Berlin (ZIB)



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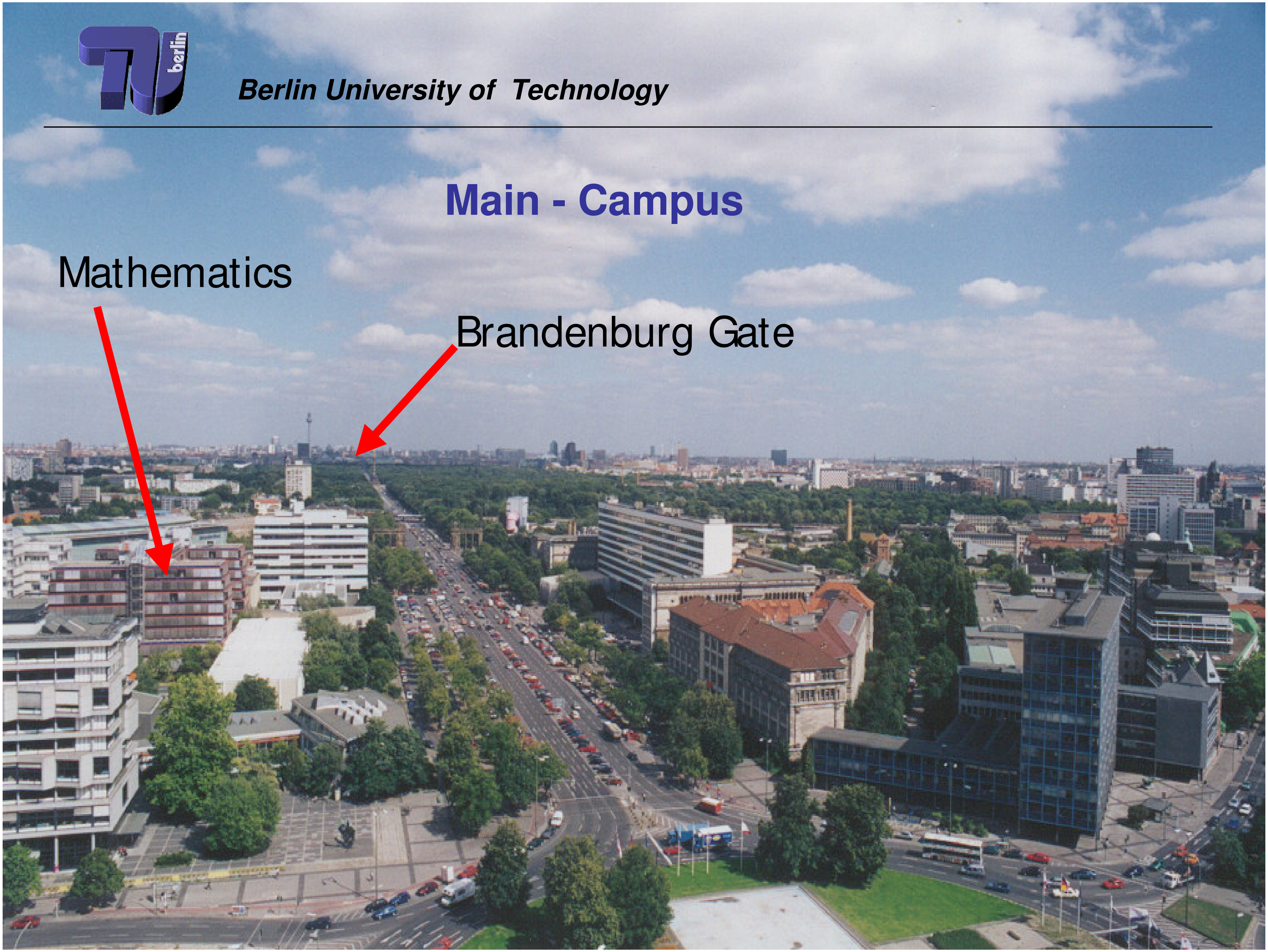
Berlin University of Technology
Main - Campus
Mathematics
Brandenburg Gate

The DFG Research Center in Berlin

supported by the German National Science Foundation

DFG Research Center

Mathematics for key technologies

Modelling, simulation, and optimization
of real-world processes

6 new chairs
70 new research positions
8 million € funding per year since 2002

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Former Lecture/ Article Titles of EURO Gold Medal Winners

- Egon Balas: “Some thoughts on the development of integer programming during my research career” (2001)
- Rainer E. Burkard: “OR Utopia” (1997)
- Jan Karel Lenstra: “Whizzkids” (1997)
- Pierre Hansen: “A short discussion of the OR crisis” (1986)
- Dominique de Werra: “What is my objective function?” (1995)
- My mulitcriteria optimization goal:
  - Minimize the title length
  - Use as few letters as possible
  - The title should have a meaning

“Or on OR”

6 letters,
3 different letters

Claude Berge
EURO Gold Medal 1989

Claude passed away on June 30, 2002

This week, a memorial conference is held in Paris

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A Childhood Dream

- I start with telling you a se
  revealed to anybody befor
- As a child I dreamt of bec
  at the Olympic Games.
- I was quite good in shot p

A Childhood Dream

- I start with telling you a secret that I never revealed to anybody before.
- As a child I dreamt of becoming a gold medalist at the Olympic Games.
- I was quite good in shot put.
- I just was not good enough (# 9 in Germany) and did not make the 1972 German olympic team.
- Receiving an EURO Gold Medal in Greece is the second best that could have happened to me.

Contents

Operational Research

- S. Vajda, (article on EURO Gold Medal Ceremony) "The three ages of Operational Research", European Journal of Operational Research 45(1990)131-134

  "I believe that the term fits awkwardly those activities which OR comprises now, but it is too late to change."

- R. L. Ackoff, "The future of Operational Research is past" Journal of the Operational Society 30(**1979**)93-104

- J. Krarup, "EURO Gold Medal 1986: A parable on two-level parallelism", European Journal of Operational Research 38(1989)274-276

  "…an interdisciplinary bastard like operational research…"

Google Search (Saturday morning)

- "operations research“
  about **929,000** hits for **"operations research"**
- "operational research“
  about **226,000** hits for **"operational research“**
- "Unternehmensforschung“
  about **9,660** hits for **“Unternehmensforschung“**
- "Unternehmungsforschung“
  about **83** hits for **“Unternehmungsforschung“**
- “Operationsforschung”
  about **719** hits for **“Operationsforschung“**
  (Mostly from medicine, though)

Contents

- Introduction
  - Where am I from?
  - Selecting a title
  - Revealing a secret
- What is OR? (A name is a name, or not?)
- OR on OR
- Answering THE hard questions
  - What can we do? Examples:
    - Linear and integer programming
    - Public transportation
    - Telecommunication
  - What should we look at?
- What is good OR?

The basic questions of philosophy

- Where do we come from?
- Who are we?
- Where are we going to?
- What is the meaning of life?

The basic questions of an OR consultant

- I made a long list, but deleted it yesterday since I thought that you would know that anyway.
- (I will try not to bore you too much.)

Operational Research: approaching it as a subject

- OR as a topic in mathematics
  - optimization
  - mathematical programming
- OR as a topic in management science
  - operations management, business information management
  - management engineering
- OR as a topic in engineering
  - industrial engineering
  - supply chain management/flexible manufacturing
- OR as a topic in computer science
- OR as a topic in psychology/sociology
- Systems Theory/Cybernetics
- Decision Sciences, Decision Aid
- …

de Werra's sweep

D. de Werra: "What is my objective function?"

European Journal of Operational Research 99(1997)207-219

2. OR is a pure science
3. OR is an open science
4. OR relies on basic sciences and on life sciences
5. OR is a natural science
6. OR is an art
7. OR does miracles

Dominique forgot: OR is an applied science

Academic OR in Berlin

- Technische Universität Berlin
  - Fakultät IV - Elektrotechnik und Informatik
    - Institut für Wirtschaftsinformatik und Quantitative Methoden
      - **Operations Research (OR)**
  - Fakultät VIII Wirtschaft und Management
    - Fachgebiet Produktionsmanagement
  - Fakultät II Mathematik und Naturwissenschaften
    - Institut für Mathematik
      - Arbeitsgruppe Algorithmische und Diskrete Mathematik R. Möhring M. Grötschel
- Freie Universität Berlin
  - Fachbereich Wirtschaftswissenschaft
    - Institut für Produktion, Wirtschaftsinformatik und **OR**
- Humboldt Universität Berlin
  - Wirtschaftswissenschaftliche Fakultät
    - Institut für **Operations Research**

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Contents

1. Introduction
   - Where am I from?
   - Selecting a title
   - Revealing a secret
2. What is OR? (A name is a name, or not?)
3. OR on OR
4. Answering the HARD questions
   - What can we do? Examples:
     - Linear and integer programming
     - Public transportation
     - Telecommunication
   - What should we look at?
5. What is good OR?

Answering the HARD questions

- What do I mean?
- I think that OR should start adressing politically relevant “global questions” seriously.
- After a few examples I will be more precise.

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1. Introduction
   - Where am I from?
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   - Revealing a secret
2. What is OR? (A name is a name, or not?)
3. OR on OR
4. Answering the HARD questions
   - What can we do? Examples of Success Stories:
     - Linear and integer programming
     - Public transportation
     - Telecommunication
   - What should we look at?
5. What is good OR?

Typical optimization problems

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

„general"
(nonlinear)
program
NLP

$$\begin{aligned} &\min c^T x \\ &Ax = a \\ &Bx \le b \\ &x \ge 0 \\ &(x \in \mathbf{R}^n) \\ &(x \in k^n) \end{aligned}$$

linear
program
LP

$$\begin{aligned} &\min c^T x \\ &Ax = a \\ &Bx \le b \\ &x \ge 0 \\ &x_i \in \mathbf{Z} \;\; \textit{for some } i \\ &(x_i \in \{0,1\} \;\; \textit{for some } i) \end{aligned}$$

(linear)
(mixed-) integer
program
IP, MIP

program = optimization problem

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Special „simple“ combinatorial optimization problems

Finding a

- minimum spanning tree
- shortest path
- maximum matching
- maximal flow through a network
- cost-minimal flow
- …

solvable in polynomial time (and very fast in practice)

Special „hard“ combinatorial optimization problems

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

NP-hard (in the sense of complexity theory)

The most successful solution techniques employ linear programming as a bounding procedure.

by courtesy of Bob Bixby

LP Progress: 1988 – 2000

- **Algorithms**

  Primal simplex in 1988 *versus*

  Best(primal,dual,Barrier) today **2360x**

- **Machines**

  800x

Net: Algorithm * Machine ~ 1 900 000x

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Linear Programming 1987-2000

„A Model that might have taken a year to solve 10 years ago, can now solve in less than 10 seconds.“

- Machine

old machine	new machine	Speedup
Sun 3/50	Pentium 4, 1.7 GHz	800
Sun 3/50	Compaq Server ES 40, 667 MHz	900
Intel 386, 25 MHz	Compaq Server ES 40, 667 MHz	400
IBM 3090/108S	Compaq Server ES 40, 667 MHz	45
Cray X-MP/416	Compaq Server ES 40, 667 MHz	10

- Mathematics

old code	new code	Estimated Speedup
XMP	Cplex 1.0	4,7
Cplex 1.0	Cplex 5.0	22,0
Cplex 5.0	Cplex 7.1	3,7
XMP	Cplex 7.1	960

Robert E. Bixby, Solving Real-World Linear Programs: A Decade and More of Progress. *Operations Research* 50 (2002)3-15.

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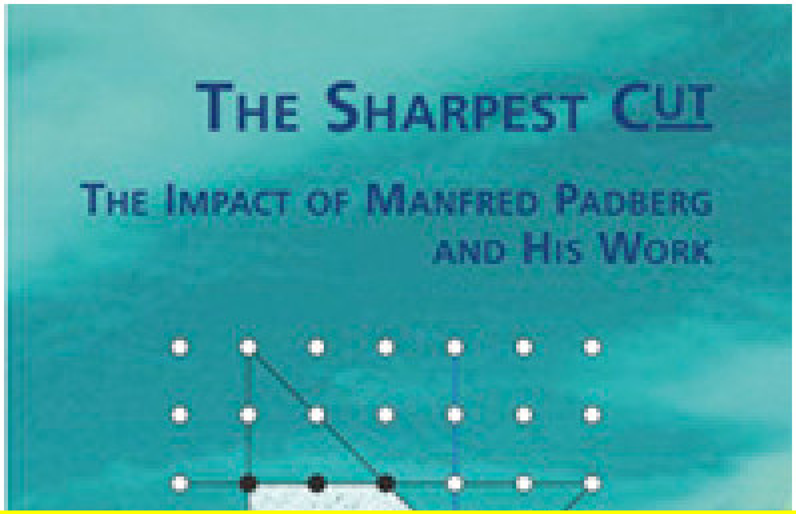
Progress in Integer Programming



This book appeared just two weeks ago.

One particularly interesting article on MIP:

Bixby et al.: LP Speedups

Table 18.2. *Speedups—1988 to 2002.*

Algorithm	
Simplex algorithms	960
Simplex and barrier algorithms	2360
Machines	
Simplex algorithms	800
Barrier algorithms	13000

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Bixby et al.: Opinion

Top computational advances during the last 15 years:

- robust dual simplex algorithms;
- linear algebra improvements;
- interior-point algorithms;
- automatic problem simplification ("presolve").

Bixby et al.: New MIP features

New features of the new generation of mixed-integer programming codes

- linear programming: stable, robust, dual simplex algorithms;
- variable/node selection: probing on dives, strong branching;
- primal heuristics: multiple heuristics applied within the search tree;
- node presolve: fast, incremental bound strengthening;
- presolve: probing in constraints;
- cutting planes: Gomory mixed-integer cuts, knapsack covers, flow covers, mixed-integer rounding (MIR) cuts, cliques, GUB covers, implied bounds cuts, path cuts, disjunctive cuts.

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Bixby et al.: MIP instances

Hard test cases:

- total models in test: 978;
- solved to optimality:
  - CPLEX 5.0: 569 (58%),
  - CPLEX 8.0: 755 (77%);
- among those not solved to optimality with CPLEX 8.0:
  - 116 had gap less than 10% (11.9%),
  - 32 had no integral solution (3.2%);
- using CPLEX 8.0 and "MIP emphasis feasibility" on the 32 models with no feasible solution:
  - 25 found no feasible solution (2.6%).

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Bixby et al.: MIP Speedups

Table 18.4. *Speedups for solvable models.*

No. models	CPLEX 5.0 time (seconds)	Geometric mean
758	> 0	12
551	> 1	33
463	> 10	59
375	> 100	97
294	> 1000	191
229	> 10000	357
189	> 100000	528

Bixby et al.: Improvement factors

Table 18.5. *CPLEX 8.0–effects of individual features.*

Feature	Degradation
No cuts	53.7
No presolve	10.8
CPLEX 5.0 presolve	3.1
CPLEX 5.0 variable selection	2.9
No heuristics	1.4
No node presolve	1.3
No probing on dives	1.1

Bixby et al.: Which cuts work?

Table 18.6. *CPLEX 8.0–effects of individual cuts.*

Cut type	Factor
Gomory mixed-integer	2.52
MIR	1.83
Knapsack cover	1.40
Flow cover	1.22
Implied bound	1.19
Path	1.04
Clique	1.02
GUB cover	1.02
Disjunctive	0.53

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The "classical" Transportation Problem in Mathematical Programming

$$\min \sum_{(i,j)\in S\times T} c_{ij}x_{ij}$$

subject to

$$\sum_{j\in T} x_{ij} = a_i \quad \forall i \in S$$

$$\sum_{i\in S} x_{ij} = b_j \quad \forall j \in T$$

$$0 \le x_{ij} (\le cap_{ij})$$

- This problem rarely occurs in real life in its pure form.
- It does appear as a subproblem of some much more complex real problems.
- It can be solved very quickly.

$S =$ sources, origins, supply

$T =$ sinks, destinations, demand

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High Quality Public Transportation: Mathematical, Social, Political, and Business Aspects

My research group at ZIB has, for more than a decade, worked on various mathematical aspects of public transportation.

- We have optimized the transport of disabled people in Berlin,
- found the minimal number of busses to run the Berlin and other city or regional bus systems,
- solved driver scheduling problems and
- many other optimization problems of this type.

High Quality Public Transportation: Mathematical, Social, Political, and Business Aspects

These problems are, in general, of very large scale and represent significant mathematical challenges. I will sketch some of the achievements briefly in my talk.

It turned out, though, that implementing solutions of such problems often creates (unexpected) social or polititical difficulties.

This is an example of a HARD question.

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High Quality Public Transportation: Mathematical, Social, Political, and Business Aspects

But what is a "good" public transportation system?

Can such a system result from deregulation?
How does one deregulate, e.g., the railway system of a country, properly?

We are currently investigating such and related issues which are highly relevant for everybody's everyday life. There are more questions than answers.

Examples of practically important and challenging transportation problems

Some of the tasks that have to be addressed:

- planning routes
- assigning vehicles
- dispatching drivers
- improving quality
- informing customers
- creating (multi-modal) links
- controlling fleets
- coordinating tours
- keeping track of jobs
- optimizing schedules
- locating vehicles
- failure management/online rescheduling

film produced by IVU

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The ZIB Transportation Team, including former members

Public Transport:	Online Transportation:
Ralf Borndörfer	Norbert Ascheuer
Fridolin Klostermeier	Sven O. Krumke
Christian Küttner	Diana Poensgen
Andreas Löbel	Jörg Rambau
Sascha Lukac	Luis Miguel Torres
Marc Pfetsch	Andreas Tuchscherer
Steffen Weider	Tjark Vredeveld

The ZIB Transportation Team spin-off companies

Intranetz:

Fridolin Klostermeier

Christian Küttner

Norbert Ascheuer

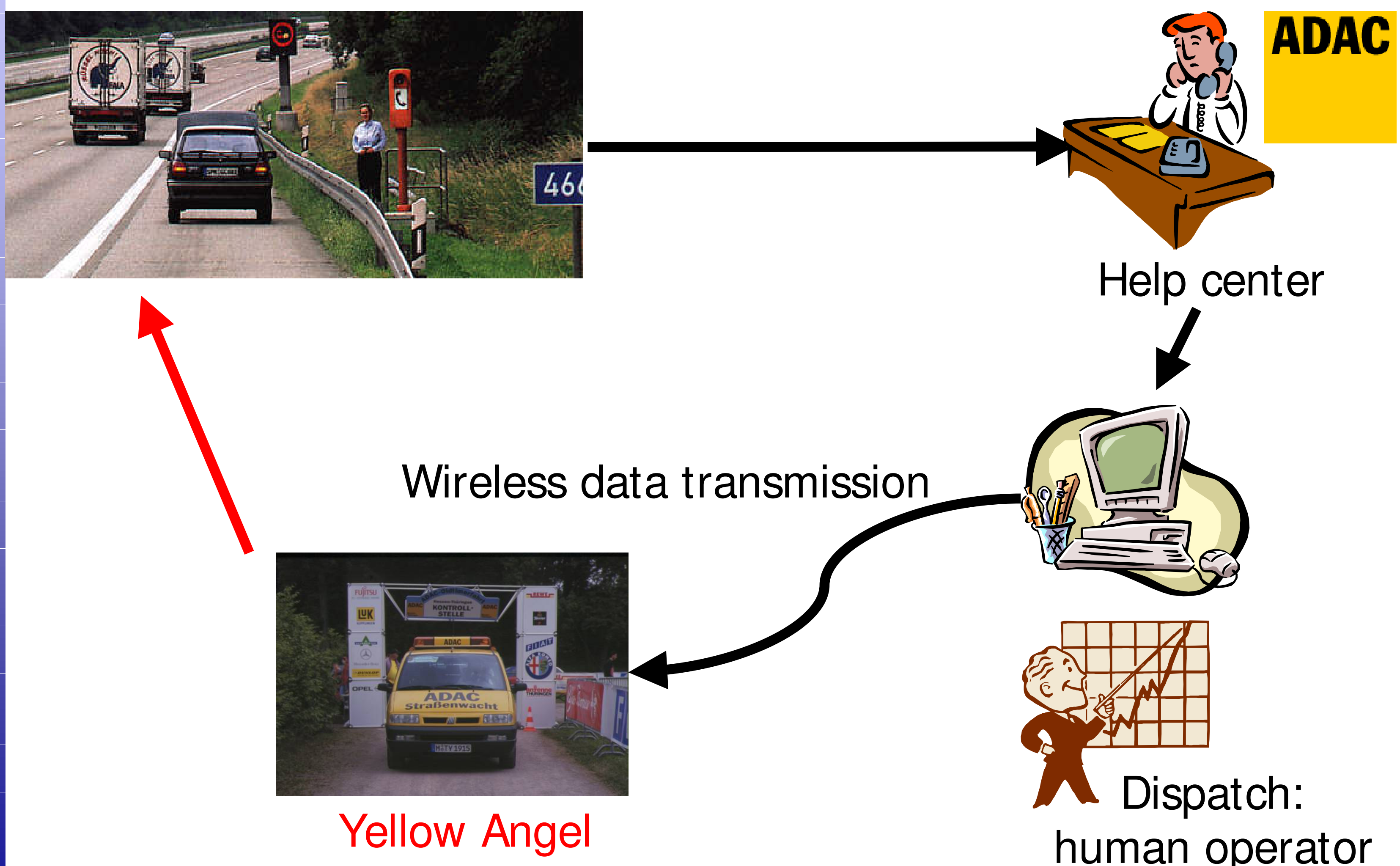
LBW:

Ralf Borndörfer

Andreas Löbel

Steffen Weider

Service vehicle planning at ADAC



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.

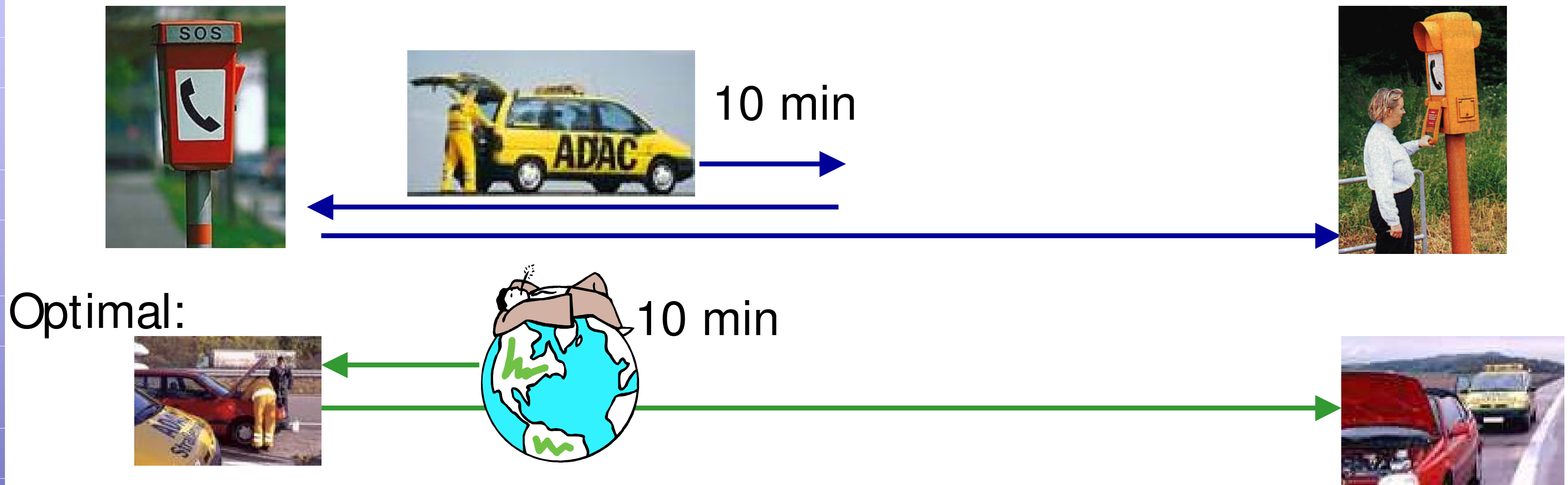
„Unit“ of the service fleet: Yellow Angel

gelber Engel

1,700 yellow angels

10,000 calls per day

Online aspects at ADAC



- Requests are not known in advance
- Decisions are based on incomplete information
- Suboptimal results
- How to evaluate an online algorithm?

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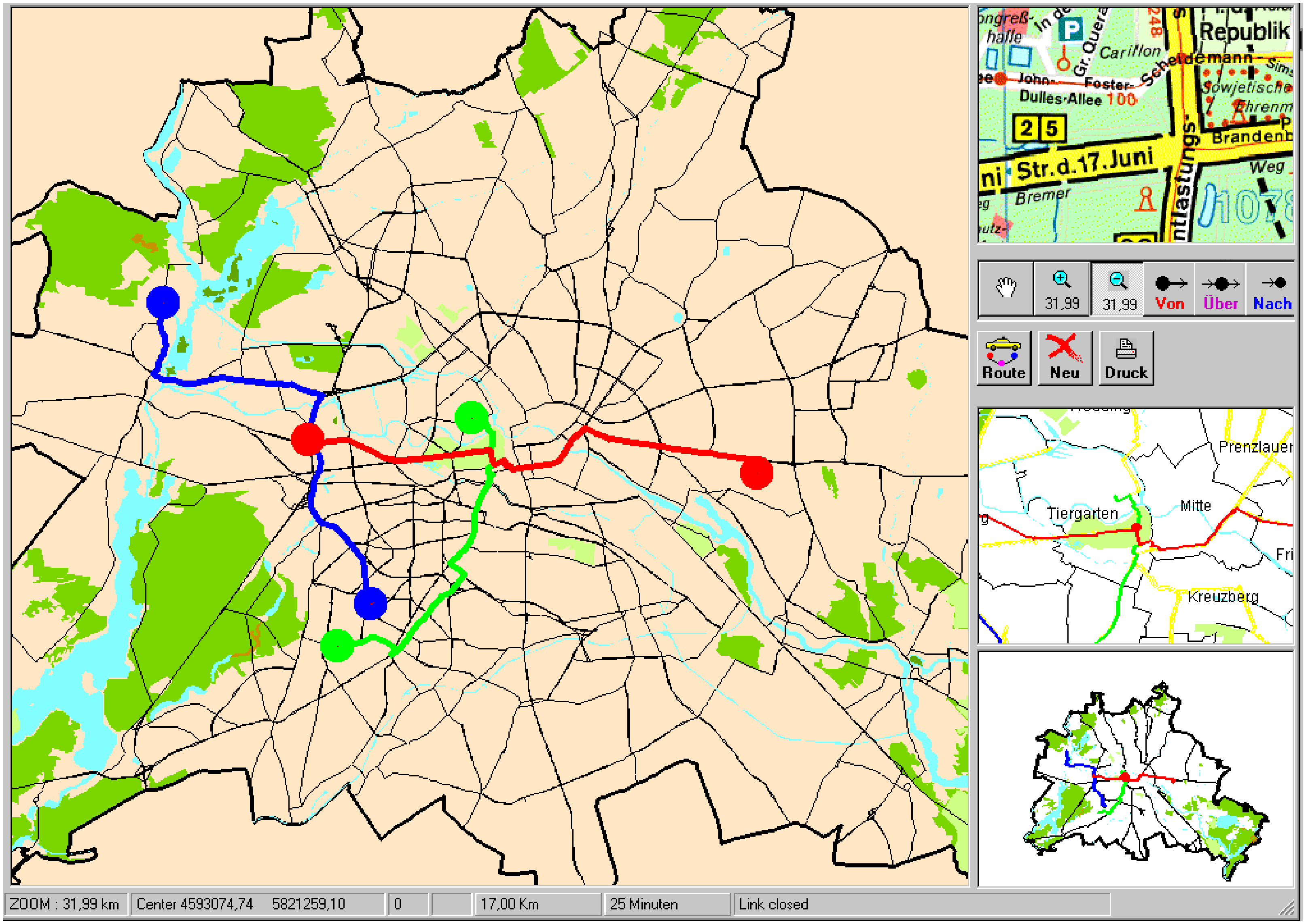
Yellow Angels

- A prototype of our dispatching software is in use at two of the five ADAC dispatching centers in Germany.
- considerable planning improvement reached
- in full use everywhere in Germany probably at the end of this year

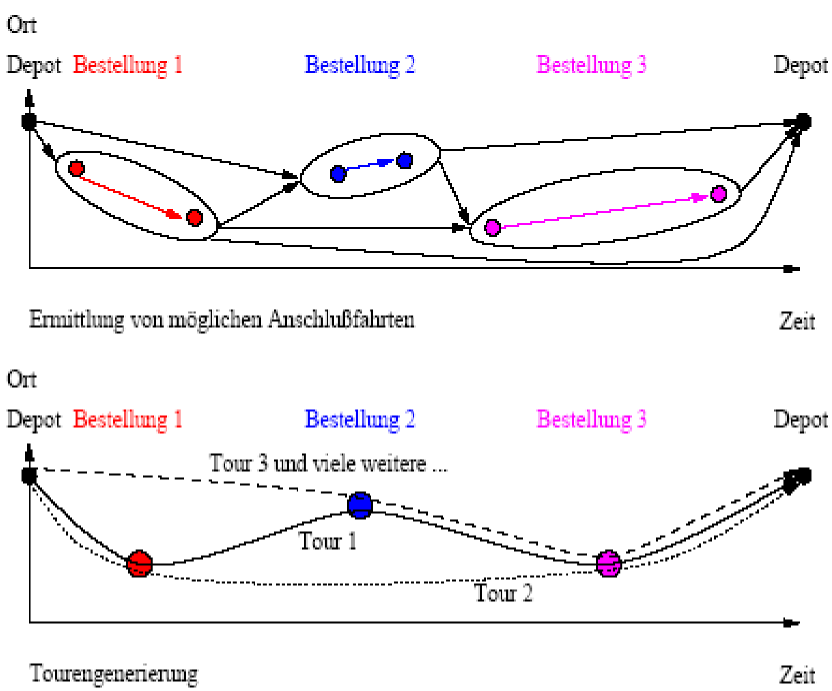
Telebus: Transportation of disabled people



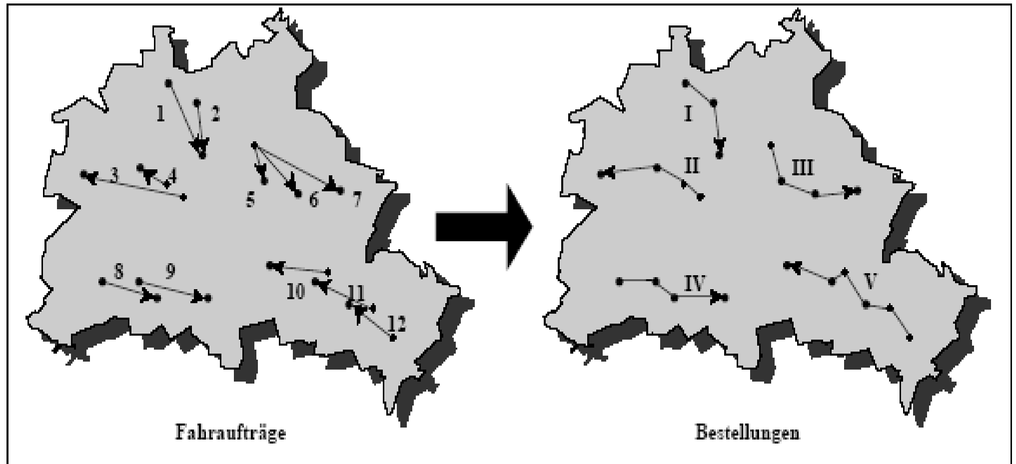
The „Telebus mathematics“

Finding a „Good“ Mathematical Model

Tourengenerierung



Die Verknüpfungsoptimierung



Vor der eigentlichen Tourenplanung werden Fahraufträge zu Bestellungen verknüpft. Z.B. Zielsammelfahrt (I: 1, 2), Einbindung (II: 3, 4), Startsammelfahrt (III: 5, 6, 7), Anbindung (IV: 8, 9), Mehrfachanbindung (V: 10, 11, 12).

Ziel: Minimierung der Besetztkilometer

Finding a „Solvable“ mathematical model: Set Partitioninging

Solution technology

We employ:

- various heuristics:
  clustering
  TSP/Routing
  improvement
- cutting planes
  based on the
  set packing and
  set covering
  polytopes
- column generation
  to dynamically
  generate „good“
  tours/variables
- branch&cut

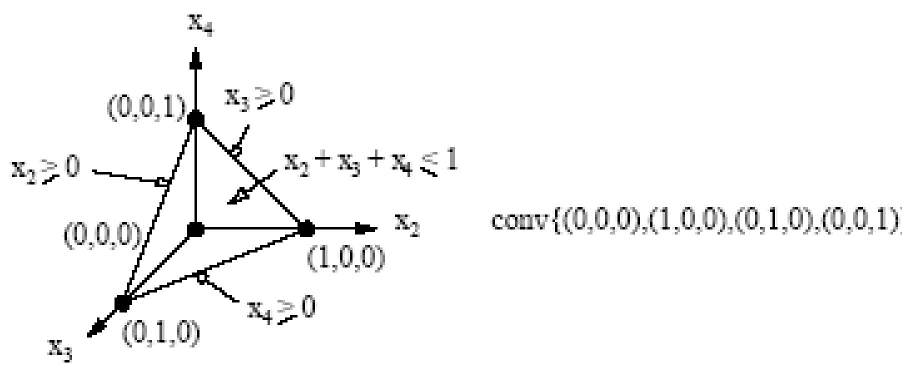
Set Partitioning

Kosten von Tour 1 = 7, von Tour 2 = 3, ...

minimiere	$7x_1 +$	$3x_2 +$	$3x_3 +$	$3x_4 +$	$2x_5$		
Fahrtwunsch 1	$1x_1 +$	$1x_2 +$	$0x_3 +$	$1x_4 +$	$0x_5$	$=$	1
Fahrtwunsch 2	$1x_1 +$	$0x_2 +$	$1x_3 +$	$1x_4 +$	$1x_5$	$=$	1
Fahrtwunsch 3	$1x_1 +$	$1x_2 +$	$1x_3 +$	$0x_4 +$	$0x_5$	$=$	1
	Tour 1	Tour 2	Tour 3	x_1,x_2,x_3,x_4,x_5		$\in$	$\{0,1\}$

Ganzzahlige Programmierung: Set-Partitioning-Modell

$$\min c^T x$$
$$Ax = 1$$
$$x \geq 0$$
$$where\ A\ is\ a\ 0/1-matrix$$



Polyedrische Kombinatorik: Cliquenungleichung

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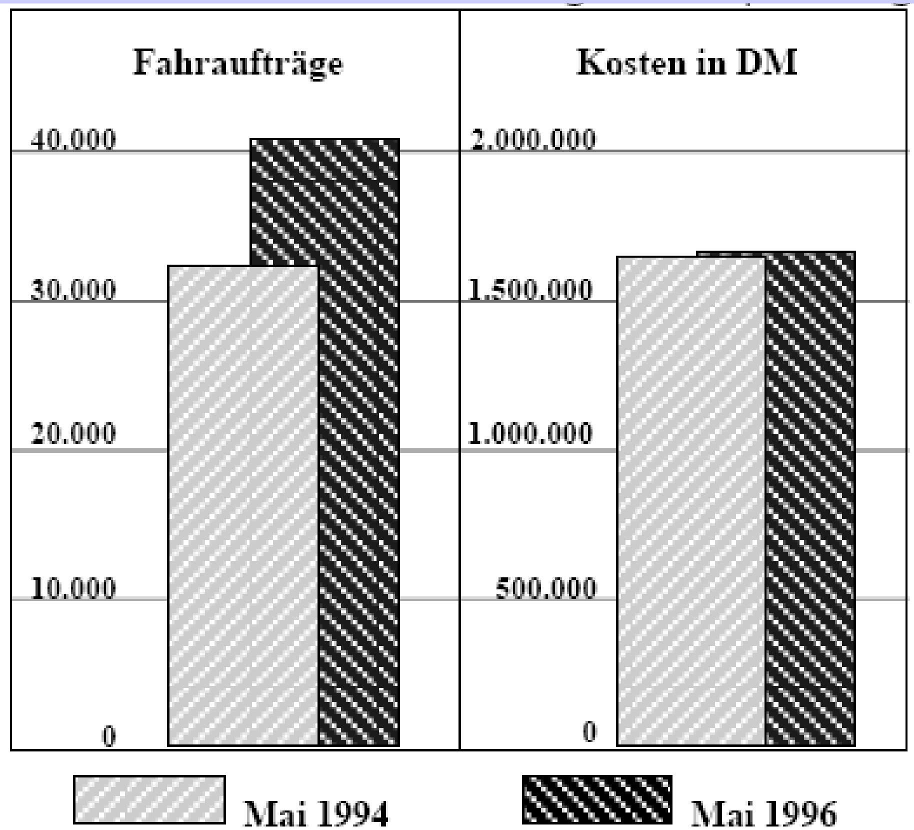
Where is the mathematics?

Improvements

We employ:

- various heuristics:
  clustering
  TSP/Routing
  improvement
- cutting planes
  based on the
  set packing and
  set covering
  polytopes
- column generation
  to dynamically
  generate „good"
  tours/variables
- branch&cut



Ergebnisse

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

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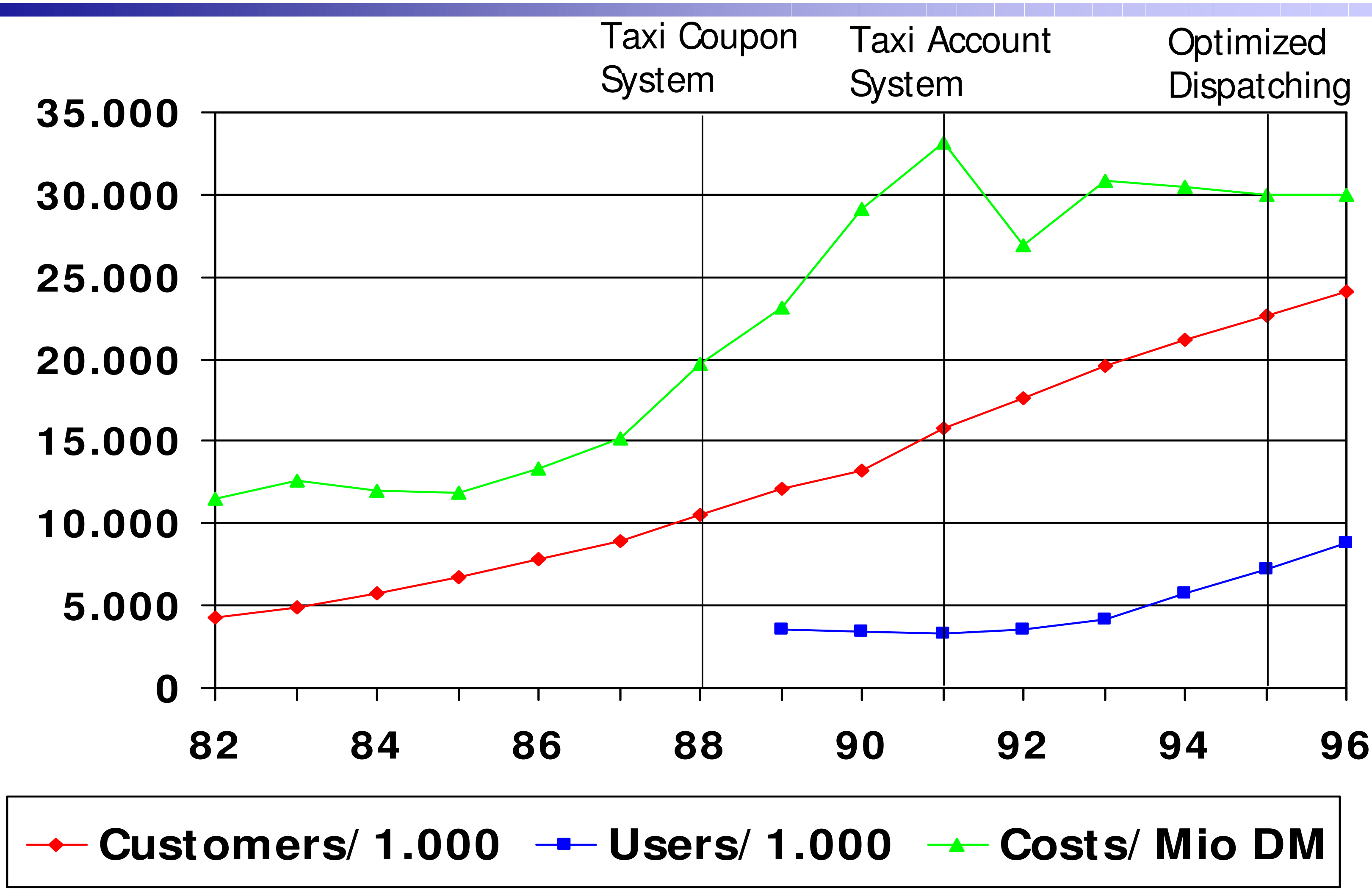
History



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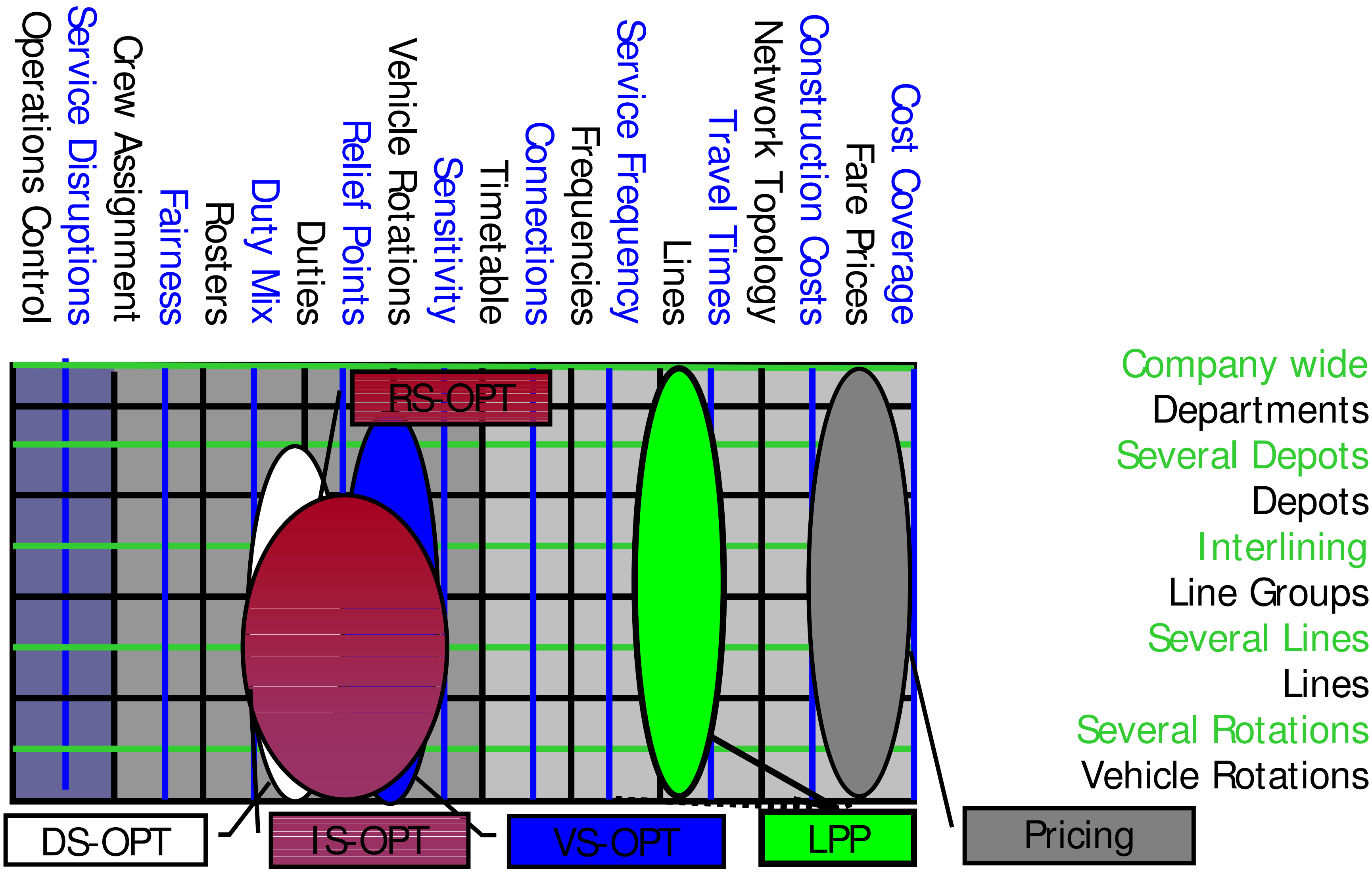
Some Telebus stories

- History: The system, newspaper reporter
- Social and political context (Berlin, BMBF)
- Industry interests (subsidies)
- Riding telebuses, psychology of customers
- Taxi and „social“ transport companies
- union influence
- psychology of employees and bus companies
- Telebus 2004: Another crisis,
  Testimony in Berlin House of Representatives

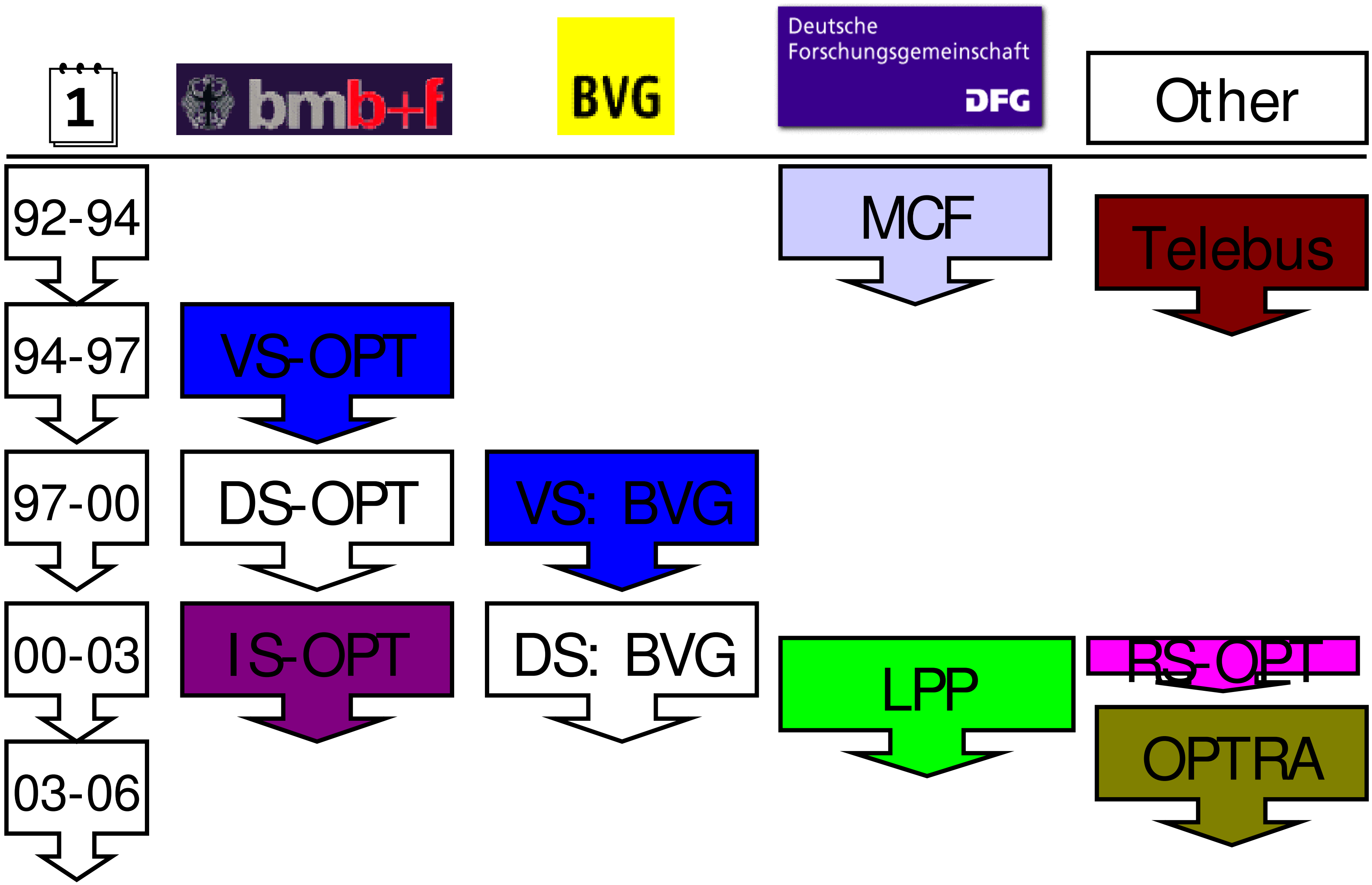
Planning Public Transportation

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

Public Transport Planning



Projects



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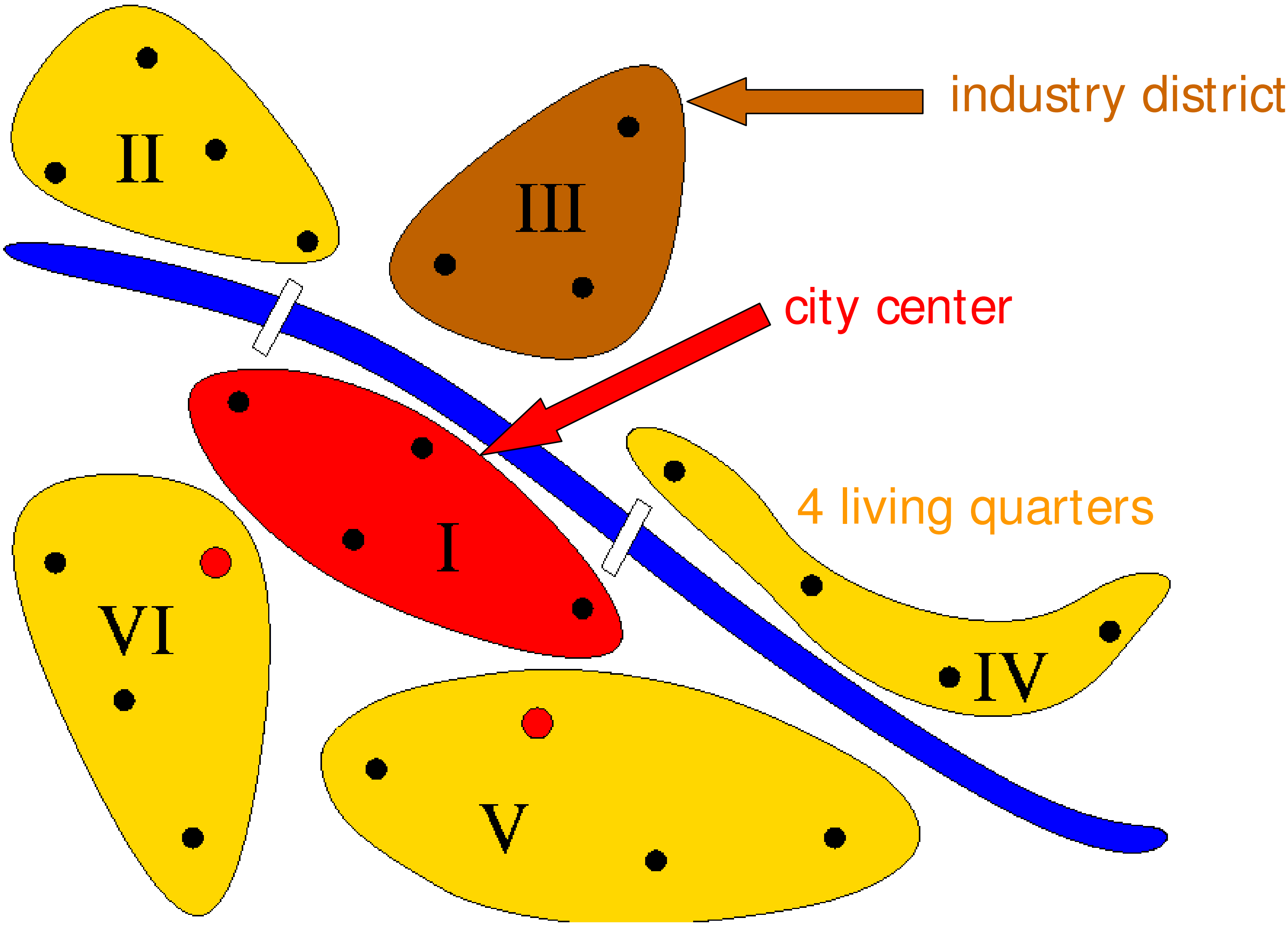
Partners

Project	Funding	Partner	Product
VS-OPT	bmb+f	ivu, BVG, SIEMENS	MICROBUS
DS-OPT	bmb+f	ivu, BVG	MICROBUS
IS-OPT	bmb+f	ivu, RVV, mdv	MICROBUS
RS-OPT	LBW	ivu	MICROBUS DIVA
Telebus	Berlin Senatsverwaltung für Wissenschaft, Forschung und Kultur		
LPP	Deutsche Forschungsgemeinschaft DFG	ivu, BVG, POTSDAM	
OPTRA	bmb+f	TU berlin, TU berlin WIP	

A HARD Question

What is a „good“ public transportation network?

Network Planning:
A didactical example city



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Origin/ Destination Matrix for the didactical example

	I	II	III	IV	V	VI
I	1500	0	2000	0	1000	500
II	500	0	3000	0	0	500
III	500	0	0	0	0	500
IV	1000	0	3000	0	500	500
V	2000	0	2000	0	500	500
VI	1000	0	1000	0	500	500

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A real Origin/ Destination-Matrix: Potsdam

Potsdam

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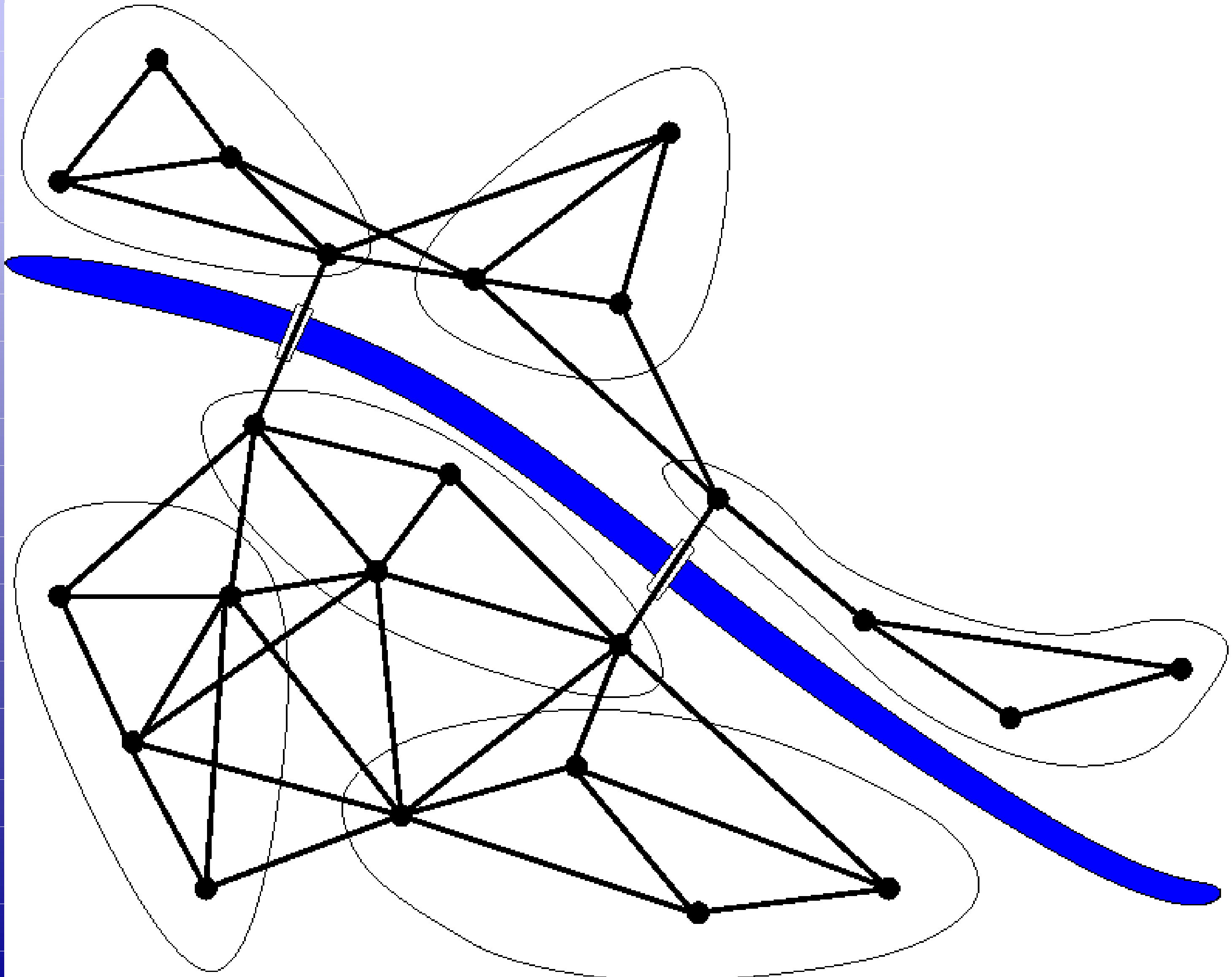
Network Planning: available streets/ tracks



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MIP Model for Network Planning

Variables: $y_p \in \mathbf{R}_+$ passenger flow on path $p \in P_{st}$

$z_a \in \{0,1\}$ use track/street a

$$\min \sum_a \gamma_a z_a + \sum_p \tau_p y_p$$

getting the data
adequate modelling

$$s.t. \quad \sum_{p \in P_{st}} y_p = d_{st} \qquad \forall s,t$$ transport all passengers

$$\sum_{p: a \in p} y_p \le u_a z_a \qquad \forall a$$ capacity constraints

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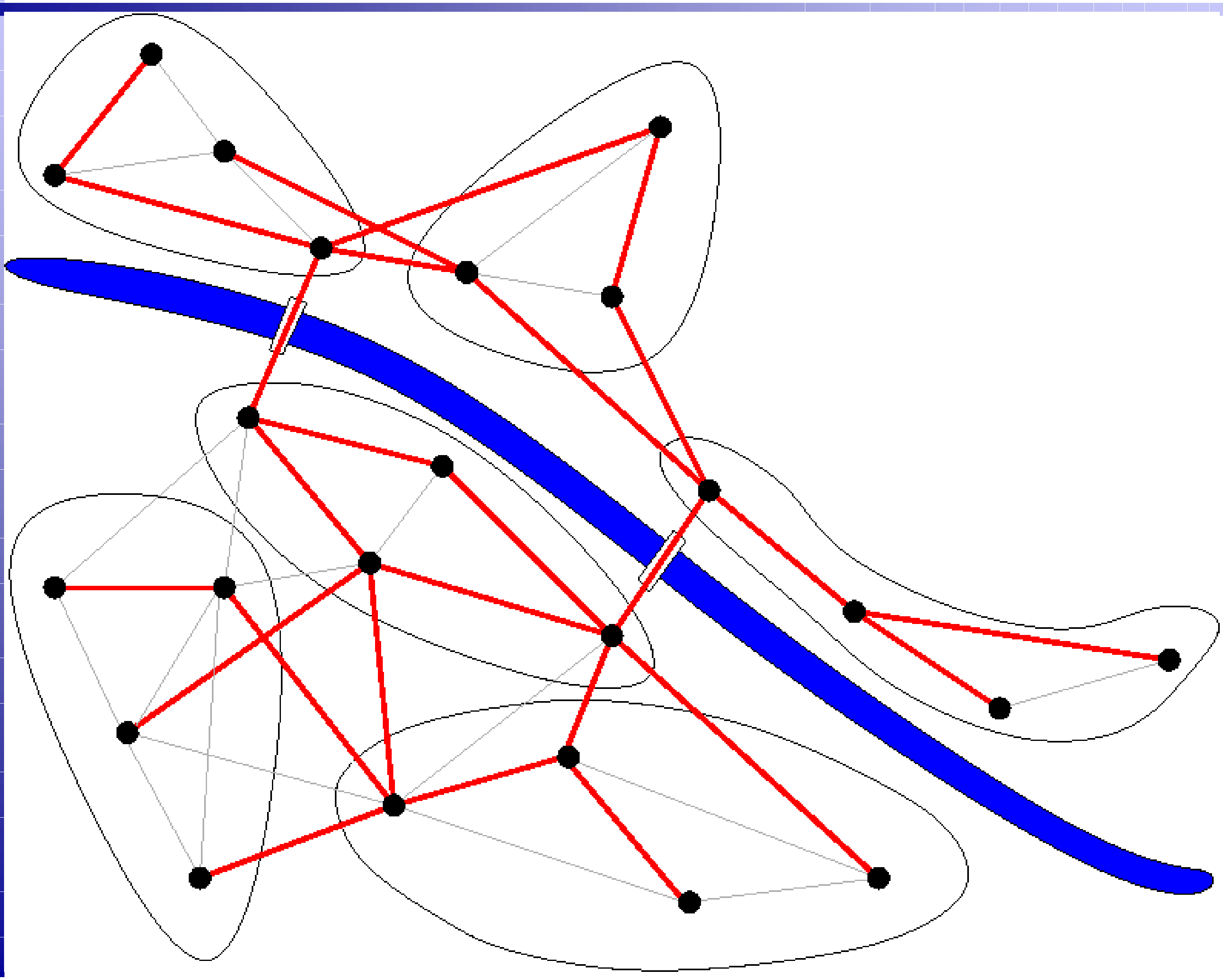
Network Planning: selected network of streets and tracks



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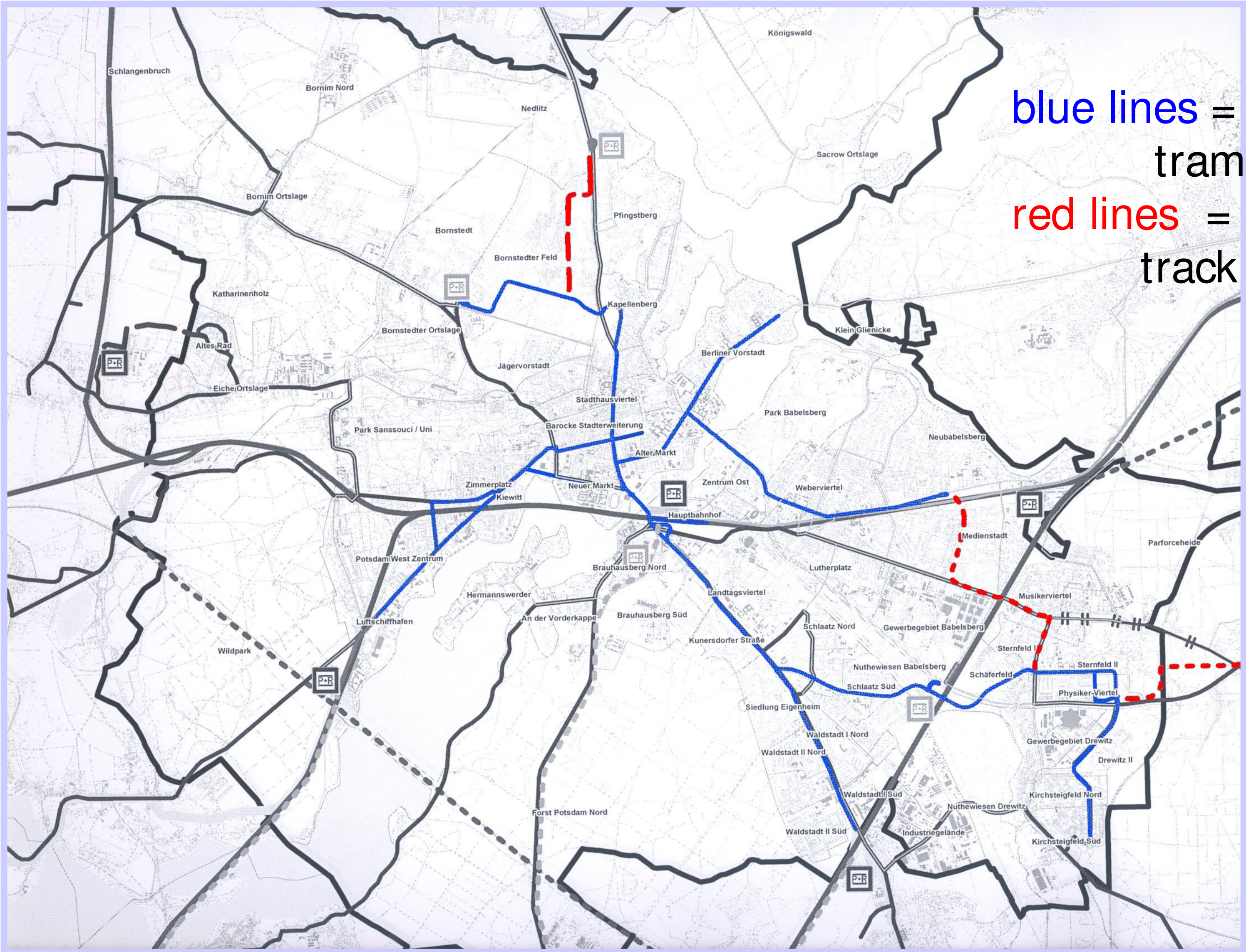
Network Planning: The Potsdam Tram Network



blue lines = existing tram tracks

red lines = suggested track extensions

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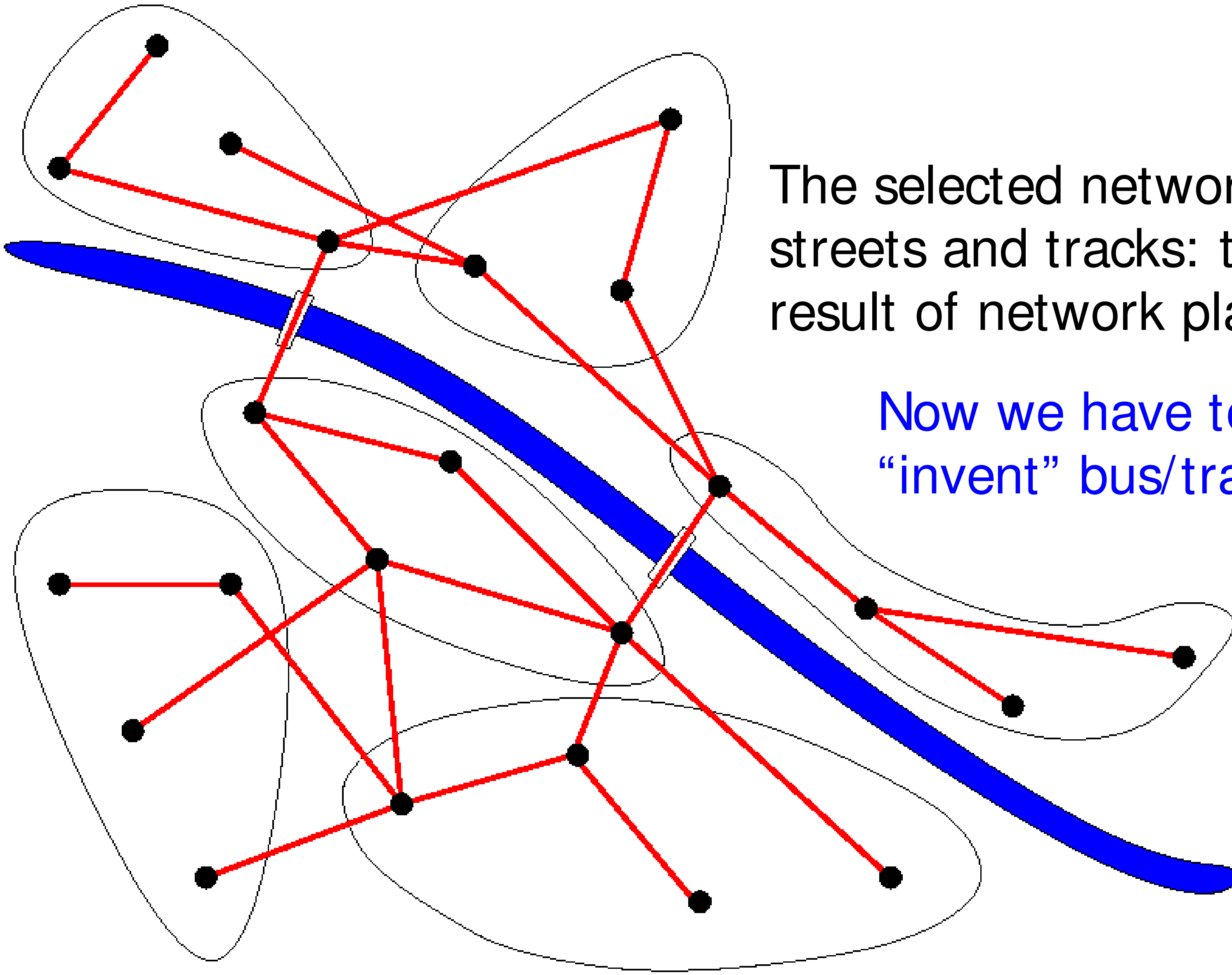
Line Planning:
our didactical example city



The selected network of streets and tracks: the result of network planning

Now we have to "invent" bus/tram lines

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MIP Model for Line Planning

Variables:

$y_p \in \mathbf{R}_+$ passenger flow on path $p \in P_{st}$

$x_\ell \in \{0,1\}$ choose line ℓ

$f_\ell \in \mathbf{R}_+$ frequency of line ℓ

huge number of variables

$$\min \sum_\ell (C_\ell x_\ell + c_\ell f_\ell) + \sum_p \tau_p y_p$$

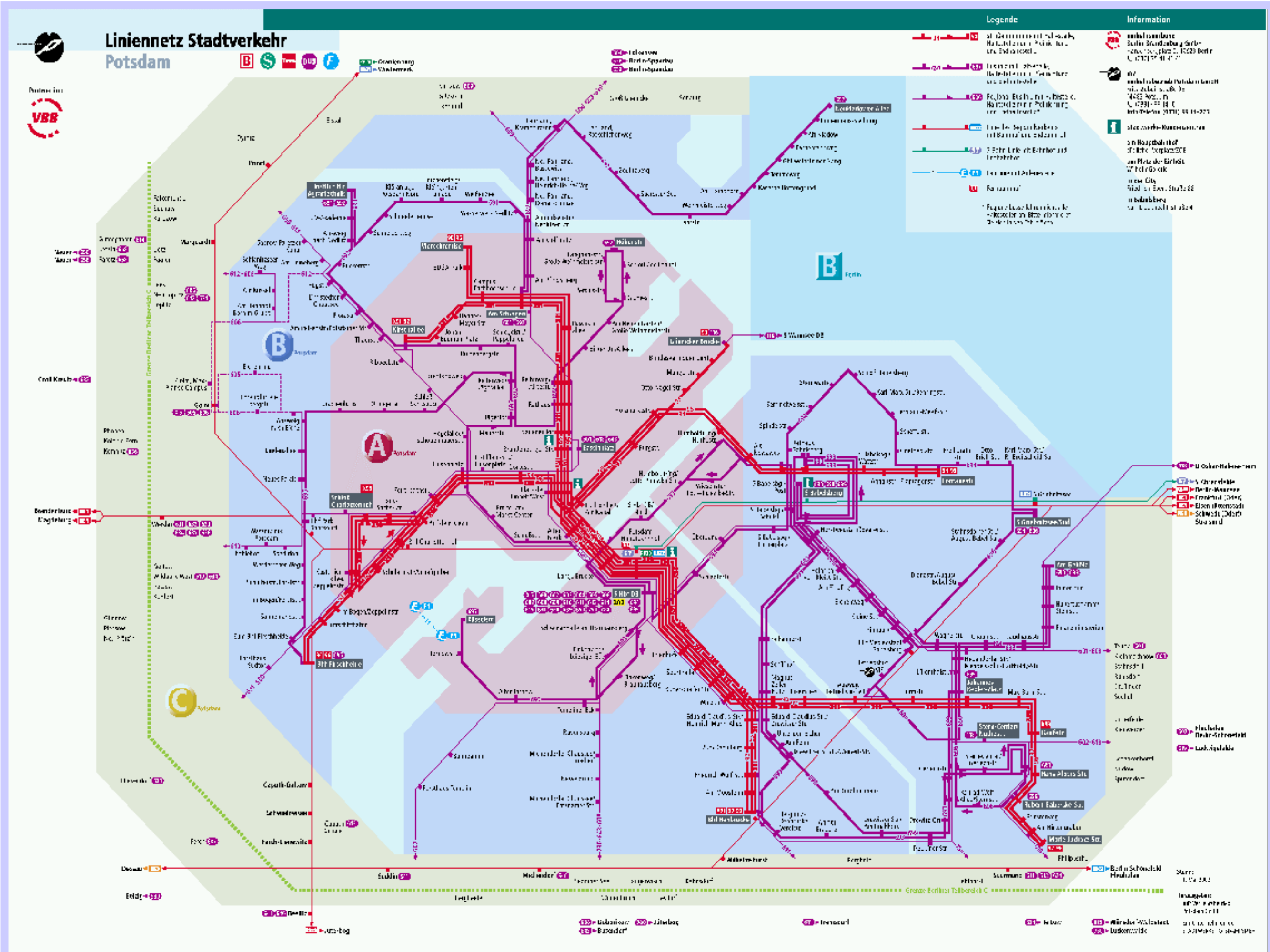
$$s.t. \quad \sum_{p \in P_{st}} y_p = d_{st} \qquad \forall s,t \qquad \text{transport all passengers}$$

$$\sum_{p: a \in p} y_p \le \sum_{\ell : a \in \ell} \kappa_\ell f_\ell \qquad \forall a \qquad \text{capacity constraints}$$

$$f_\ell \le F x_\ell \qquad \forall \ell \qquad \text{frequency bounds}$$

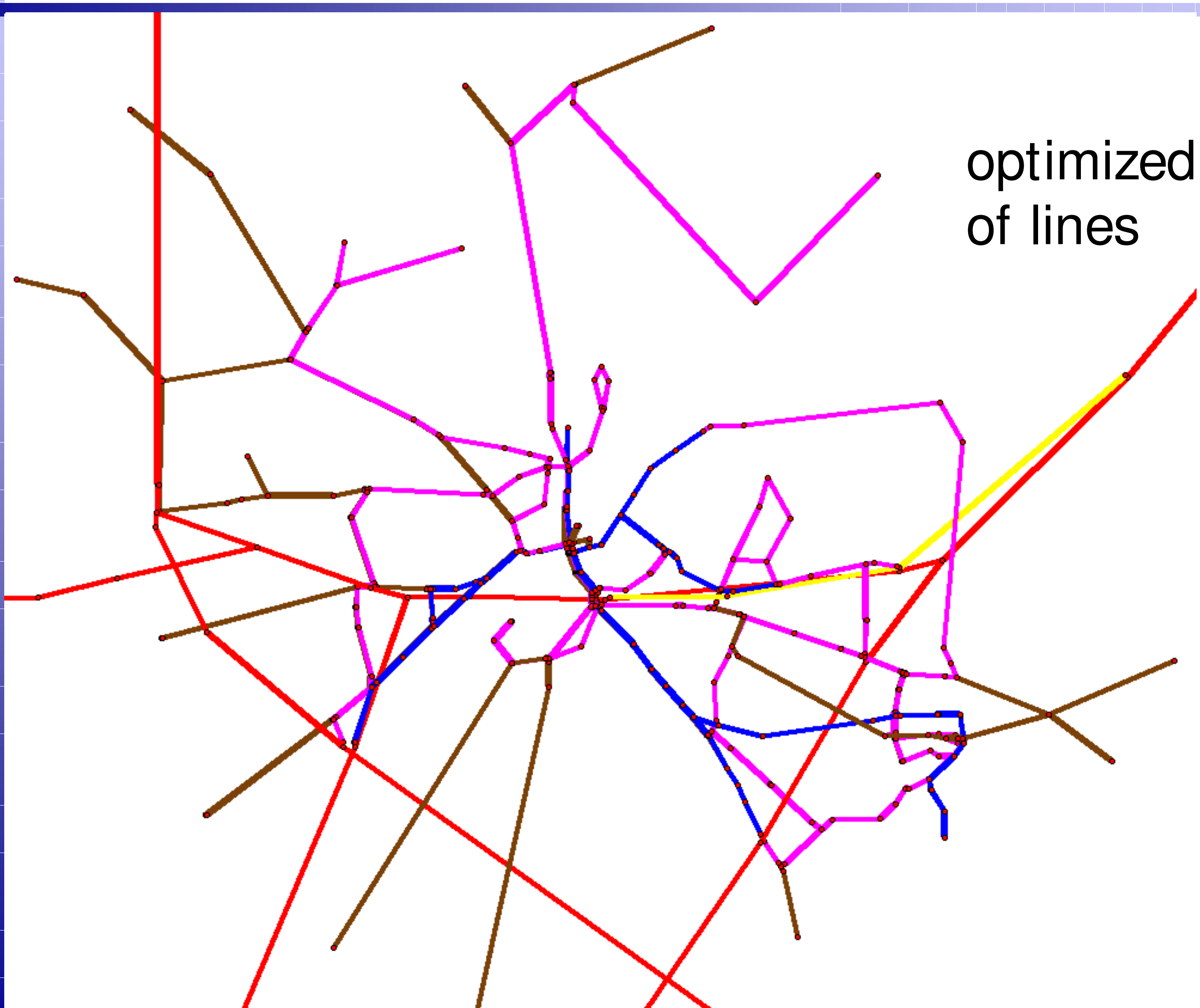
$$\ldots \qquad \text{other linear constraints}$$

The currently existing Potsdam Network of Lines



- bus
- tram
- S-Bahn
- regional train

Network of all Public Transportation Lines in Potsdam



optimized system of lines

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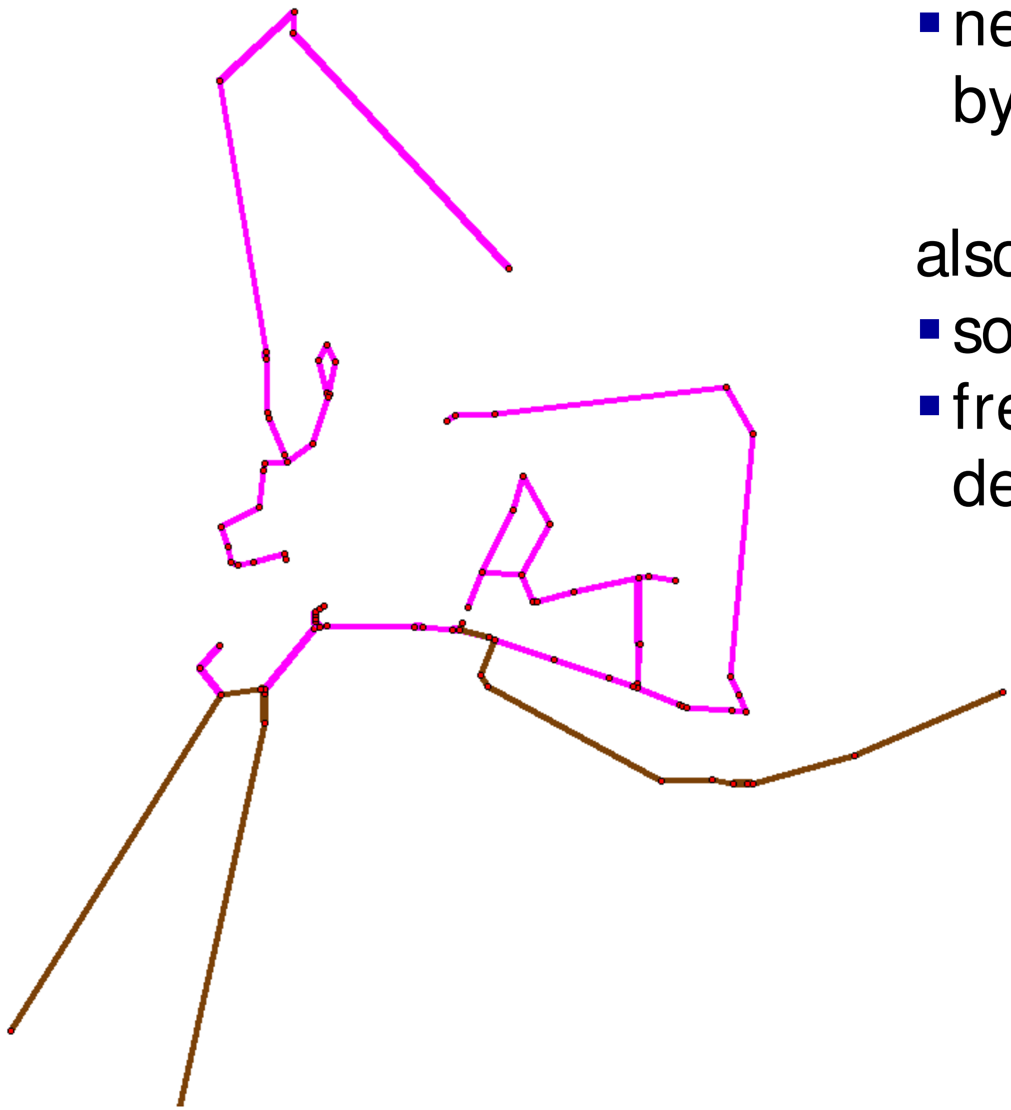
New Lines in Potsdam



- new lines suggested by optimization

also (but not drawn):

- some lines removed
- frequencies of lines determined

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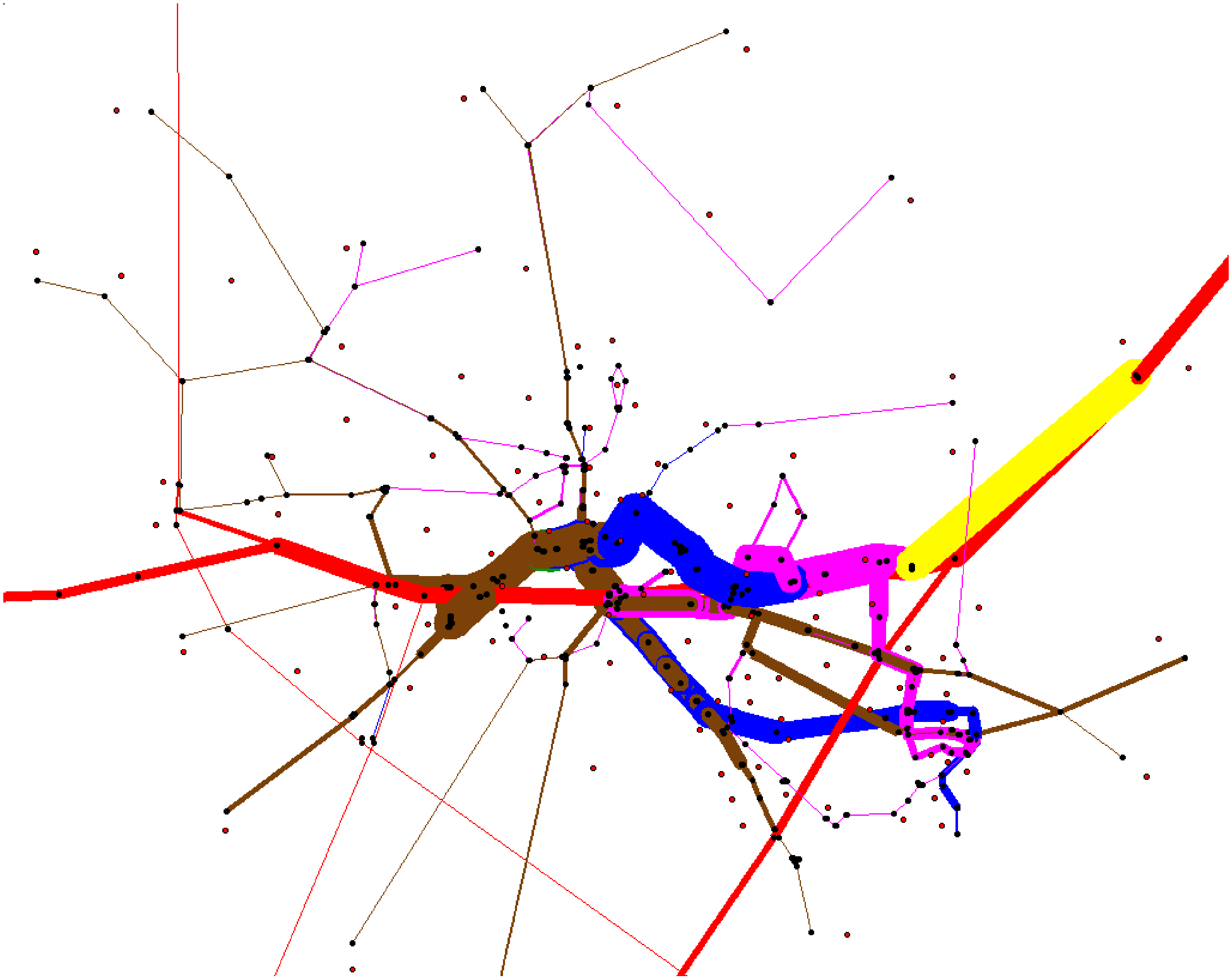
Passenger Flow in the new Potsdam Network of Lines



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Planning prices and frequencies

- Ansatz
  - „Controlling“ demand via prices and travel times
  - Price system = Individual price + ???
  - Maximize profit
  - Electronic Ticketing
- Status
  - Research project
  - Data?
  - Mathematical models ?
  - Giant amount of literature on topics of questionable value for practice (versions of local elasticities)

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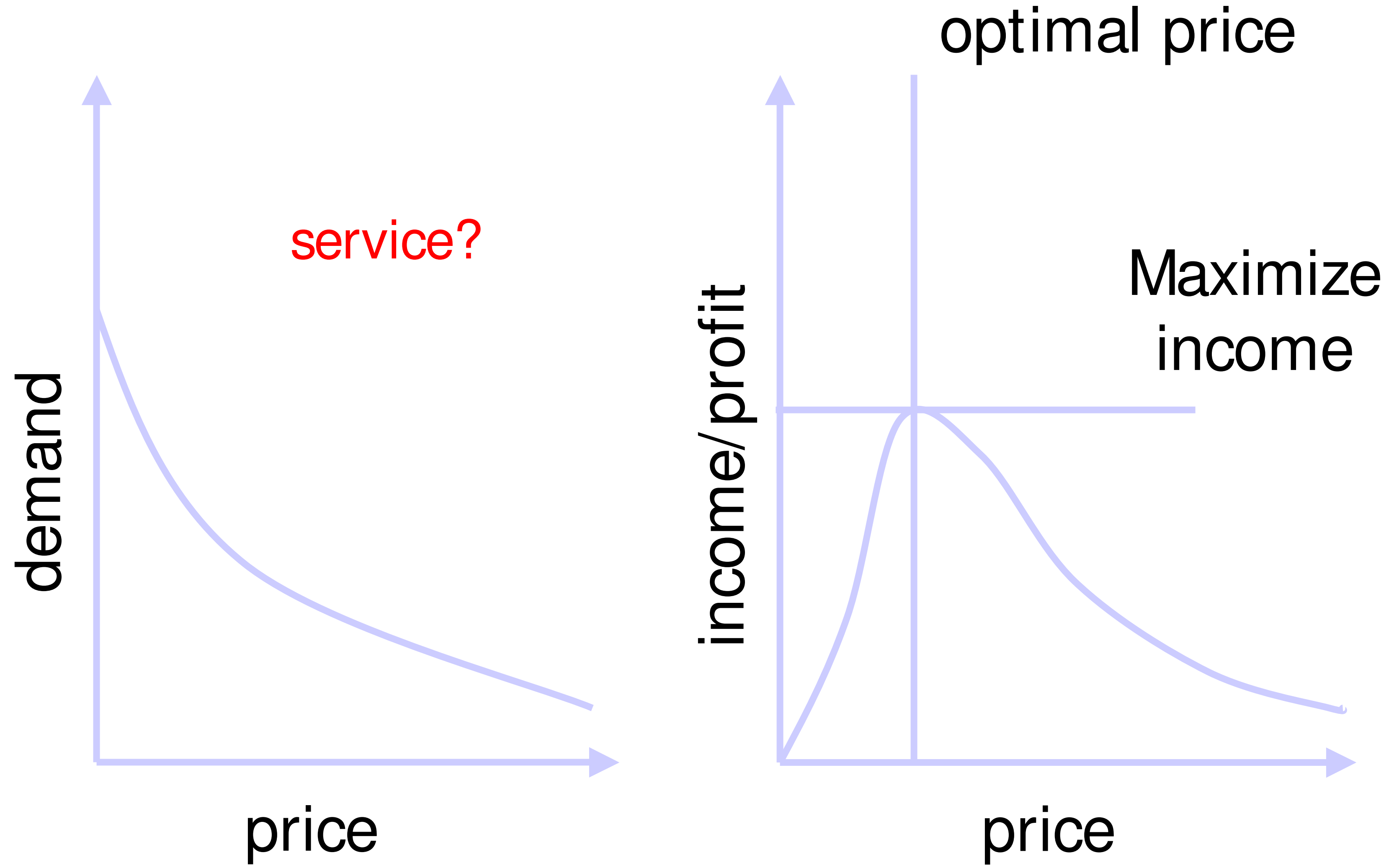
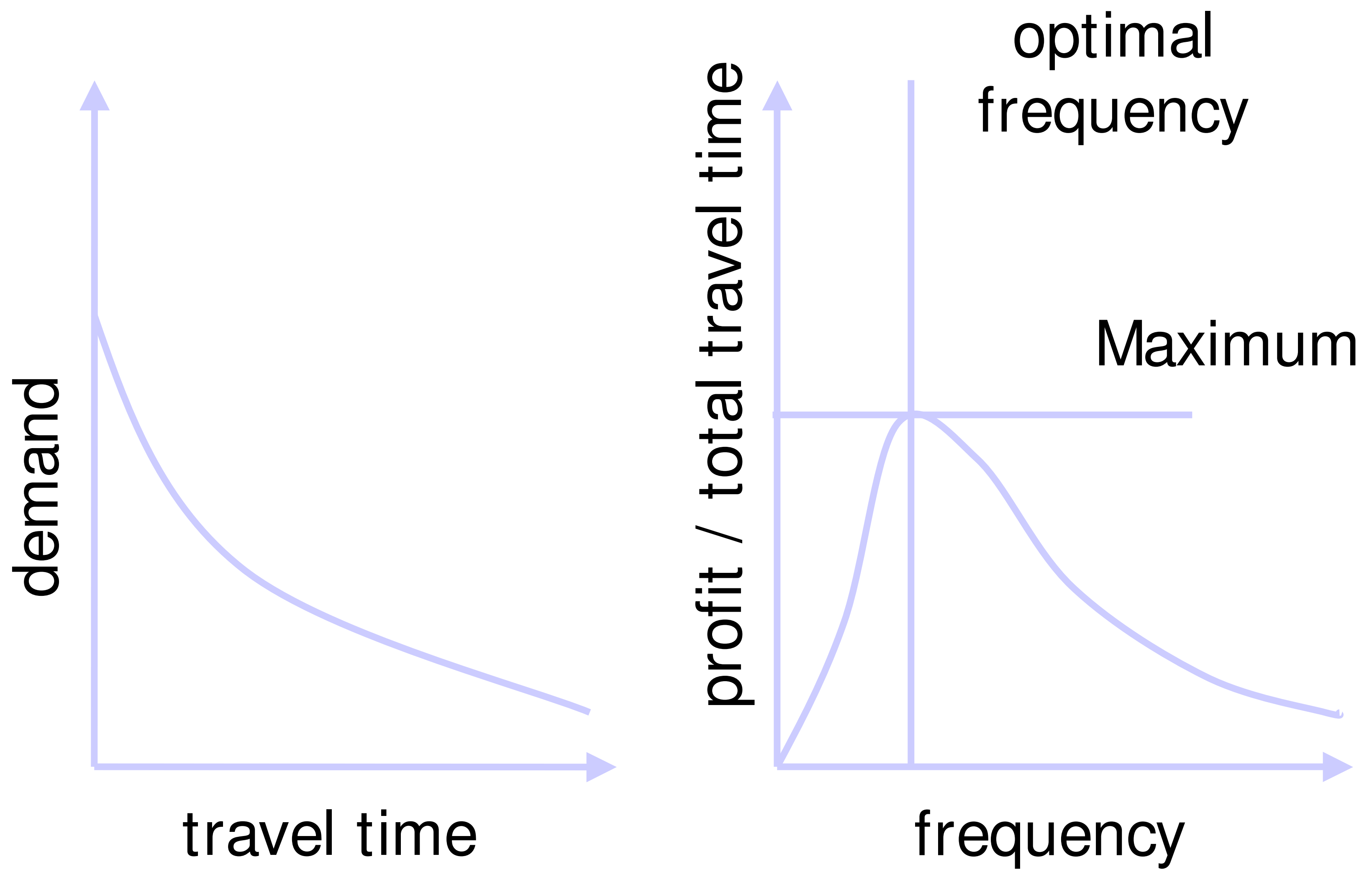
Planning prices



Planning frequencies & synchronized timetables



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Vehicle Scheduling

VS-OPT

a code developed at ZIB,
maintained and distributed by spin-off company

LBW GbR (Löbel, Borndörfer & Weider)

Mathematical Model and Algorithmic Approach:

Multicommodity Flow model solved by
Lagrangean relaxation and dynamic column generation

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IP Model for Vehicle Scheduling

$$\min \sum_{d \in D} \sum_{ij \in A^d} c_{ij}^d x_{ij}^d$$

$$\begin{array}{rcll} \sum_{d \in D} \sum_{tj \in A^d} x_{tj}^d & = & 1 & \forall t \in T \quad \text{(Flow Requ.)} \\ \sum_{d \in D} \sum_{tj \in A^d} x_{tj}^d - \sum_{d \in D} \sum_{it \in A^d} x_{it}^d & = & 0 & \forall t \in T, d \in D \quad \text{(Flow Cons.)} \\ \sum_{dt \in A^d} x_{dt}^d & \leq & \kappa_d & \forall d \in D \quad \text{(Capacities)} \\ x & \in & \mathbf{Z}_+^A & \quad \text{(Integrality)} \end{array}$$

- D – Depots
- T – Timetabled Trips

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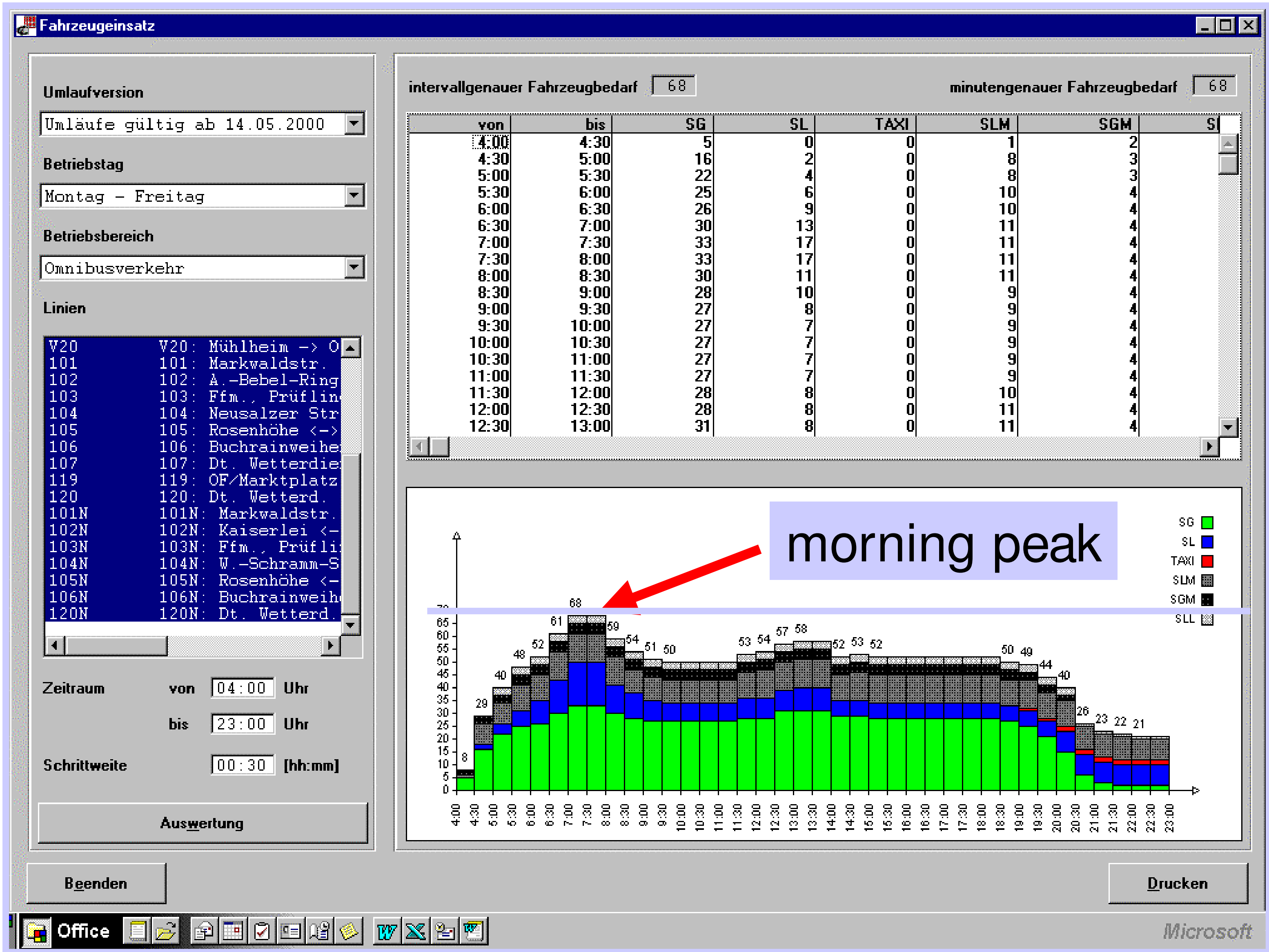
vehicle utilization



von	bis	SG	SL	TAXI	SLM	SGM
4:00	4:30	5	0	0	1	2
4:30	5:00	16	2	0	8	3
5:00	5:30	22	4	0	8	3
5:30	6:00	25	6	0	10	4
6:00	6:30	26	9	0	10	4
6:30	7:00	30	13	0	11	4
7:00	7:30	33	17	0	11	4
7:30	8:00	33	17	0	11	4
8:00	8:30	30	11	0	11	4
8:30	9:00	28	10	0	9	4
9:00	9:30	27	8	0	9	4
9:30	10:00	27	7	0	9	4
10:00	10:30	27	7	0	9	4
10:30	11:00	27	7	0	9	4
11:00	11:30	27	7	0	9	4
11:30	12:00	28	8	0	10	4
12:00	12:30	28	8	0	11	4
12:30	13:00	31	8	0	11	4

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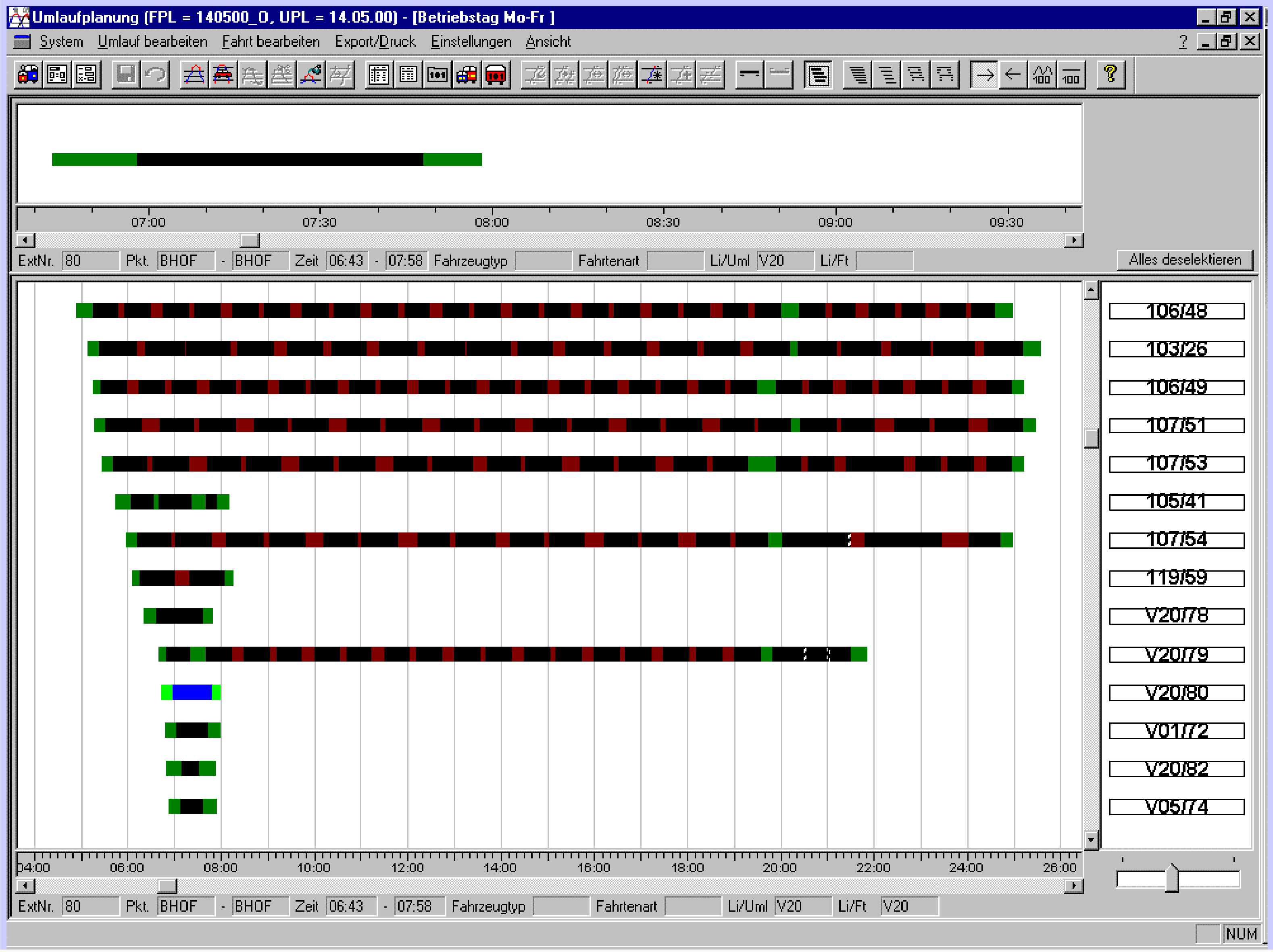
several vehicle schedules



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VS-OPT employed in Berlin (BVG)

- **Real Really Large-Scale Optimization**
  - **28.000 scheduled trips** (worldwide largest known instance)
  - **100 million degrees of freedom** (of 400 mio possible)
  - **optimization of a whole transportation company**
  - **no heuristic simplifications**
  - **„Lagrangean Pricing“-technique**
- **Mathematical quality guarantee**
  - **fleet minimal solution**
  - **at most 1% off minimal cost**
- **Added value**
  - **Scenario analysis**
  - **Sensitivity analysis**
  - **Stability, Fixing, Freezing, Outsourcing, etc.**
- **Running time**
  - **Minutes on standard PCs**

In other words, we have a multicommodity flow problem with 100 million integer variables and can solve it in a few minutes on a laptop

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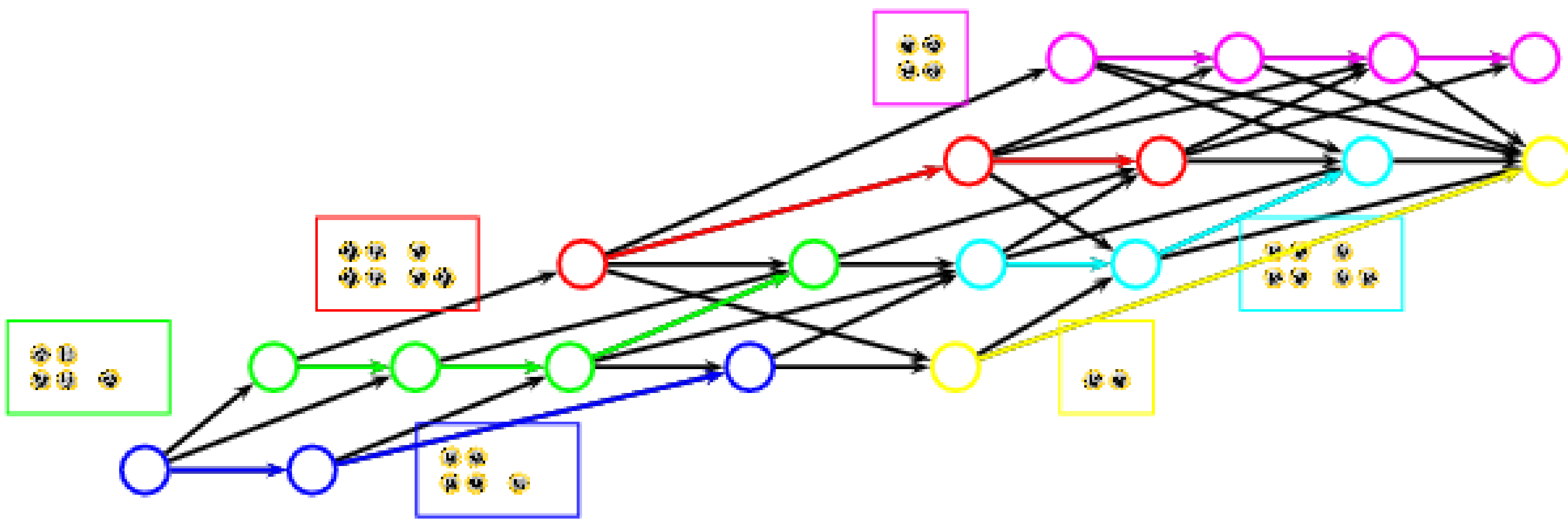
Mathematical duty scheduling DS-OPT



- Types of duties
  - Investigating whole paths
  - supplementary duty elements
- 2.000 duty elements:
  - 50.000 nodes
  - 280.000 links (edges)
  - ∞ duties

ZIB
Martin Grötschel

IP Model for Duty Scheduling

$$\min \sum_{j \in J} c_j x_j + \sum_{b \in B} p_b^+ s_b^+ + \sum_{b \in B} p_b^- s_b^-$$

$$\begin{aligned} \sum_{j \in J} a_{ij} x_j &= 1 \quad \forall i \in I && \text{(Tasks)} \\ \sum_{b \in B} d_{bj} x_j + s_b^+ - s_b^- &= d_b \quad \forall b \in B && \text{(Mix)} \\ x &\in \{0,1\}^J && \text{(Integrality)} \end{aligned}$$

- I – Tasks
- J – Duties
- B – Mix (Base) Constraints

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DS-OPT

- Lagrangean Shortest Path Pricing
  - Linear Resource Constraints
  - Resource Constrained Shortest Path Model
  - Lagrange Relaxation of Linear Constraints
    - Shortest Path Lower Bound
- LP Heuristic
  - Dual Ascent
  - Box Step
- Branch-and-Generate Heuristic
  - Fixing on Links

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DS-OPT Computational Results

Name	KS 1	KS 2	KS 3	TR	MI (I)	M (S)	WI	BN
Areas	4	2	2	1	4	1	1	1
Duty Types	3	5	3	3	4	3	3	4
Capacities	5	5	3				1	
Averages				2				
Tasks	4,345	4,345	4,345	2,867	1,317	2,436	4,453	3,014
Nodes	142.261	116.569	91.365	50.979	160.882	42.724	66.602	71.331
Arcs	1,2 Mio	2 Mio	2 Mio	851.160	3 Mio	1,8 Mio	4 Mio	977.701
Duties	114	114	117	103	87	223	252	361
Time	1 d	1 d	1 d	0,5 d	4 h	1 d	0,5 d	0,5 d

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Some Users

VS-OPT	DS-OPT
ATC/ Terni (I)	ATC/ Terni (I)
Athen (U) (GR)	
Berlin (D)	Berlin (D)
Bonn (D)	Bonn (D)
Connex (D)	Connex (D)
DB Regio (D)	DB Regio (D)
Geilenkirchen (D)	
	Ennepetal (D)
Genua (I)	Genua (I)
Mailand (U) (I)	Mailand (U) (I)
München (S) (D)	München (S) (D)
Norgesbus (N)	Norgesbus (N)
Rhein-Neckar (S) (D)	Rhein-Neckar (S) (D)
Wiesbaden (D)	Wiesbaden (D)

Optimization Results

	Vehicle Scheduling			Duty Scheduling		
BVG	manual	VS-OPT		manual	DS-OPT	
Bus	195	157	19,5%	n.a.	=	0,0%
SWB	manual	VS-OPT		manual	DS-OPT	
Bus	201	196	2,5%	280	268	4,3%
Tram	n.a.	=	0,0%	120	117	2,5%
VER	manual	VS-OPT		manual	DS-OPT	
Bus	n.a.	-2	n.a.	155	141	9,1%
ESWE	manual	VS-OPT		manual	DS-OPT	
Bus	*		*	280	40	14,3%

Auf Sparkurs zum Ziel

Systematisierter Einsatz

Die neuen Optimierungsmethoden, die die BVG jetzt nach und nach nutzen will, stammen vom Konrad-Zuse-Zentrum für Informationstechnik und garantieren nach Roß' Angaben Einsparungen von maximal 100 Millionen Mark im Jahr. „Sie sind nötig, um unser Angebot in dieser schweren Lage stabilisieren und dem Einsparungsdruck überhaupt standhalten zu können."

WISSENSCHAFT UND PRAXIS
Rheinischer Merkur
Nummer 39 · 26. September 1997
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INFORMATIK / *Ein Lehrbeispiel, wie sich Mathematik und Wirtschaft ergänzen*

Auf Sparkurs zum Ziel

Das Berliner Busnetz kostet jährlich Millionen. Mit Hilfe moderner Software könnte man auf gewaltige Zuschüsse verzichten.

VASCO ALEXANDER SCHMIDT

Die Mathematik ist die Wissenschaft abstrakter Probleme. Deshalb erscheint sie so oft als weltabgewandte Spielerei. [illegible]

Stadt aushängen, auf Knopfdruck und ohne Umwege über eine Druckerei im eigenen Haus produzieren. Nach und nach wurden diese Werkzeuge eingeführt. Das jetzt installierte Optimierungsmodul für die Umlaufplanung von Straßenbahnen und Bussen ist der bisher bedeutendste Schritt der Zusammenarbeit.

Komfortable Hilfe

Zwar werden in Deutschland für die Verkehrsplanung meist schon Computer eingesetzt; diese aber unterstützen die Planer oft nur als ein einfaches, wenn auch komfortables Hilfsmittel. Andere Verkehrsunternehmen, etwa die Hamburger Hochbahn AG, setzen Com- [illegible]

man sie noch nicht einmal vollständig im Computer speichern könnte", verrät Andreas Löbel, Wissenschaftlicher Mitarbeiter von Martin Grötschel. „Pro Spalte gibt es aber nur drei Einträge, die von Null verschieden sind." Das bedeutet, daß sich die Matrix stark vereinfachen läßt. Und genau diese Eigenschaft machen sich die Mathematiker zunutze. So versucht ihr Algorithmus zuerst mit einem Teil der Matrix zu operieren. Findet er für diesen kleinen Teil eine Lösung, so vergrößert er nach und nach das Problem, bis er eine Lösung für die gesamte Matrix gefunden hat.

Pfiffige Programme

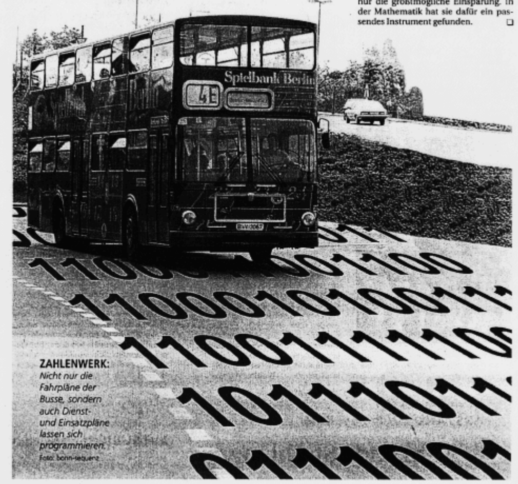
Von der Mathematik spüren die Planer bei der BVG wenig. Nicht einmal Großrechner werden gebraucht – so pfiffig wurde das System programmiert. Je nach Teilproblem dauert die Bearbeitung wenige Stunden oder sogar nur Minuten. „Das System wurde gut aufgenommen, da die Planer in kürzester Zeit verschiedene Szenarien testen und vergleichen können", berichtet Uwe Strubbe, der als Projektleiter bei der IVU für die Entwicklung des fertigen Softwareprodukts zuständig ist.

Auch Martin Grötschel betont den Nutzen für den Planer mehr als das Einsparungspotential: „Wir geben den Leuten Hilfsmittel in die Hand, die Kosten zu sparen: Ob dabei am Ende etwas eingespart oder der Service kostenneutral verbessert wird, ist nicht unsere, sondern eine politische Frage."

Die Politik freilich erwartet zur Zeit nur die größtmögliche Einsparung. In der Mathematik hat sie dafür ein passendes Instrument gefunden.

Systematisierter Einsatz

Die neuen Optimierungsmethoden, die die BVG jetzt nach und nach nutzen will, stammen vom Konrad-Zuse-Zentrum für Informationstechnik und garantieren nach Roß' Angaben Einsparungen von maximal 100 Millionen Mark im Jahr. „Sie sind nötig, um unser Angebot in dieser schweren Lage stabilisieren und dem Einsparungsdruck überhaupt standhalten zu können." [illegible]



ZAHLENWERK: *Nicht nur die Fahrpläne der Busse, sondern auch Dienst- und Einsatzpläne lassen sich programmieren.* Foto: bonn-sequenz

RHEINISCHER MERKUR
POLITISCH.KOMPETENT.ANDERS.

Artikel erschienen am 26. Sep 1997

The Psychology of Improvement

- Company goals
- Manager goals
- Dispatcher goals

- The 15% rule

Martin Grötschel

IP Model for Integrated Scheduling

$$\min \sum_{d\in D}\sum_{ij\in A^d} c_{ij}^d x_{ij}^d + \sum_{j\in J} c_j y_j$$

$$\sum_{d\in D}\sum_{tj\in A^d} x_{tj}^d = 1 \quad \forall t\in T \quad \text{(Trips)}$$

$$\sum_{tj\in A^d} x_{tj}^d - \sum_{it\in A^d} x_{it}^d = 0 \quad \forall t\in T, d\in D \quad \text{(V-Flow)}$$

$$\sum_{dt\in A^d} x_{dt}^d \le \kappa_d \quad \forall d\in D \quad \text{(V-Cap)}$$

$$\sum_{j\in J} a_{ij} y_j = 1 \quad \forall i\in t\in T \quad \text{(Tasks)}$$

$$\sum_{d\in D}\sum_{tj\in A^d} x_{tj}^d - \sum_{j\in J} a_{ij} y_j = 0 \quad \forall i\in t\in H \quad \text{(Coupling)}$$

$$x_{it}^d, y_j \in \{0,1\} \quad \text{(Integrality)}$$

- T – Timetabled Trips   D – Depots
- H – Deadhead Trips   I – Tasks

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IS-OPT

- Lagrangean Relaxation on Coupling Constraints
  - Proximal Bundle Method
  - Approximate Solution of Vehicle and Duty Scheduling Components
- Branch-and-Generate Heuristic
  - Fixing Deadhead Trips

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Trassenbörse = track auctioning

European Union:

- Establish a rail traffic market
- open the market to competition
- Deregulate/Regulate this market

History of our project

Trassenbörse = track auctioning

What is the goal of the deregulation attempts?

General answer: More traffic at lower cost, better service

How do you measure?

Our answer: in terms of willingness to pay (Zahlungsbereitschaft)

What is the „good“ of this market?

Our answer: Fahrplantrasse

= timetabled dedicated track section

= use of railway infrastructure in time and space

= brief: “timetabled track”

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Public Transportation Summary

- Possible savings in public transport
- Can public transport break even?
- Where are the bottlenecks?
- What can OR do?
- Multi-modality considerations
- individual vs. public transport?

- What is a „good“ transportation system? (HARD question)

Martin Grötschel

Contents

ZIB Telecom Team

The Telecom Group

Andreas Bley

Andreas Eisenblätter

Martin Grötschel

Thorsten Koch

Arie Koster

Roland Wessäly

Adrian Zymolka

Associates

Manfred Brandt

Sven Krumke

Frank Lutz

Diana Poensgen

Jörg Rambau

Clyde Monma
(BellCore, ...)

Mechthild Opperud
(ZIB, Telenor)

Dimitris Alevras (ZIB, IBM)

Christoph Helmberg (Chemnitz)

ZIB Partners from Industry

Bell Communications Research

Telenor (Norwegian Telecom)

E-Plus (acquired by KPN in 01/2002)

DFN-Verein

Bosch Telekom (bought by ?)

Siemens

Austria Telekom (Italia Telecom?)

T-Systems Nova (T-Systems, Deutsche Telekom)

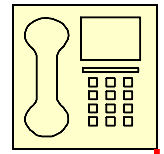
KPN

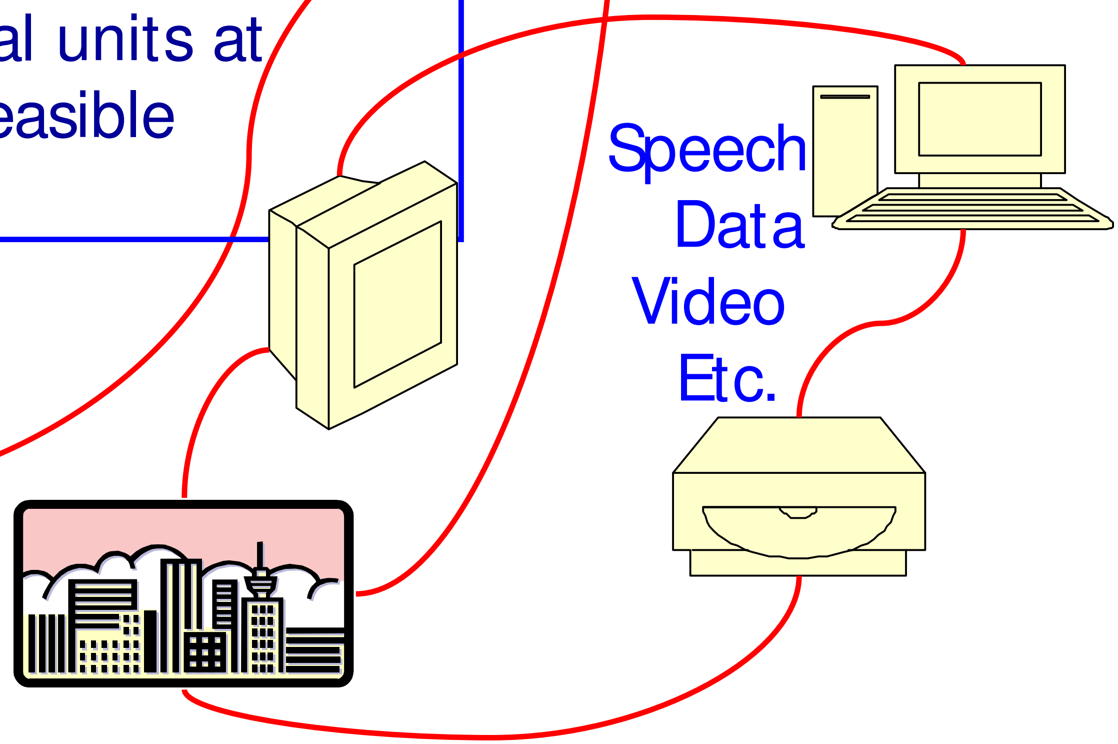
Telecel-Vodafone

Atesio (ZIB spin-off company)

What is the Telecom Problem?

Design excellent technical devices and a robust network that survives all kinds of failures and organize the traffic such that high quality telecommunication between very many individual units at many locations is feasible at low cost!





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What is the Telecom Problem?

Design excellent technical devices and a robust network that survives all kinds of failures and organize the traffic such that high quality telecommunication between very many individual units at many locations is feasible at low cost!

This problem is too general to be solved in one step.

Approach in Practice:

- Decompose whenever possible
- Look at a hierarchy of problems
- Address the individual problems one by one
- Recompose to find a good global solution

Cell Phones, Mathematics, and OR

Designing mobile phones
- Task partitioning
- Chip design (VLSI)
- Component design

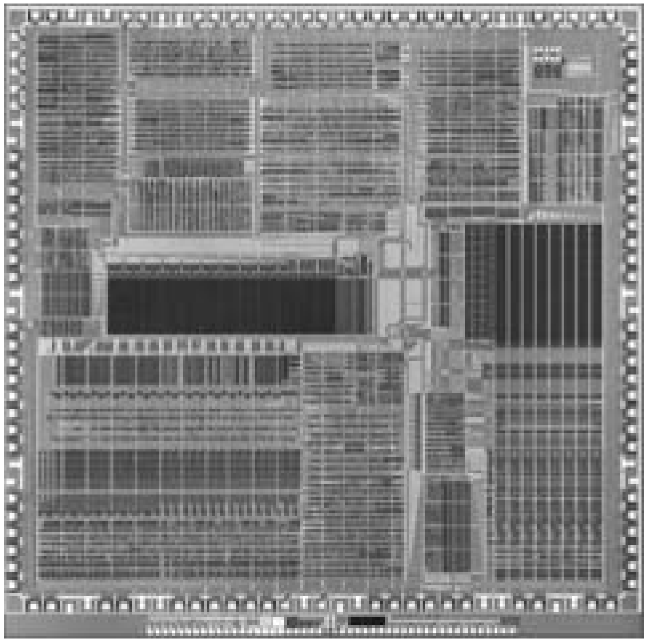
- Computational logic
- Combinatorial optimization
- Differential algebraic equations

Producing Mobile Phones
- Production facility layout
- Control of CNC machines
- Control of robots
- Lot sizing
- Scheduling
- Logistics

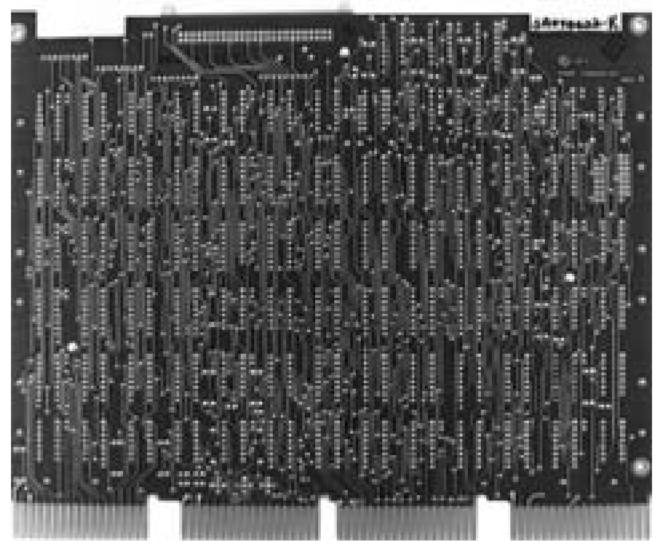
- Linear and integer programming
- Combinatorial optimization
- Ordinary differential equations

Marketing and Distributing Mobiles
- Financial mathematics
- Transportation optimization

Design and Production of ICs and PCBs



Integrated Circuit (IC)



Printed Circuit Board (PCB)

Problems: Logic Design, Physical Design

Correctness, Simulation, Placement of Components, Routing, Drilling,...

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Siemens Problem

printed circuit board da4

Fig. A8

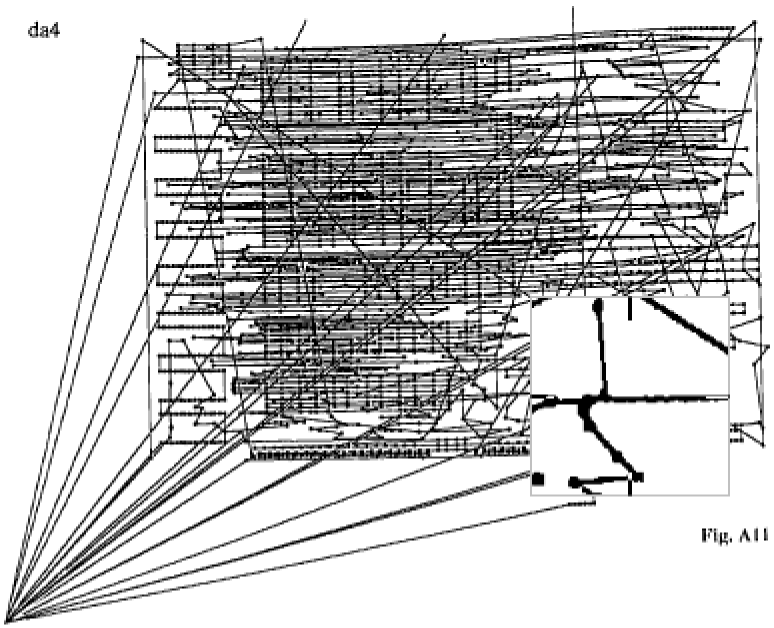

Fig. A11

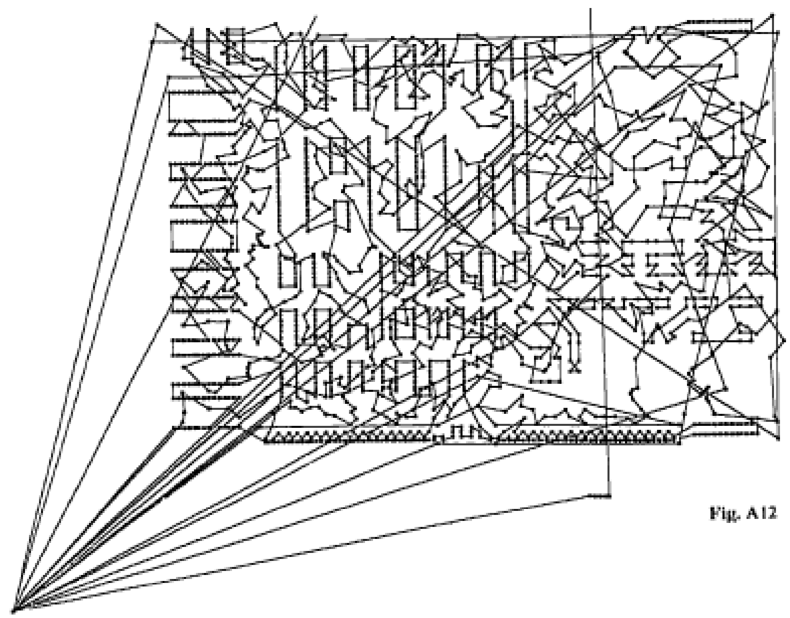

Fig. A12

before

after

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Network Design: Tasks to be solved Some Examples

- Locating the sites for antennas (TRXs) and base transceiver stations (BTSs)
- Assignment of frequencies to antennas
- Cryptography and error correcting encoding for wireless communication
- Clustering BTSs
- Locating base station controllers (BSCs)
- Connecting BTSs to BSCs

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Network Design: Tasks to be solved Some Examples (continued)

- Locating Mobile Switching Centers (MSCs)
- Clustering BSCs and Connecting BSCs to MSCs
- Designing the BSC network (BSS) and the MSC network (NSS or core network)
  - Topology of the network
  - Capacity of the links and components
  - Routing of the demand
  - Survivability in failure situations

Most of these problems turn out to be Combinatorial Optimization or Mixed Integer Programming Problems

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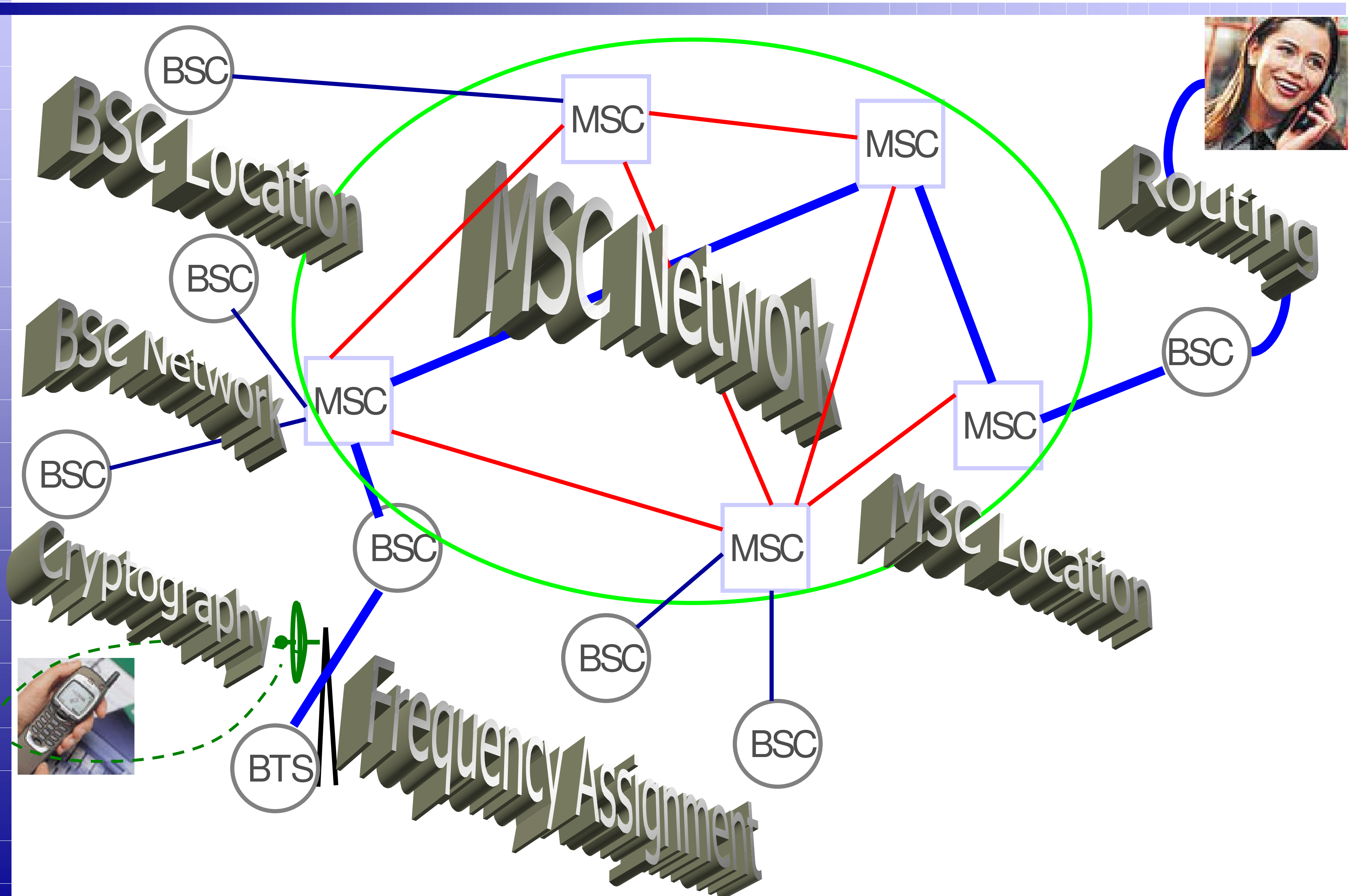
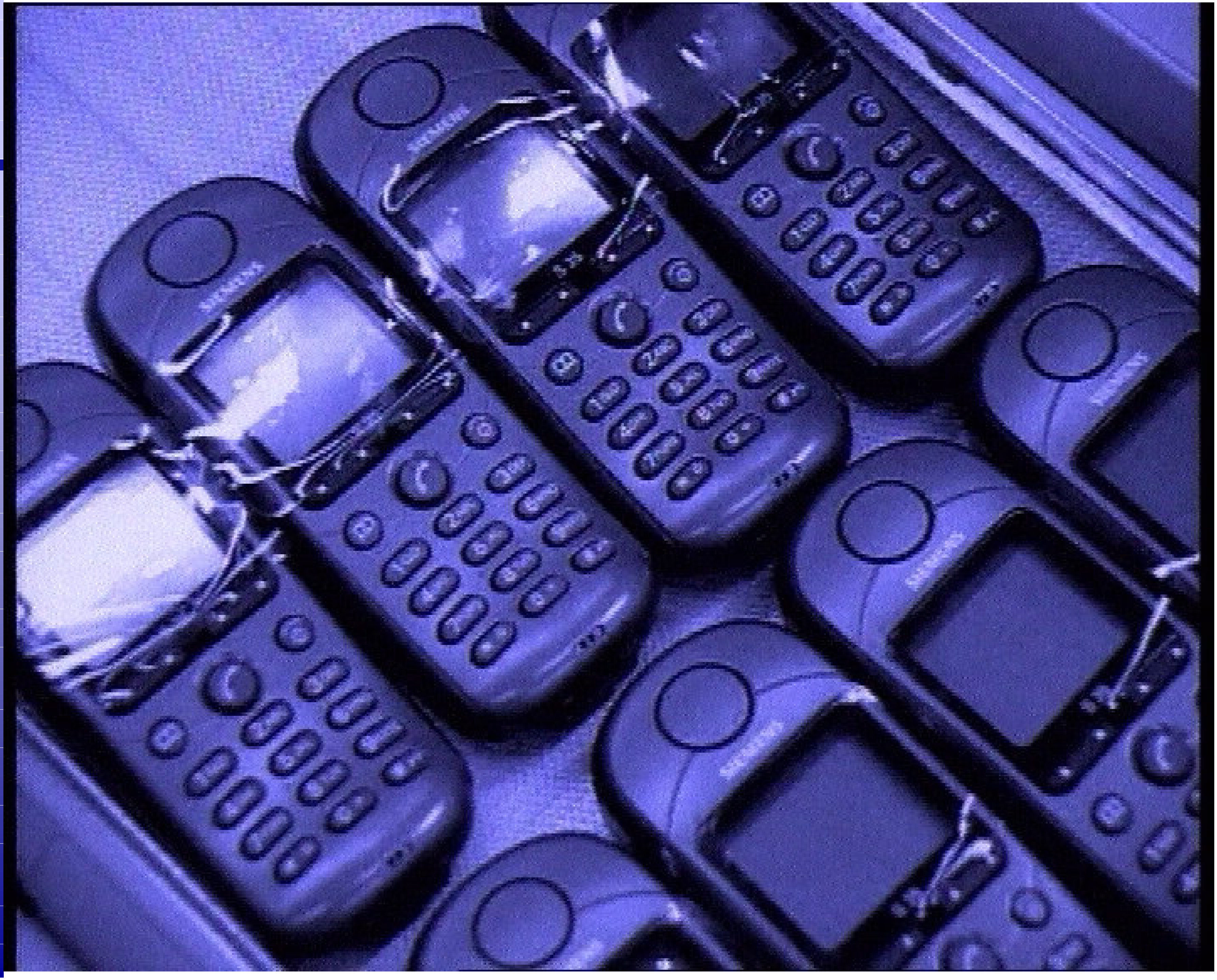
Connecting Mobiles: What´s up?



ZIB
Martin
Grötschel

FAP Film



Frequency Planning Problem

Find an assignment of frequencies to transmitters that satisfies

- all separation constraints
- all blocked channels requirements

and either

- avoids interference at all

or

- minimizes the (total/maximum) interference level

Minimum Interference Frequency Assignment Problem

Integer Linear Program:

$$\min \sum_{vw \in E^{co}} c_{vw}^{co} z_{vw}^{co} + \sum_{vw \in E^{ad}} c_{vw}^{ad} z_{vw}^{ad}$$

$$s.t. \quad \sum_{f \in F_v} x_{vf} = 1 \qquad \forall v \in V$$

$$x_{vf} + x_{wg} \leq 1 \qquad \forall vw \in E^{d}, |f-g| < d(vw)$$

$$x_{vf} + x_{wf} \leq 1 + z_{vw}^{co} \qquad \forall vw \in E^{co}, f \in F_v \cap F_w$$

$$x_{vf} + x_{wg} \leq 1 + z_{vw}^{ad} \qquad \forall vw \in E^{ad}, |f-g| = 1$$

$$x_{vf}, z_{vw}^{co}, z_{vw}^{ad} \in \{0,1\}$$

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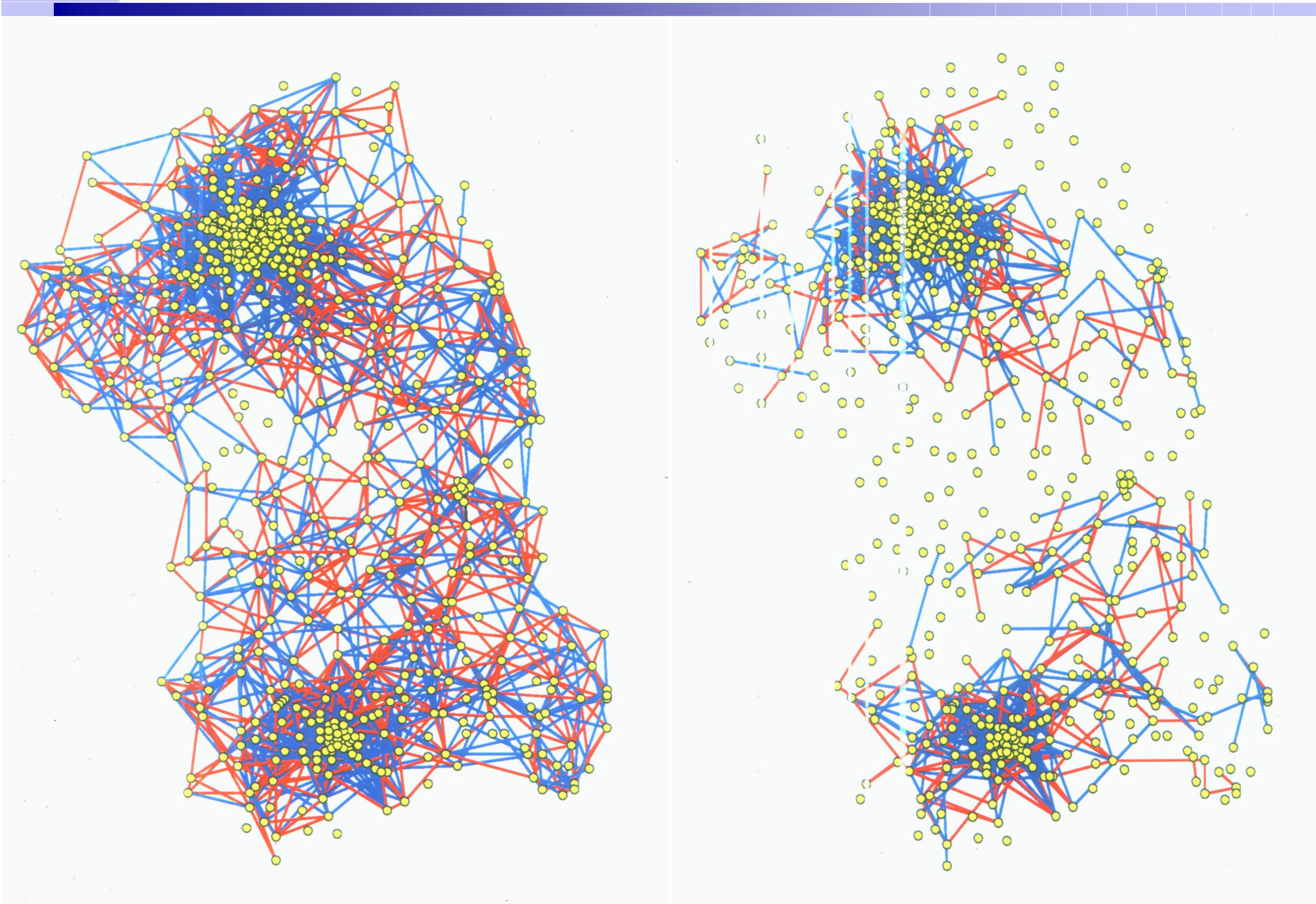
Region Berlin - Dresden



2877 carriers

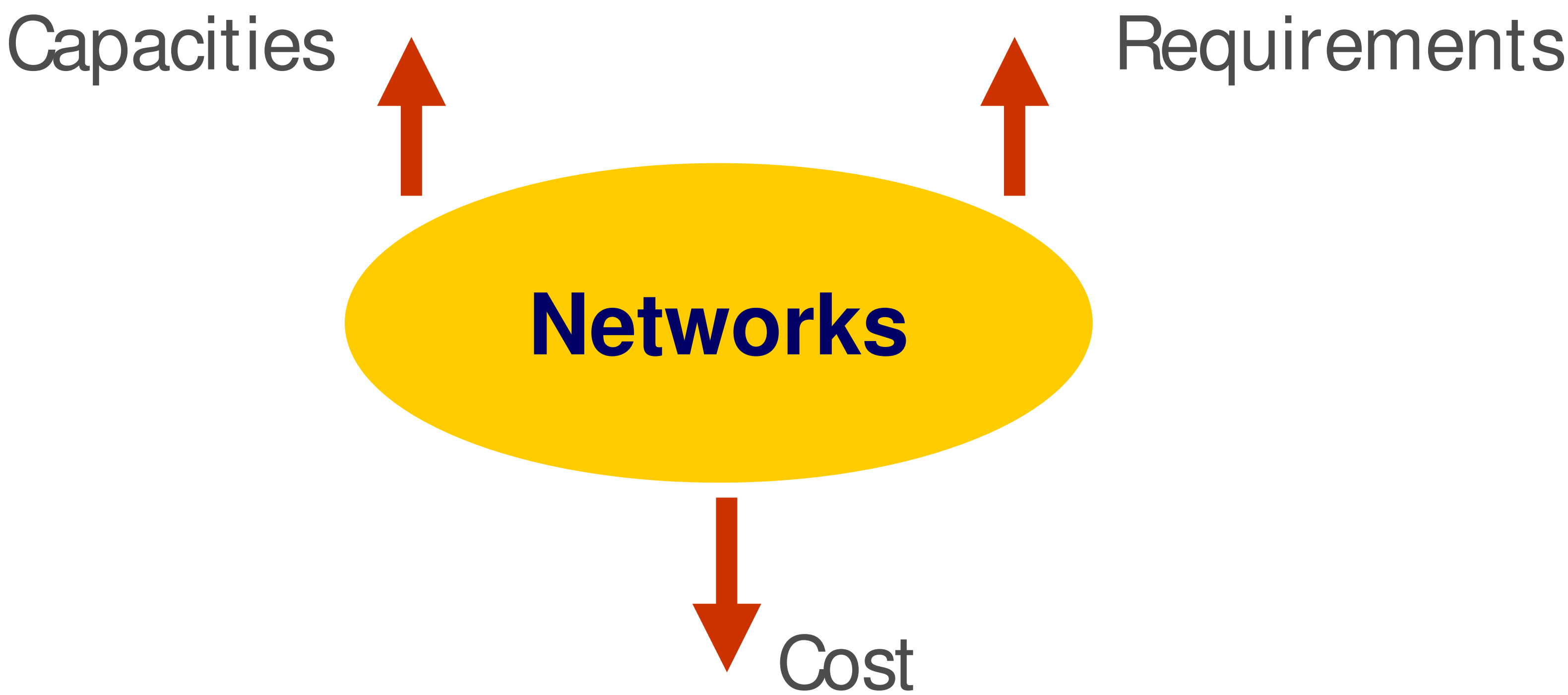
50 channels

Interference reduction: 83.6%

The UMTS Radio Interface

- Completely new story

Network Optimization



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What needs to be planned?

- Topology
- Capacities
- Routing
- Failure Handling (Survivability)

- IP Routing
- Node Equipment Planning
- Optimizing Optical Links and Switches

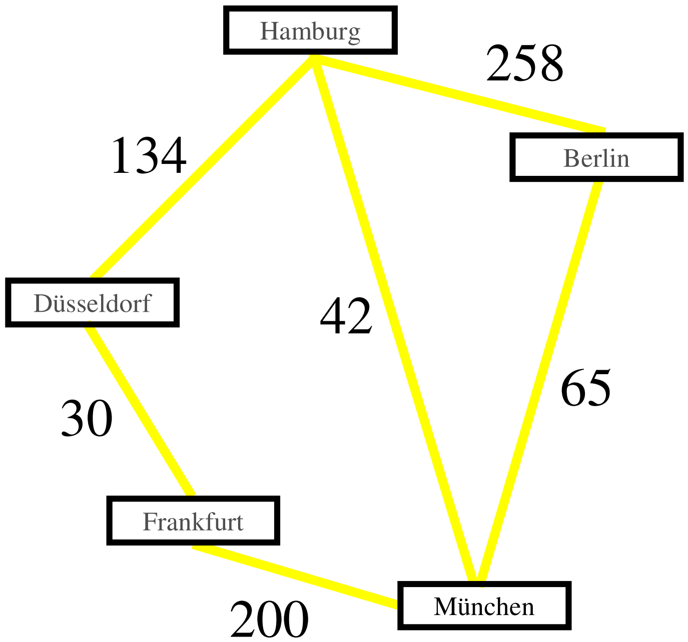
DISCNET: A Network Planning Tool

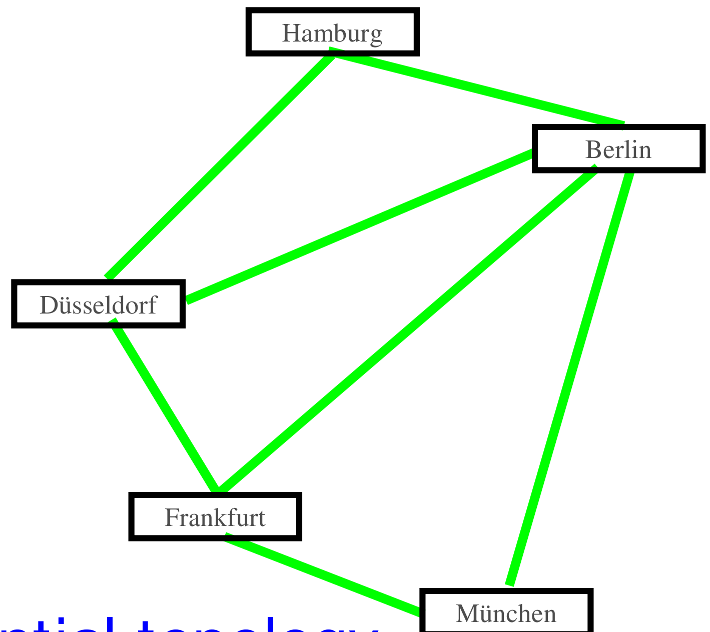
(Dimensioning Survivable Capacitated NETworks)

Atesio ZIB Spin Off

The Network Design Problem

Communication Demands





Potential topology
&
Capacities

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Mathematical Model

$$\min \sum_{e \in E} \sum_{t=1}^{T_e} k_e^t x_e^t$$

$$x_e^t \in \{0,1\} \quad e \in E, t = 1, \ldots, T_e$$

$$x_e^{t-1} \geq x_e^t \quad e \in E, t = 1, \ldots, T_e$$

$$y_e = \sum_{t=0}^{T_e} c_e^t x_e^t \quad e \in E$$

$$y_e \geq \sum_{uv \in D} \sum_{P \in \mathrm{P}_{uv}^0 : e \in P} f_{uv}^0(P) \quad e \in E$$

$$d_{uv} = \sum_{P \in \mathrm{P}_{uv}^0} f_{uv}^0(P) \quad uv \in D$$

$$f_{uv}^s(P) \geq 0 \quad s \in S, uv \in D_s, P \in \mathrm{P}_{uv}^s$$

- ✓ topology decisison
- ✓ capacity decisions
- ✓ normal operation routing
- ✓ component failure routing

$$\sum_{P \in P_{uv}^s \cap P_{uv}^0} f_{uv}^0(P) + \sum_{P \in P_{uv}^s : e \in P} f_{uv}^s(P) \geq \sigma_{uv} d_{uv} \quad s \in S, uv \in D_s$$

$$\sum_{uv \in D_s} \Big(\sum_{P \in P_{uv}^s \cap P_{uv}^0 : e \in P} f_{uv}^0(P) + \sum_{P \in P_{uv}^s : e \in P} f_{uv}^s(P) \Big) \leq y_e \quad s \in S, e \in E_s$$

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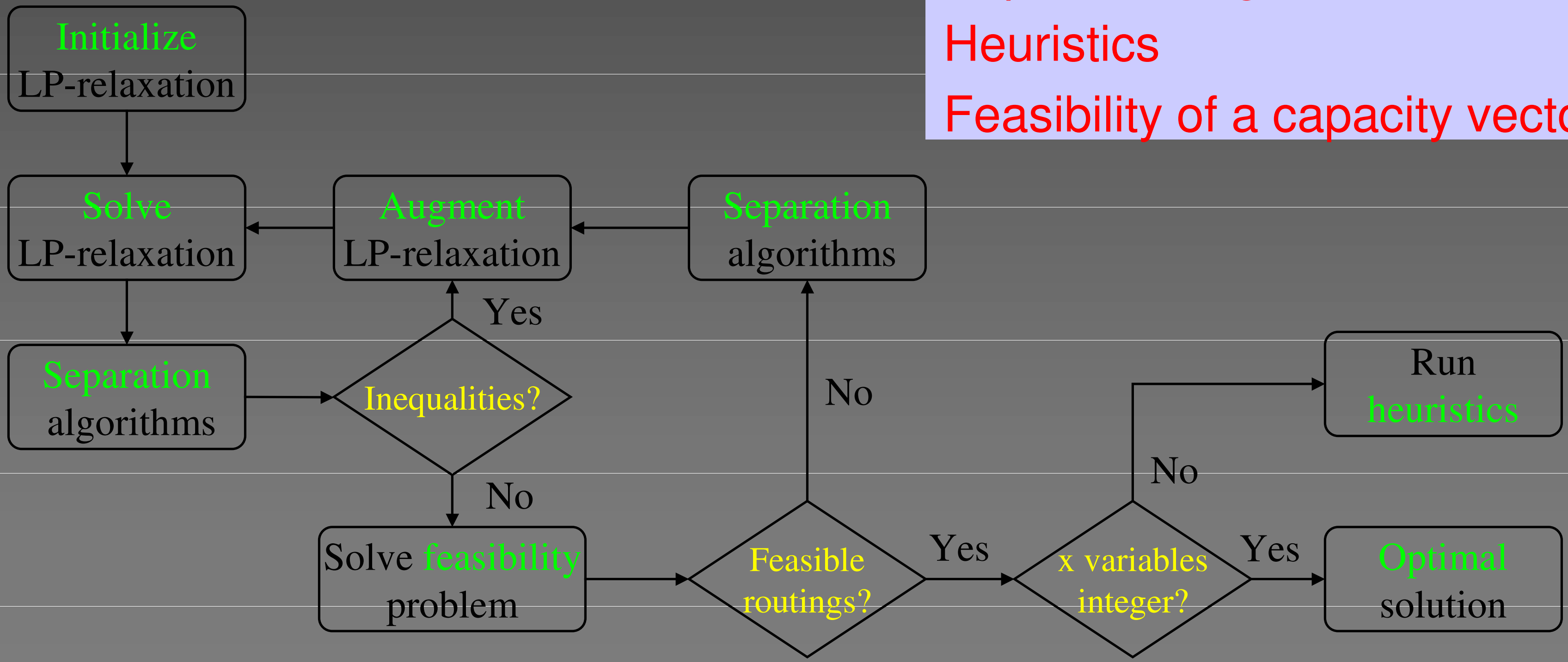
Flow chart

LP-based approach:

- Polyhedral combinatorics
- Valid inequalities (facets)
- Separation algorithms
- Heuristics
- Feasibility of a capacity vector



Finding a Feasible Solution?

Heuristics

- Local search
- Simulated Annealing
- Genetic algorithms
- ...

Manipulation of

– Routings
– Topology
– Capacities

Problem Sizes

Nodes	Edges	Demands	Routing-Paths
15	46	78	> 150 x 10e6
36	107	79	> 500 x 10e9
36	123	123	> 2 x 10e12

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How much to save?

Real scenario
- 163 nodes
- 227 edges
- 561 demands

PhD Thesis:

wessaely@atesio.de

→

34% potential savings!

==

> hundred million dollars

Summary

Telecommunication Problems such as

- Frequency Assignment
- Locating the Nodes of a Network Optimally
- Balancing the Load of Signaling Transfer Points
- Integrated Topology, Capacity, and Routing Optimization as well as Survivability Planning
- Planning IP Networks
- Optical Network Design
- and many others

can be succesfully attacked with optimization techniques.

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Contents

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Summary Telecommunication

The OR approach

- Helps understanding the problems arising
- Makes much faster and more reliable planning possible
- Allows considering variations and scenario analysis
- Allows the comparision of different technologies
- Yields feasible solutions
- Produces much cheaper solutions than traditional planning techniques
- Helps evaluating the quality of a network.

There is still a lot to be done, e.g.,
for the really important problems,
optimal solutions are way out of reach!

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The OR Challenges

- Finding the right ballance between flexibility and controlability of future networks
- Controlling such a flexible network
- Handling the huge complexity
- Integrating new services easily
- Guaranteeing quality

- Finding appropriate Mathematical Models
- Finding appropriate solution techniques (exact, approximate , interactive, quality guaranteed)

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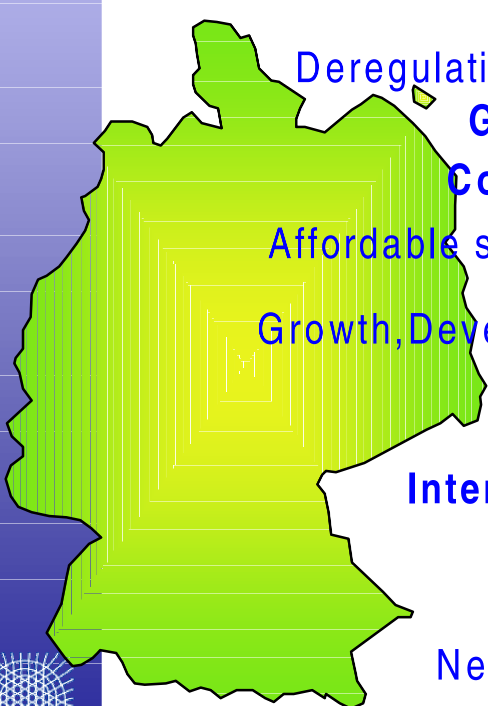
The Network Business will Change

Courtesy Dr. Winter (E-Plus)

The good „old world“

Fast deployment of
new services and
applications

The enlarged „new world“



Deregulation

Globalization

Competition

Affordable services

Growth,Development

Paradigm Changes

Flexibility

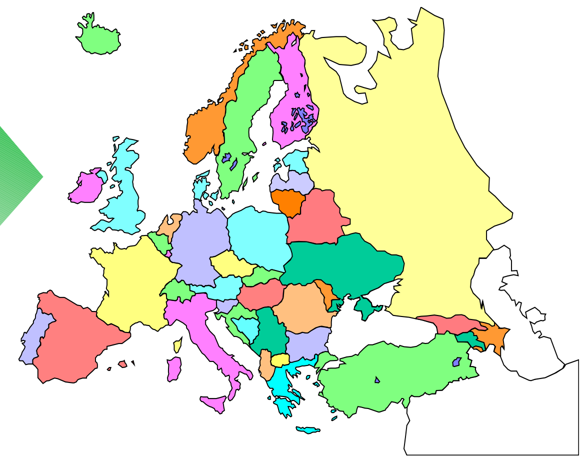
Speed

Internet

Mobilität

Convergence

New Technologies

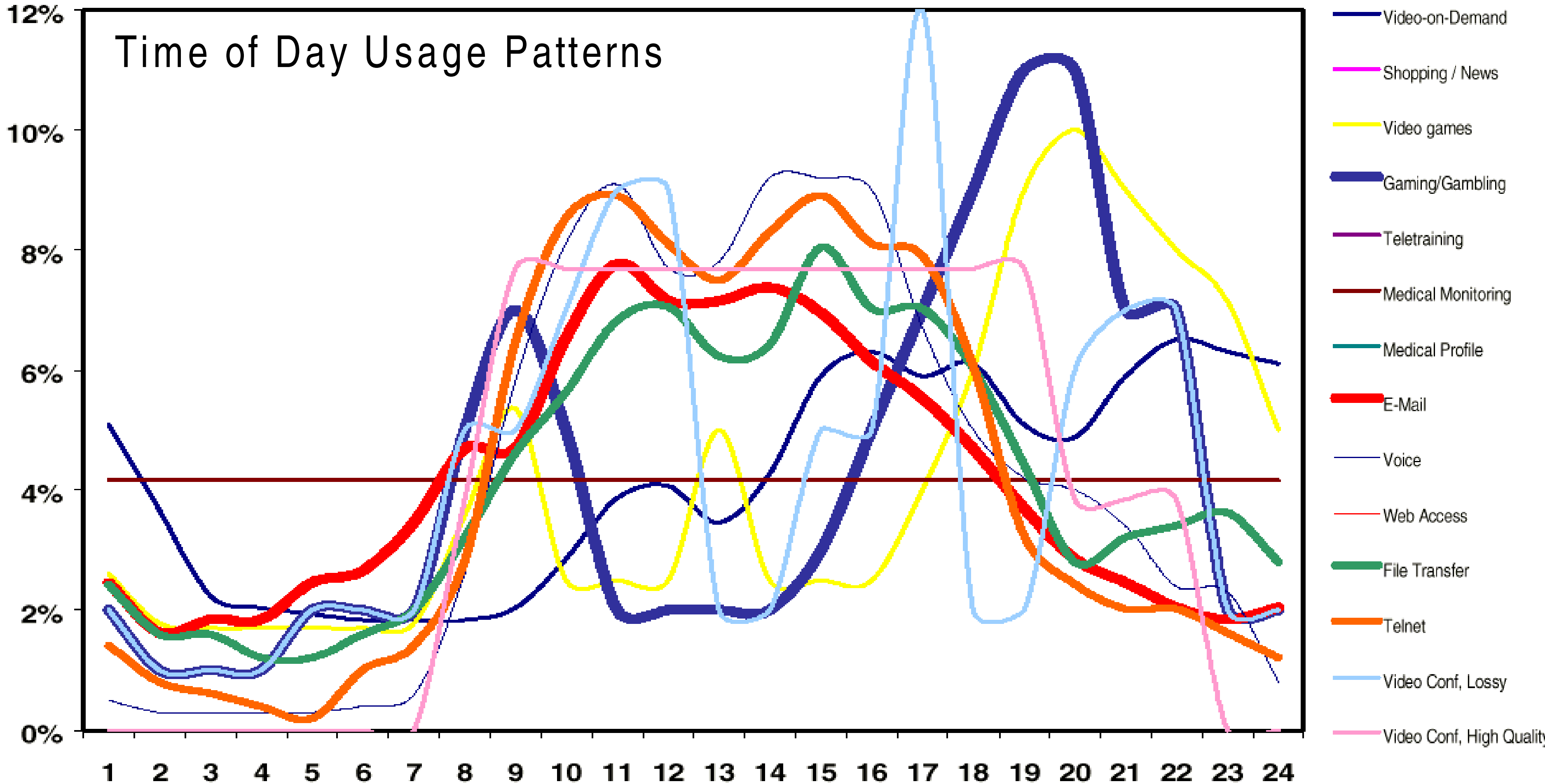


A flexible and powerful
Network infrastructure
Independent
Of the services

Growing custumer numbers
And growing infrastructure

Integrating Variable Multimedia Services

Courtesy Dr. Winter (E-Plus)



The OR Challenges

- What is a good telecommunication network?

Contents

1. Introduction
   - Where am I from?
   - Selecting a title
   - Revealing a secret
2. What is OR? (A name is a name, or not?)
3. OR on OR
4. Answering the HARD questions
   - What can we do? Examples of Success Stories:
     - Linear and integer programming
     - Public transportation
     - Telecommunication
   - What should we look at?
5. What is good OR?

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What is good OR?

Staying in touch
with everybody

Challenges

- first line of the text outlining the conference theme: "One of the most important concerns of the European Union is the ensuring and continuous improvement of goods and services within the Europe of today and tomorrow."
- We (the OR community) have not given enough thought so far to what we mean by "improvement of goods and services".

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Challenging Questions

- What is a GOOD public transportation system?

Directly related to the conference theme:

- What is a GOOD telecommunication system?

Even more directly refering to the conference theme:

- Is the Internet really beneficial?
  For whom? Under what rules?....
- ....

Directions

I am myself a person preferring to address questions

- that can be quantified precisely
- that have clean data and
- that have clear objectives and
- that can be modeled nicely.

However, I think we should start addressing problems seriously

- that can’t be quantified precisely
- that don’t have clean data and
- that don’t have clear objectives and
- that can’t be modeled nicely.
- but that are of higher political and social relevance

Directions

OR has the potential – employing its interdisciplinary strength – to contribute to other issues such as:

- unemployment
- fair trade
- safe water supply
- energy supply, in particular renewable energy
- electronic services (not only their management)
- …

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Directions

- P. Hansen, “A short discussion of the OR crisis”
  European Journal of Operational Research 38(1989)277-281

  “No general agreement seems to have been reached about its methodology, and the directions in which it should evolve. … There are many ways to live a life of OR, to discover new results and apply them, and thus to enjoy OR’s truth and beauty.”

R. Burkard, “OR Utopia”
European Journal of Operational Research 119(1999)224-234

“The borders of OR Utopia have yet another quality: people can come and go, without passport. There is no quota for foreigners… OR Utopia…is a peaceful border between OR, mathematics, and computer science, …management science, economy, logistics, …”

Science in the View of the Public

- I am concerned since I see downfalls of scientific fields such as nuclear technology that has made many promises and brought fear.
- The same is presently happening to biotechnology (many people are simply afraid of the progress announced).
- Similar tendencies are currently coming up in nano technology.

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OR in the View of the Public

- OR has to watch out that it keeps the right balance and people do not start getting afraid of OR.
- I see tendencies in public talks of company bosses, politicians, journalists, and union leaders that optimization means nothing but eliminating jobs, cutting down services, etc.

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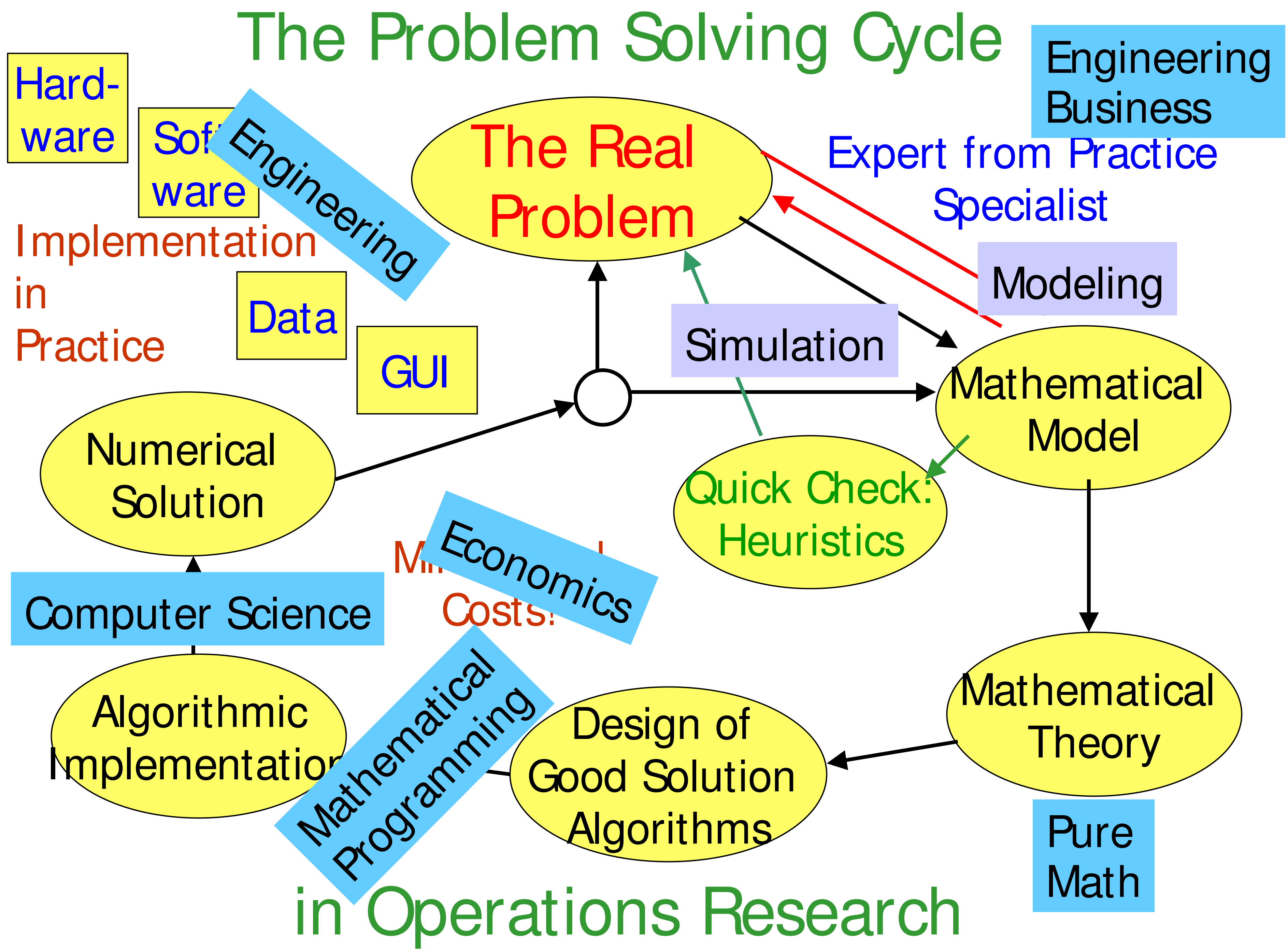
The Problem Solving Cycle
Engineering
Business
Hard-
ware
Sof
ware
Engineering
The Real
Problem
Expert from Practice
Specialist
Modeling
Implementation
in
Practice
Data
GUI
Simulation
Mathematical
Model
Numerical
Solution
Quick Check:
Heuristics
Mi
Economics
Costs!
Computer Science
Algorithmic
Implementation
Mathematical
Programming
Design of
Good Solution
Algorithms
Mathematical
Theory
Pure
Math
in Operations Research

my advice

- Don’t care about definitions of OR
- Let us not define the field OR, let us just be OR (OR stands for itself, no interpretation)
- Be flexible with your goals and approaches
- Enjoy the stuff that you do
- Position yourself depending on your own needs, goals, and wishes and that of your company or academic institution
- OR is a subversive science (addition to de Werra)
- OR is a transdisciplinary discipline

my advice

Try to contribute to

- science
- society
- business
- with the tools that you have, respecting the work and contributions of others, at your best possible level.

Or on OR

The End

Martin Grötschel

20th European Conference on Operational Research

EURO XX, Rhodes, Greece

July 7, 2004

Martin Grötschel

- Institute of Mathematics, Technische Universität Berlin (TUB)
- DFG-Research Center "Mathematics for key technologies" (FZT 86)
- Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)

groetschel@zib.de http://www.zib.de/groetschel

Thanks for your patience