Optimization of Gas Networks

TU Berlin
Summer Semester 2012
Lecture on June 21, 2012

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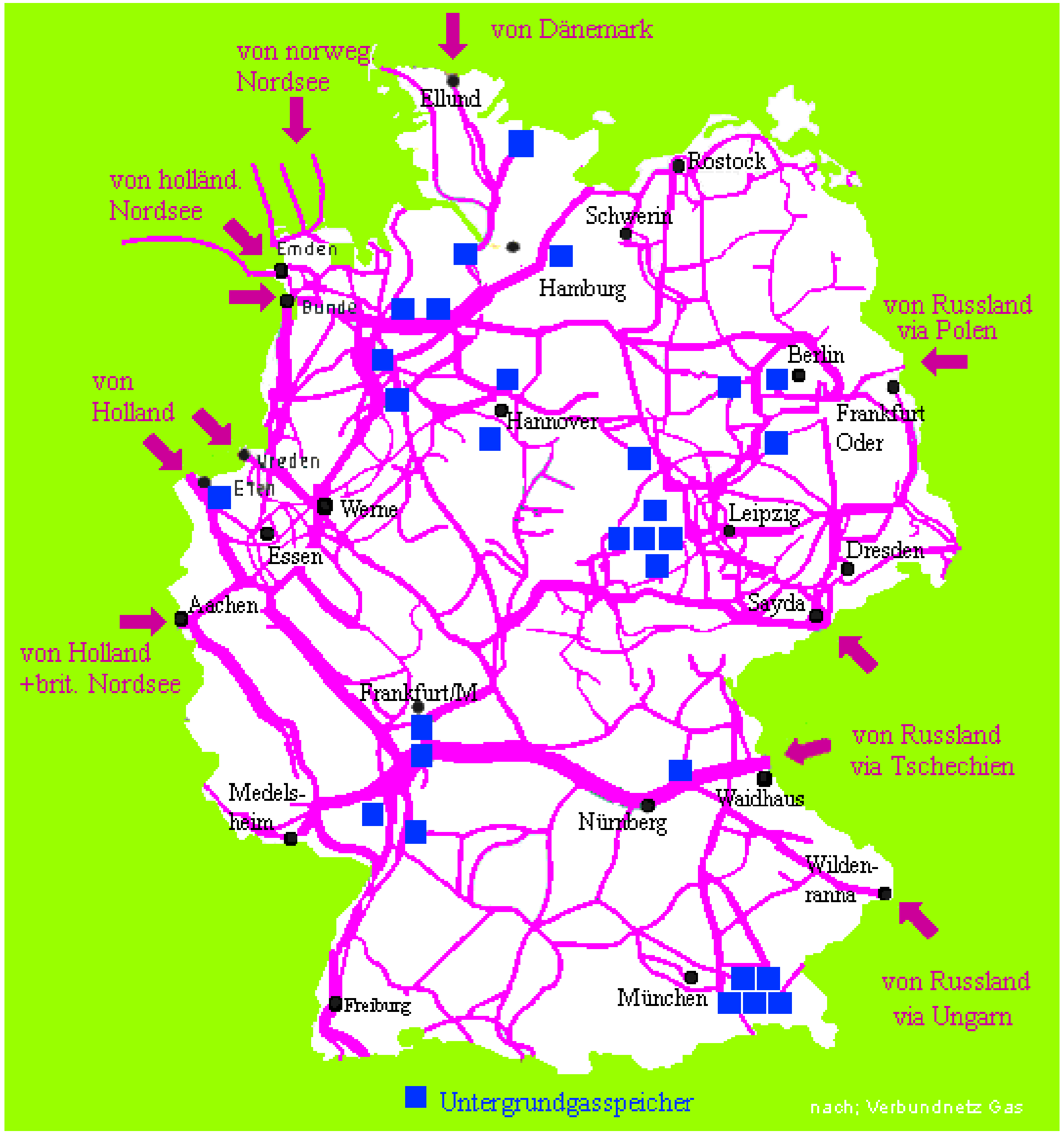
German backbone gas pipeline system



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Our main industry partner

Open Grid Europe
The Gas Wheel

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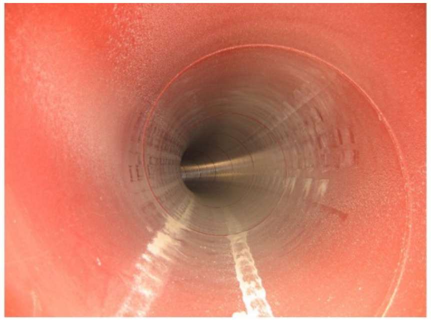
Who we are and what we do

- Headquartered in Essen, 1,800 employees
- 85 years of experience in the gas business
- We plan, construct, operate and monitor Germany's largest natural gas transmission system

Who we are and what we do

- 50 % of gas consumed in Germany flows through the OGE network
- We operate and develop our natural gas transmission system for our customers - this means that we and our pipeline companies ensure safe operation and handle all the processes involved in gas transmission
- We are committed to shaping framework conditions for natural gas transmission system operation in Europe

Our Network

➢ The Natural Gas Transmission System

- Total length of about 12,000 km (equivalent to length of German autobahn network)
- 140 GW peak load in 2010 (equivalent to installed capacity of all electric power plants in Germany)
- 27 compressor stations with 96 units
- Round about 200 of metering and pressure regulating plants

Liberalisation of gas markets

Far-reaching changes in recent years
(regulation)

Nowadays trading and transmission are unbundled

Entry-Exit model:

- Capacity booking throughout Germany is easy (network operators cooperate)
- Capacities are freely allocable
  (full flexibility to trade between entry and exit points)
- Tariffs depend on the entry and exit points, not on the routing. The regulator sets the upper limit of the sum of the allowable annual revenues

Tasks

- Network operators have to maximise their offering of freely allocable capacities
- Denial of capacity requests has to be justified
- Each flow situation within the bounds of the booked capacities has to be realizable with the contracted pressures
- Network expansion decisions have to be taken optimally

The Network Planning Department

About 20 people work on issues such as capacity planning and network expansion planning

Approach:

- Network Planning department identifies a small number of expertise-based restrictive transport scenarios
- Simulation of the network with the identified restrictive scenarios to stress the network and to gain information regarding network capacities
- Active elements of the network are configured manually for each scenario to come to a feasible network state during the simulation
- THIS IS VERY TIME-CONSUMING

We aim at developing an algorithm to solve large scale

Stochastic Mixed-Integer Non-Convex

Non-Linear Constraint Programs

to global optimality!

Of course, this goal cannot be reached.

But we will make an attempt to integrate as many aspects as possible.

And we have a real-world challenge.

This is MATHEON's mission!

But at least we are not as crazy as the law makers!

GasNZV § 2 Begriffsbestimmungen

Im Sinne dieser Verordnung bedeutet

3. **Ausspeiseleistung**
   das maximale Volumen pro Stunde in Normkubikmeter, das der Netzbetreiber auf Grund einer **Buchung** an einem Ausspeisepunkt für den Transportkunden vorhält;

4. **Bilanzkreis**
   die Zusammenfassung einer beliebigen Anzahl von Einspeisepunkten oder Ausspeisepunkten mit der Möglichkeit, Abweichungen zwischen Einspeisungen und Ausspeisungen zu saldieren;

6. **Buchung**
   das Erwerben von Kapazitätsrechten;

9. **Freie Kapazität**
   das maximale Volumen pro Stunde in Normkubikmeter am Ein- oder Ausspeisepunkt, das sich aus der Differenz zwischen **technischer Kapazität** und der Summe der **gebuchten Kapazitäten** für diesen Punkt ergibt;

13. **Technische Kapazität**
   das Maximum an fester Kapazität, das der Netzbetreiber unter Berücksichtigung der Systemintegrität und der Erfordernisse des Netzbetriebs Transportkunden anbieten kann;

(2) Netzbetreiber haben frei zuordenbare Kapazitäten anzubieten, die es ermöglichen, gebuchte Ein- und Ausspeisekapazität ohne Festlegung eines Transportpfades zu nutzen.

Die Rechte an gebuchten Kapazitäten (Kapazitätsrechte) berechtigen den Transportkunden, im Rahmen gebuchter Kapazitäten Gas an jedem gebuchten Einspeisepunkt für die Ausspeisung an jedem gebuchten Ausspeisepunkt im betreffenden Netz oder Teilnetz bereitzustellen.

Die Ausübung von Kapazitätsrechten darf der Netzbetreiber nicht von einer zusätzlichen hydraulischen Prüfung abhängig machen,....

(3) Transportkunden ist zu ermöglichen, Ein- und Ausspeisekapazitäten unabhängig voneinander, in unterschiedlicher Höhe und zeitlich voneinander abweichend zu buchen.

GasNZV § 6 Ermittlung frei zuordenbarer Kapazitäten

(1) Vor der Zuteilung von Einspeise- und Ausspeisekapazitäten haben Netzbetreiber die verfügbaren Kapazitäten nach § 4 Abs. 2 zu ermitteln. Sie weisen für jeden Einspeisepunkt eine Einspeisekapazität und für jeden Ausspeisepunkt eine Ausspeisekapazität aus.

(2) Die erforderlichen Berechnungen von Transportkapazitäten einzelner Leitungen oder von definierten Leitungsabschnitten sowie die Durchführung von Lastflusssimulationen erfolgen nach dem Stand der Technik.

(3) Führt die Berechnung der Transportkapazitäten nach den vorstehenden Absätzen insbesondere wegen:

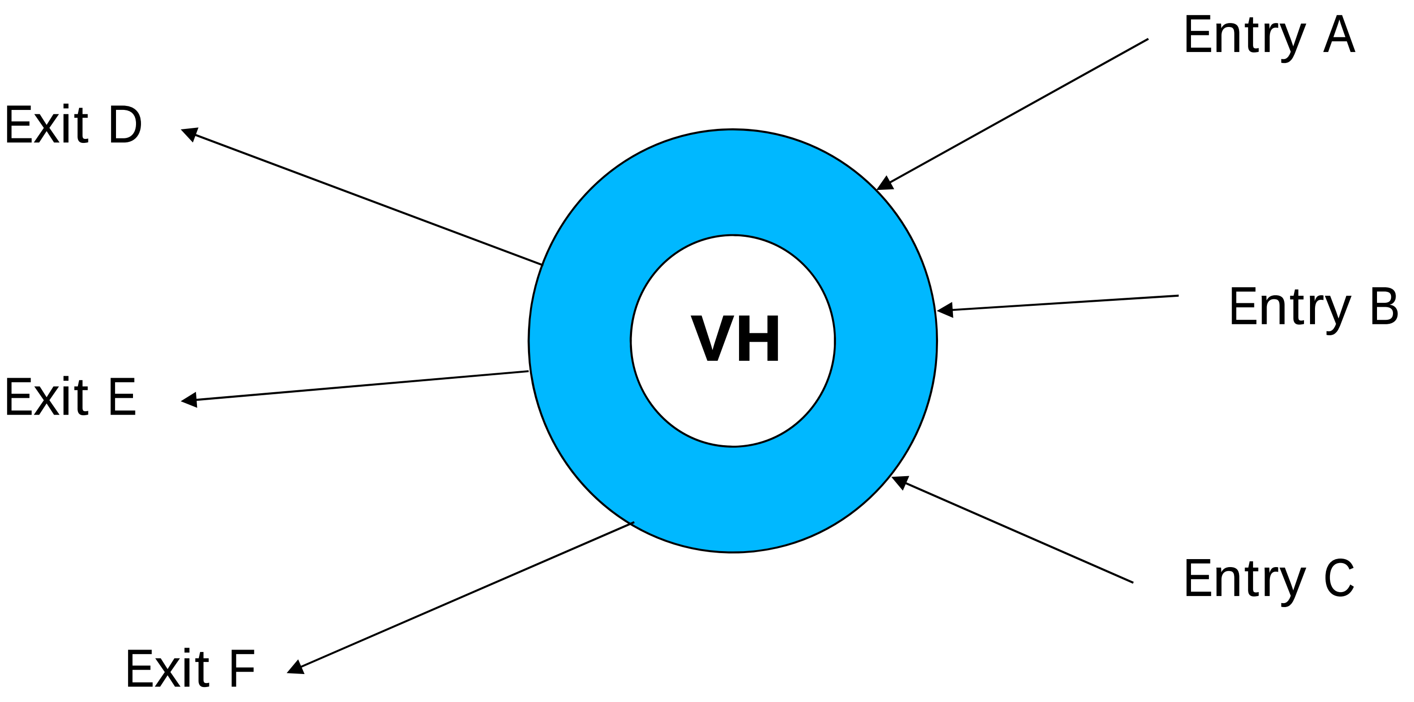
1. der hohen Anzahl von zu berücksichtigenden Lastszenarien,

2. der Größe des Netzes oder

3. physikalischer Engpässe.

zu dem Ergebnis, dass Kapazitäten nicht oder nicht in einem ausreichenden Maß im gesamten Netz frei zuordenbar angeboten werden könnten, haben die Netzbetreiber wirtschaftlich zumutbare Maßnahmen zu prüfen, um das Angebot frei zuordenbarer Kapazitäten im gesamten Netz zu erhöhen.

All intermediate nodes of the transport network are aggregated to a single node, the Virtual Trading Point / Virtueller Handelspunkt (**VH**).



As a result, the path of gas transport is transparent to the gas traders. We call the model transport path independent (transportpfadunabhängig), §4(2)

Booking, Nominating, and Balance Circle

By **booking** a certain capacity, a trader reserves the right to get a certain amount of gas transported through the network.

By **nominating** a previously booked capacity, a trader actually requests the transport of the nominated amount through the network.

Booking of capacities is done independently at entries and exits.
When booking entry capacity there is no need to name the exit and vice versa.

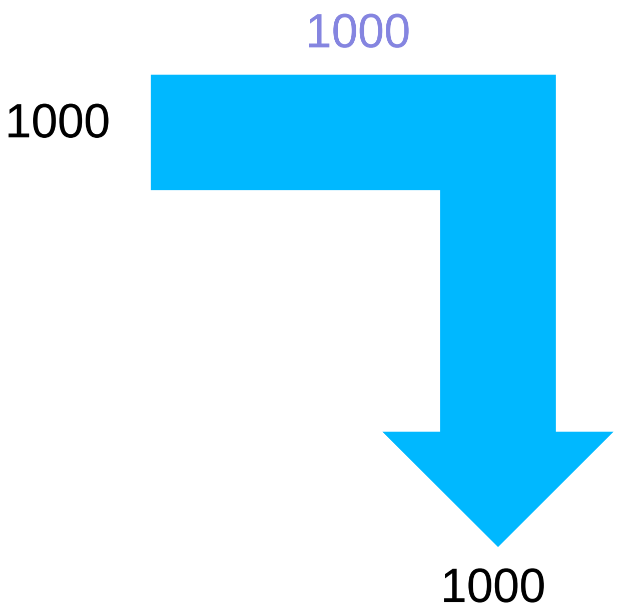
The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

Once a number of traders agree to exchange gas, all nominate previously booked capacities and build a so called **balance circle** (Bilanzkreis). The Gas Transport Company now has the obligation to take and deliver the nominated amount of gas at the specified entries and exits.

Since the gas demand is usually unknown (temperature dependent) to the consuming companies, they have to book the anticipated maximum capacity. As a result the nominated capacities are usually much lower than the booked ones.

One Picture Explains Some Difficulties

A trivial pipeline network

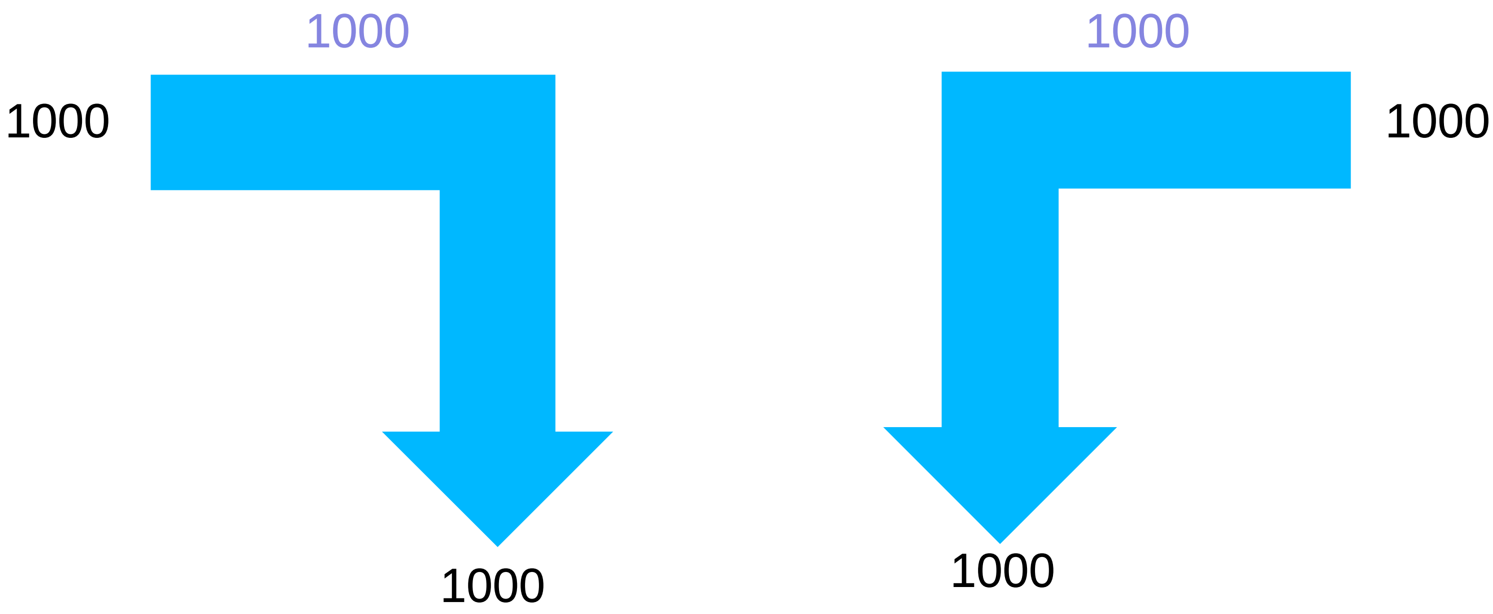


The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

Technische Kapazität
das Maximum an fester Kapazität, das der Netzbetreiber unter Berücksichtigung der Systemintegrität und der Erfordernisse des Netzbetriebs Transportkunden anbieten kann.

One Picture Explains Some Difficulties

We add another pipe...



The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

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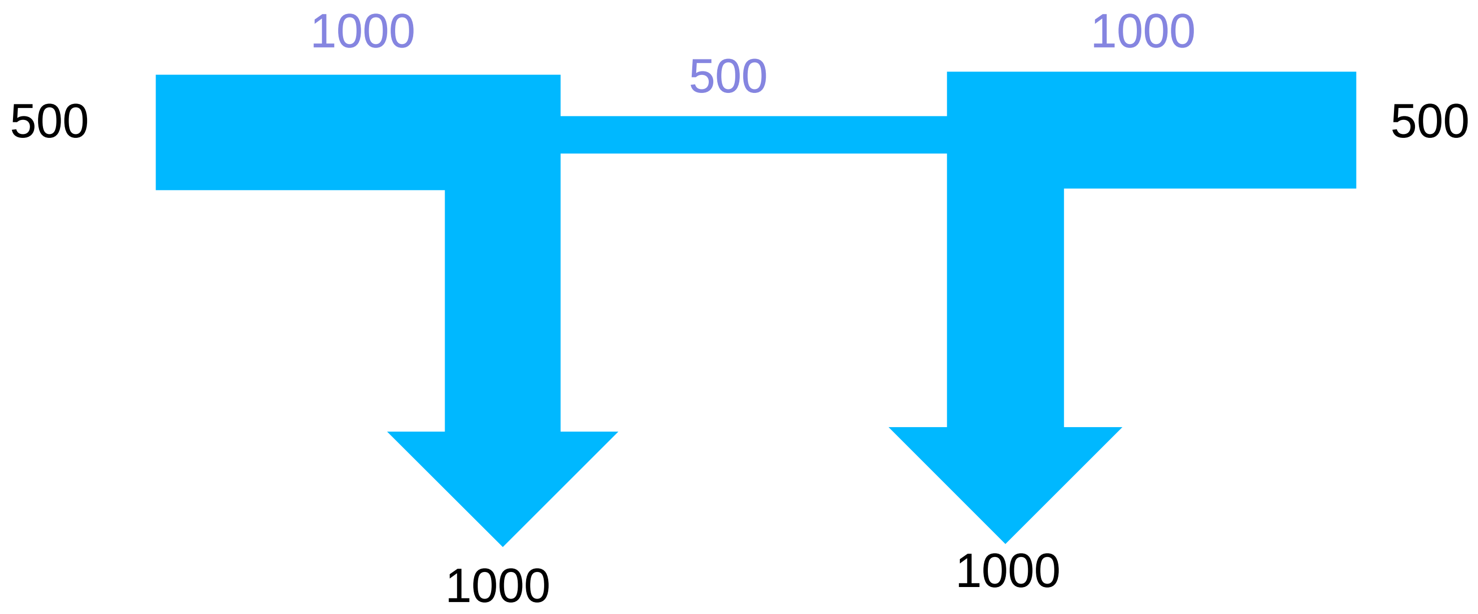
One Picture Explains Some Difficulties

...and a new connection.



The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

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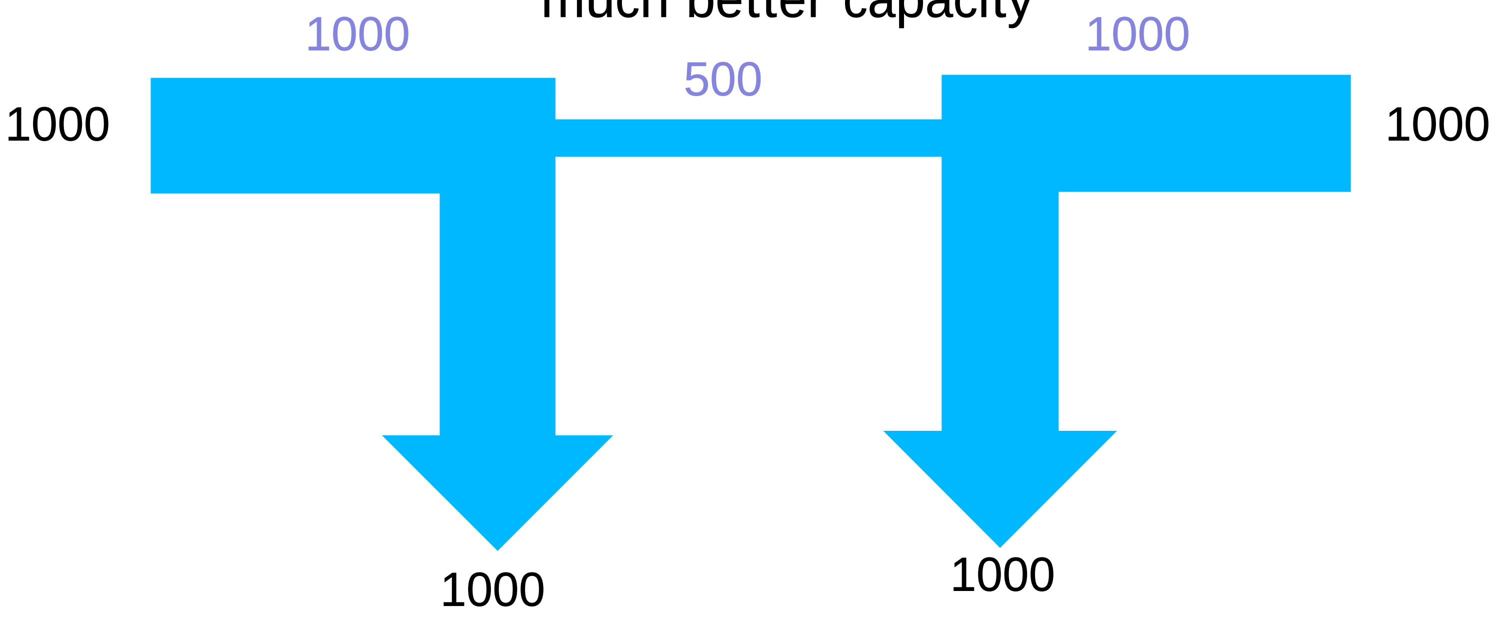
One Picture Explains Some Difficulties

But the network can provide
much better capacity



The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

Technische Kapazität
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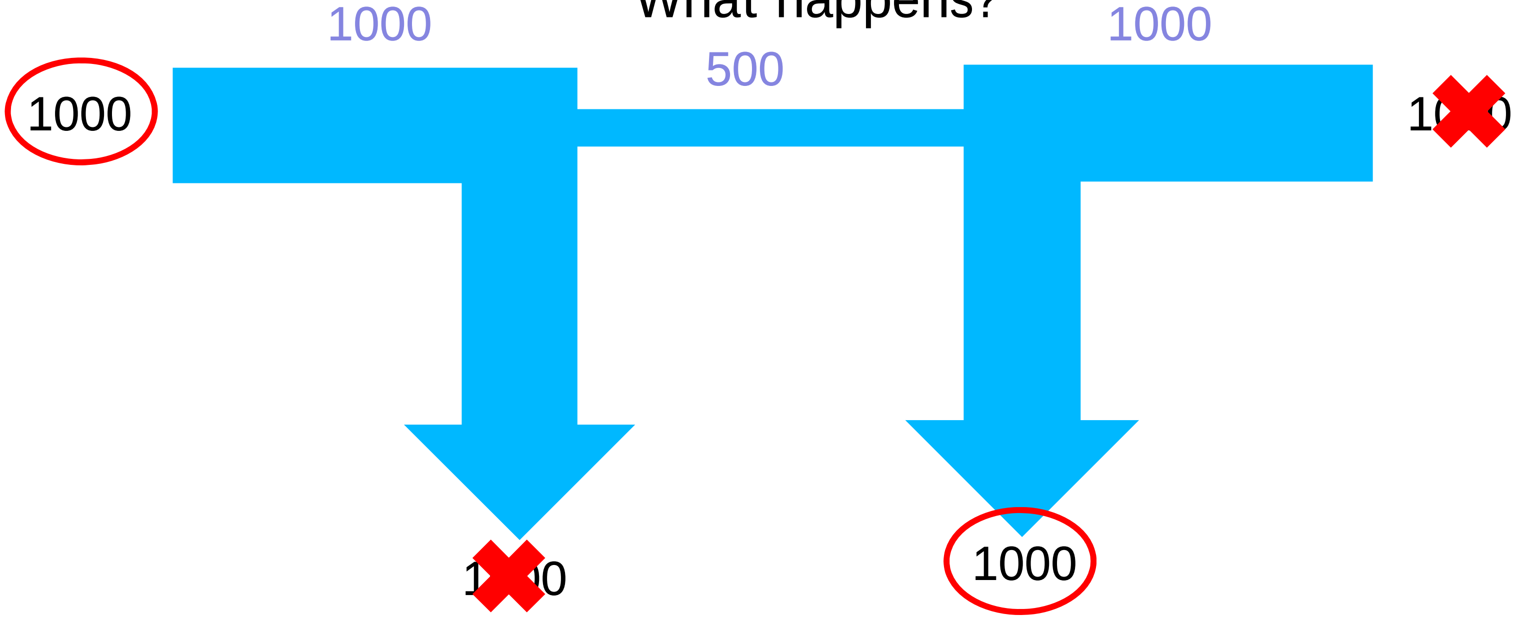
One contract is cancelled.
What happens?



The Gas Transport Company has to ensure that if they accept the booking, the gas can be delivered to all exits.

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Some Questions

- Given the existing bookings and the knowledge of previous customer behavior: Can a specific new booking request be accepted?

  The transport companies are required to
  publicly denote their free capacities at each entry and exit.

- How to compute this capacity? (Using which assumptions?)

- The transport companies are required to extend their network to accept more bookings. How? Where?

Contents

Martin Grötschel

Who am I?

Currently:

- Mathematics professor at TU Berlin
- Vice president of the Konrad Zuse Center for Information Technology Berlin (ZIB)
- Plus many administrative jobs (IMU, ESB,...)

Formerly:

- Chair of the DFG Research Center MATHEON

Important in this context:

- 30 years experience in running (more than 30) projects with industry partners in areas such as: energy; infrastructure; telecommunication; production; logistics, traffic and transport; VLSI design

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Modelling

There are many facets of modelling:

- mathematics/OR/physics/economics
- chemistry
- engineering
- architecture
- art
- ...

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Mathematical Modelling: What is that?

Beginning with observations

- of our environment
- a problem in practice of particular interest or
- a physical, chemical, or biological phenomenon

and with guiding/tailored experiments:

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

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Simulation

There are many misconceptions of the word:

- mathematics/OR/physics/economics
- chemistry
- engineering
- architecture
- art
- ...

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Simulation

- Simulation, Simulator or simulate are derived from the latin words ***simulare*** and ***similis .***
- They mean: pretend to be or the same sort.

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Simulation

- „Computation“ of several (close to reality) variants of a mathematical modell aimimg at:
  - „validation“of the correctness of a modell
  - investigation of typical instances in the modell framework, e.g., to avoid experiments or to test some functionality (crash-test)
  - good predictions (weather)
  - computation of reasonble solutions for the control of a system in practice (control of transport and logistics-systems)

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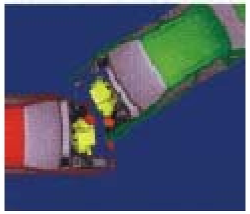
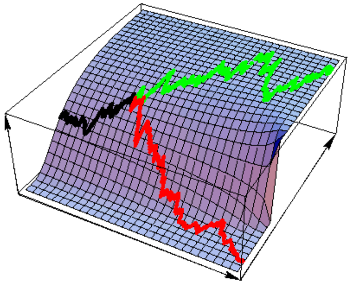
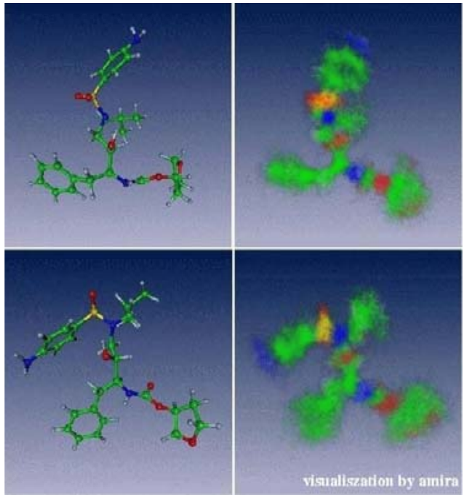
Simulation

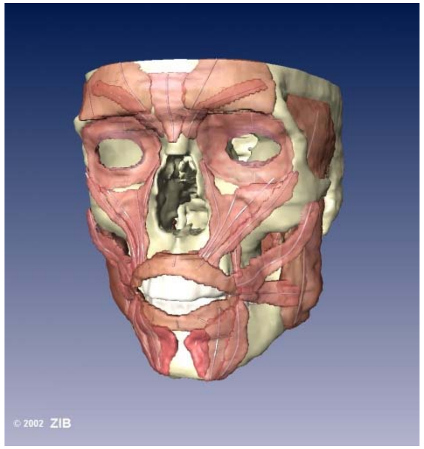
- Computation of instances by varying several parameters
- Parameters of a car crash test, e.g.:
  speed, material stiffness, various angles





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





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

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Tsunami Model Simulation

What simulation cannot do!

In contrast to a frequent belief in enginering and management science:

- Simulation can’t optimize, can’t even find local minima!
- Simulation can’t even decide infeasibility!
- Simulation can’t disprove anything!

- Simulation may be able to find a feasible solution, but is not able to prove its quality (near optimality, quality guarantee).
- Auction results need to be “court proof”. Simulation can’t provide legally unchallengeable results. (Auctions!)

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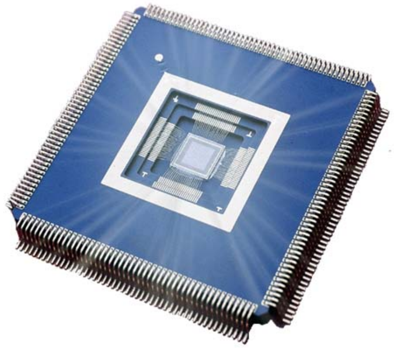
Satisfiability of Logical Formulas & Chip Design Verification:

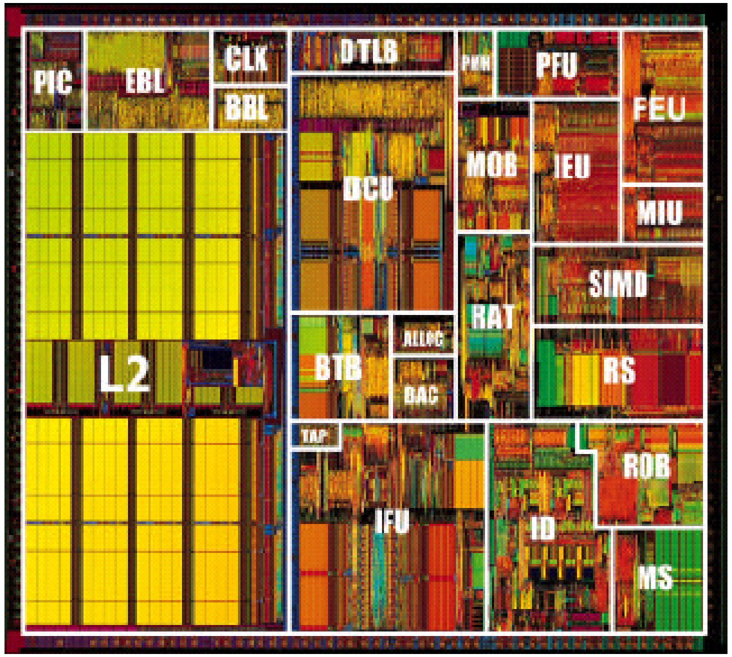
$$(\neg x_1 \vee x_2) \wedge (x_1 \vee x_2 \vee x_3) \wedge (x_1 \vee \neg x_2) \wedge (x_1 \vee x_2 \vee \neg x_3) \wedge (\neg x_1 \vee \neg x_2)$$

- A truly important application:

  Verification von Computer Chips and "Systems on Chips"

- A logic design is correct if and only if a system of certain logic formulas is false.





Property Checking

- Given:
  - a chip specification in a hardware modelling language (e.g. VHDL, Verilog)
  - a property of the registers in the circuit
- Question:
  - Is the property valid for all possible register values that satisfy the constraints of the chip specification?
- There may be 2^{1000} states.
  How can you find that one of these states is wrong (leading to a possibly hazardous chip error) by simulating some states?

Property Checking

- How does one decide whether an existing gas network is good enough for an expected demand?
- Check 50 cases?

Simulation: the positive side

Simulation is indispensable, though

- to handle situations too complicated to model exactly
- to obtain a „good“ understandig of complex situations
- to see whether the simplifications are justified
- to check solutions of models

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Optimization

Misuse of the word in:

- industry and the public
- other sciences

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Kalyanmoy Deb: *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. (!?)
- 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. (simply wrong) Thus, EAs are ideal candidates for solving multi-objective optimization problems. (Why?)

Kalyanmoy Deb: ***Multi-objective optimization using evolutionary algorithms*** (Wiley, 2001)

- Constraints are inevitable in any real-world optimization problem. (Deep observation)

- In order to widen the applicability of an optimization algorithm in various different problem domains, natural and physical principles are mimicked to develop *robust* optimization algorithms. Evolutionary algorithms and simulated annealing are two examples of such algorithms. (just claims)

Typical optimization models (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) program NLP

$$\min c^T x$$
$$Ax = a$$
$$Bx \le b$$
$$x \ge 0$$

linear program LP

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

(linear) integer program IP, MIP

program = optimization problem

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Our plan

We aim at developing an algorithm to solve large scale

Stochastic Mixed-Integer Non-Convex
Non-Linear Constraint Programs

to global optimality!

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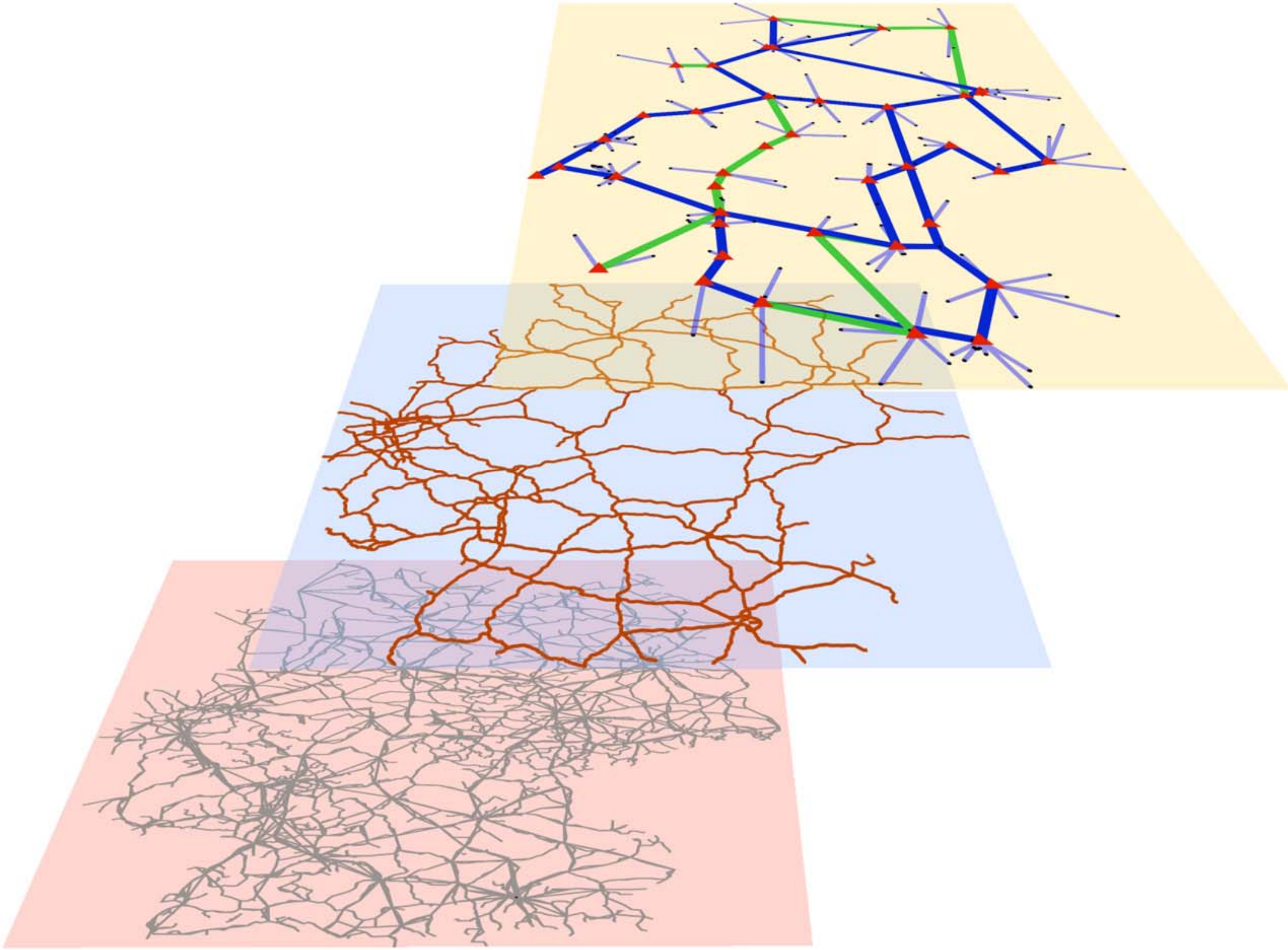
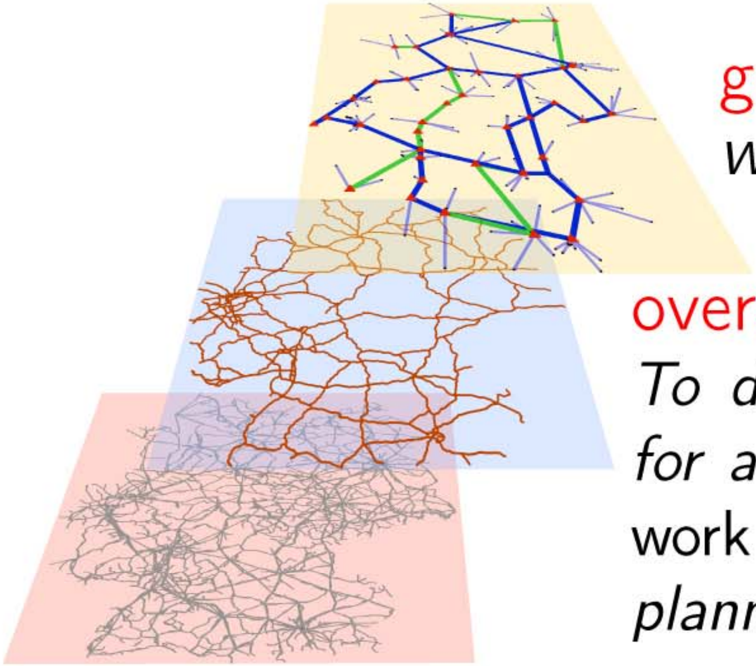
Networks



MATHEON Networks: Our Vision



guiding question:

what constitutes a good network?

overall goal:

To develop theory, algorithms, and software for a new, advanced level of integrated network optimization *that addresses network planning problems as a whole.*

examples:

- line planning and timetabling in public transport
- fiber and UMTS telecommunication network design
- harbor and factory logistics

MATHEON Networks: Industry Partners

OneSpin Solutions

DB

ViP Verkehrsbetrieb Potsdam GmbH

ILOG

Nokia Siemens Networks

PSI

HHLA

Lufthansa

atesio

Kollmorgen Steuerungstechnik

DFN Deutsches Forschungsnetz

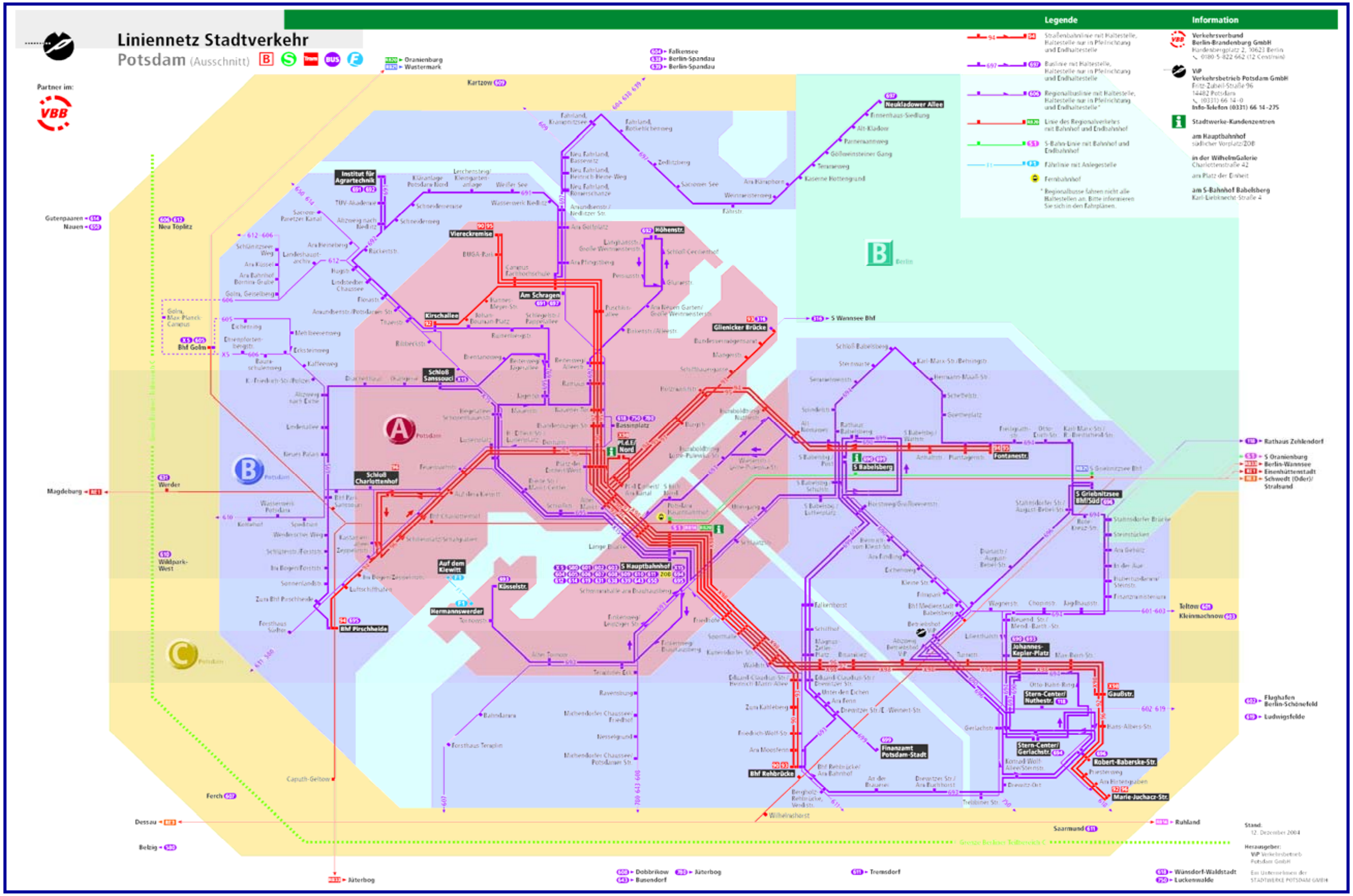
IBM

T.A. Cook

ptv traffic mobility logistics.

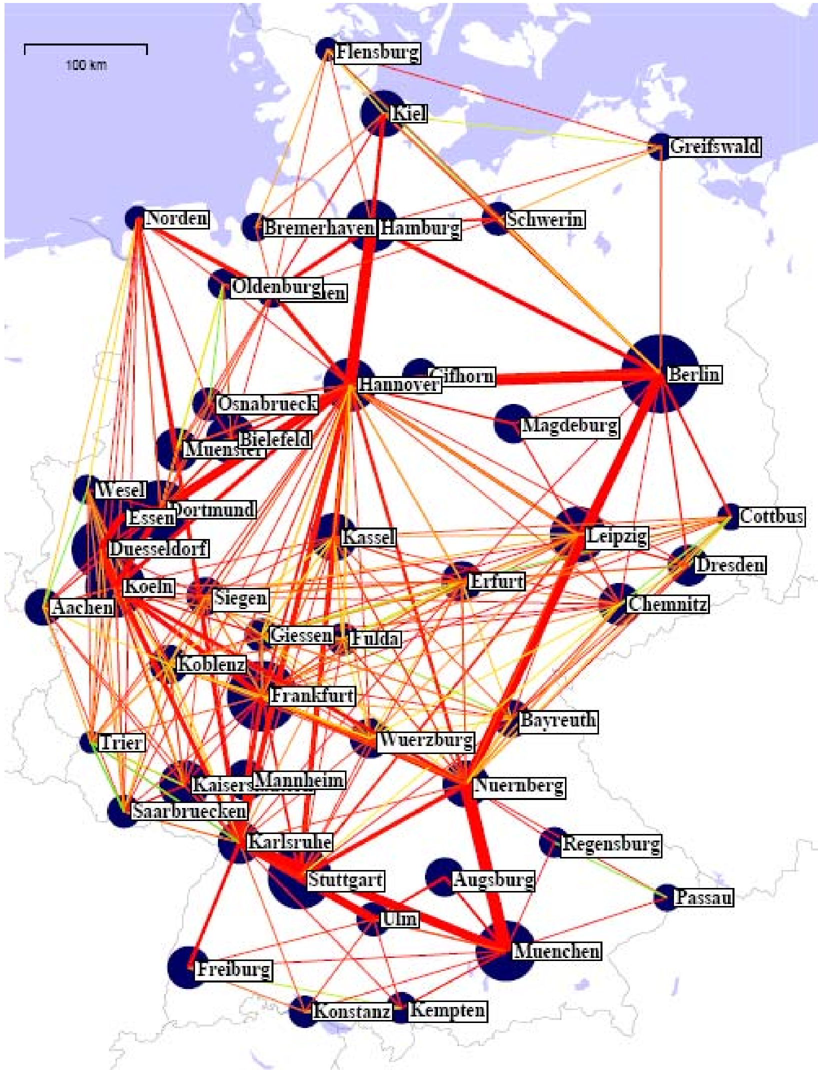
e·on Gastransport

Network, Line and Fare Planning (Potsdam)

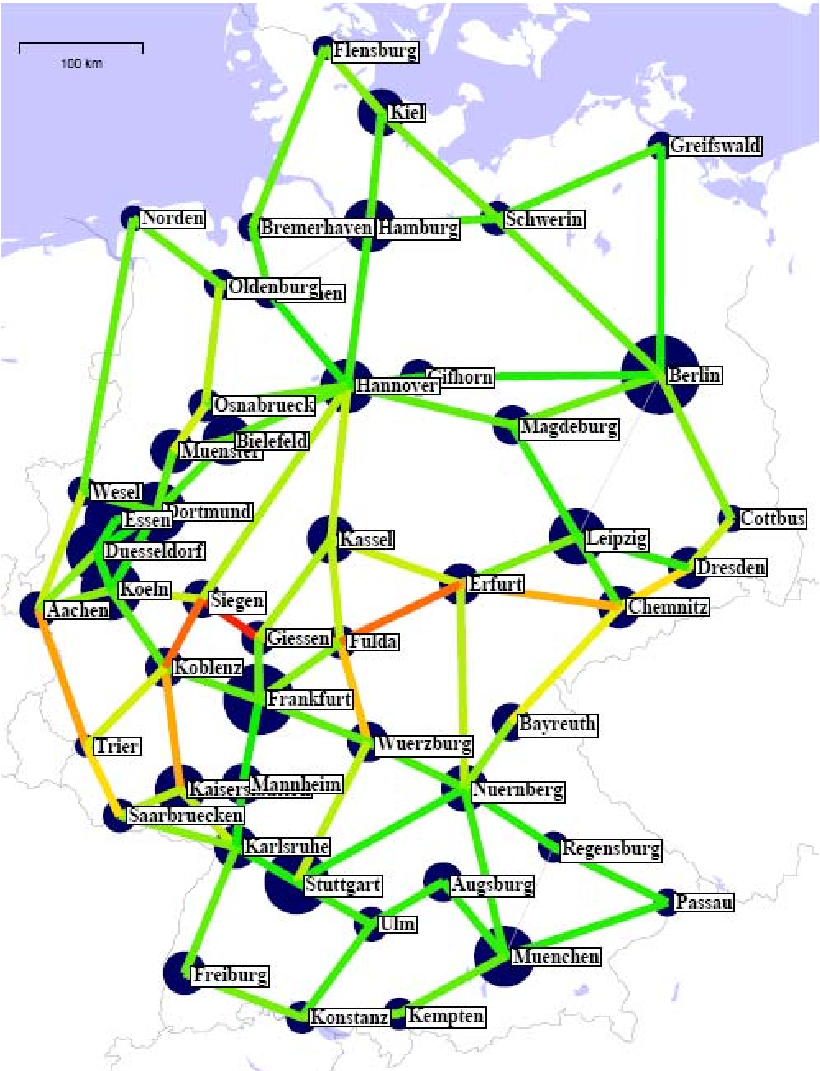


Telecommunication Network Design

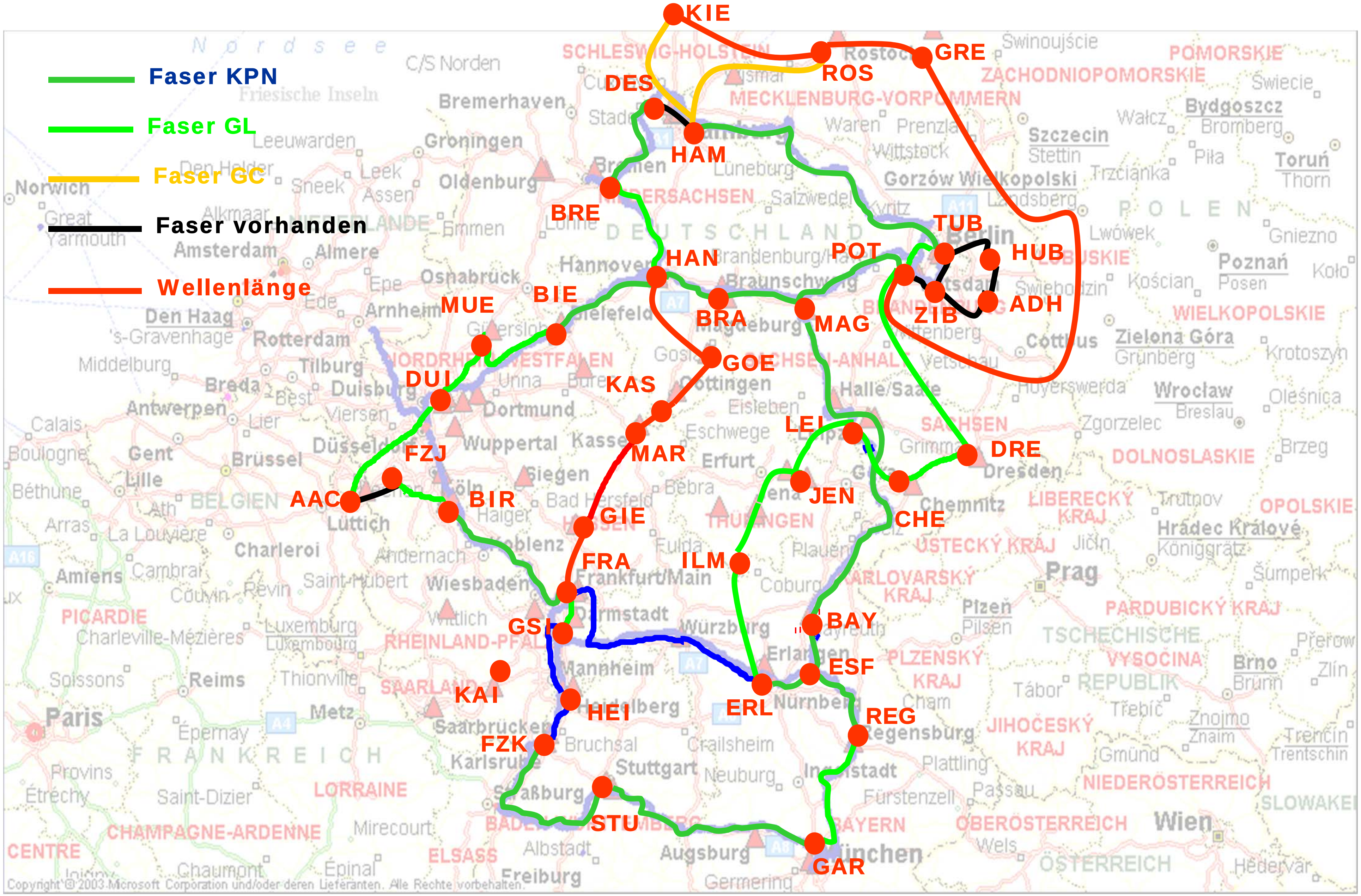
Logical connections: solution



Physical connections: solution



Location- and Network Topology Planing: solvable to optimality in practice



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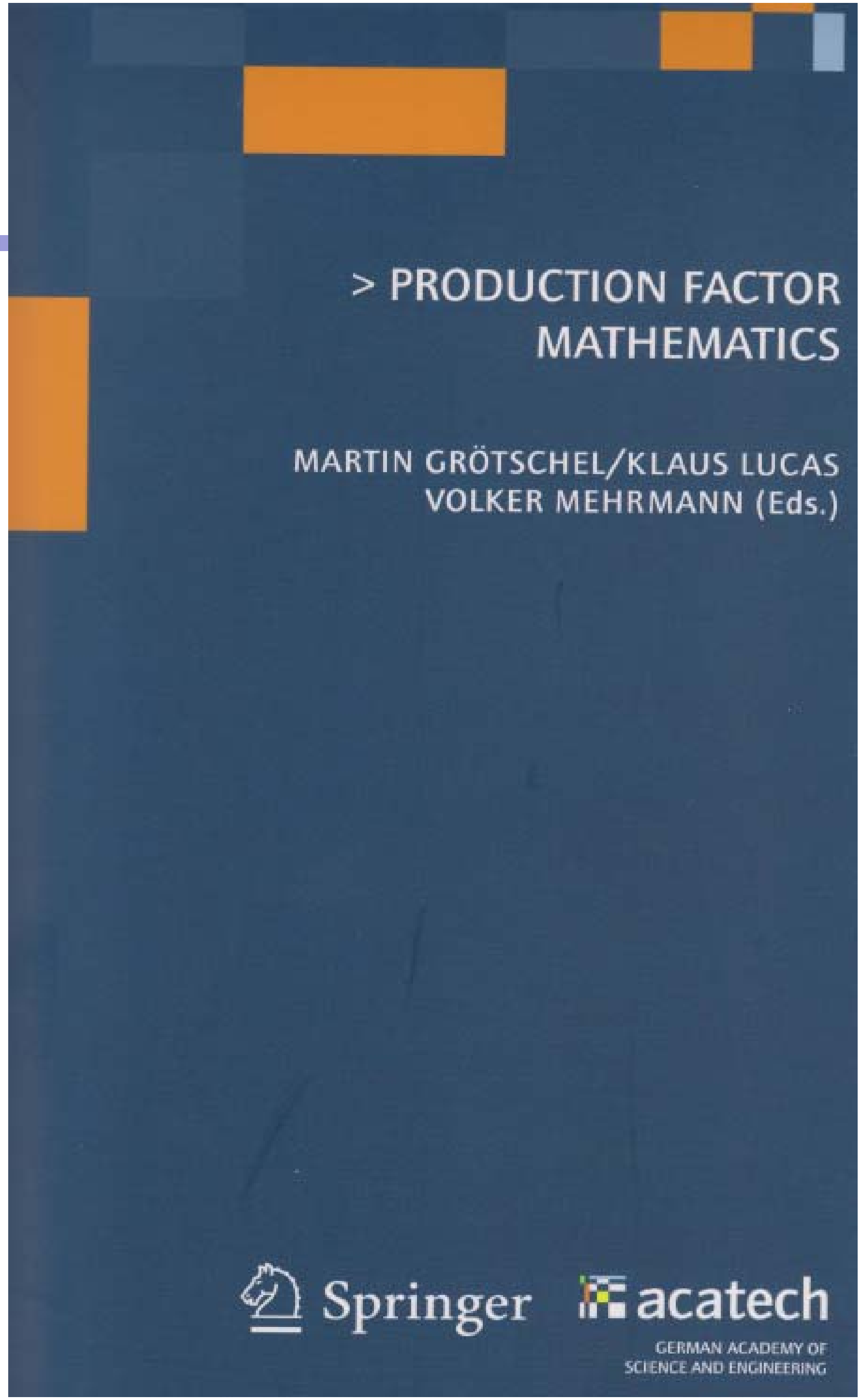
acatech
German National Academy of Engeneering



Preface
Production Factor Mathematics

The terms *maximization, best possible combination, constraints* point already at the utilization of mathematics. The influence of mathematics is not restricted to the employment of optimization technology, though. Mathematics enters deeply into the design of products, the layout of production processes, and supply chains. Mathematics delivers the language to describe scientific, technological, and economic processes in an abstract way. It enables the modelling, simulation, and optimization of products and processes before their realization is started. Mathematics is not only a production factor for the improvement of products and services, it also proves to be a key technology in mastering complex technologies and a basic science for innovations. It is the goal of this book to substantiate these general statements by describing concrete cases where these roles of mathematics become apparent.

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Gas Transport Optimization

Challenges in the Optimization of Gas Transport:

- ▷ Gas transport itself
- ▷ Gas network capacity planning
- ▷ Understanding of the legal deregulation rules of the gas transport market from a mathematical point of view
- ▷ Development of the associated mathematical solution technology

```
SCIP version 1.1.0 [LP solver: Clp 1.10.0]
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presolving:
(round 1) 7 del vars, 7 del conss, 43 chg bounds, 6 chg sides, 6 chg coeffs,
(round 2) 7 del vars, 12 del conss, 55 chg bounds, 93 chg sides, 93 chg coeff
(round 3) 7 del vars, 12 del conss, 59 chg bounds, 131 chg sides, 131 chg coe
(round 4) 7 del vars, 12 del conss, 60 chg bounds, 153 chg sides, 153 chg coe
(round 5) 7 del vars, 12 del conss, 60 chg bounds, 159 chg sides, 159 chg coe
(round 6) 7 del vars, 12 del conss, 60 chg bounds, 159 chg sides, 159 chg coe
presolving (7 rounds):
 7 deleted vars, 12 deleted constraints, 60 tightened bounds, 0 added holes,
 567 implications, 0 cliques
presolved problem has 120 variables (102 bin, 0 int, 1 impl, 17 cont) and 114
      1 constraints of type <varbound>
    113 constraints of type <linear>
transformed objective value is always integral (scale: 1)
Presolving Time: 0.03

  node  | left  |LP iter| mem |mdpt |  dualbound   | primalbound  |  gap
      1 |     0 |   160 | 557k|   0 | 2.968620e+01 |      --      |   Inf
      1 |     0 |   613 | 773k|   0 | 2.803725e+01 |      --      |   Inf
*     4 |     3 |  1085 |1035k|   3 | 2.500000e+01 | 6.000000e+00 |  76.00%
R    17 |     3 |  2000 |1029k|  10 | 2.500000e+01 | 1.200000e+01 |  52.00%
*    32 |     7 |  2396 |1039k|  12 | 2.500000e+01 | 1.400000e+01 |  44.00%
R    43 |    10 |  2734 |1050k|  13 | 2.500000e+01 | 1.500000e+01 |  40.00%
   3200 |   112 | 47790 |1950k|  30 | 2.400000e+01 | 2.100000e+01 |  12.50%
   3400 |    69 | 50532 |1883k|  30 | 2.398028e+01 | 2.100000e+01 |  12.43%

SCIP Status        : problem is solved [optimal solution found]
Solving Time (sec) : 7.36
Solving Nodes      : 3549
Primal Bound       : +2.10000000000000e+01 (9 solutions)
Dual Bound         : +2.10000000000000e+01
Gap                : 0.00 %
```

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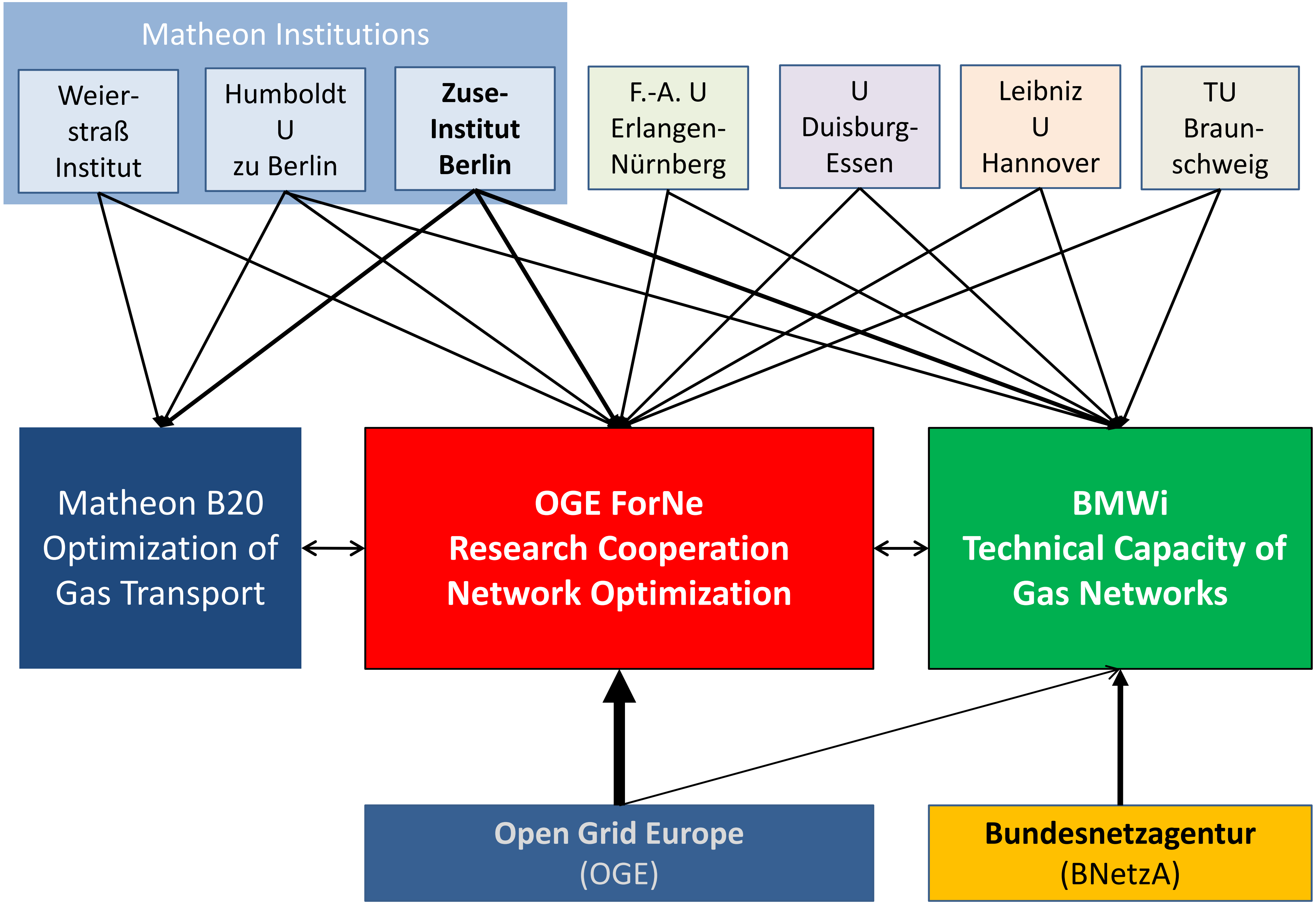
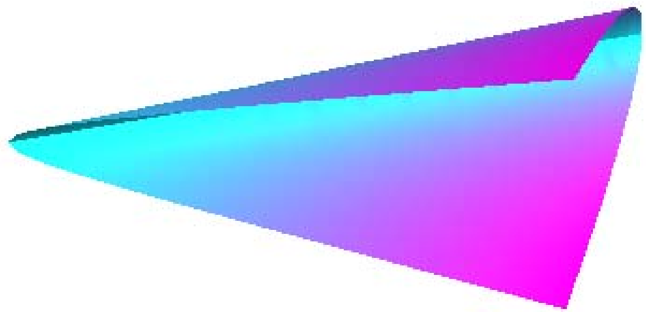

Matheon Institutions
Weier-straß Institut
Humboldt U zu Berlin
Zuse-Institut Berlin
F.-A. U Erlangen-Nürnberg
U Duisburg-Essen
Leibniz U Hannover
TU Braun-schweig
Matheon B20 Optimization of Gas Transport
OGE ForNe Research Cooperation Network Optimization
BMWi Technical Capacity of Gas Networks
Open Grid Europe (OGE)
Bundesnetzagentur (BNetzA)

Modelling Aspects of Gas Transportation

Nonlinear Nonconvex:

- Loss of pressure over pipes:

$$p_u^2 - p_v^2 = c q_{uv}^2$$



- Power of compressor:

$$f_{uv} = \gamma \left(\left(\frac{p_v}{p_u} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right) q_{uv} \leq f_{uv}^{\max}$$

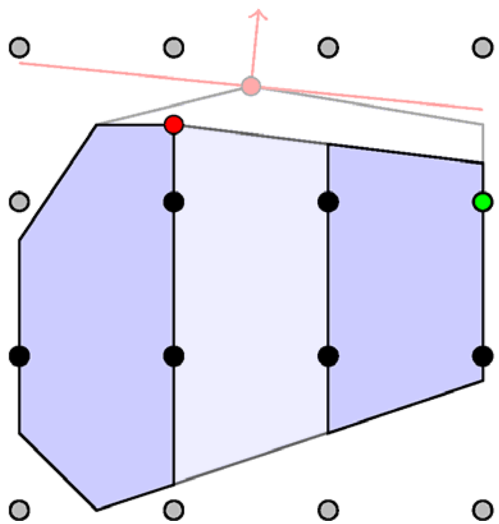
Mixed-Integer:

- Flow direction

$$s_{uv} = 0 \vee s_{vu} = 0$$

- Coupling constraints

$$\begin{aligned} q_{uv} &\leq q_{uv}^{\max} s_{uv} \\ p_u - p_v &\leq M r_e + \overline{d}_e s_{uv} - \underline{d}_e s_{vu} \end{aligned}$$



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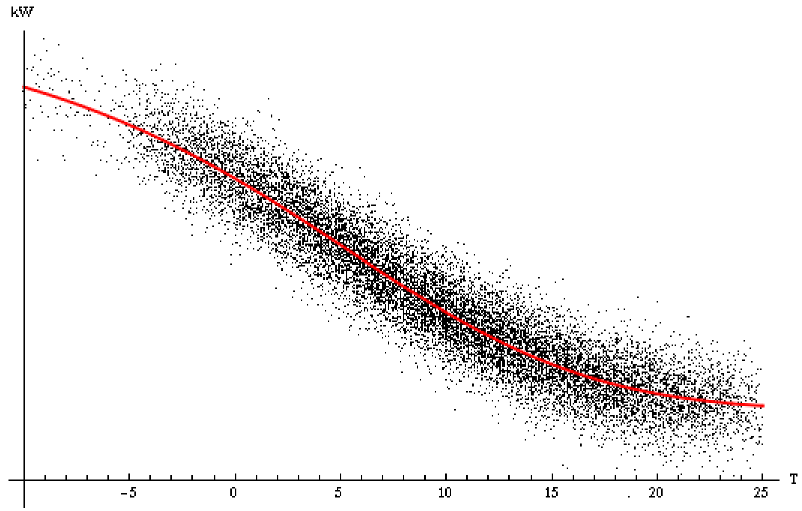
Modelling Aspects of Gas Transportation

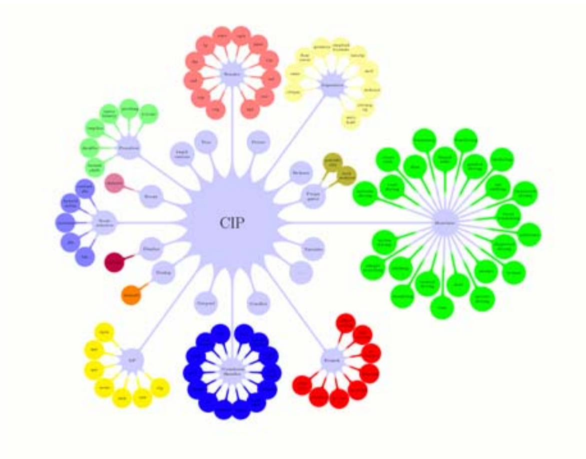
Uncertainty:

- Stochastic nomination at exits
- Unknown nomination at entries



Constraint Integer Programming:

- combines SAT, MIP, and CP
  - ➢ strong modeling capability
  - ➢ full power of MIP solving techniques



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Compressor station

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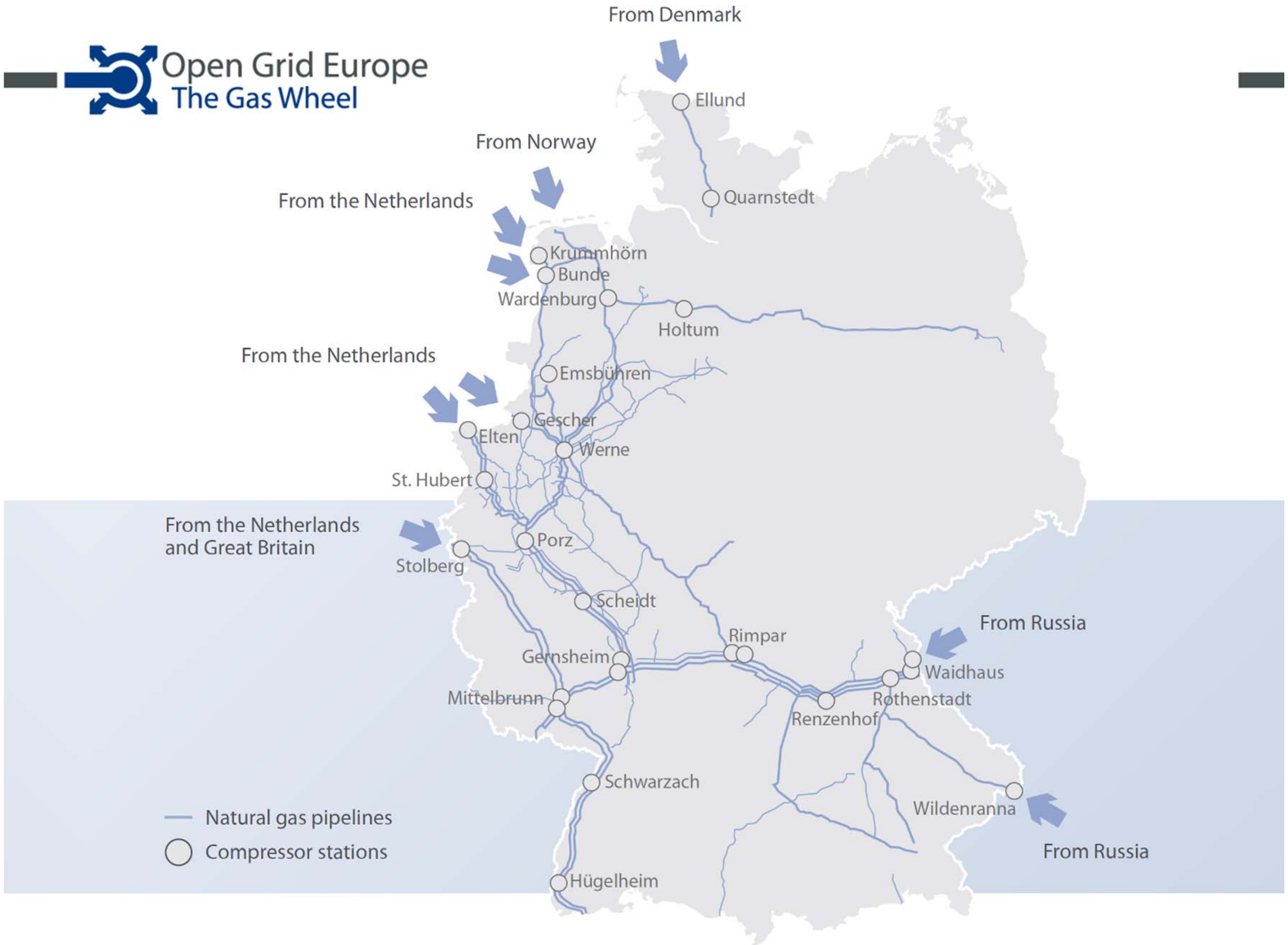

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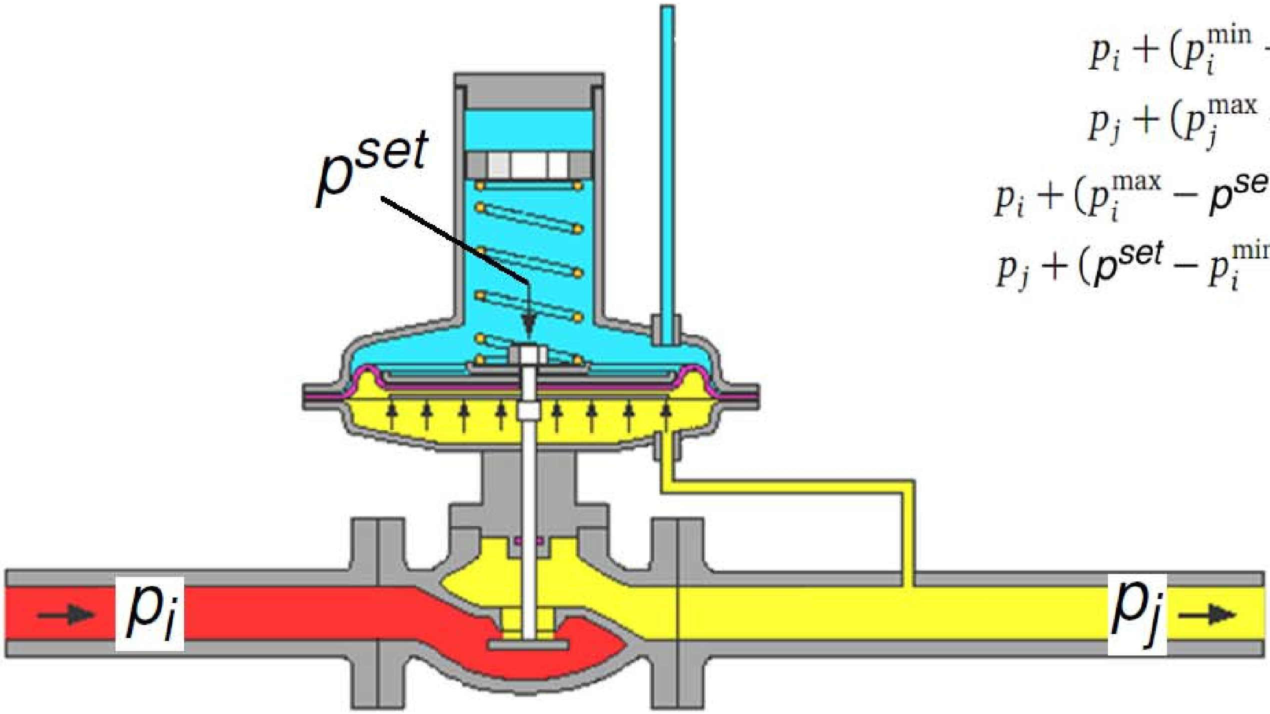
Modelling of a control valve



$$
\begin{aligned}
p_i + (p_i^{\min} - p^{set})r &\geq p_i^{\min}\\
p_j + (p_j^{\max} - p^{set})s &\leq p_j^{\max}\\
p_i + (p_i^{\max} - p^{set})(s-r) &\leq p_i^{\max}\\
p_j + (p^{set} - p_i^{\min})(s-r) &\geq p^{set}\\
p_j - p_i &\leq (p_j^{\max} - p_i^{\min})(1-s)\\
p_i - p_j &\leq (p_i^{\max} - p^{set})(r-s+1)\\
q_e &\leq q_e^{\max} s\\
q_e &\geq q_e^{\min}(s-r)\\
r &\leq s\\
r,s &\in \{0,1\}
\end{aligned}
$$

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Project Goals

Use modern mathematics to develop tailored algorithms to tackle

- Validation of nominations
- Verifying booked capacities
- Determining technical capacities
- Topology optimisation

… automated and with higher quality

Underlying problem class:

Very large-scale mixed-integer nonlinear stochastic program

Team and Timeline

Team of 30 members, OGE and research partners

- **2008** Initial Meeting, 3 Information Workshops
- **2009** Formal project start
- **2010** Basic research
- **2011** Validation of nominations
- **2012** The other project goals
- **2013** Ready for production as of spring

FORNE

Forschungskooperation Netzoptimierung

with

Open Grid Europe (OGE)

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Contents

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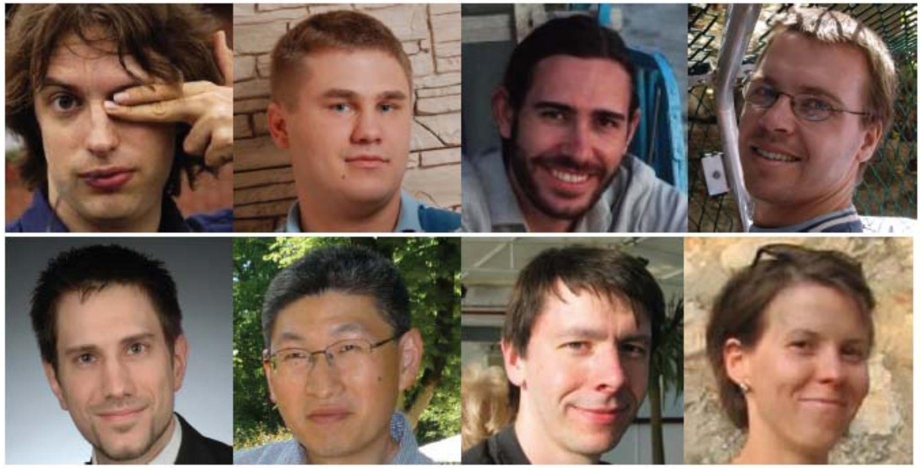
ZIB LP/MIP/MINLP Group

- Tobias Achterberg (IBM)
- Thorsten Koch
- Marc Pfetsch (TU Braun.)

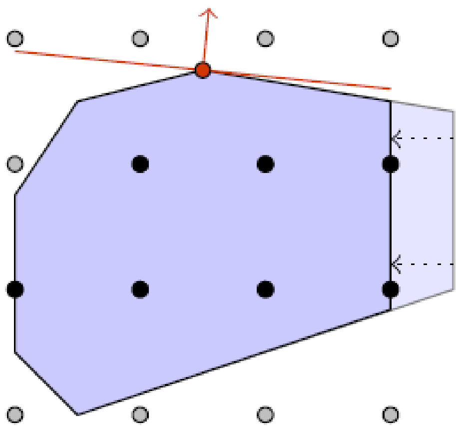
- Timo Berthold
- Gerald Gamrath
- Ambros Gleixner
- Stefan Heinz
- Matthias Miltenberger
- Yuji Shinano
- Stefan Vigerske
- Kati Wolter



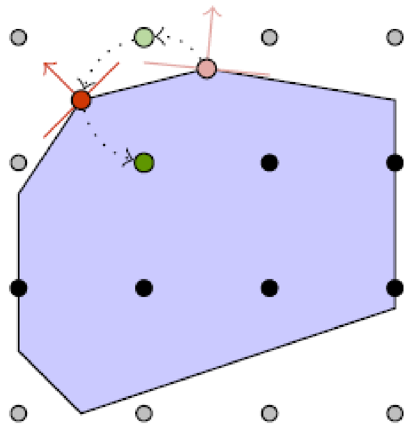
- Gregor Hendel
- Alexandra Kraft
- Michael Winkler

MIP Solver Techniques

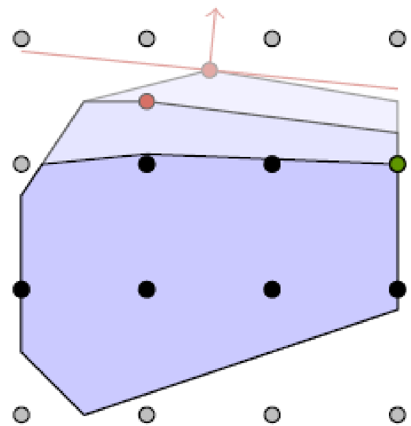
Presolving



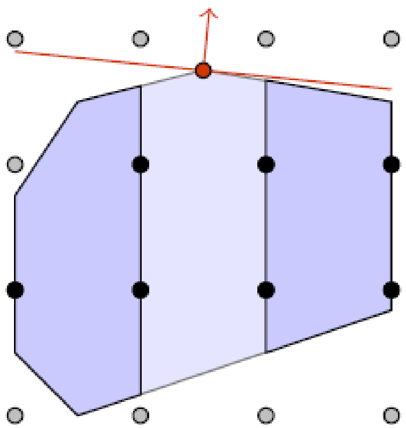
Primal Heuristics



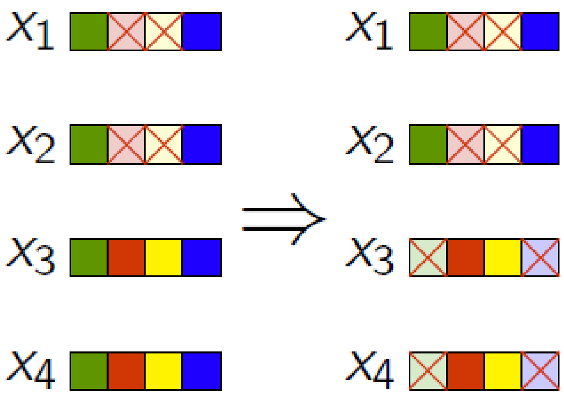
Cutting Planes



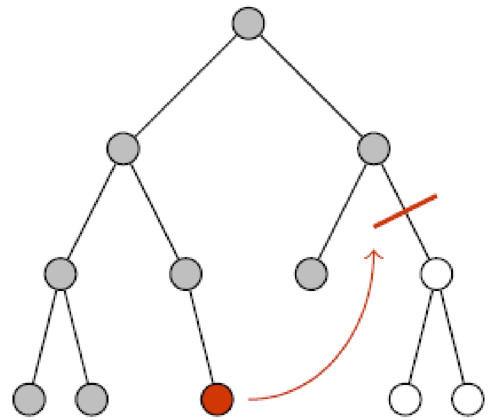
Branch & Bound



Domain Propagation



Conflict Analysis



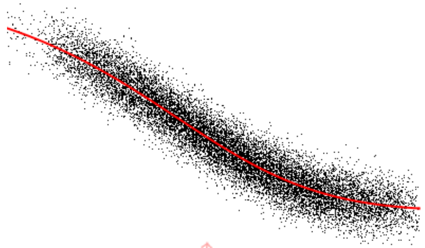
Aspects of Gas Transportation

The OGE problem is a:

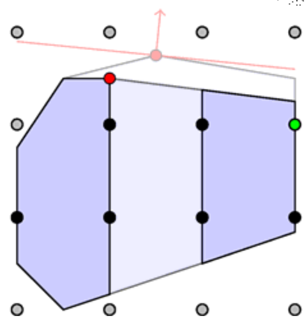
- Stochastic
- Mixed
- Integer
- Non
- Linear
- Constraint
- Program

It consists of:

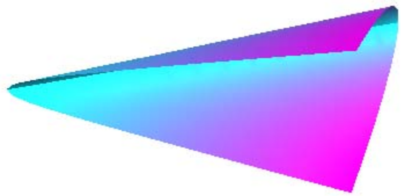
- Stochastic Part



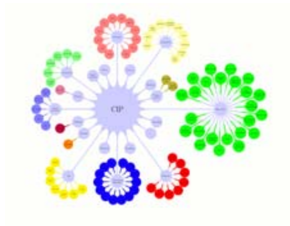
- Mixed Integer Part



- Non-Linear Part



- Constraint Integer Programming Part



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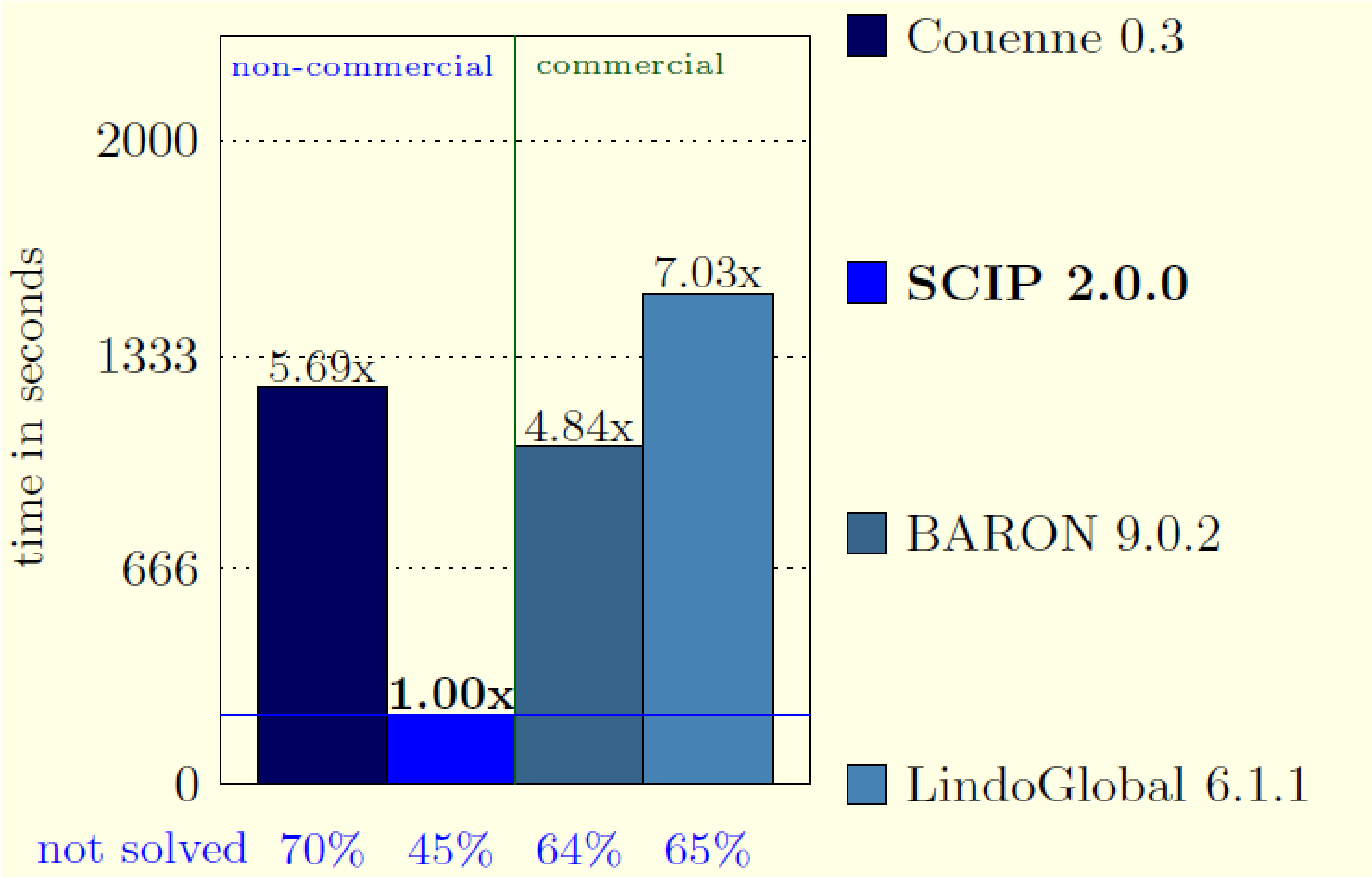
92 convex and non-convex MIQCP



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Challenges

- First steps are made to treat the stationary case.
- We are better than experience based methods.
- Laws/rules are mathematically inconsistent. What to do?
- From stationary to transient
- Expansion planning
- Including storage
- Pipeline as additional storage
- Integrating and simultaneously controlling all energy supply systems of a region
- Planning sustainable energy supply

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Optimization of Gas Networks

Thanks for your attention

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