25 years of Optimization: how to Survive Industry Projects as a Mathematician

Thorsten Koch

5th conference of the EURO Practitioners' Forum
University of Coimbra, Oct 2024

Chair of
Software and Algorithms
for Discrete Optimization

Department:
Applied Algorithmic
Intelligence Methods

3 reasons why a question in industrial optimization might be difficult to answer

1. The question is not well defined,
   i.e., the modeling is intricate. Very often, in industry, problems are involved and multi-layered. Determining a precise definition of the problem, the input and output data, and mapping this to a mathematically well-defined computable optimization problem can be challenging.

   - Given a solution can you decide if it is feasible to the original problem?
   - Given two solutions can you decide which one is better?

2. The data needed to solve the problem is not fully available.
   Many companies struggle hard to consolidate their IT. Getting out precise numbers is often surprisingly hard. One fundamental reason is decomposition, which has been necessary, at least in the past, to counter complexity. As a result, everyone only sees either a very little or very simplified part of the whole picture, and it is very hard to impossible to collect and the data into a coherent set.

   - Can you check whether the data is complete, correct, and consistent?
   - Is data on possibilities available?

3. The resulting problem is computationally hard to solve.
   Since the complexity class of discrete optimization problems often is NP-hard or worse, this is not surprising. However, experience shows, that solving particular instances works surprisingly well and that usually, the main reason for the inability to solve a problem is its size. For example, the likes of SAP, Amazon, Google, Huawei all have extremely large-scale supply-chain-type problems at hand. But not so many others. And there are surprisingly few small challenging real-world problems unless the time allowed for solving is very short.

The (good?) old times

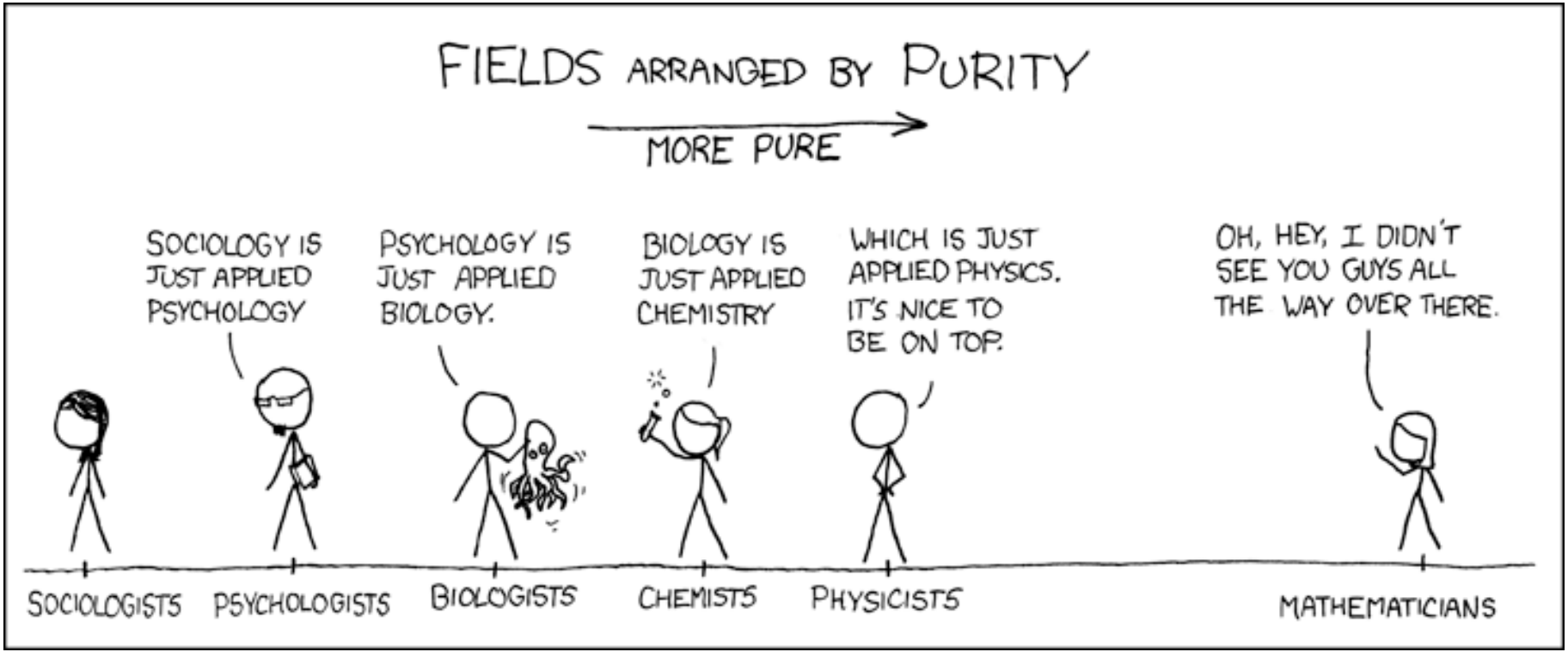
- Originally, there was little “science”.
- Where people used scientific ways, it was to solve real world problems: Archimedes (287-212 ad), 郭守敬 (Guo Shoujing, 1231-1316), Newton (1642-1726), Babbage (1791-1871), Gauß (1777-1855), … and then they tried to contrive generalizations.
- In the end you had to convince your king to feed you, therefore “pure” science, where no practical question is at issue is a rather new idea.

In modern times (about from nineteenth century):

- University was an elite education aimed at providing candidates for its own progeny and higher administration. Less than 10% of a annual cohort were attending university.
- Professors were not expected to do anything particular useful.
- If research turned up some noticeable result, the only way to make it available to the rest of the world was by publishing in printed widely circulated journals. Those journals were run by societies and universities.,
  e.g., Oxford University Press was founded in 1586.

https://de.toonpool.com/cartoons/Good%20old%20days_298215

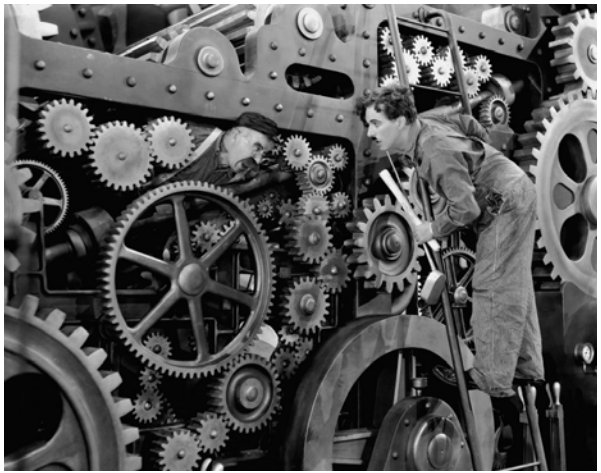
Pure and applied



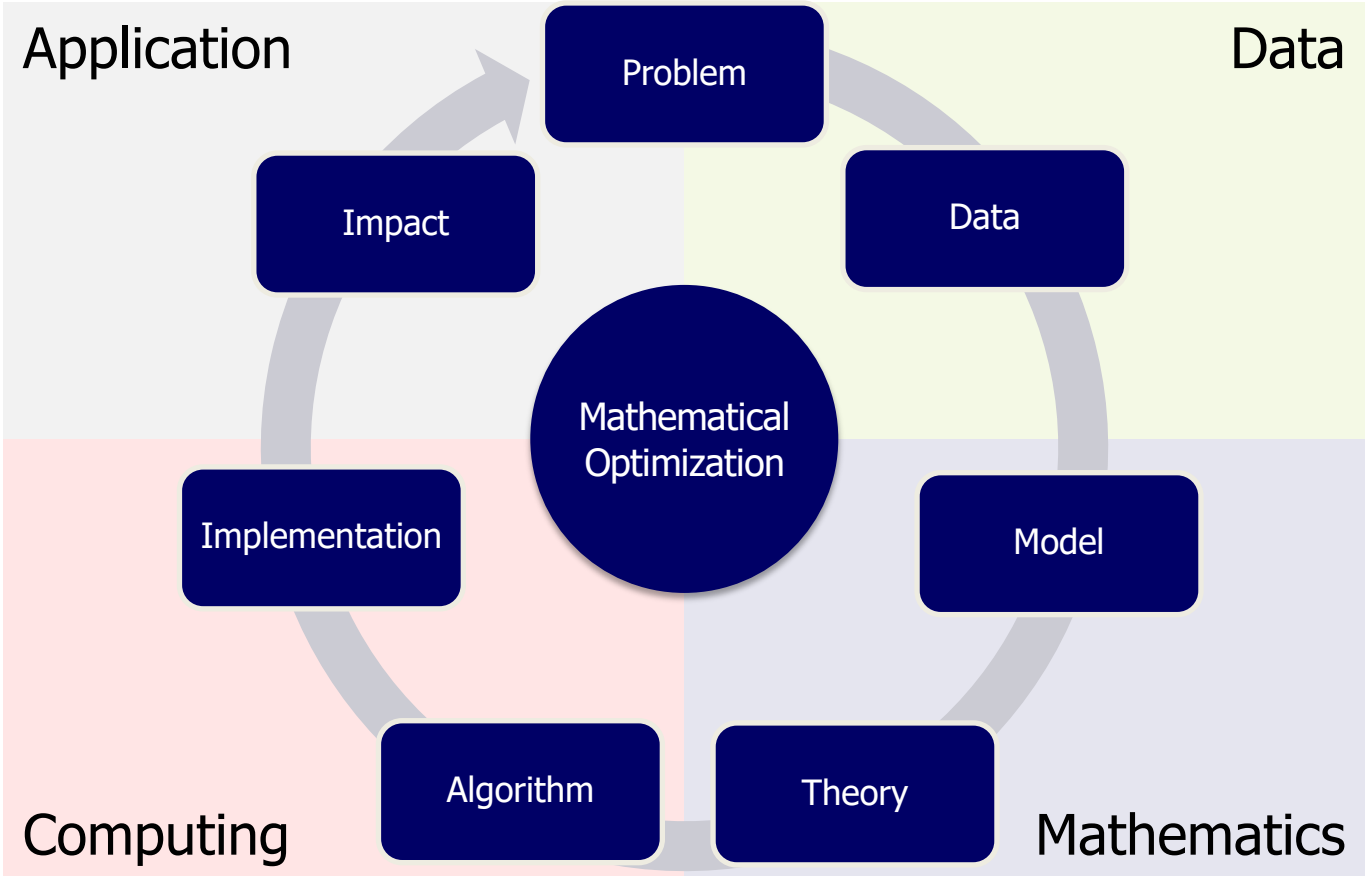
https://www.xkcd.com/435

This situation changed starting in the 1960s and particularly from the 1980s.

- The governments wanted more people to study.
  As of now, in some countries over 50% of a cohort are receiving tertiary education.
- As a result, more money had to be spent on universities and education.
- By the 1980s it was perceived that public entities were not run efficiently and were wasting public money. The *"New public management"* movement started, leading to an increased economization of government run parts of the society.
- And a major goal of it was to **make universities more (cost) efficient.**
- From the 1960s it was also perceived that universities were run by an elitist inbreed of old men.
- There was demand for more **democratization, transparency, and participation.**
- In the very end, we are talking about a resource allocation problem, i.e. operations research.



Core idea of OR

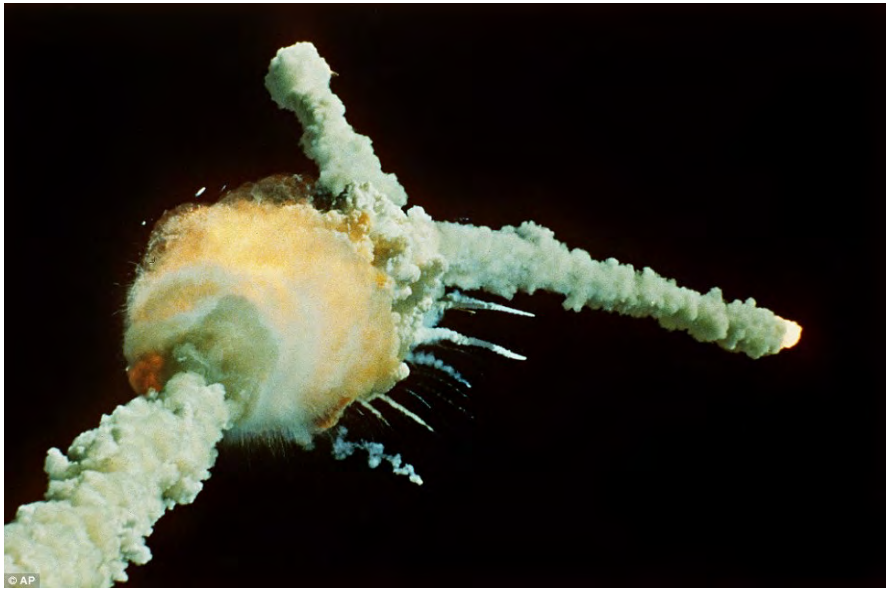


Even applied mathematicians …

- are not applying the mathematics they develop, this is done by the engineers, computer scientists, physicists, etc.
- often do not know/understand the problem they try helping to solve.
- might be more interested in nice mathematics than in the underlying problem (which they do not know/understand anyway)

As a result,

- It is up to the user of mathematics to explain the problem
- It is up to the user to find applicable mathematics
- The user might not entirely understand the mathematics involved
- It might be difficult to decide if and which mathematical approach is applicable
- The mathematical model used might not be well suited to the algorithms



- What does **Research** mean?
- I means the outcome is not yet determined.
- A research project can succeed by showing that it is not possible to achieve the initial goal.
- Research is conducted by systematically trying untested paths and devising new methods.

- **We start with a real-world task**
- to identify, understand and describe such a task, collaboration with (industry) practitioners is indispensable
- **there is a basic conflict of interests between companies and academia:**
  - Academia wants challenging problems with theoretical appeal
  - Industry prefers quick practical solutions
- challenging industrial size optimization problems are usually at least NP-hard
- access to real-world data is indispensable to find solution approaches
- the amount of work to (pre)process the data can becoming prohibitive
- **Research may fail**
- even new practical results may be hard to publish in scientific journals

Drawbacks of applied projects

- Can be very interdisciplinary
- You need an industry partner
- You are not completely free on deciding the subject
- Applied projects take longer
  (understand problem, prepare data, program)
- A substantial part of the work in unpublishable in math journals
- There is a higher risk of failure
- There are more reasons to fail / more parties involved
- **You have to adapt the approach to the problem not vice-versa**
- Projects will need more resources
- Somebody might try your results in practice

Advantages of applied projects

- They can be very interdisciplinary
- Somebody cares about the results
  - The problem is important (at least to somebody)
    - Resources (money, …) because somebody needs the problem to be solved
- Can have (immediate) impact in the real world

This is not to say that basic pure mathematical research is not important. But experience shows that it is sometimes quite difficult to explain this to anybody who is not a pure mathematician. Probably, because they first do not understand the problem to be solved and then why anybody would want to solve it in the first place.*

Benefit for Society

- A main part of the German economy is based on manufacturing
- Both the manufacturing processes as the products have to be technologically advanced to be competitive

- Therefore constant innovation is necessary

- Time from theory to finished product matters
- Knowledge transfer from research to industry matters

- We believe that mathematics can play an important role here

The gap

- Research means it is unclear whether and how something it is possible.
- Once research has established a possible path into practice, implementing this path is called development.
- Between finding that something is in principle possible and having a clear path to actually do so on an industrial scale, there is a gap.
- Sometimes many things have to be combined. While for each part it is clear that it should be feasible, it is unclear whether it is possible to glue them successfully together.

In theory there is no difference between theory and practice.
In practice there is.

(In academia, there is no difference between industrial work and academic work. In industry, there is.)

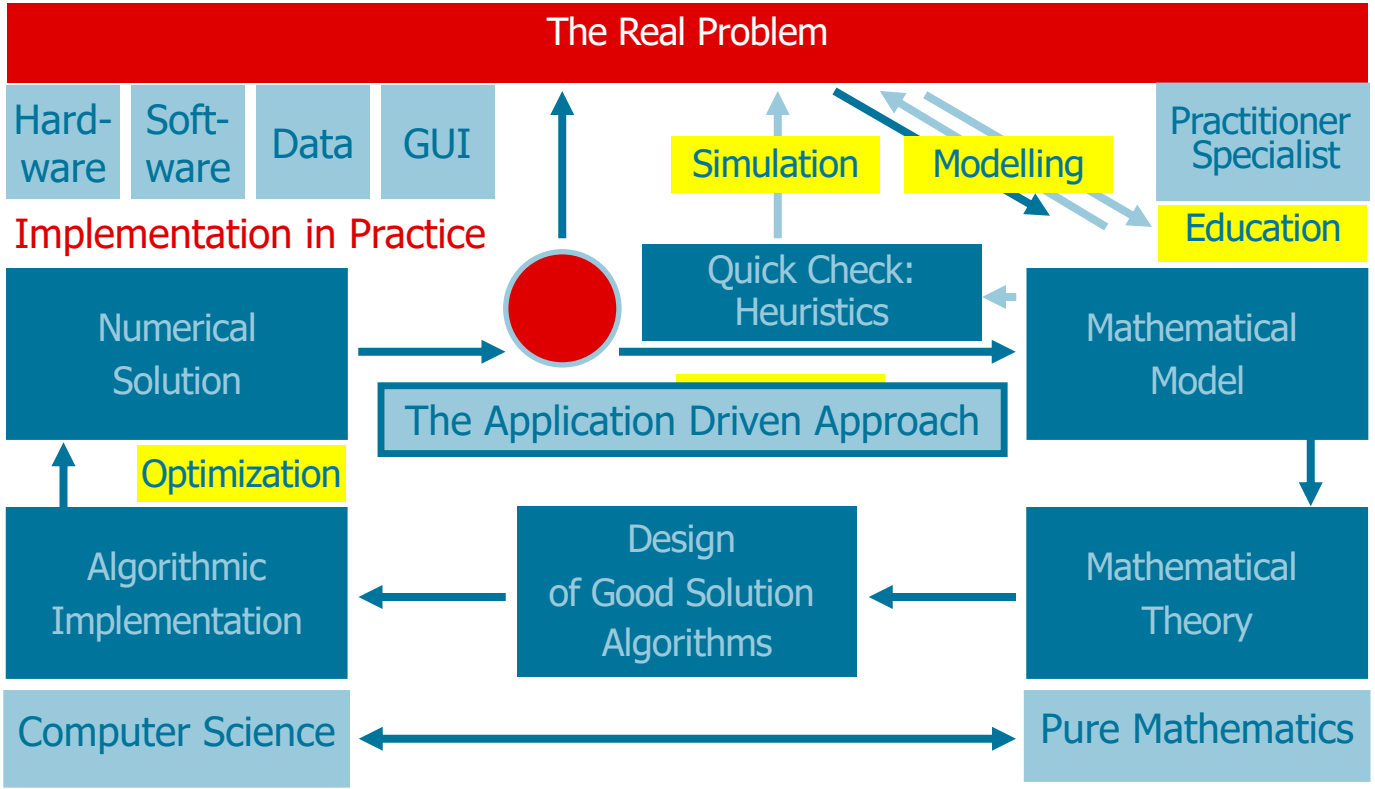
Why isn‘t it considered innovative if a solution works in industrial practise?
Guido Sands, ABB

Slight contradictions

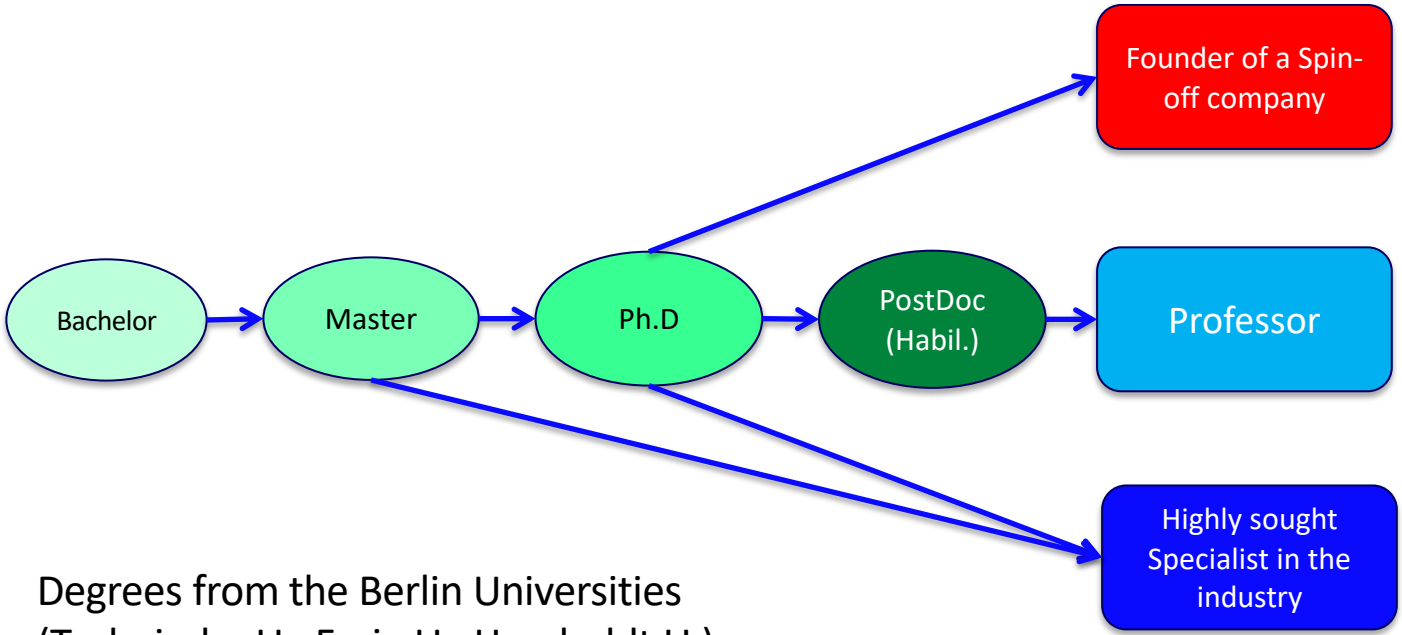
- You want to build up know-how
- Need of persistence

- You have to stay innovative
- Necessary to keep open to new ideas

The problem solving cycle



Qualification in industry related project oriented top level research



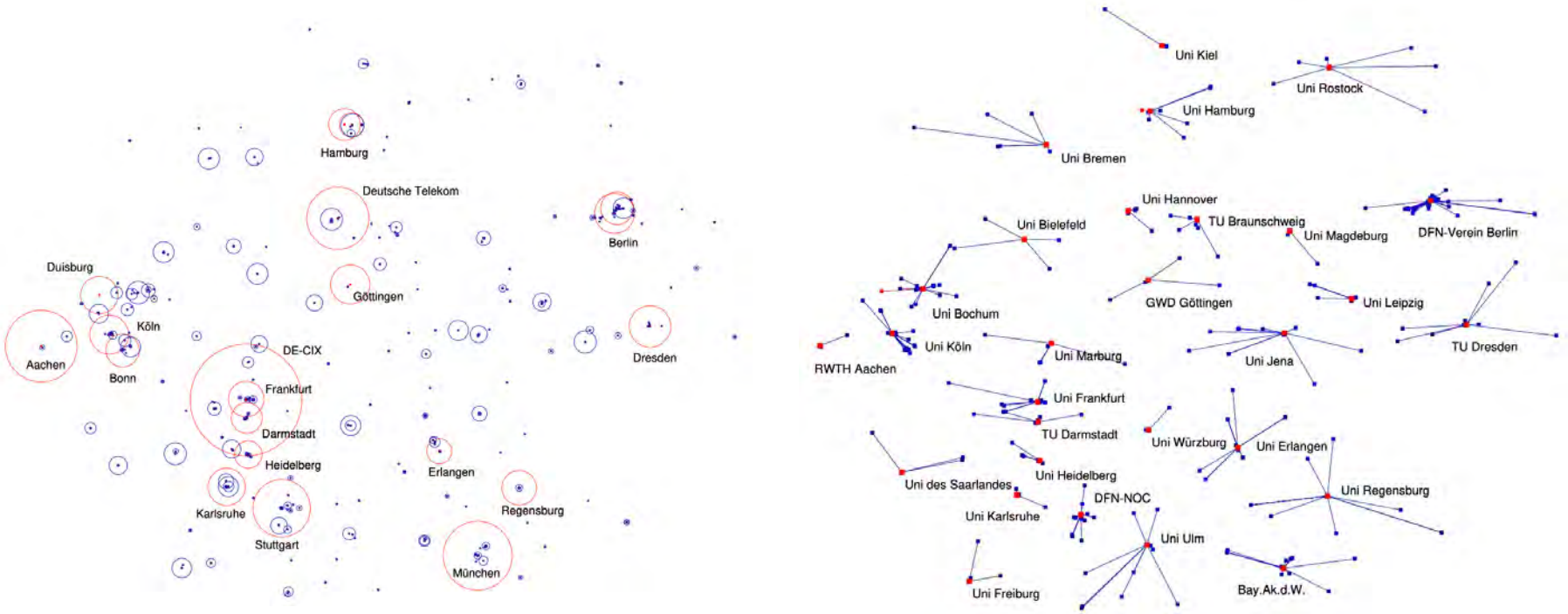
Degrees from the Berlin Universities
(Technische U., Freie U., Humboldt U.)

EXPERIENCES

Some projects

- Planning of the DFN G/X-Win Internet Backbone network
  (actually, Germany's biggest IP network, connection all the universities.)
- GSM coverage and capacity planning together with E-Plus
- Study for Australia's Patrick Corporation regarding the handling of containers in their Sydney container terminal
- Project with Siemens on Chip Design verification.
- Gas pipeline network capacity and extension planning, together with Open Grid Europe

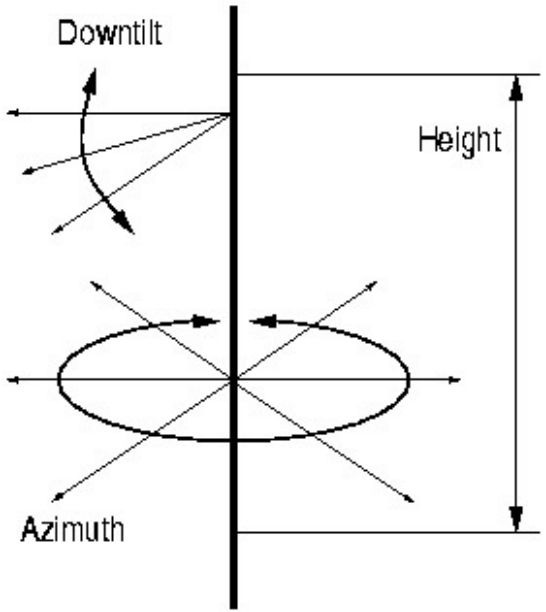
G-Win Backbone Design

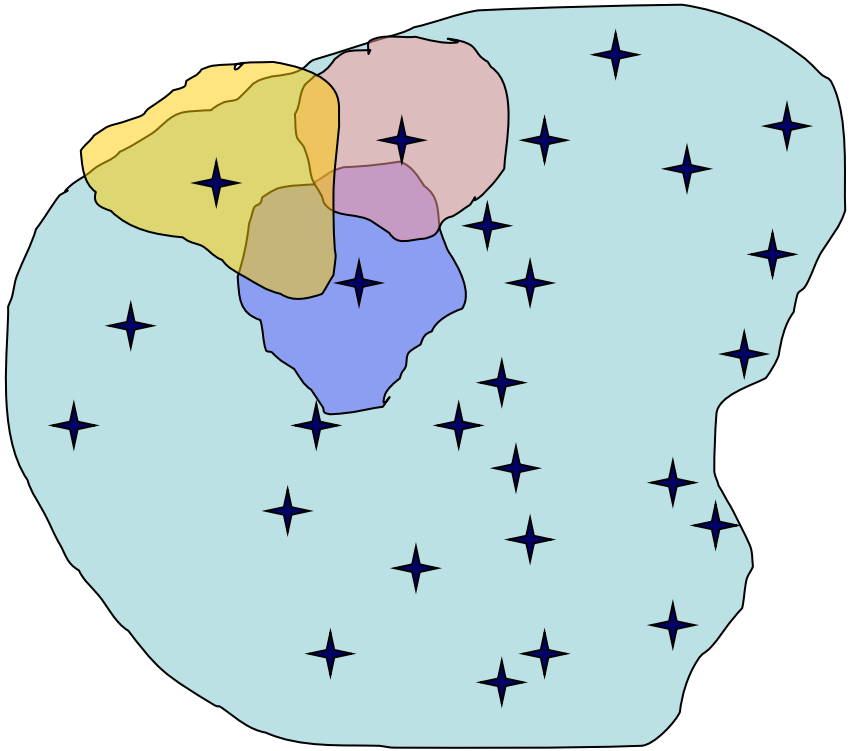


Iteratively “solved”, in the hardly any choices left.

GSM (2G) Cellular network planning

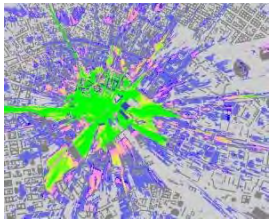
Problem: Select base station locations and their configurations to maximize coverage





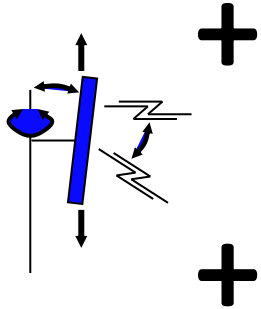
Isotropic Prediction

- Available for each potential antenna location



Antenna Configuration

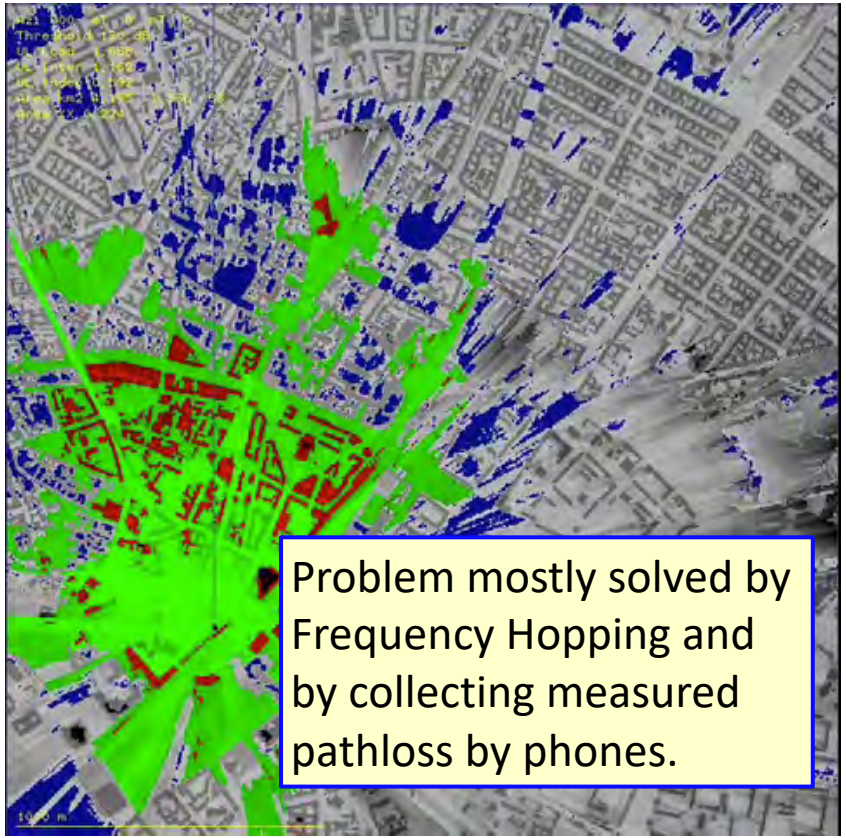
- Azimuth
- Tilt
- Height



Antenna Diagram

- Signal propagation in different directions

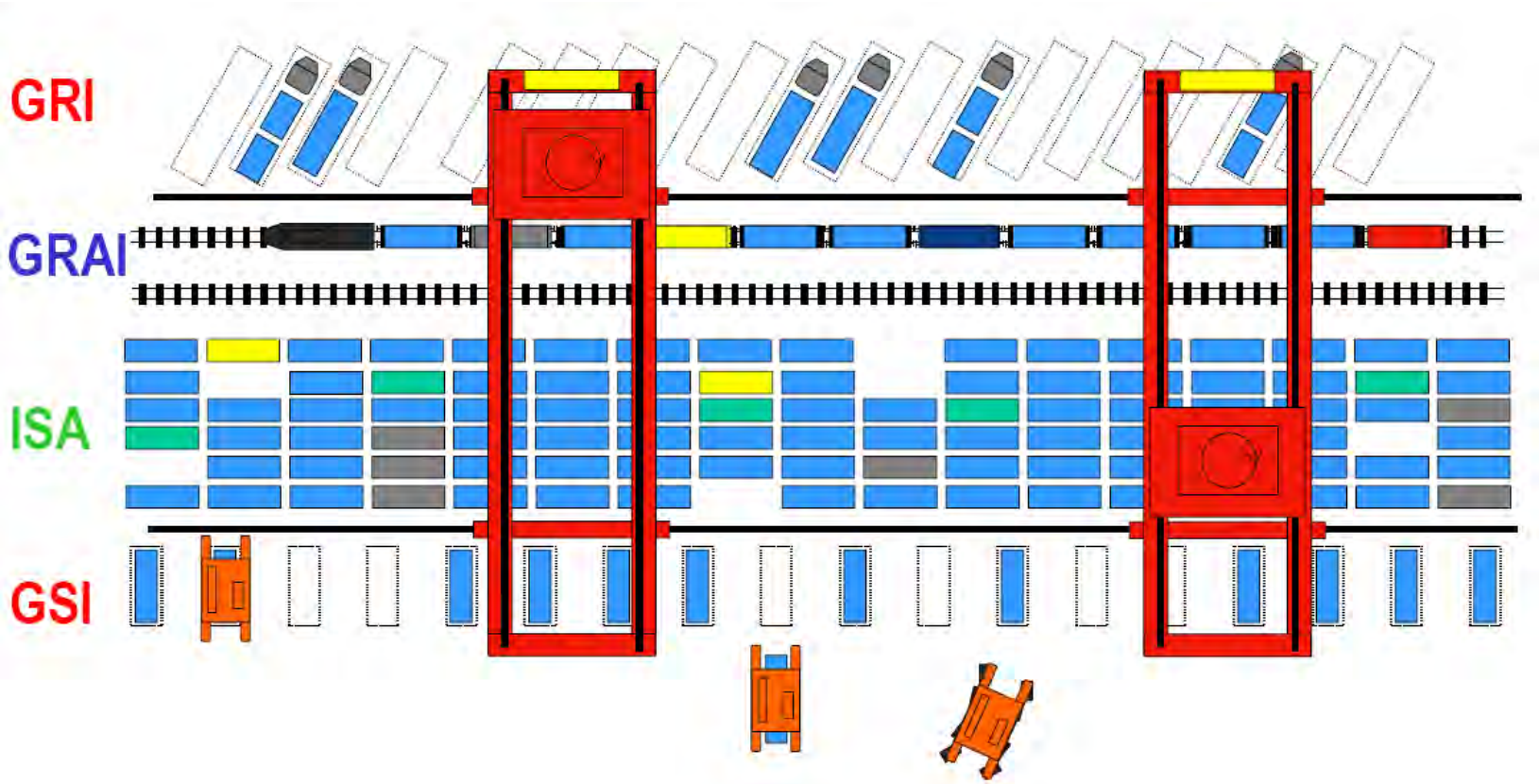
Antenna Prediction

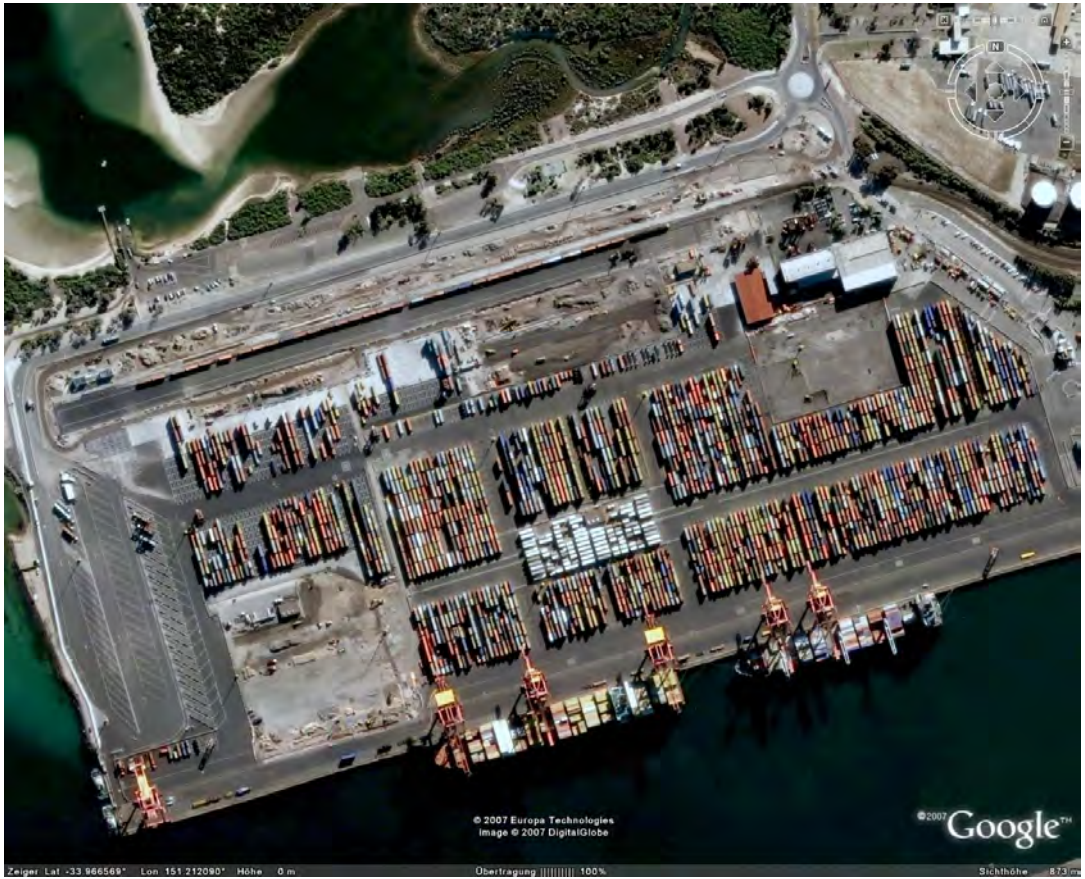


Problem mostly solved by Frequency Hopping and by collecting measured pathloss by phones.

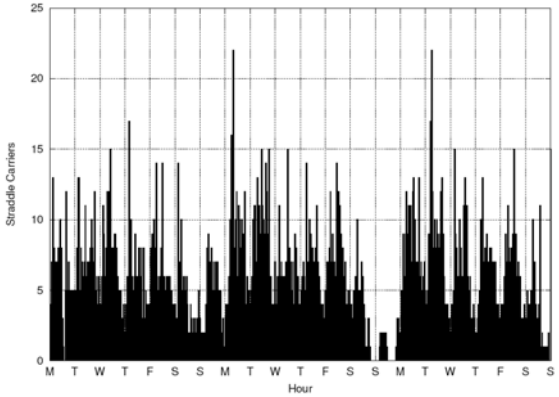
Container Terminal Bottlenecks

New Terminal Design with Intermediate Stacking Area

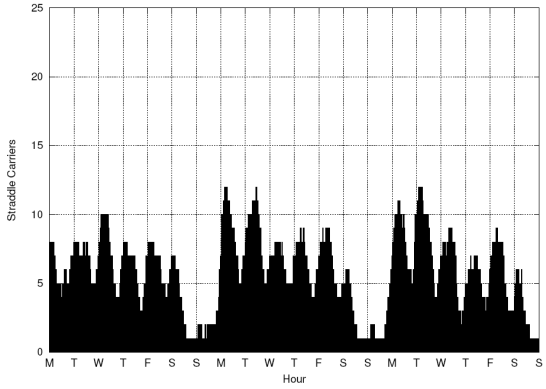



© 2007 Europa Technologies
Image © 2007 DigitalGlobe
©2007 Google™

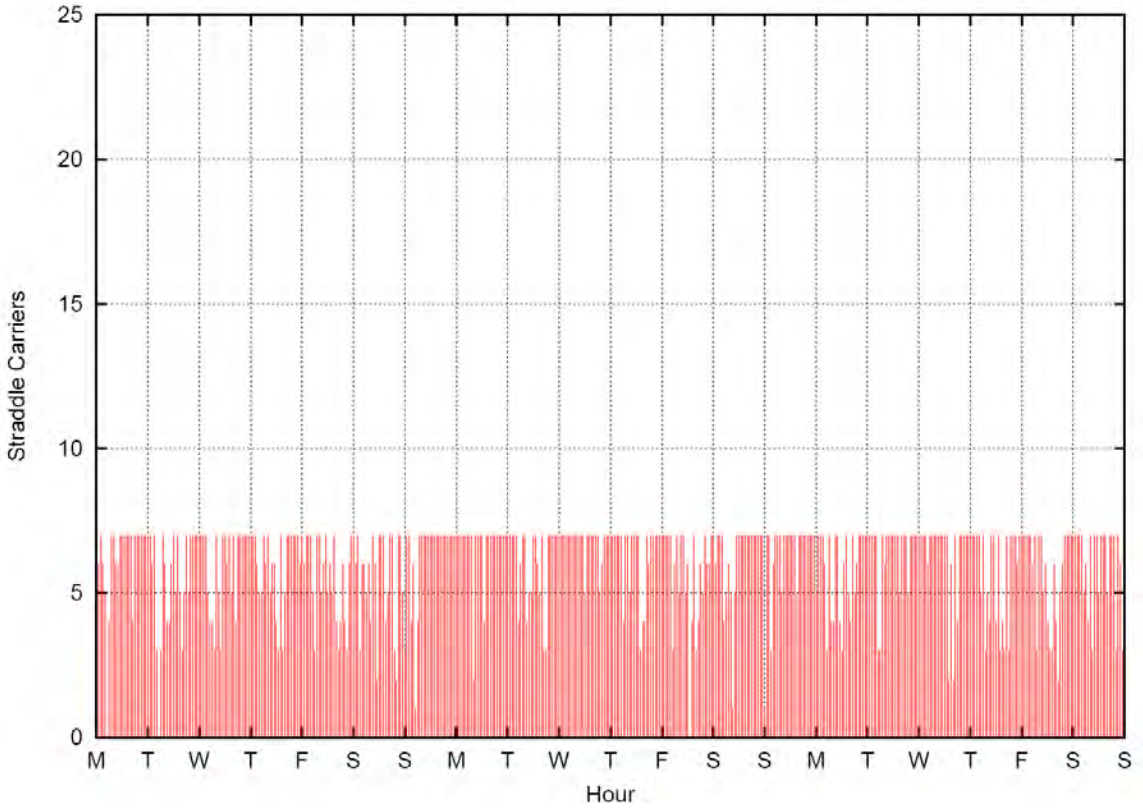
Number of Straddle Carriers needed



1 h average (22)



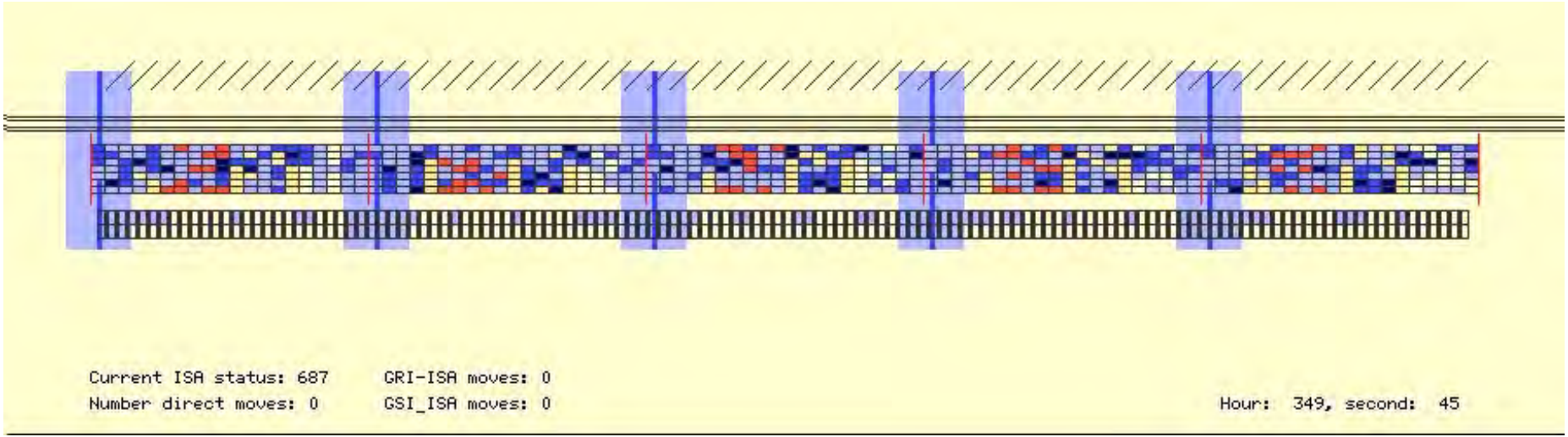
8 h average (12)



Strategic IP result (7)

Operational Decision-making: Online Algorithm

The strategic planning has leveled the field to the point where a simple online algorithm can succeed.



Conclusions

The strategic IP works very well:

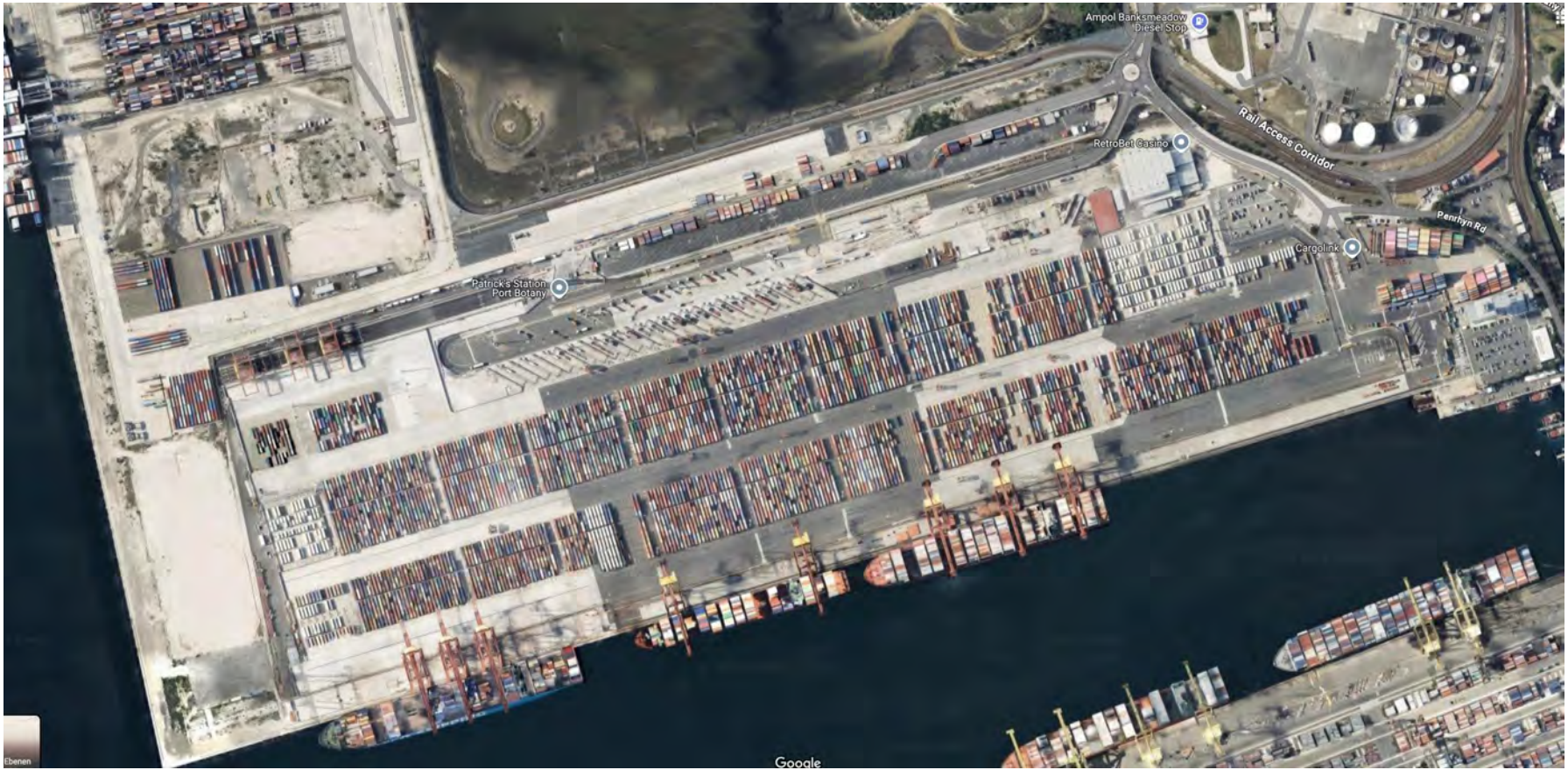
It computes feasible schedules that are globally optimal.

The global perspective ensures we do not paint ourselves in the corner.

The Space-time Divisioning leads to very efficient RMG operations.

The capacity of the ISA is heavily depending on the time needed for loading/unloading operations.

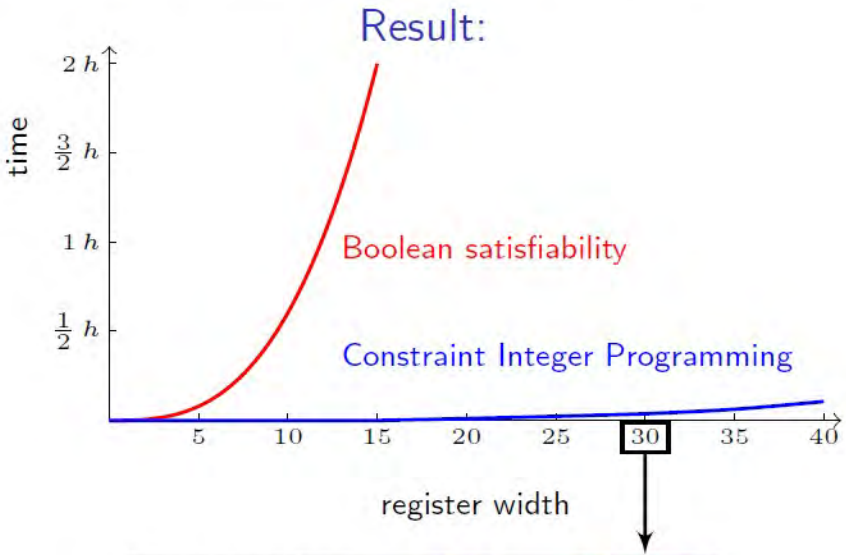
If the ISA is correctly dimensioned and intelligently controlled, it allows top performance for the landside operation with minimum resource requirements.


Ampol Banksmeadow Diesel Stop
Rail Access Corridor
RetroBet Casino
Penrhyn Rd
Cargolink
Patrick's Station Port Botany
Ebenen
Google

Chip Verification

Goal: (computer-)proof, that a design is free of errors

Method: property checking using CIPs



constraints	422	152026
variables	3714	50756

Infineon technologies

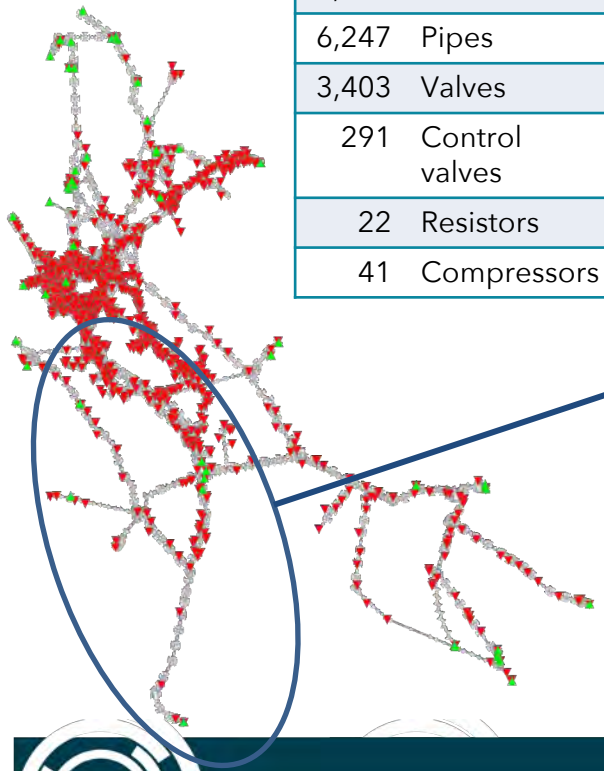
OneSpin SOLUTIONS

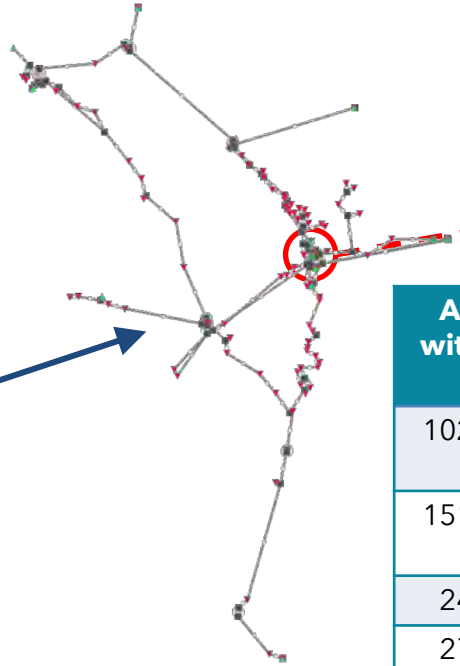
Duration: 2003-2008

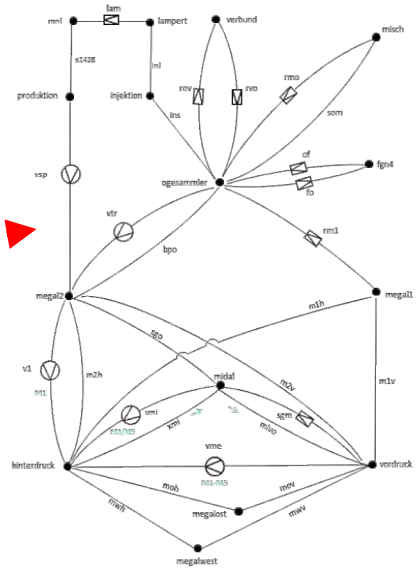
Algorithms and Certificates for Exact Mixed Integer Programming
Dissertation by
Leon Eifler
TU Berlin, 2024

Determine Transient Gas Flows with Network Optimization

Full Network	
1,194	Entries+Exits
6,247	Pipes
3,403	Valves
291	Control valves
22	Resistors
41	Compressors



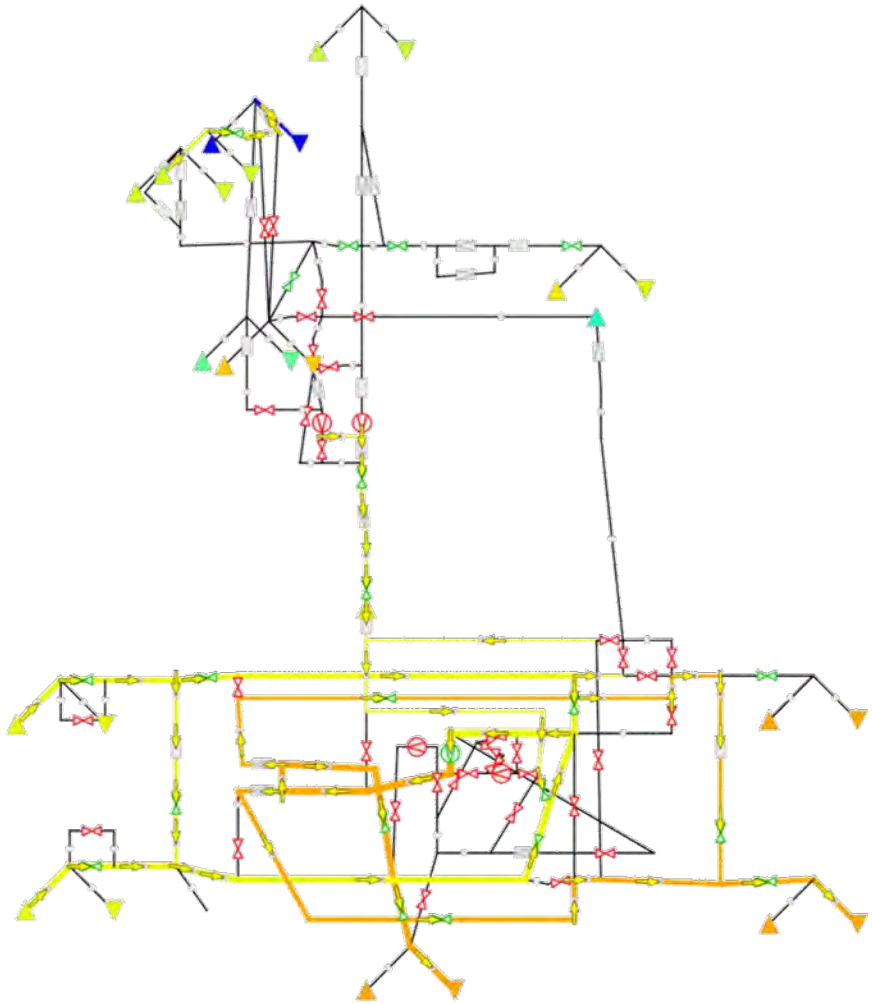


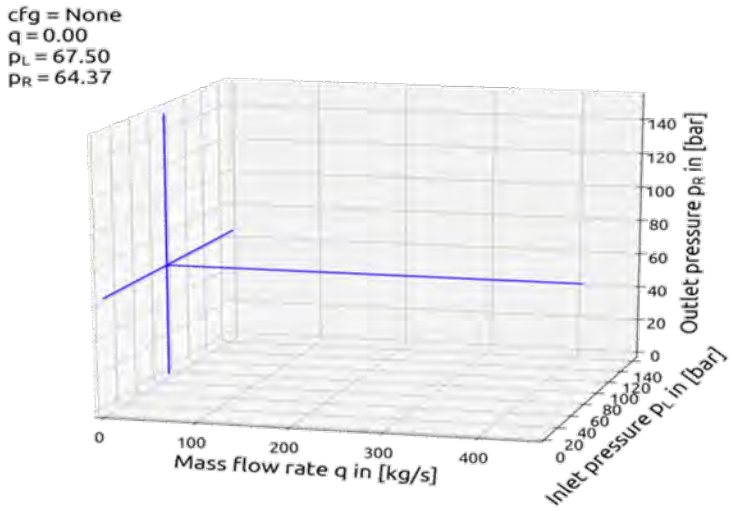


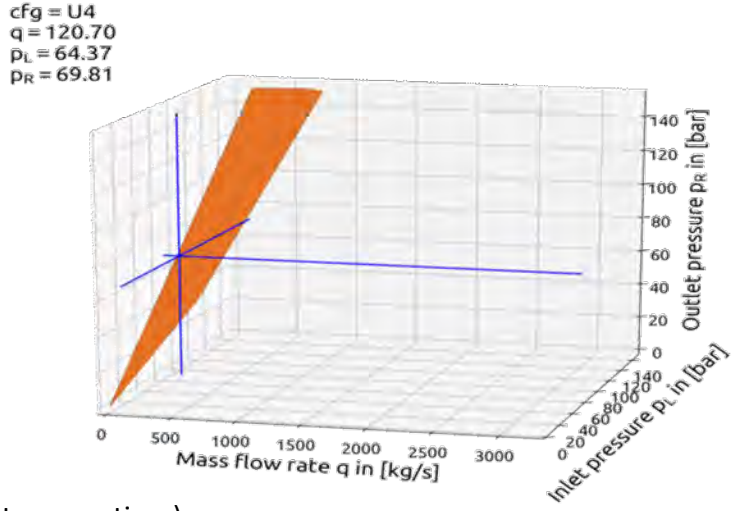
Aggregated subnet with high level station model	
102/124	Entries+Exits
151/964	Pipes
24/81	Valves
27/50	Control valves
0/11	Resistors
16/16	Compressors

The Combinatorics of Gernsheim

- 30,000,000,000,000,000 mathematically possible combinations of valve and compressor states.
- 200,000 feasible operation modes identified based on practitioners knowledge.
- 1,285 relevant operation modes extracted using analytical evaluation of historical data.







Pressure levels (color)

Amount of flow (line thickness)

Flow direction (arrows)

Element usage (red/green syms)

Current point of operation for the two active compressors in the station (Blue lines cross)

Feasible operating range for chosen set of machines:
Orange: a single machine
Blue: multiple parallel machines

Demonstrator: Station control for a flow direction change (series of states over time)

Mixed-Integer Pr ol

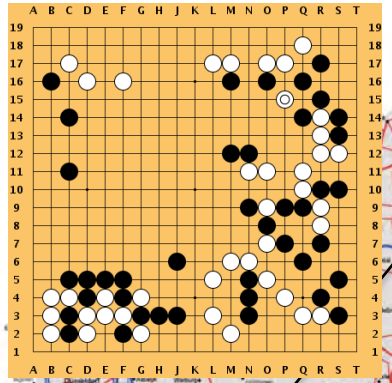
Momentum equation

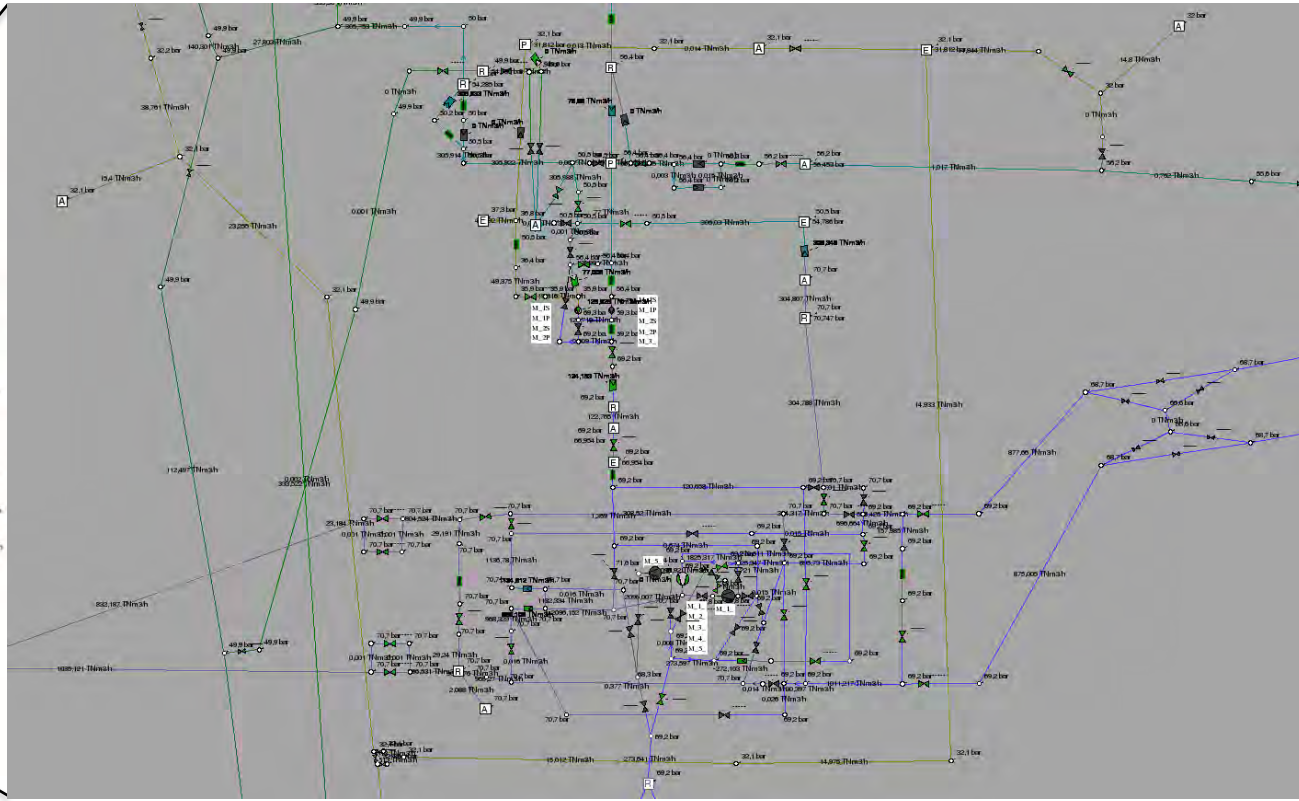
Pressure loss

Valves

Flow direction

Complex Networks: Reality is more involved than games





Used in production: SCIP-Jack

Consider (small-scale) network design instance with:

|V| = 12,715, |E| = 20,632, |T| = 475

Using generic flow formulation with CPLEX 12.10/Gurobi 9.0: **cannot be solved within 48 hours**.

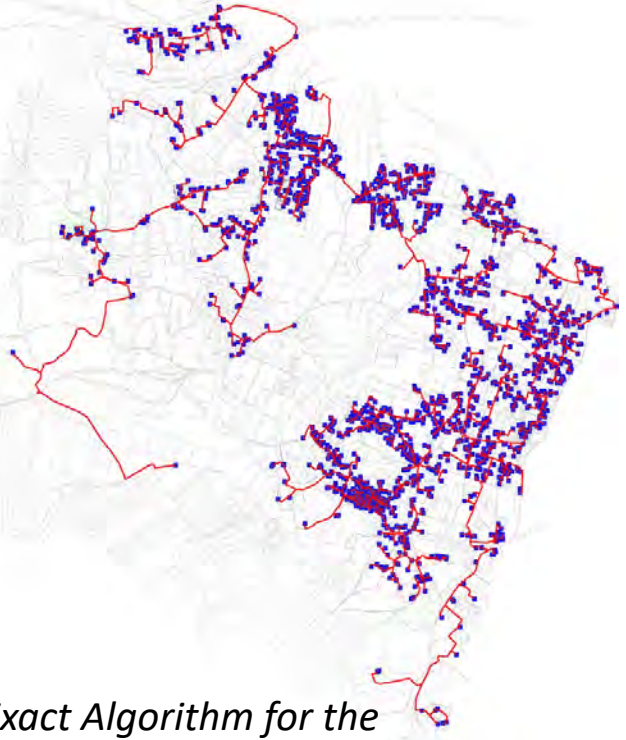
SCIP-Jack: Solves this to optimality in 0.3 seconds

Largest (real-world) instance solved by SCIP-Jack so far

|E| = 32,388,930.

For larger problems CPLEX/Gurobi run out of memory almost immediately with 64 GB RAM.

Network telecommunication design for Austrian cities, see *New Real-world Instances for the Steiner Tree Problem in Graphs* (Leitner et al., 2014)



Combining NP-Hard Reduction Techniques and Strong Heuristics in an Exact Algorithm for the Maximum-Weight Connected Subgraph Problem, Rehfeldt, K., 2019, doi: 10.1137/17M1145963

DATA!

We ask everybody of you to provide the following information:

1. A JSON file with some information about you.
2. A picture of yourself (or an avatar if you don’t want your picture online).
3. A picture of the place where you stay.

We will assemble the pictures to a virtual group photo and a slide show and use the provided information to optimize the composition of the learning groups.

The file with the information about you should be
in JSON Format (ISO/IEC 21778:2017).
https://en.wikipedia.org/wiki/JSON

The file with your picture should be
in JPEG format (ISO 10918-1) and have a size of 512 × 512 pixels.
https://en.wikipedia.org/wiki/JPEG

The file with your place should be
in JPEG format (ISO 10918-1) and have a size of 1920 × 1080 pixels.

The JSON file should contain the following fields

Field Name	Type	Description
Name	String	Your full name in your native language
Email	String	email address you used for registration at CO@Work
Country	String	country of origin as an ISO 3166-1 Alpha-2
Languages	Array of Strings	List of all languages you speak as ISO 639-1 codes. Use capital case if you are fluent in the language and lower case if you only have limited knowledge.
Motto	String	motto/aphorism characterizing you to write under your picture
Clearance	String	I herewith grant the organizers the right to use and share the attached pictures for purposes related to CO@Work
Skill	Integer [0-100]	How would you rate your Skill in Computational Optimization
Level	Integer [1-5]	What is your current level of education: 1 = Undergraduate, 2 = Master's student, 3 = PhD student, 4 = Postdoc or professional, 5 = Prof.
Tools	Array of Strings	Which optimization software tools have you used: None, Xpress, Gurobi, SCIP, Copt, CPlex, HiGHS, GAMS, AMPL, …
CourseProject	Boolean	Have you worked on a real-world optimization problem (e.g., energy, logistics, finance) in a course project?
ResearchProject	Boolean	Have you worked on a real-world optimization problem (e.g., energy, logistics, finance) in an academic project?
IndustryProject	Boolean	Have you worked on a real-world optimization problem (e.g., energy, logistics, finance) in an industry project?
Experience	Integer [0-3]	0 = I have not implemented any, 1 = I used prebuilt implementations, 2 = I implemented optimization algorithms from scratch, 3 = I have developed advanced/custom optimization algorithms

JSON File Example

```
{ "Name": "Thorsten Koch“, "Email": "koch@zib.de", "Country": "DE",
"Languages": [ "DE", "EN", "la" ],
"Motto": "The code was hard to write, it should be hard to read",
"Clearance": "I herewith grant the organizers the right to use and
share the attached pictures for purposes related to CO@Work",
"Skill": 92, "Level": 5,
"Tools": [ "Cplex", "Xpress", "Gurobi", "Copt", "SCIP" ],
"CourseProject": false, "ResearchProject": true,
"IndustryProject": true, "Experience": 3
}
```

Please submit the files as follows:

- *LastnameFirstname* should be the English transcription of your name
- The name of the JSON file should be *LastnameFirstname*.**json**
- The name of the file with your picture should be *LastnameFirstname*.**jpg**
- The name of the file with the picture of your place should be *LastnameFirstname*-**place**.**jpg**
- All 3 files should be **attached** to an email
- Send the email to coaw-data@zib.de
- The subject of the email should be CO@Work: Data for *LastnameFirstname*
- *Please, as soon as possible (e.g. today!)*

113 Emails + 12 Updates/corrections

With error: ~78, let's say 2/3

```
CO@Work : Data for PeterPeng
CO@Work: Data For PeterPeng
CO@Work: Data for Peter Peng
Data for PeterPeng
CO@Work: Data for LastnameFirstname
```

Deadline 18.09 at 20:00

18.09.24, 20:00
18.09.24, 20:17
18.09.24, 20:31
18.09.24, 21:00
18.09.24, 21:03
18.09.24, 21:05
18.09.24, 21:35
18.09.24, 22:36
18.09.24, 23:39
00:32
10:42

Picture sizes

200	x	200
428	x	512
500	x	500
512	x	513
519	x	519
524	x	289
623	x	623
1280	x	720
1310	x	494
1326	x	820
1620	x	1080
1697	x	1934
1920	x	1920

Some Errors

- *LastnameFirstname* not **lastnamefirstname** or **Lastname Firstname**
- The extension of the image files should have been .jpg, not **.jpeg**, or **.JPG**.
- *LastnameFirstname*-**place.jpg** not **_place** or **-Place**
- In 13 cases the email address was not the one used for the registration, including: [your_email@example.com]
- 2 times the Motto was empty
- The Clearance did not have a “.” or "\x93,\r\n" at the end, no line break in the middle, and **CO&Work** is also wrong, as is **hereby, here with**.
- Many cases were (probably) the editor changed " to “ or ” or inserted a line break making the JSON invalid.
- Languages wrong type [DE, EN, fr], CourseProject wrong type, ResearchProject wrong type, IndustryProject wrong type.
- Field Motto missing “Moto”, field Country wrong type, field Languages missing “Language”, field IndustryProject missing “Industryroject”.
- …

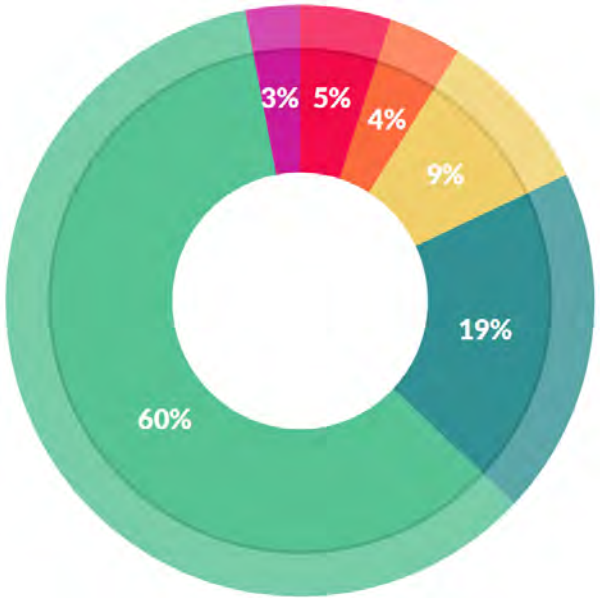
Non existing ISO-639 language codes:

P0	1
SE	1
CZ	1
GR	1
CN	1
VN	2
cn	2
AL	1
KG	1
ua	1

JSON parsing errors

```
Expecting property name enclosed in double quotes: line 1 column 2 (char 1)
Expecting property name enclosed in double quotes: line 1 column 3 (char 2)
Expecting property name enclosed in double quotes: line 1 column 2 (char 1)
Expecting property name enclosed in double quotes: line 2 column 5 (char 6)
Invalid control character at: line 7 column 129 (char 299)
Invalid control character at: line 7 column 99 (char 272)
Invalid control character at: line 4 column 99 (char 250)
Invalid control character at: line 4 column 99 (char 223)
Invalid control character at: line 6 column 99 (char 261)
Invalid control character at: line 4 column 99 (char 263)
Expecting value: line 3 column 10 (char 144)
Expecting value: line 10 column 5 (char 184)
Expecting value: line 6 column 10 (char 122)
Expecting value: line 8 column 5 (char 141)
Expecting value: line 3 column 10 (char 119)
Expecting ',' delimiter: line 1 column 32 (char 31)
Expecting ',' delimiter: line 7 column 5 (char 168)
Expecting ',' delimiter: line 1 column 28 (char 27)
Expecting ',' delimiter: line 1 column 32 (char 31)
Expecting ',' delimiter: line 1 column 32 (char 31)
Expecting ',' delimiter: line 1 column 26 (char 25)
```

Data Scientists spend time on ...



What data scientists spend the most time doing

- Building training sets: 3%
- Cleaning and organizing data: 60%
- Collecting data sets; 19%
- Mining data for patterns: 9%
- Refining algorithms: 4%
- Other: 5%

Cleaning Data

from Cloud Flowers Data Science Report 2016

http://visit.crowdflower.com/rs/416-ZBE-142/images/CrowdFlower_DataScienceReport_2016.pdf

Data

You would think a …

- … cellular network operator knows where its base stations are located?
- … fixed network operator can tell where the parts of its network are connected?
- … chemical company knows how many plants they have?
- … 5 m long pipeline cannot have a height difference from end-to-end of 100 m?

- Many companies have their data in Excel.
  There is no formal validation or referential integrality check.
- If they did formal validation, usually they found there was information they needed which they could not input and they started to “reuse” some data fields.
- If there is not at least 1 error per 100 data sets you are not looking hard enough.
- Usually, the data changes all the time.
- They might not want to give it to you.
- The data might just not exist.

The first result of an optimization project is usually to improve the quality of planning data available at the company.

Project!

How to convince the industry people that you can help them:

- They are the specialists for the topic not you.
- Be aware they do not want a result that says:
  We can prove there exists a unique solution.
- Even if you know something about their business, regardless whom you ask, they will tell you : “We are special”
  Corollary: Since everybody is special, they are all equal.
- If you try to convince them by showing something similar, they might have a very narrow view with little abstraction ability.
- If asked, how much you can improve on the current solution, the correct answer is 15%
  (see G. Dueck, DMV-Mitteilungen, 2003, 44-45)

Sometimes a company will suggest to do a pilot project first:

- The unspoken expectation is that you put in more resources than what you are paid for.
- Chances for a continuation project are as good with or without a pilot project.
- You will have trouble to get up your prices again afterwards.
- If you do this, the default has to be the continuation. Just suggest the right to drop out at a certain point in case of failure.

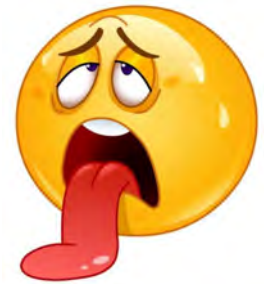
Making a contract

- Deliverables
- Intellectual property rights (patents)
- 3rd party code
- Don’t do maintenance
- Right to publish
- Right to give talks
- Right to cooperate with others (incl. NDA conditions)
- Right to continue afterwards with others (competitors)
- Rights on data (esp. afterwards)
- What to do if the industry partner does not keep their milestones?

Remember: The contract is basically useless, as you will never sue and can do little later on.

The company will involve lawyers.
Your institute or university might do also:

- Lawyer like to dispute by attrition and exhaustion.
- They usually do not understand what the project is really about.
- They have no problem to argue at length about how to distribute the members of the empty set.
- They are obsessed with low probability worst cases.
- They try to cover all cases without any formal method and often without understanding the concept.
- They will usually not converge unless by
  massive time pressure and order from above.
- They are necessary and will take time.
- You do not understand the implications of their writing.



The project setup / classical approach

We have a problem to solve,

The project setup / classical approach

we have a teacher,

The project setup / classical approach

… and we have a very determined

Now, the student supervised by the teacher attacks the problem.

This is what we call the classical “Hero Approach”.

The project team

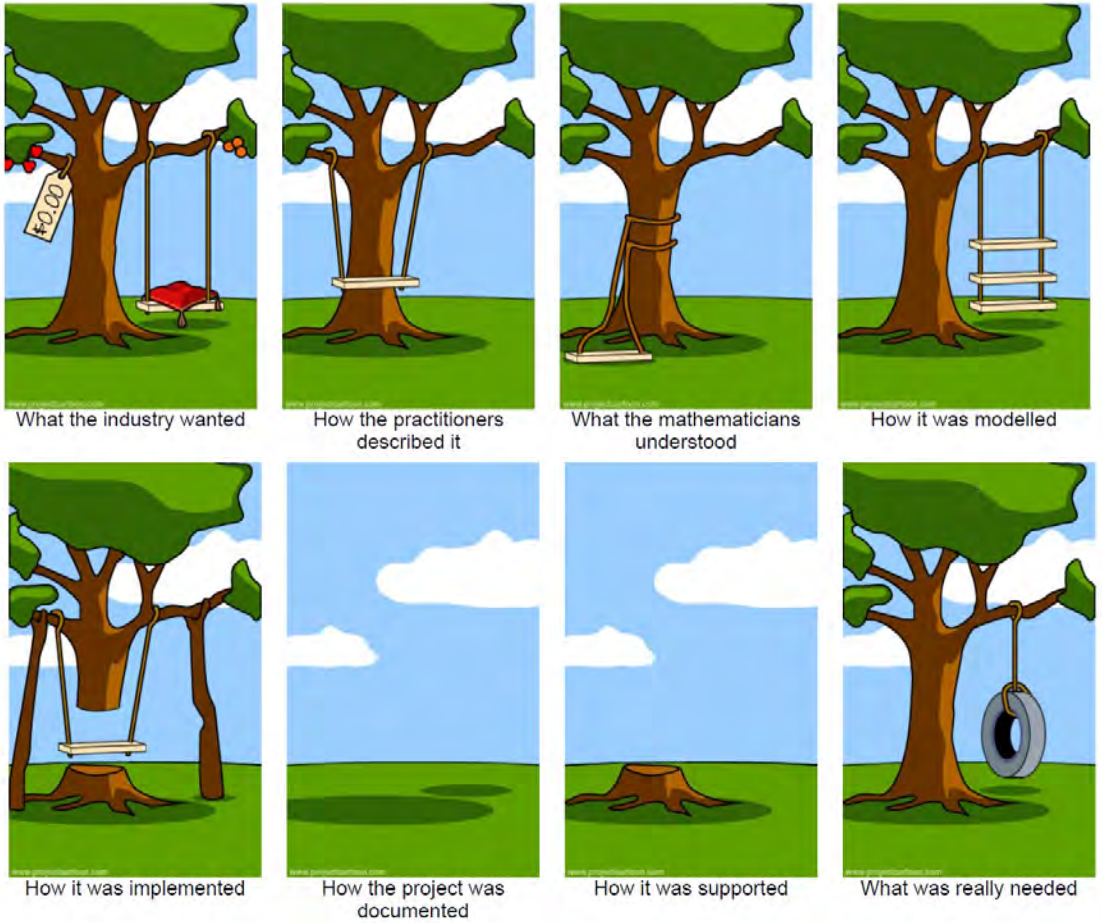
What if the problem is too big and you need a whole team to tackle it?

Maybe you do not have the necessary expertise and need to cooperate with other institutions.

Mathematical research usually has no suitable infrastructure to run big projects with non-disjunctive tasks.

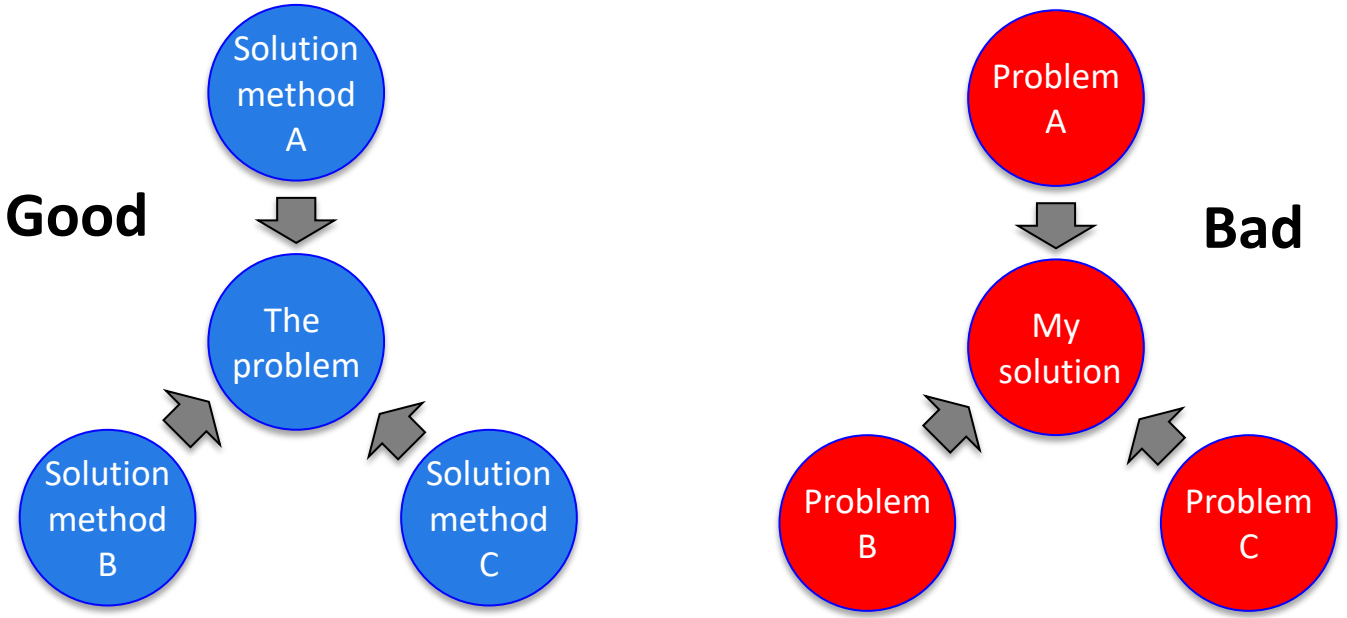
Details!

Describing the problem



Think and act problem centric

- It is more important to solve the right problem than to solve the problem right.
- Identifying the problem is half of the way to the solution.

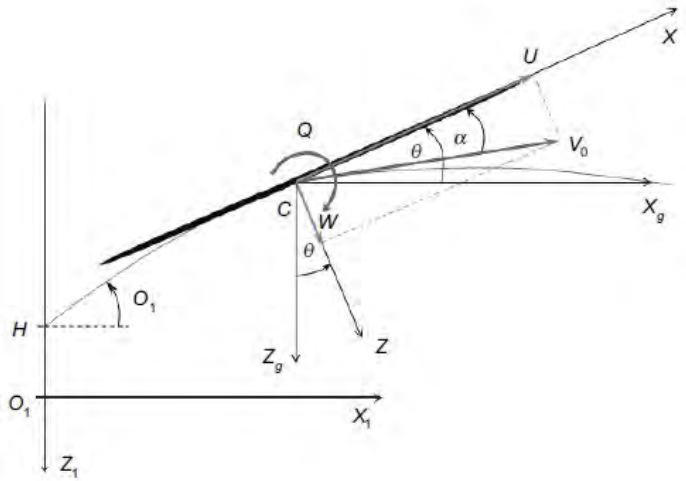


The same words may have different meanings in different Communities:

Speak the language of the problem owner

- Technical terms
- Mother tongue
- Their problem is your problem and your solution has to become their solution.
- Do not trust assumptions.
- Convince the decision makers – not only the techies.

Javlin throwing: Theory



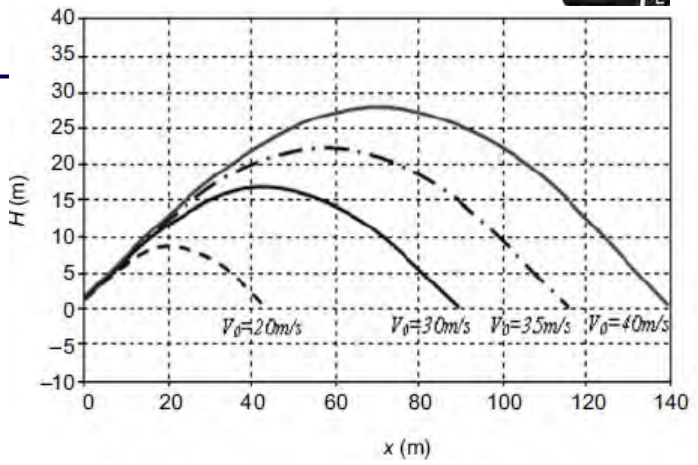
$$\frac{d}{dt}\left(\frac{\partial T^*}{\partial U}\right)+\frac{\partial T^*}{\partial W}Q=Q_U^*$$

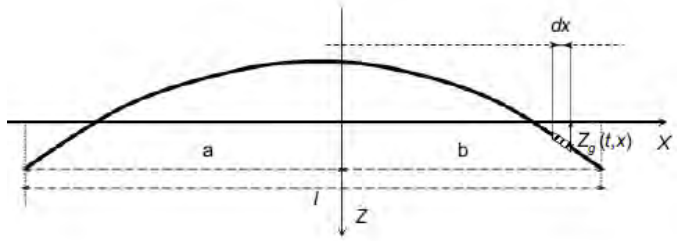
$$\frac{d}{dt}\left(\frac{\partial T^*}{\partial W}\right)+\frac{\partial T^*}{\partial U}Q=Q_w^*$$

$$\frac{d}{dt}\left(\frac{\partial T^*}{\partial Q}\right)+\frac{\partial T^*}{\partial U}W-\frac{\partial T^*}{\partial W}U=Q_Q^*$$

$$\frac{d}{dt}\left(\frac{\partial T^*}{\partial q}\right)-\frac{\partial T^*}{\partial q}+\frac{\partial V_{zg}}{\partial q}U=Q_q^*$$

(11)





Mathematical Modeling and Numerical Simulations of Javelin Throw
J. Maryniak, E. Ładyżyńska-Kozdraś, E. Golihska
J. of Human Movement, Vol. 1 (2009), 16-20

Javlin throwing: Sports

Javelin throwing: Real life practice

The improvement potential is always 15%

- 5% ⇨ “So much we save by simply pushing the employees.”
- 10% ⇨ “Sounds poor. We could do similar ourselves if we would get as much money as you ask for.”
- 20% ⇨ “this sounds very ambitious. You must remember: if we give you the money, we have to promise 20% to our boss. We dare not to do this.“
- 30% ⇨ “Braggart! Get out!”

From this it follows that you have to say 15%.

- I said 15% and immediately got a signature
- I said 13 % ⇨ “Why such a crooked number? How could you be so precise?”
- I said 14%, same result.

I stayed at 15 percent. Always 15 percent. Only 15 percent. All nodded, everybody satisfied. I had discovered an absolute Natural constant!

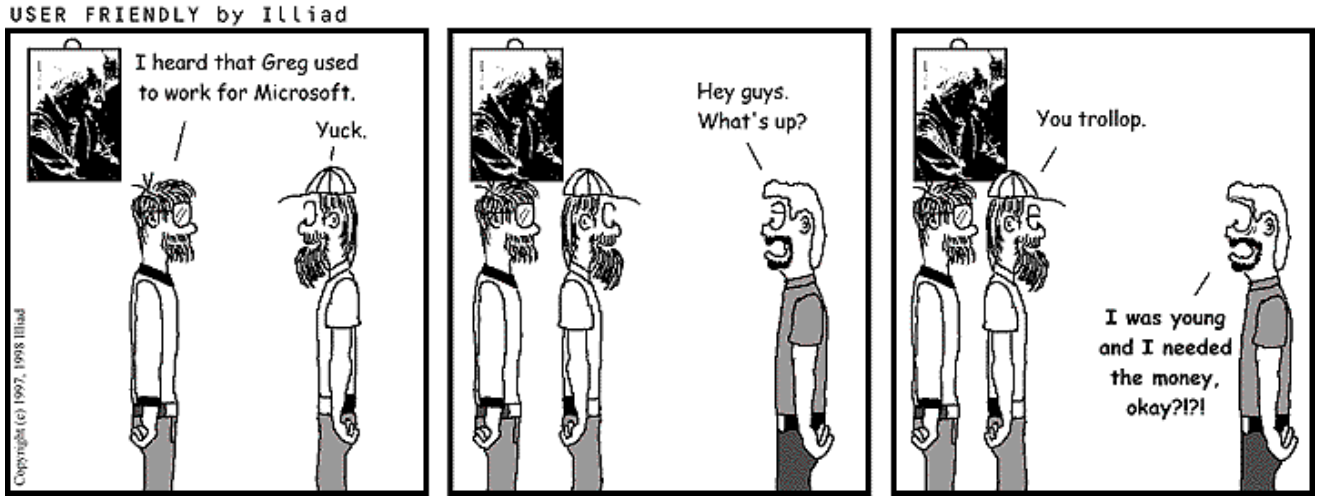
Mathematics always saves 15%. Completely regardless of the Problem!

15 Prozent. QED. Oder gibt es schon falsche Fünfzehner?! Gunter Dueck. Das Sintflutprinzip. Springer. 2000

Why do real-world projects at all?

- take a lot of time and effort
- can fail miserably
- often lack theoretical appeal
- results may be hard to publish

- have impact in the real-world
- challenging because rules are set
- improve something people use
- somebody actually cares about the result



WRONG ANSWER!

The way to real-world applications

	Problem definition	Real world constraints	Data	Code
Pure research	None	None	None	None
Applicable research	General	Unknown	Random/Simplified	Whatever
Applied research	General	Maybe	Random/Simplified	Whatever
Case study	Simplified	Some	Simplified	Whatever
Planning application	Simplified	Some more	Simplified/Real	Production
Control application	Complete	all	Real	24/7

How to make optimization solutions work in industrial practice? Have the right people with the right mindset!

- Industry is full of optimization problems, but they are often not obvious – identifying them is part of the job.
- Excellent mathematics which fits to the challenges of the application is necessary but not sufficient for success.
- Having the right people with the right mindset is a key to success.

Why isn't it considered innovative, if a solution works in industrial practice?

The final test of a theory is its capacity to solve the problems which originated it.

George Dantzig (1963) in

Linear Programming and Extensions

Fragen

有問題嗎

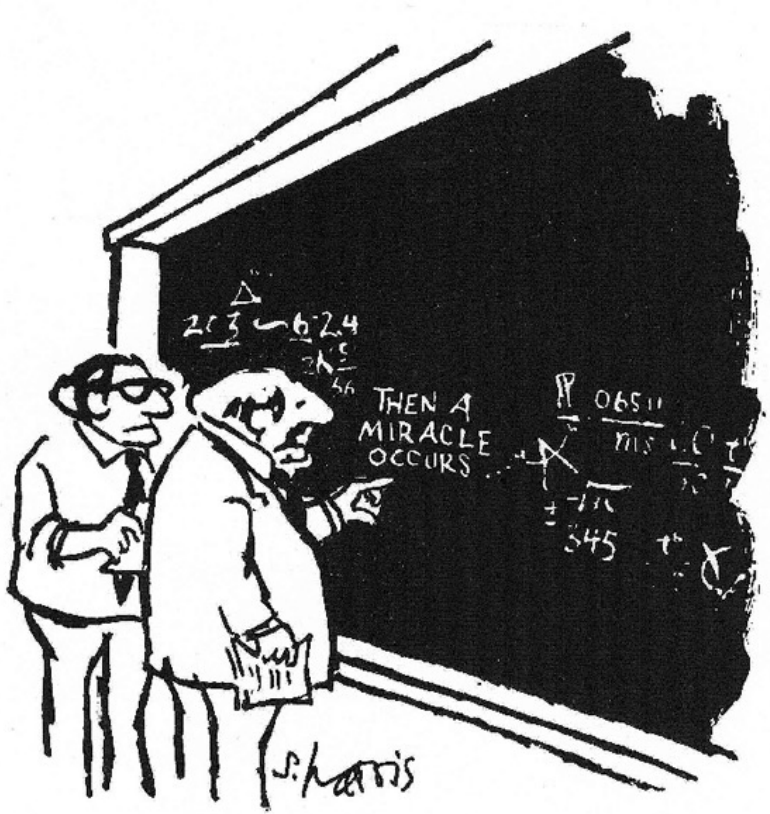
คำถาม

質問

Вопросы

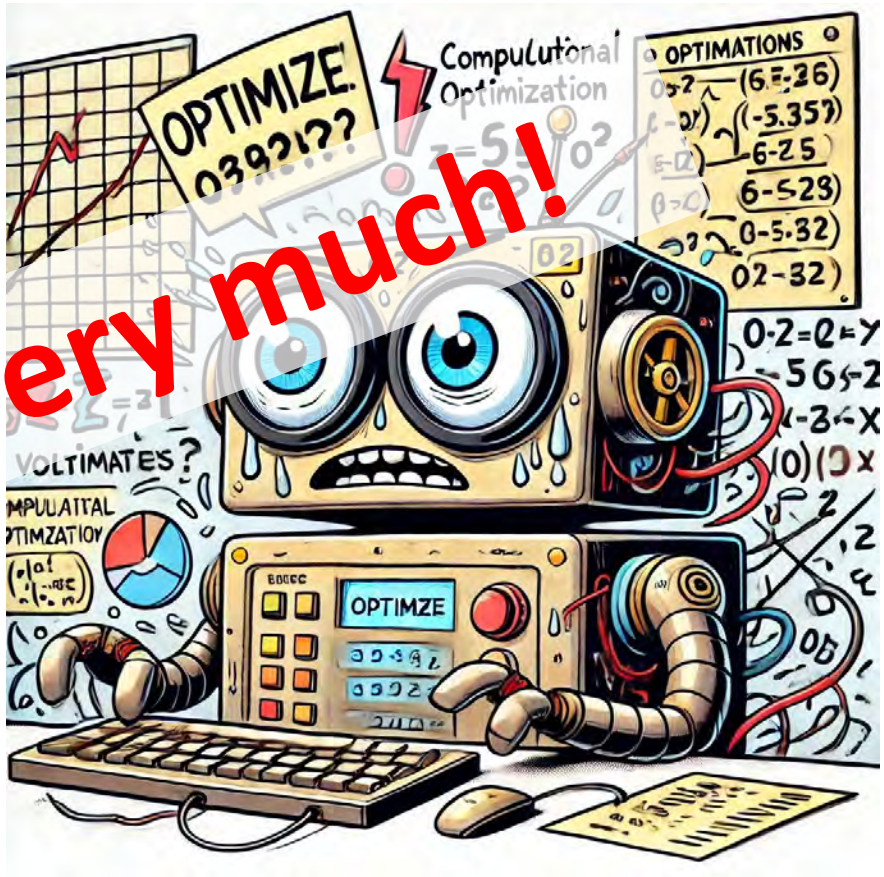
Questions

Câu hỏi



"I think you should be more explicit here in step two."


Thank you very much!


OPTIMIZE
Computational Optimization
OPTIMATIONS
OPTIMZE