A Flow-Based Solver for Large-Scale Combinatorial Optimization (Applied to the Swiss Federal Railways)

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SBB CFF FFS

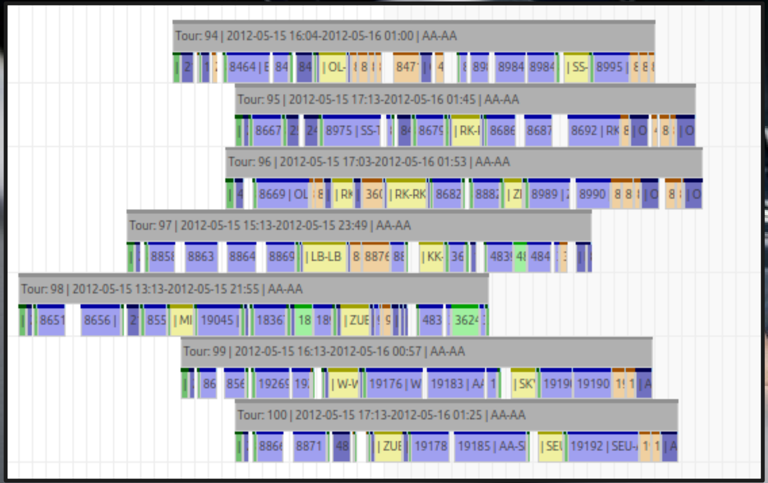
Success Story: Crew Diagramming

massive planning challenge

per planning day swiss-wide

20000+ train legs

1000+ shifts



3000+ train drivers

70+ depots

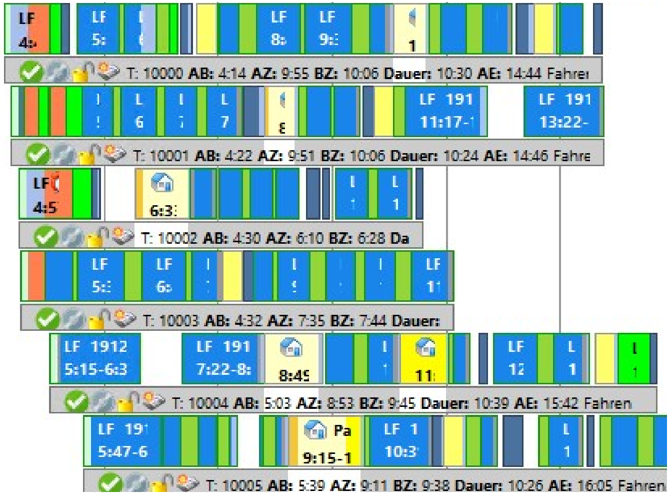
Crew Diagramming

Instance

- Tasks: start-/end-time, start-/end-location
- Data: depots, qualifications, service trip options

Task

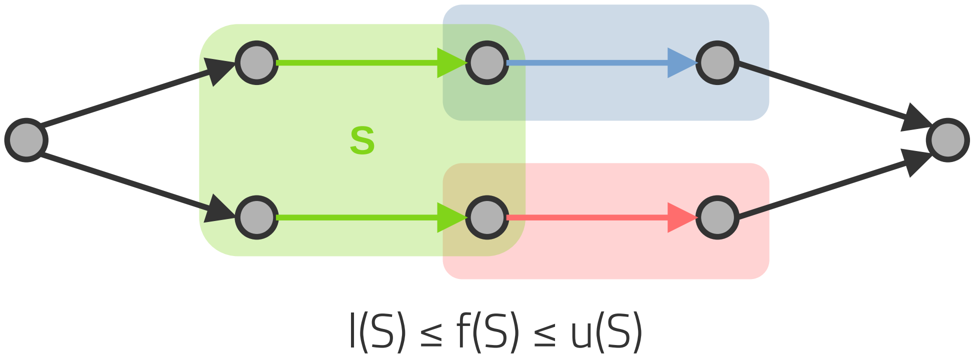
Minimize the number of crew diagrams such that each task is contained in exactly one crew diagram and labor rules are satisfied, e.g. consistency (geographic, temporal, qualifications), max. worktime, breaks, etc.



Set Constrained Flow

Instance

- Graph: G
- For each edge: cost c_e
- Edge sets: $S_1,\ldots,S_k$
- For each set S:
  - lower bound l(S)
  - upper bound u(S)



Task

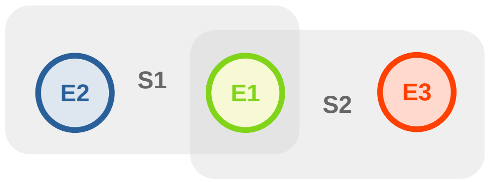
Minimize total edge-flow costs over all conserving flows such that l(S) ≤ f(S) ≤ u(S) for all S

Facts

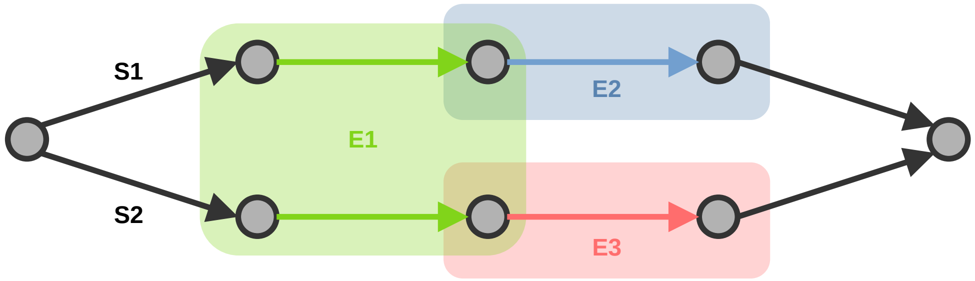
Set Constrained Flow

- NP-complete
- Direct special cases
  - Minimum Cost Flow
  - Set Cover
  - Crew Scheduling
- MIP formulation
- Dantzig-Wolfe

Set Cover



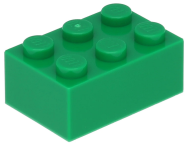
SCF Formulation



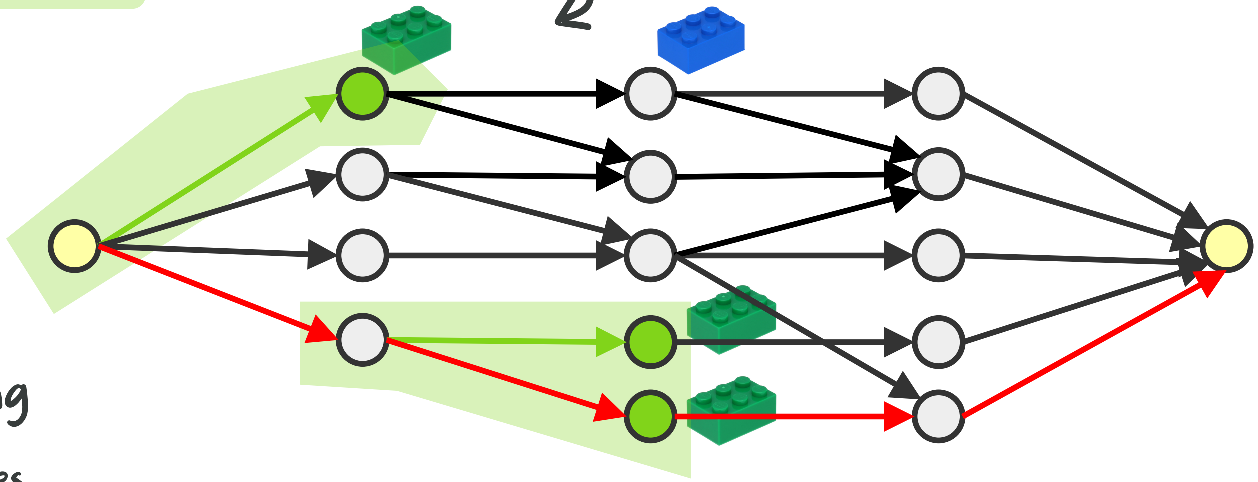
$1 \leq f(E_i) \leq \infty,\ i = 1,2,3$

Modeling

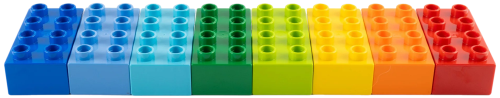
These models can be massive – billions of transitions



task

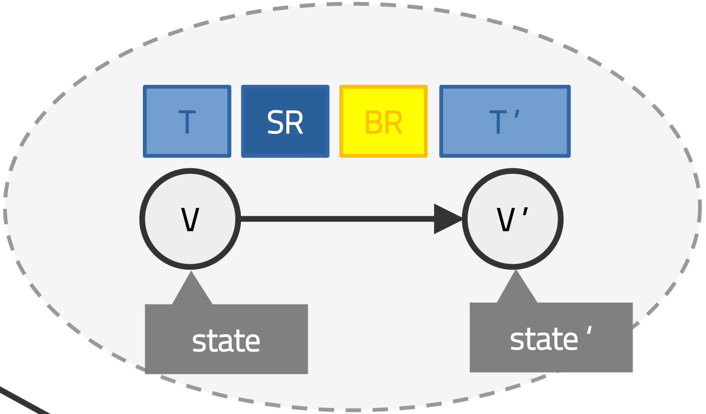


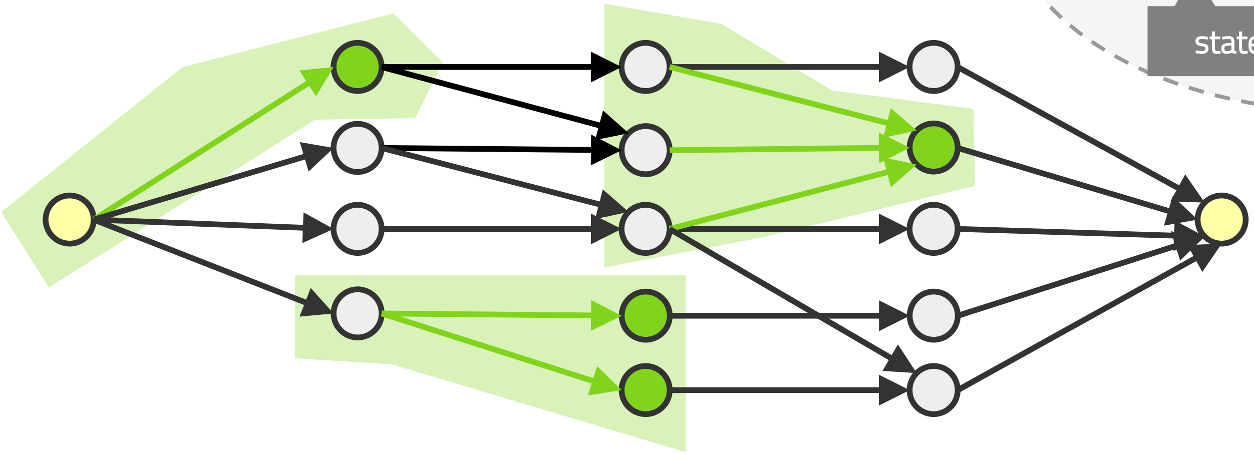
Flexibility in modeling use–case specific rules



task sequence

Crew Diagramming



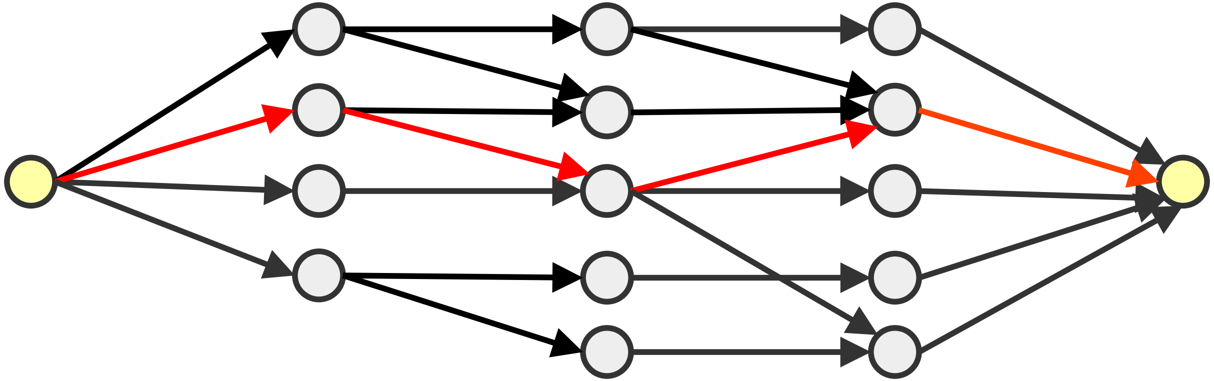


depot

crew task

$1 \leq fl(S) \leq 1$

Crew Diagram = Path

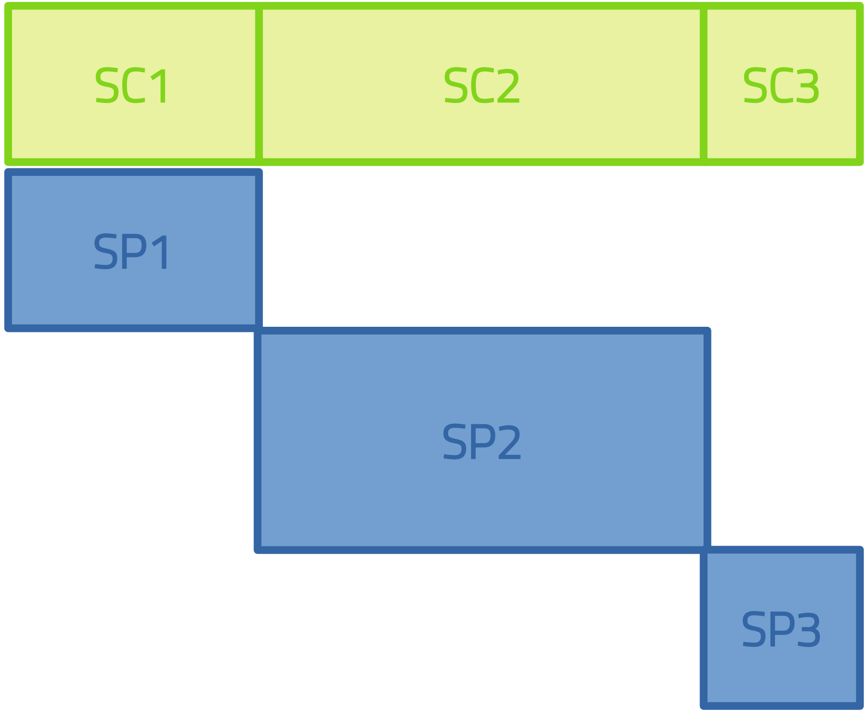


Sub problem: Shortest Path

Crew Diagramming:

- By 1 ≤ fl(S) ≤ 1, the flows degenerate to paths
- and the network is a DAG

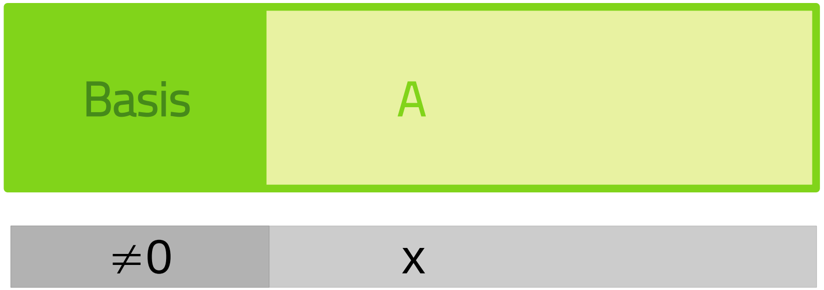
Column Generation



Approach

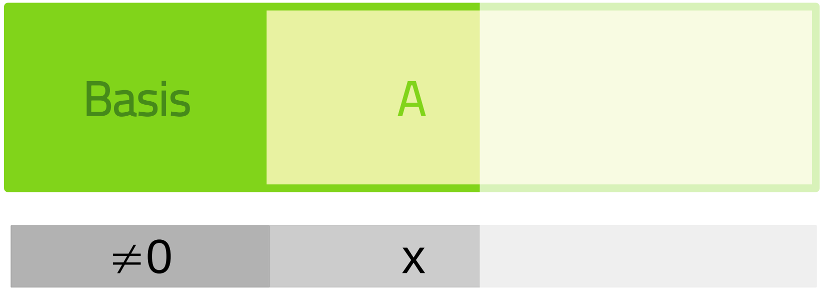
- Dantzig-Wolfe network decomposition needed
- **Master problem:** Set Constraints
- **Sub problems:** Shortest Paths
- Scalable parallelization
- Heuristic for IP rounding

Full and Restricted Master Problems



Full Master LP

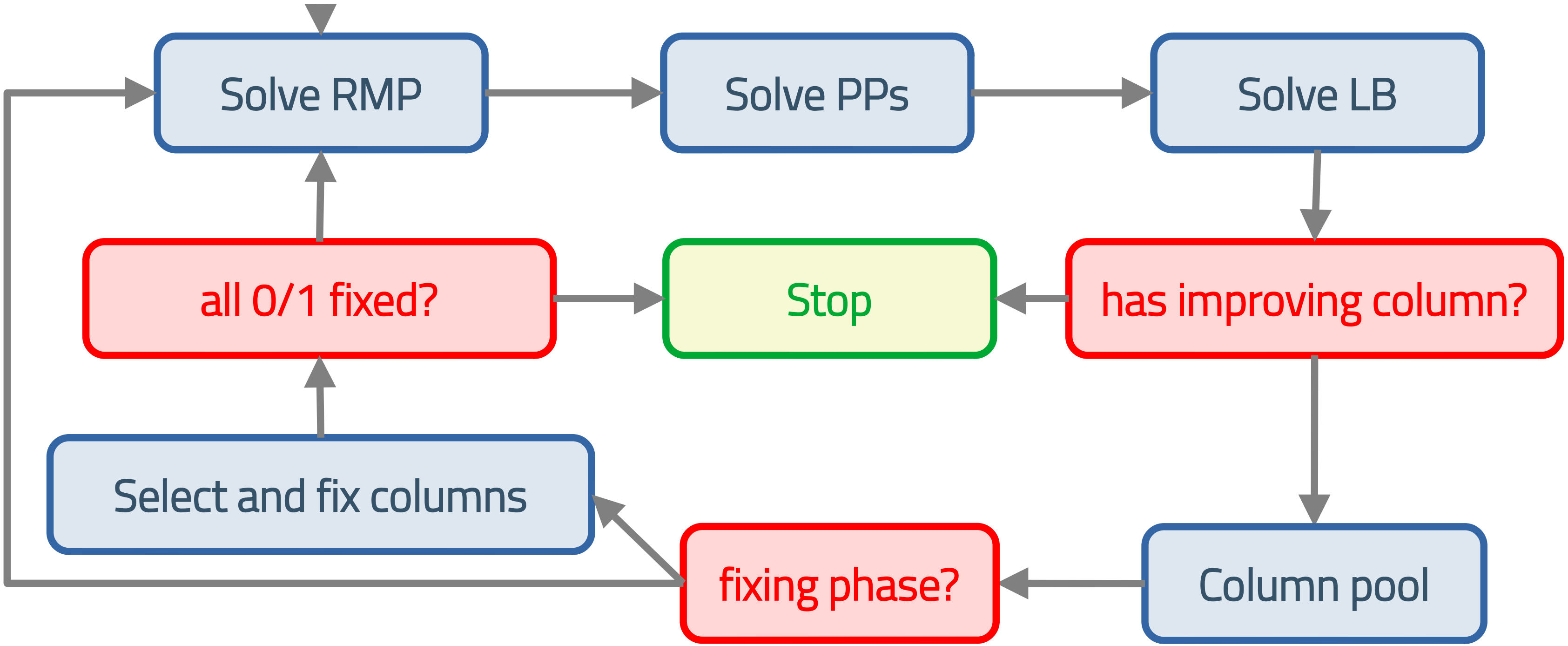
over all possible sub problem solutions can be very, very, very large.



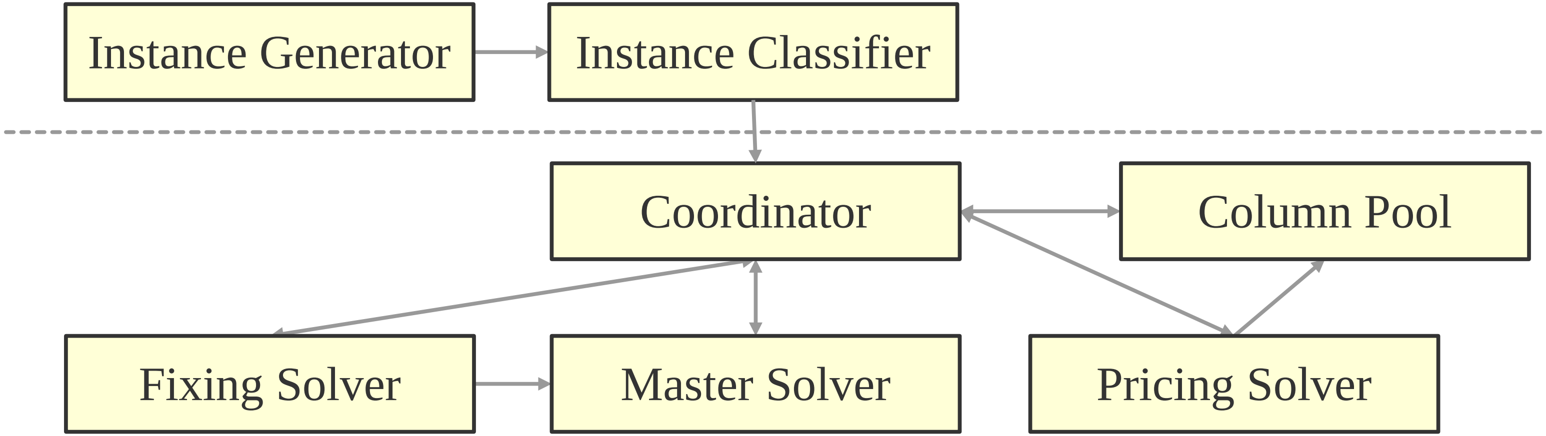
Restricted Master LP

most of LPs non-basis columns are hidden (= variable implicitly forced zero). Promising columns generated on the fly.

Column Generation Main Loop



Solver Architecture



Optimizing Switzerland

Instance

- Tasks: 12’988
- Depots: 69

Formulation

- Vertices: 882’796
- Edges: 1’350’972’506
- Edge constraint sets: 11’871

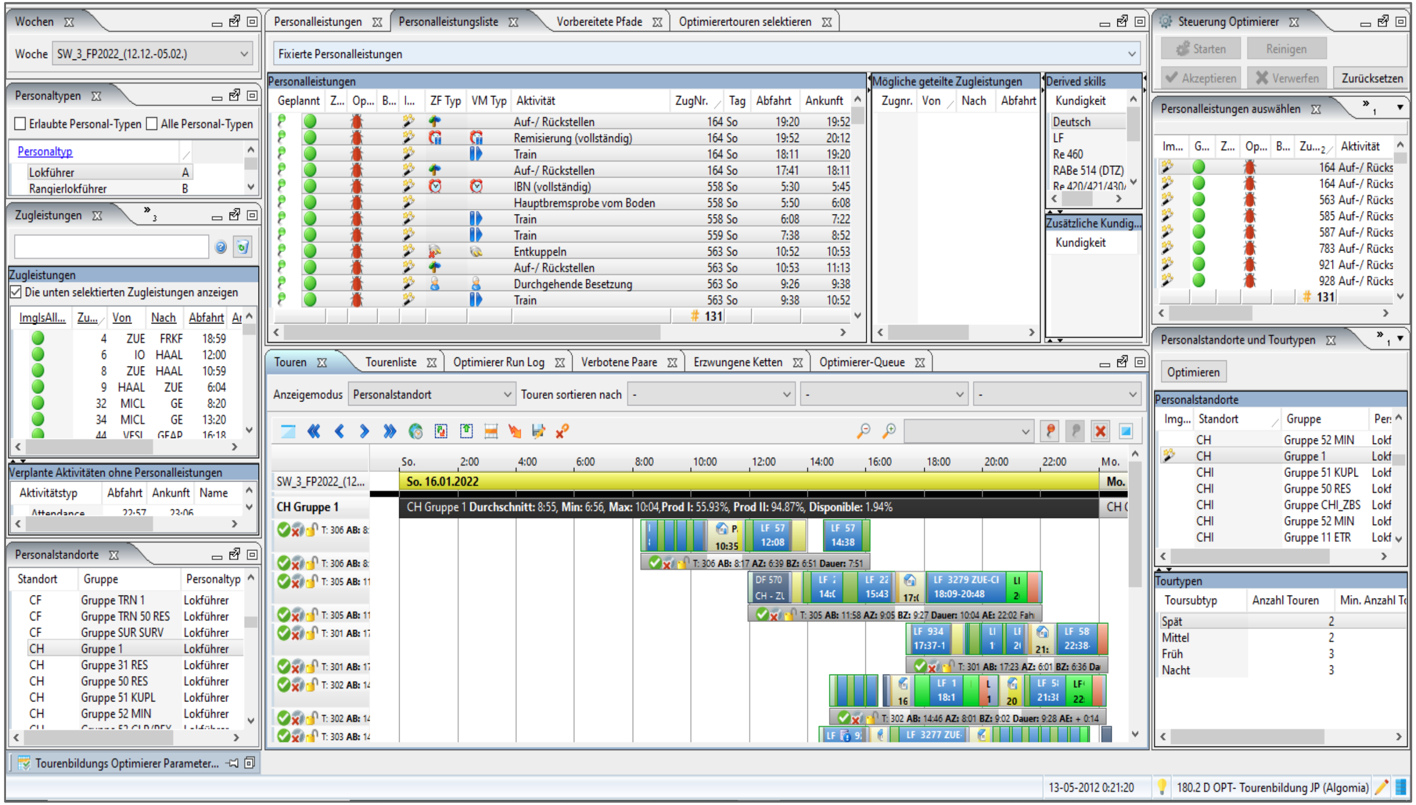
Dantzig-Wolfe Decomposition

- Sub problems: 404’035

Results

Nr.	Name	D, G	T	m	k	Time	LB	Value	Gap [%]
1	Avg depot 1	$1, 2$	556	16190245	370	575s	3835.68	3848	0.33
2	Avg depot 2	$1, 3$	784	7068272	515	205s	7331.53	7497	2.20
3	Large depot 1	$1, 8$	2096	150605068	1334	3.03h	37880.79	38342	1.20
4	Country 1	$34, 69$	12982	1350972506	11871	42.9h	1177.87	1200	1.87
5	Country 2	$34, 66$	15192	853239517	9241	27.1h	1244.69	1256	0.90
6	Country 3	$34, 67$	20041	2315427477	12244	104.0h	1158.01	1213	4.74

Optimization System at the Swiss Federal Railways



Capabilities

Scenario Manager

- Define instances with crew requirements, depots, etc.
- Implement soft knowledge by forbidden pairs, forced sequences, skill-preserving trips
- Define parameter profiles influencing planning parameters, runtime, solution quality
- Provides Gantt-visualization and constraint checking

Optimizer “Phoenix”

- Distributed computing over multiple servers
- Snapshot serialization & restart for long running optimizations

Impact & Key Takeaways

Journey from distrust to genuine mutual respect

- **Multi-year collaboration** between planning department and optimization team
- Manage expectations by teaching planners what the optimizer can do, and **what it can't**
- Explaining the run results to planners and **implement their feedback**
- Building railway **domain knowledge** and deep understanding in the optimization team

Optimization is by now established at SBB

- Has demonstrated substantial value in **strategic simulations** and in achieving **savings targets** (multi million CHF per year, recurring)
- Shortage of skilled planners and **retrirement of planning-gurus** is compensated, which is otherwise not easy to achieve

"We have the optimization knowledge and the rock technology to ~~solve~~ your scheduling challenge.

algomia

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