

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

Abstract: NeurIPS 2025, ScaleOPT Workshop

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Alexander Souza, Algomia  
[alexander@algomia.com](mailto:alexander@algomia.com)





**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

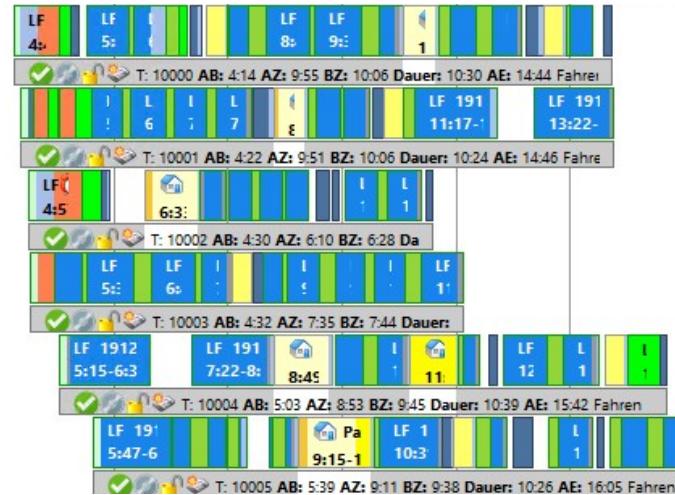
# Crew Diagramming

## Instance

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

## Task

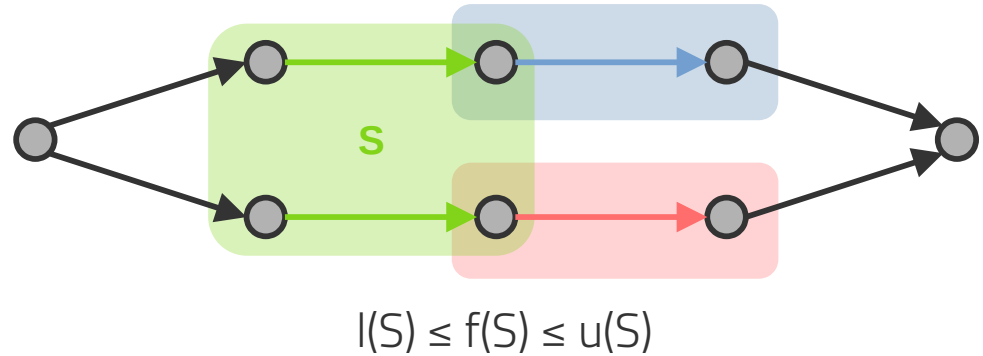
Minimize the number of crew diagrams such that each task is contained in exactly one crew diagram and labor rules are satisfied, e.g. consistency (geographic, temporal, qualifications), max. worktime, breaks, etc.



# Set Constrained Flow

## Instance

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



## Task

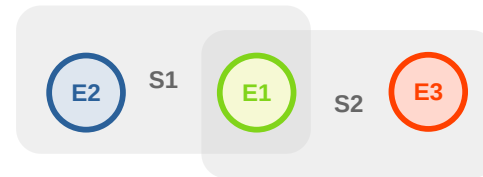
Minimize total edge-flow costs over all conserving flows such that  $l(S) \leq f(S) \leq u(S)$  for all  $S$

# Facts

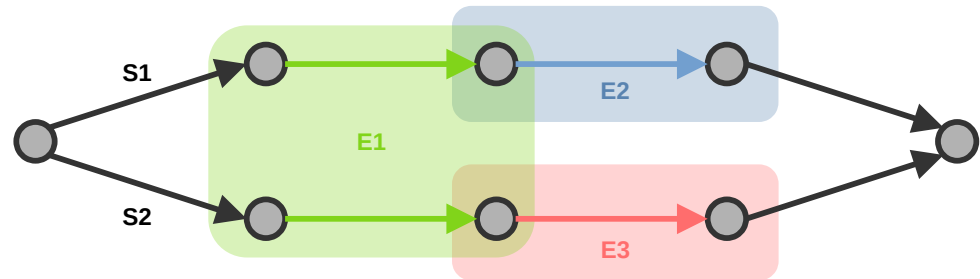
## Set Constrained Flow

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

## Set Cover



## SCF Formulation



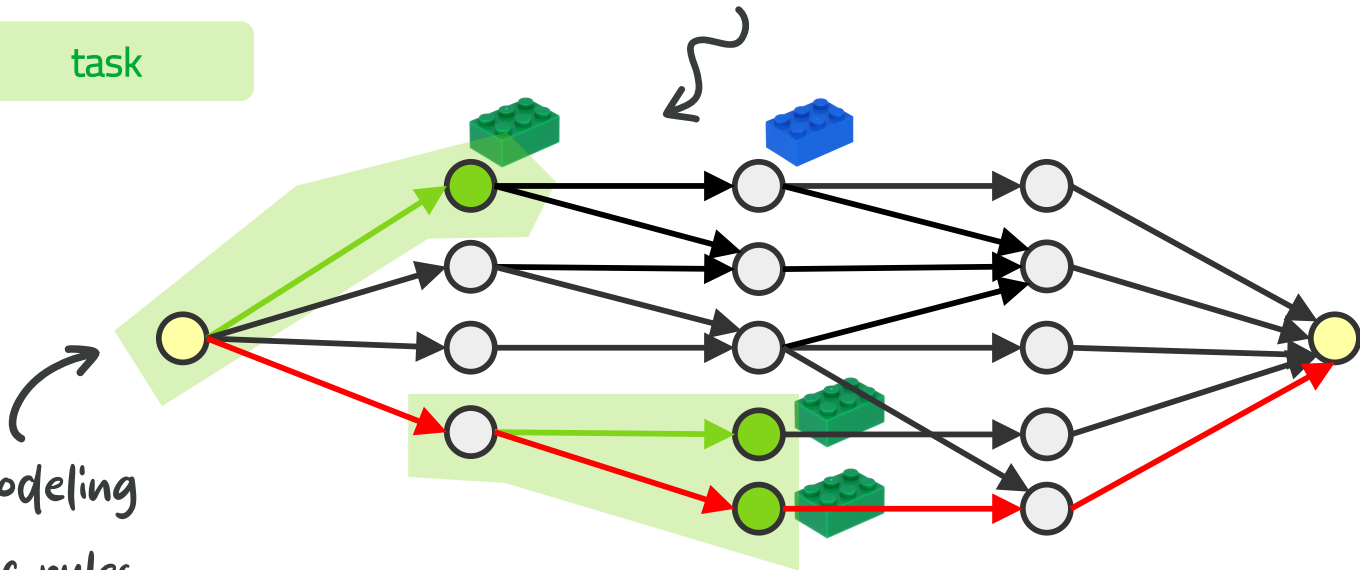
$$1 \leq f(E_i) \leq \infty, i=1,2,3$$

# Modeling

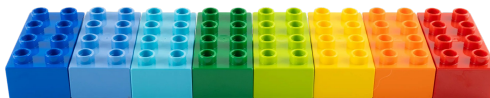
These models can be massive – billions of transitions



task



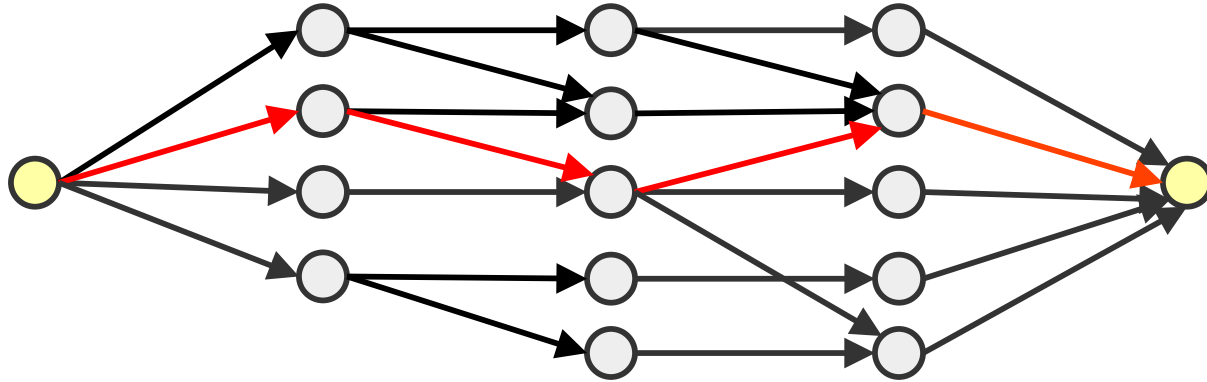
Flexibility in modeling use-case specific rules



task sequence



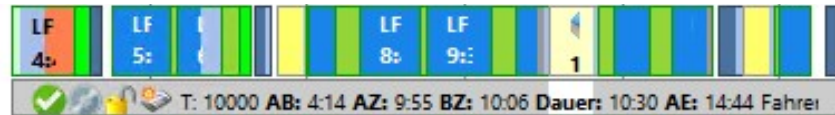
# Crew Diagram = Path



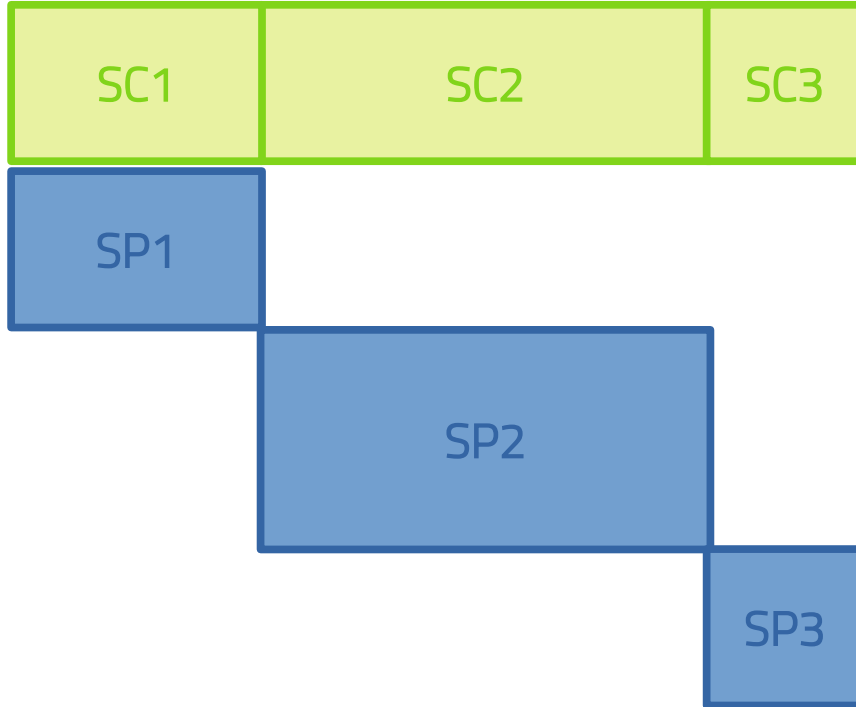
Sub problem: Shortest Path

Crew Diagramming:

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



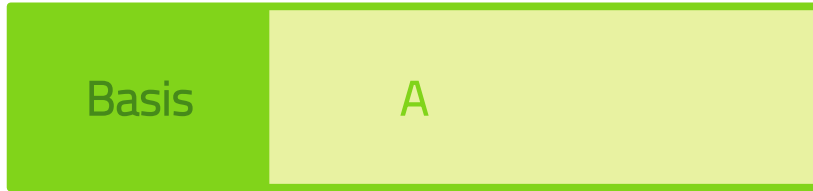
# Column Generation



## Approach

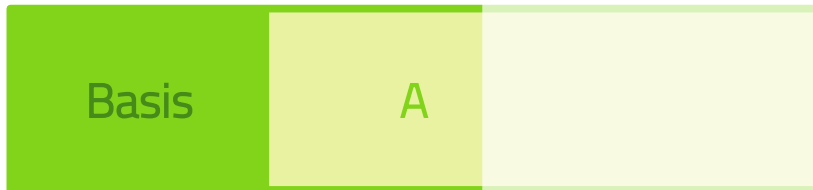
- Dantzig-Wolfe network decomposition needed
- **Master problem:** Set Constraints
- **Sub problems:** Shortest Paths
- Scalable parallelization
- Heuristic for IP rounding

# Full and Restricted Master Problems



## Full Master LP

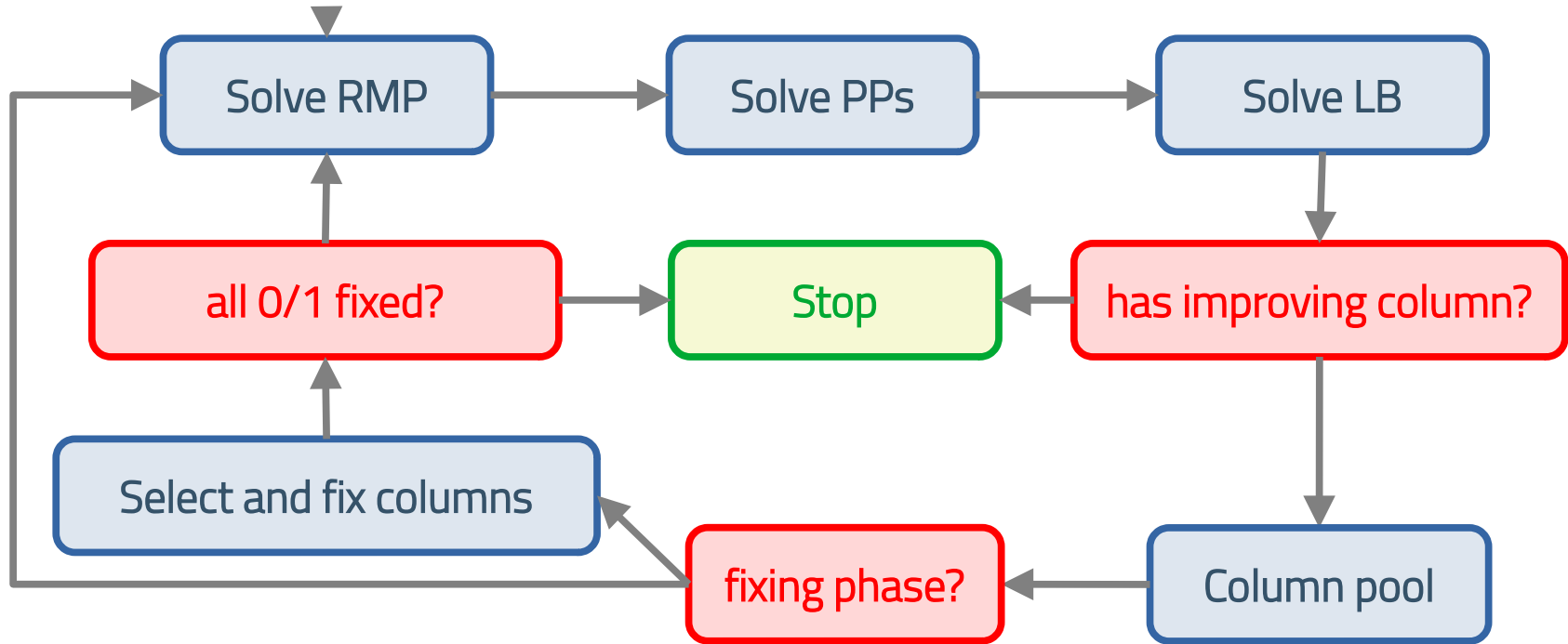
over all possible sub problem solutions can be very, very, very large.



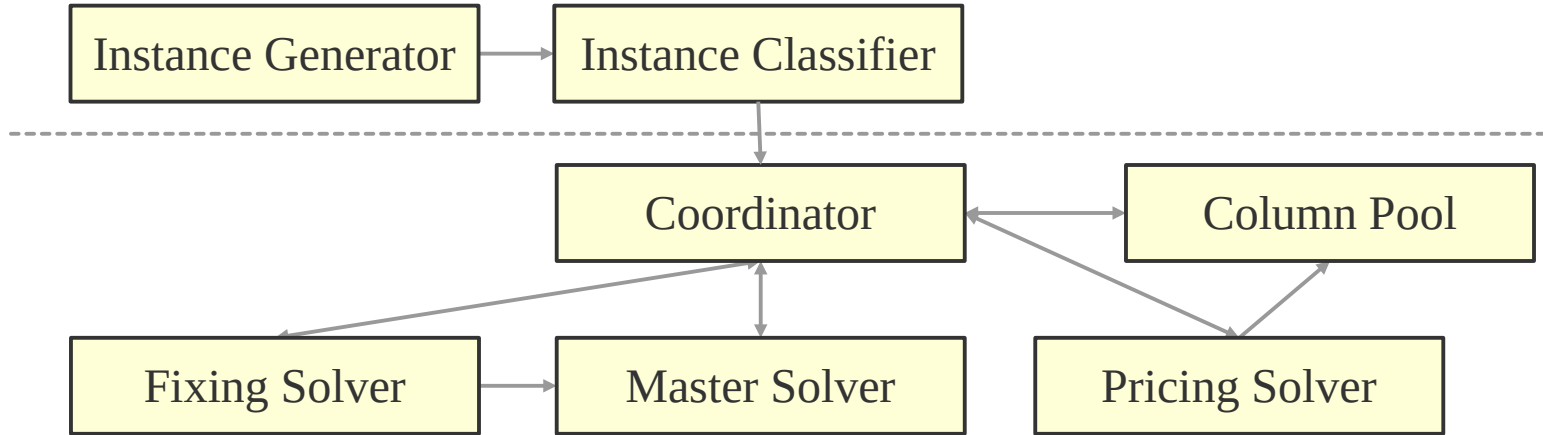
## Restricted Master LP

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

**Personalleistungen**

Geplant	Z...	Op...	B...	L...	ZF Typ	VM Typ	Aktivität	ZugNr.	Tag	Abfahrt	Ankunft
●							Auf-/ Rückstellen	164 So	19:20	19:52	
●							Remisierung (vollständig)	164 So	19:52	20:12	
●							Train	164 So	18:11	19:20	
●							Auf-/ Rückstellen	164 So	17:41	18:11	
●							IBN (vollständig)	558 So	5:30	5:45	
●							Hauptbremsprobe vom Boden	558 So	5:50	6:08	
●							Train	558 So	6:08	7:22	
●							Train	559 So	7:38	8:52	
●							Entkuppeln	563 So	10:52	10:53	
●							Auf-/ Rückstellen	563 So	10:53	11:13	
●							Durchgehende Besetzung	563 So	9:26	9:38	
●							Train	563 So	9:38	10:52	

**Zugleistungen**

Img...	Zu...	Von	Nach	Abfahrt	Ar...
●	4	ZUE	FRXK	18:59	
●	6	IO	HAAL	12:00	
●	8	ZUE	HAAL	10:59	
●	9	HAAL	ZUE	6:04	
●	32	MICL	GE	8:20	
●	34	MICL	GE	13:20	
●	44	VFSI	RFDP	16:18	

**Personalstandorte**

Standort	Gruppe	Personaltyp
CF	Gruppe TRN 1	Lokführer
CF	Gruppe TRN 50 RES	Lokführer
CF	Gruppe SUR SURV	Lokführer
CH	Gruppe 1	Lokführer
CH	Gruppe 31 RES	Lokführer
CH	Gruppe 50 RES	Lokführer
CH	Gruppe 51 KUPL	Lokführer
CH	Gruppe 52 MIN	Lokführer
CH	Gruppe 53 CUPL	Lokführer

**Tourtypen**

Toursubtyp	Anzahl Touren	Min. Anzahl T...
Spät	2	
Mittel	2	
Früh	3	
Nacht	3	

**Personalleistungen auswählen**

Img...	G...	Z...	Op...	B...	Zu...	Aktivität
●						164 Auf-/ Rüks
●						164 Auf-/ Rüks
●						563 Auf-/ Rüks
●						585 Auf-/ Rüks
●						587 Auf-/ Rüks
●						783 Auf-/ Rüks
●						921 Auf-/ Rüks
●						928 Auf-/ Rüks

**Optimierer-Queue**

Task	Start	End	Duration
LF 57	12:00	14:38	139
LF 57	14:38	17:00	139
LF 934	17:37-1	21:00	139
LF 1	18:1	21:31	139
LF 51	21:31	22:00	139

13-05-2012 0:21:20 180.2 D OPT- Tourenbildung JP (Algomia)

# 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 **retirement 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**

**Alexander Souza, CEO**

**[alexander@algomia.com](mailto:alexander@algomia.com)**

**+41 78 664 96 76**

