An optimization-based dispatching support tool for maximizing punctuality: an implementation in Stavanger

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Train Dispatching

- Train movements are controlled by human operators (*dispatchers*)
- Dispatchers control railway traffic by switches, traffic lights, phone calls etc.
- When trains deviate from the official timetable, dispatchers must take re-routing and re-scheduling decisions.
- The goal is to alleviate overall delays, knock on effects and to return to the official timetable as soon as possible.

"Traditional" Train Dispatching

- Each dispatching central is responsible for the train movements in a region.
- Each dispatcher is responsible for a line or parts of a line that is under the control of the given central.
- General lack of "sophisticated" decision support.
- All up to experience and a set of predetermined rules.
- Yet, solving a complicated optimization problem!

The Train Dispatching (optimization!) problem

The Train Dispatching problem

Given

a railway network with its current and (near-) future status, a set of trains with their current positions, expected speeds and a timetable

Find in real time:

a route for every train and a conflict-free schedule minimizing (a measure of) the deviation from the wanted timetable

- Very hard combinatorial optimization problem (in theory and practice)
- Each decision may have sistemic consequences, but dispatchers have only a local perspective.

On the existing systems

- Automatic-route setting systems supporting the dispatchers are already in operations in railway lines in Europe

- With few exceptions such systems are not equipped with optimization, (e.g., they apply rules)

- This is **despite** a **huge literature**, starting in the '80s (and earlier)
- Almost two decades of laboratory and field experiments
- **Clear benefits** of applying **optimization** to (real-time) dispatching

Why this gap between theory and application?

1. The real world is very complicated:

"there is an incredible number of practical details, exceptions, peculiarities to be handled in an implementation, <u>making the development of the optimization algorithm the easiest part</u>"

quoting by heart after a personal phone call with Markus Montigel, CEO of **systransit**, chair of Swiss Section of **IRSE** (institution of railway system engineers)

My Reply: true, but we have learned how to tame such complexity

Why this gap between theory and application?

2. The current signalling systems (hardware and dispatching protocols) are not adequate (D'Ariano 2010)

Reply: true, but

a. *many railways are undergoing a complete renewal of signalling systems* (recent examples: Denmark and Norway)

b. *Even with the current systems it is possible to improve performances of purely "manual" dispatching (from personal experience in underground and railway systems)*

Why this gap between theory and application

3. Operators are still skeptical over automatic route setting systems because of previous flops (Carlo Mannino)

Reply: true, but

a. *Former attempts were based on "wrong techniques"* (expert or rule based systems, poor heuristics)

b. *Recent real-life experiments and systems actually in operation show that automatic dispatching is possible*

Why this gap between theory and application?

4. Operators are bound to the technology offered by the large manufacturers, not necessarily the most advanced.

This is probably the major obstacle to innovation!

Reply:

a. Recent tenders show a certain degree of emancipation

b. We still need more audacity…

The Train Dispatching optimization model

- We solve the dispatching problem by using optimization models and algorithms

$$\begin{array}{ll} \min c(t) & \\ t_v - t_u \geq l_{uv} & (u,v) \in F \\ (t_w - t_v \geq l_{vw}) \vee (t_u - t_z \geq l_{zu}) & \{(v,w),(z,u)\} \in A \\ t \in R^n & \end{array}$$

Mathematcal optimization model

Dispatching can be represented by a ***mathematical model***

- *Variables represent times (when is it leaving?) and decisions (who goes first?)*
- *Equations and inequalities represent physical and logical costraints*
- *Objectives are also represented by a function of the decision variables*

Choosing the right model

- Models (instances) can (in principle) be solved by commercial solvers
- Practical dispatching instances **cannot** be tackled in this way
- Different mathematical models may lead to very different computing times
- Comparisons of three models for train dispatching show gigantic differences

	Time Indexed					Disjunctive					Flow	
Inst.	cols	rows	nonz.	CPU	LB	Cols	Rows	nonz.	CPU	LB	CPUfl	LB
I1	2085	6765	227778	01:03	6315	55	90	194	0.0023	6315	0.0006	6315
I2	3410	10028	612866	01:00	4080	51	77	168	0.0009	4080	0.0003	4080
I3	3524	19863	762239	01:06	10610	81	135	292	0.0021	10610	0.0009	10610
I4	4989	28326	1578784	01:08	59031	79	124	270	0.0014	59031	0.0005	58875
I5	4097	27895	1106254	02:04	11960	93	157	340	0.0026	11960	0.001	11960
I6	4536	21146	889083	00:09	7175	215	403	1092	0.0012	7175	0.0005	7175
I7	5045	27671	1E+07	01:01	9425	99	173	372	0.0017	9425	0.0004	9425
I8	5174	30761	1069484	01:05	11825	111	201	432	0.0018	11825	0.0009	11825

From the model to the algorithms

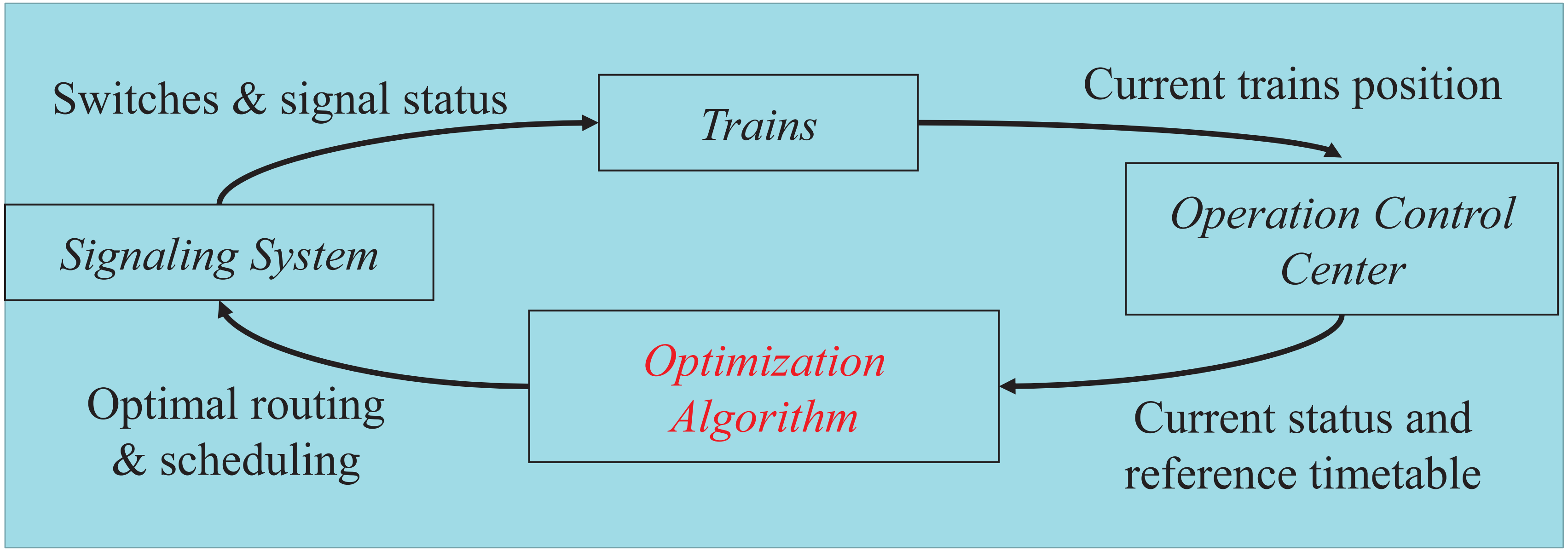
- Once the problem is represented, we need to solve the model by an algorithm
- Possible to apply commercial solvers – typically fails on interesting instances
- Need to develop *ad-hoc* solution algorithms
- *Heuristic algorithms can find solutions to the model satisfying all constraints*
- *Exact algorithms find the best possible solution, e.g. the one minimizing delays.*

Conflicting needs:

- *Fast algorithms because of stringent time limits*
- *Realistic models* (taking into account all relevant aspects of the real world)
- Quality of the solutions (heuristic, exact)

The dispatching loop

- The solution algorithm is embedded in the dispatching loop (few seconds)



- The current trains position is gathered from the field
- *The optimization algorithm* computes an *optimum plan*
- The plan is implemented by sending signals and moving switches

An efficient algorithm

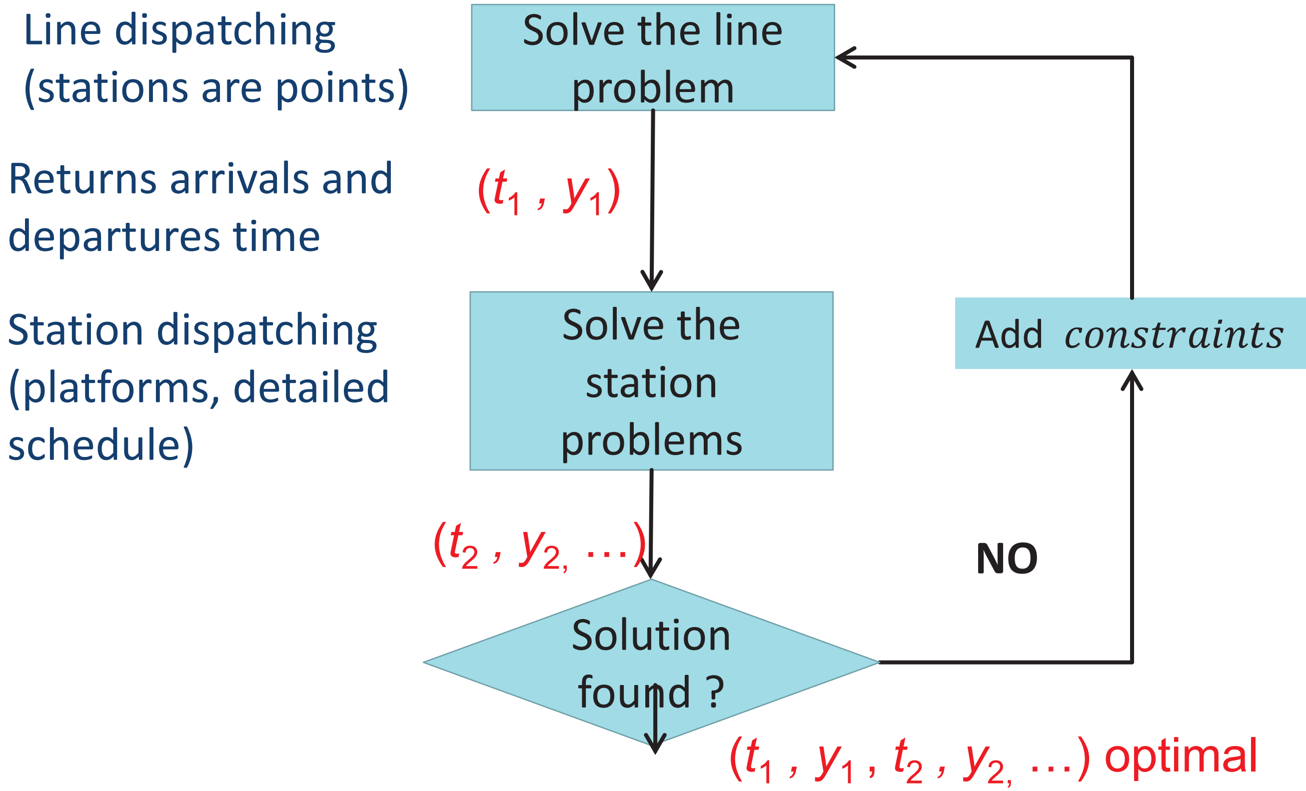
- To tackle real-life problems we developed a novel decomposition algorithm
- It mimics the natural decomposition in dispatching areas
- Solves a sequence of dispatching problems on the line and in the stations
- Questions:

  - how to combine the solutions of the subproblems into an overall solution

  - how to converge to an optimal solution?

- We manage to give a positive answer to these questions by applying *Bender's decomposition*

Train Dispatching and Benders' decomposition



- Can be implemented as a heuristic or exact, depending on the single blocks, feedback technique and termination criteria

A heustic implementation: Regional lines in Italy

System developed for Bombardier Transportation, currently in operation in 7 lines/regions (ca. 650 km and 140 stations)

Milano - Mortara, Parma - SanZeno and Trento - Bassano (North Italy)

Orte - Terontola - Foligno (Central Italy)

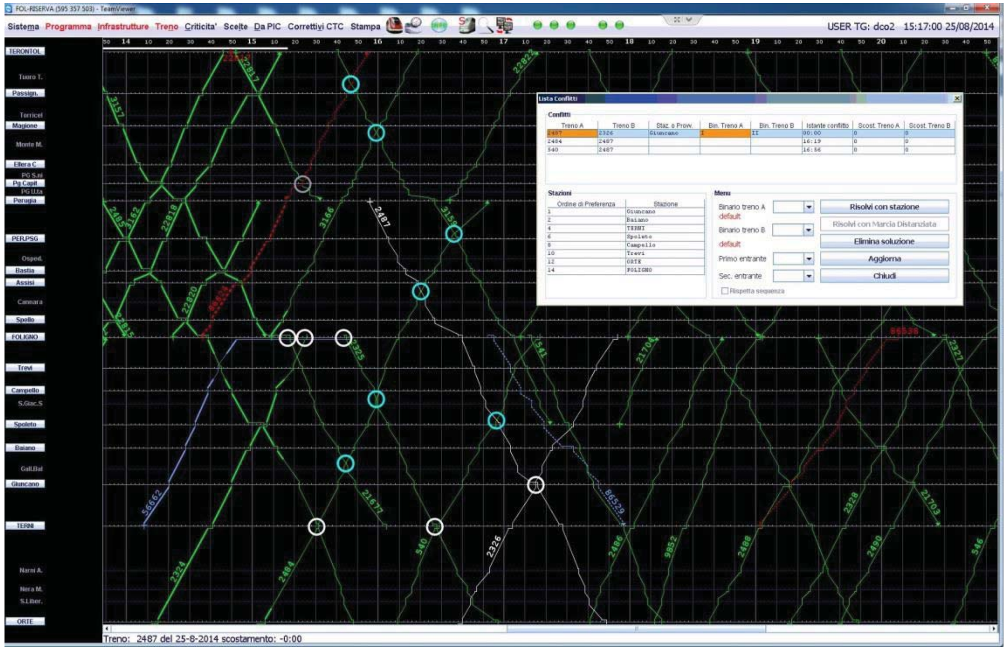
Siracusa - Gela , - Trapani , - Caltanisetta (South Italy)

Regional lines in Italy

A heuristic implementation: Regional lines in Italy

The system supports the dispatchers by

- *Identifying all potential conflicts*
- *Ranking possible solutions*
- *Possible direct enforcing dispatching decisions (automatic route setting)*



Suggestions accepted by dispatchers 94% of times on average.

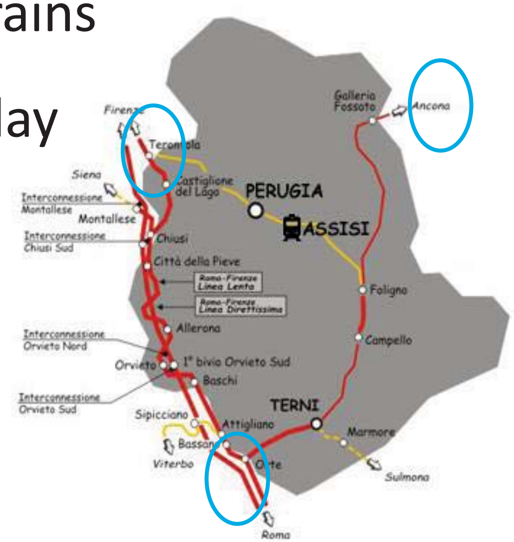
Heuristics VS Exact Approaches

- **Heuristics** are typically fast, scale up well, produce acceptable solutions
- But: **heuristics may fail** to find existing solutions (rare, but possible)
- **Exact algorithms**: always find solutions, when they exist
- Exact algorithms: Always find best possible solution (at termination).

How important is optimality ?

Optimal solutions are better than good ones

- Benchmarking the algorithm with current solutions in Italy
- "Triple" regional line, centered in Foligno, using our heuristics
- A "natural" Key Performance Indicator: # of delayed trains
- Comparisons on 4 delay classes for 130 trains in one day



	Delay ranges (mins)				Performance	
Method	≤ 5 min	≤ 10	≤ 15	15+	Time (s)	# fails
Heuristic	85 %	87 %	89 %	11%	0.7	413
Exact	91 %	95 %	97 %	3 %	4.3	10

Tests run 29.1.2013

- OBS: larger improvement can be expected on more congested lines

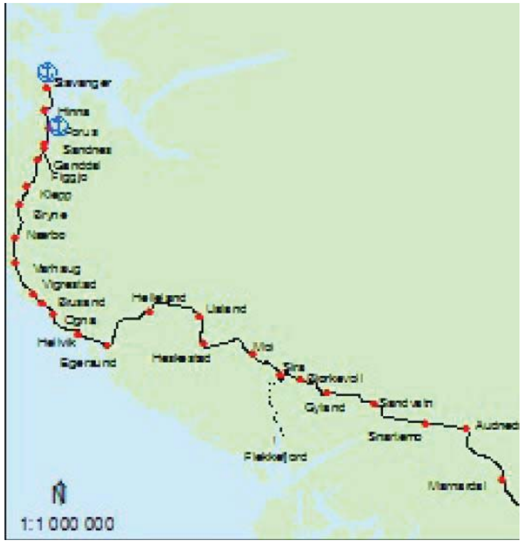
An exact implementation: Stavanger-Moi (Norway)

- An automated dispatching system "powered" by an exact dispatching algorithm was put in operation in Stavanger in February 2014.

- From Stavanger to Moi (Jærbanen),   123 km, 16 stations,

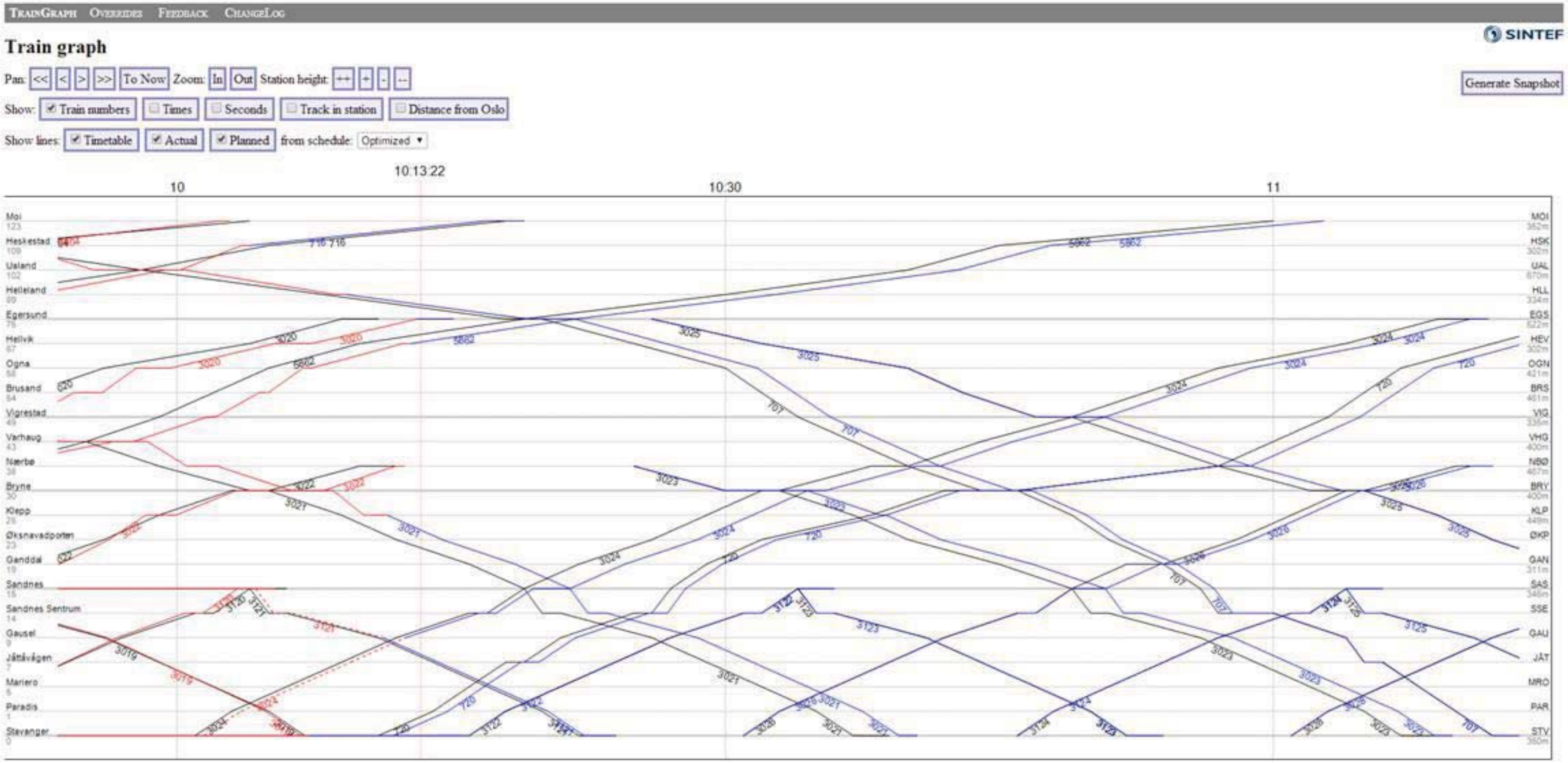
  single- and double-tracks.

- Up to 120 trains per day.

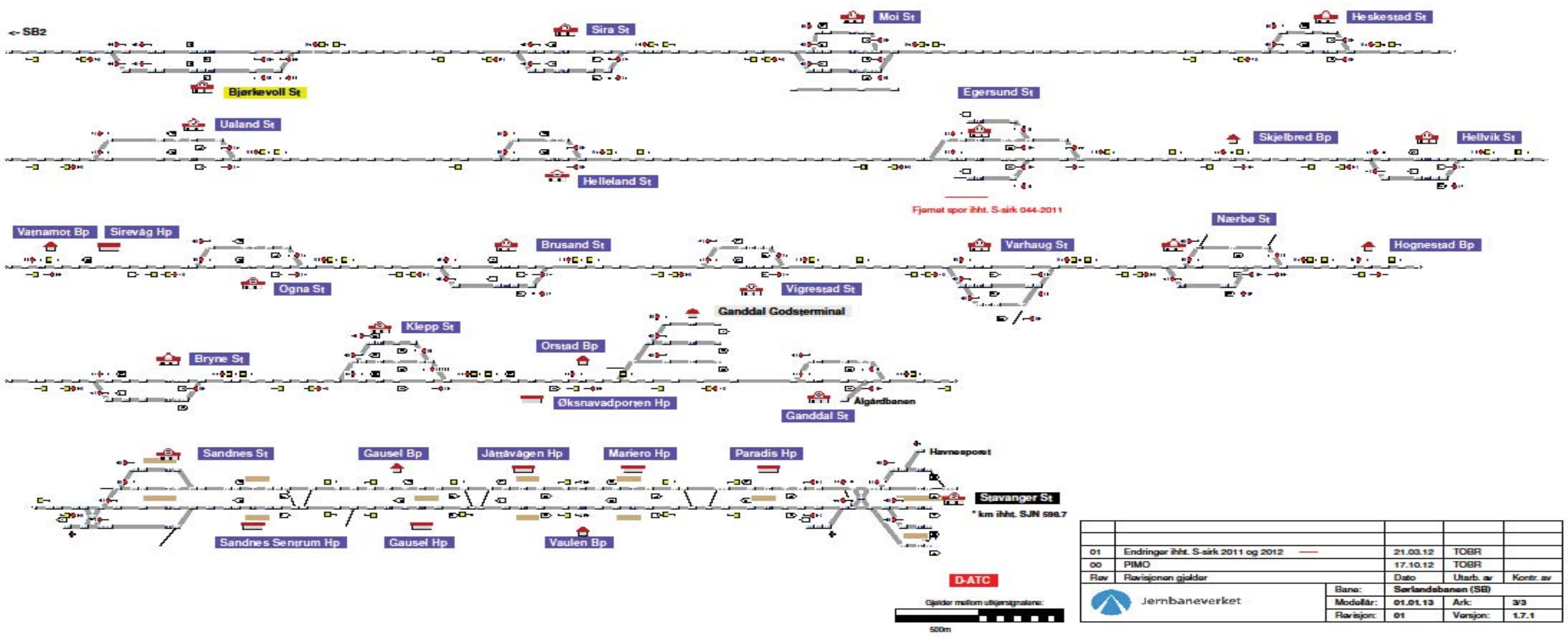


- Solutions are presented to dispatchers through a space-time diagram (Train Graph)

Stavanger-Moi: the Train graph



Stavanger-Moi (Norway)



Stavanger-Moi: some facts

- Between 3000 and 5000 average calls to the algorithm per day
- Over 90% solved to optimality within 10 seconds

More details to be found in:

- "An exact decomposition approach for the real-time train dispatching problem", *Operations Research* (published online January 12 2015)
- *"*Optimal Train Dispatching by Benders'-like reformulation*"*, *Transportation Science* (to appear)

A classification of optimization-based dispatching systems

- A few dispatching systems have by now be put in operation
- Classification of implemented dispatching systems

	What	Technique	Where	From
MASS TRANSIT	Terminal Stations	Exact: branch&bound	Milano	2007*
MAIN LINE	Regional Lines	Heuristic	Italy	2011
	Regional Lines	Heuristic	Latvia	2015**
	Regional Lines	Exact: Benders'	Norway	2014
	Large Stations	Heuristic/Exact: MILP	Italy	2015

* dismissed in 2008 (due to entire system renewal)
** still under comminssioning

Recognitions for the Stavanger dispatching system

- Winner of "Best Application" award at the 2014 AIRO conference (Italian Operational Research Society)
- Received an enthusiastic letter from the Norwegian Ministry of Transportation
- Published on top journals (*Operation Research* , *Transportation Science*)
- Very appreciated by management in JBV and NSB

Presentation given by Øystein Risan, head of traffic department at NSB

Improved punctuality and fewer cancellations!

- Happier passengers, more customers.
  - Increased revenue and reduced need for subsidies.
  - Reduced cost due to reduced need for slack

- More reliable and cost efficient freight transport on rail.
  - Shifting freight from road to rail.
  - Reduced cost due to reduced need for slack

- Fewer devations from the official timetable enables 'tighter' timetables
  - Increased capacity of existing infrastructure at no/low additional cost!

- Positive environmental impact

NSB

Letter from the Norwegian Ministry of Transportation

DET KONGELIGE
SAMFERDSELSDEPARTEMENT

Statsråden

SINTEF Teknologi og Samfunn
Veg og samferdsel
Postboks 4760 Sluppen
7465 TRONDHEIM

Deres ref	Vår ref	Dato
	15/448	04.032015

Vellykket forskningsprosjekt om effektivisering av togstyring

Det er med stor tilfredshet jeg registrerer at forskere fra SINTEF har vunnet i forskningskonkurransen AIRO Award 2014. Jeg forstår at dette er et prosjekt som også har fått priser tidligere, både i 2009 og i 2012. Dette er imponerende, og jeg ønsker å gratulere alle bidragsyterne med vel utført arbeid.

Det prisbelønte arbeidet dreier seg om å effektivisere togledelse og optimalisere framføring av tog, noe som er av stor betydning for de reisende og for effektiv godstransport.

Jeg er opptatt av å gjøre jernbanen til et attraktivt transportmiddel. Dette skal vi få til gjennom effektivisering og reformer som bygger på et godt kunnskapsgrunnlag. Vi trenger forskningsbasert kunnskap for å få til framtidsrettede og nyttige løsninger i transportsektoren. SINTEF-prosjektet er et godt bidrag til en bedre togstyring som jeg håper kommer til nytte for brukerne så snart som mulig.

Med hilsen

Ketil Solvik-Olsen