Sustainable Public Transport

Anita Schöbel

University Kaiserslautern-Landau and Fraunhofer Institute for Industrial Mathematics ITWM

15. August 2024

Content of the talk

Sustainable mobility

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) $=$

$$\boxed{\text{no. of inhabitants}} \cdot \boxed{\text{trips per inhabitant}} \cdot \boxed{\text{km per trip}} \cdot \boxed{\text{energy per km}} \cdot \boxed{\text{emissions per energy}}$$

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) $=$

$\boxed{\text{no. of inhabitants}} \cdot \boxed{\text{trips per inhabitant}} \cdot \boxed{\text{km per trip}} \cdot \boxed{\text{energy per km}} \cdot \boxed{\text{emissions per energy}}$

family issue	life style	location problem	mode choice	engineering

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) =

no. of inhabitants	·	trips per inhabitant	·	km per trip	·	energy per km	·	emissions per energy
family issue		life style		location problem		mode choice		engineering
not our business		home-office, leisure time		minimize travel distances		make sustainable modes attractive		improve modes

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) =

no. of inhabitants	·	trips per inhabitant	·	km per trip	·	energy per km	·	emissions per energy
family issue		life style		location problem		mode choice		engineering
not our business		home-office, leisure time		minimize travel distances		**make sustainable modes attractive**		**improve modes**

Make sustainable modes more attractive to passengers

What is attractive ?

Fast, affordable, reliable

Public transport

- Few transfers
- high frequencies
- good connections

Ride-pooling

- short waiting times
- fair tariff structure
- easy to handle

Biking

- many cycle paths
- safe places to leave the bike
- enough space on the streets

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) =

$\boxed{\text{no. of inhabitants}}$ ·	$\boxed{\text{trips per inhabitant}}$ ·	$\boxed{\text{km per trip}}$ ·	$\boxed{\text{energy per km}}$ ·	$\boxed{\text{emissions per energy}}$
family issue	life style	location problem	mode choice	engineering
not our business	home-office, leisure time	minimize travel distances	**make sustainable modes attractive**	**improve modes**

Improve modes themselves

What to improve ?

pollution, source of energy

Vehicles

- electric vehicles
- better engines

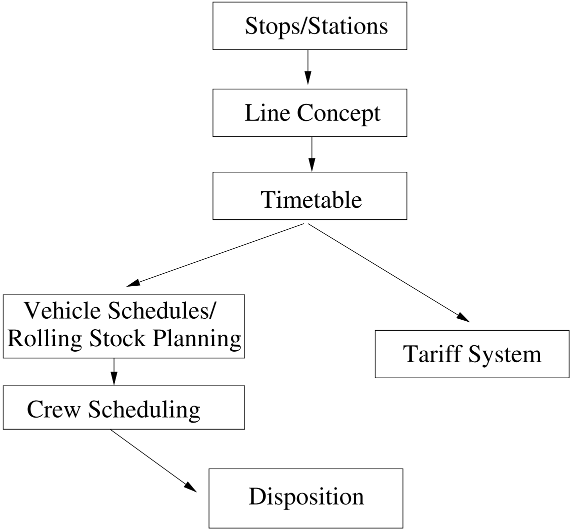
Logistics

- regenerative energy
- skip stops

Behavior

- avoid acceleration when driving
- chose routes which avoid slopes

The planning process in public transportation



Literature

. . . is numerous and still increasing

. . . see **many** books and **many more** research papers!

An upcoming overview paper:

Hickman and Schöbel: 50 years of Operations Research in Public Transport, 2025

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

European Association of Operations Research

- 31 member societies
- 4 (good!) journals: European Journal of . . . : EJOR, EJDP, EJTL, EJCO
- 33 working groups
  - Transportation
  - Quantum OR
  - . . . many more

EURO

THE ASSOCIATION OF EUROPEAN OPERATIONAL RESEARCH SOCIETIES

As president I invite you to our 50th Anniversary Conference!

- 22.-25. June 2025 in Leeds
- Many actions on

  50 years of Operations Research

EURO2025
CELEBRATING THE 50th ANNIVERSARY
LEEDS

End of Commercial Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

Optimize public transport

In this talk:

Under a restricted budget make public transport as **good** as possible.

What is good ?

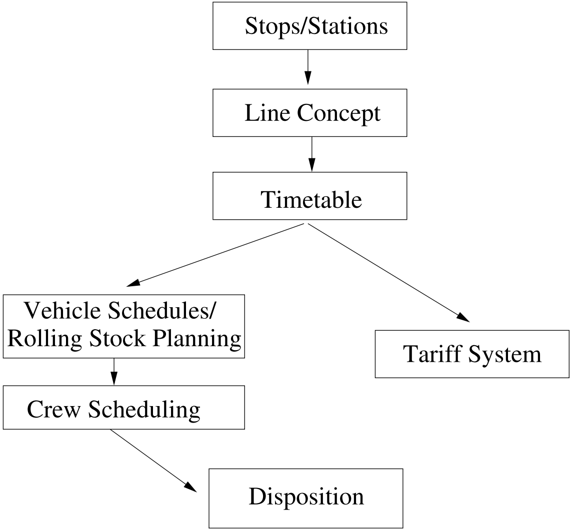
Passengers:

- Convenient (traveling times, transfers) $\rightarrow$ Line planning
- Reliable $\rightarrow$ Delay management
- Under a given budget $\rightarrow$ Integrated planning

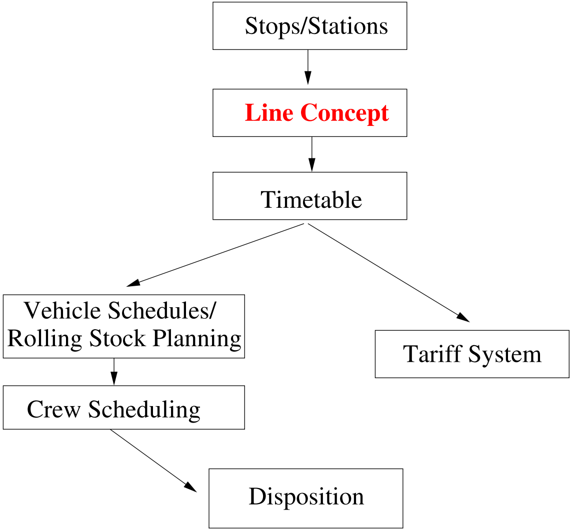
Content of the talk

1. Towards sustainable mobility
2. Making public transport more attractive
    - Line Planning
    - Delay Management
    - Integrated planning
3. Improve the modes themselves
4. Multi-modal planning
5. The end

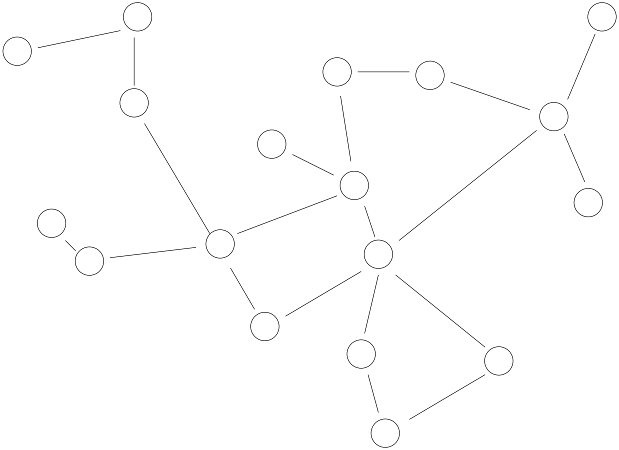
How to plan the lines?



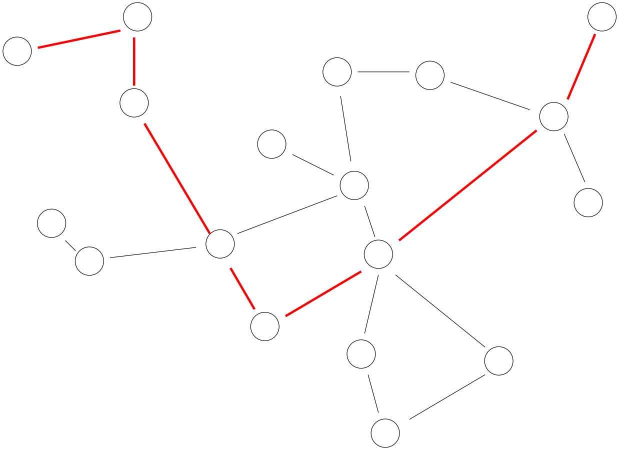
How to plan the lines?



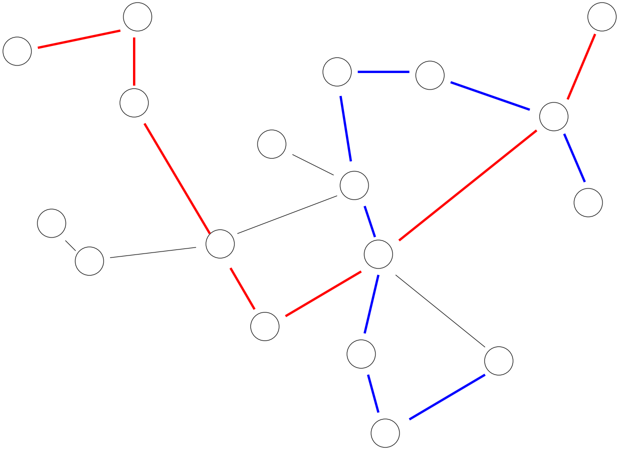
Example



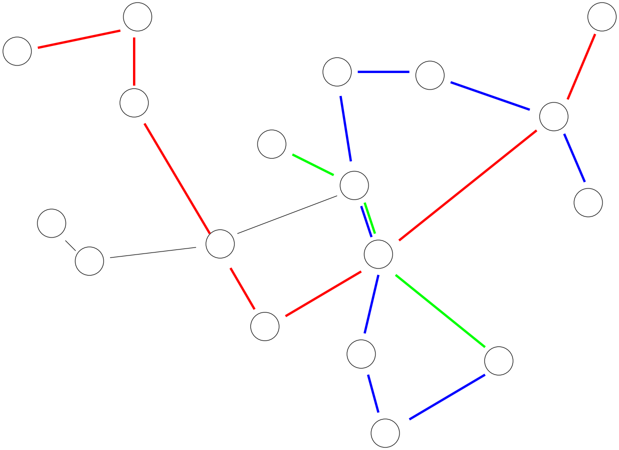
Example



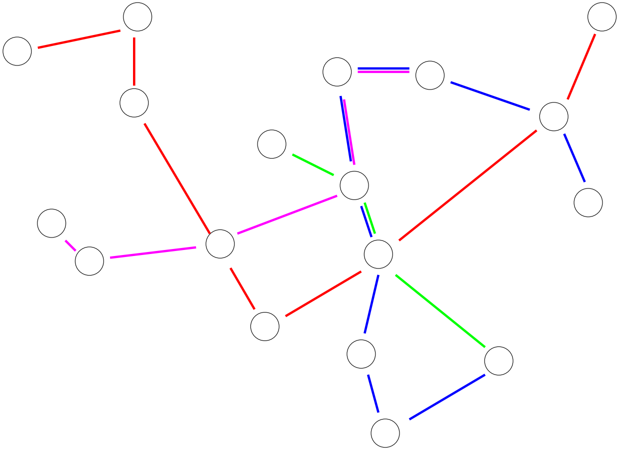
Example



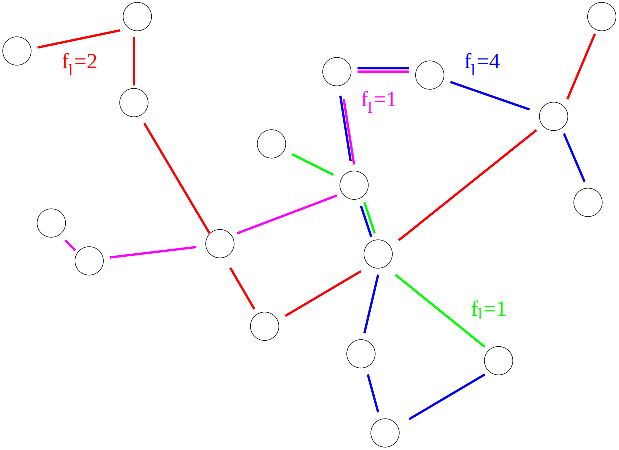
Example



Example



Example



Line planning in the literature

Many different models exist!

- Choice of goals
- How to measure costs and traveling time
- Different algorithms

first paper Patz (1925)

surveys: Guihare and Hao (2008), Kepaptsoglou and Karlaftis (2009), Schöbel (2012), Farahani et al (2013), Schöbel and Schmidt (2025)

Cost model

If a line pool $\mathcal{L}^{Pool}$ is given:

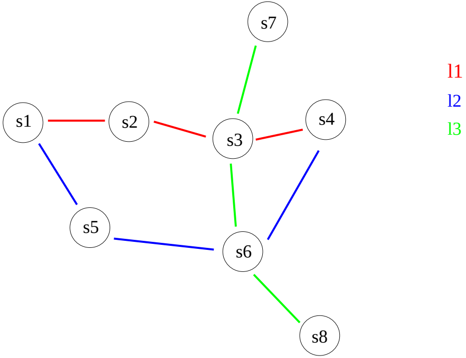
$$f_\ell = \text{frequency of line } \ell$$

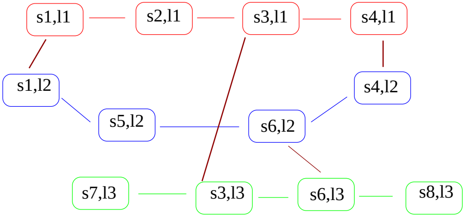
$$\begin{aligned} \text{min} \quad & \sum_{\ell \in \mathcal{L}^{Pool}} \mathrm{cost}_\ell \cdot f_\ell \\ \text{s.t.} \quad & f_e^{\text{min}} \leq \sum_{\ell : e \in \ell} f_\ell \leq f_e^{\text{max}} \text{ for all } e \in E \\ & f_\ell \quad \text{positive integer} \end{aligned}$$

Model for minimizing the perceived traveling time

$$\text{PerTravelTime} = k_1 \cdot \text{ Riding Time } + k_2 \cdot \text{ number of transfers}$$

Can be computed in the Change & Go graph:





Model for minimizing the perceived traveling time

To take track of the passengers' paths we need a lot of variables:

$$x^a_{st} = \begin{cases} 1 & \text{if activity } a \in \mathcal{A} \text{ is used on a shortest path from } s \text{ to } t \text{ in } \mathcal{N} \\ 0 & \text{otherwise} \end{cases}$$

$$y_\ell = \begin{cases} 1 & \text{if line } \ell \text{ is established} \\ 0 & \text{otherwise} \end{cases}$$

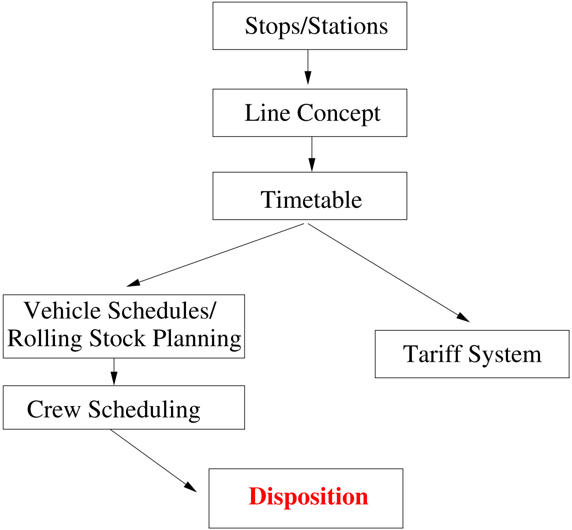
$$\min \sum_{s,t \in V} \sum_{a \in \mathcal{A}} W_{st} \text{time}_a x^a_{st}$$

$$\begin{array}{rrcl} \text{s.t.} & x^a_{st} & \leq & y_l \text{ for all } s,t \in V, \ell \in \mathcal{L}, a \in \ell \\ & \Theta x_{st} & = & b_{st} \text{ for all } s,t \in V \text{ with } C_{st} > 0 \\ & \sum_{l \in \mathcal{L}} y_\ell cost_\ell & \leq & B \\ & x^a_{st}, y_\ell & \in & \{0,1\} \end{array}$$

Content of the talk

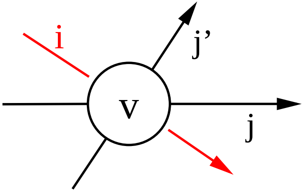
1. Towards sustainable mobility
2. Making public transport more attractive
    - Line Planning
    - Delay Management
    - Integrated planning
3. Improve the modes themselves
4. Multi-modal planning
5. The end

Delay management



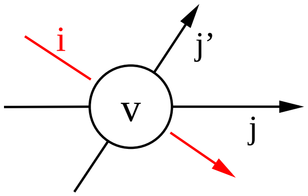
The delay management problem

Train i arrives at a station with a delay.



The delay management problem

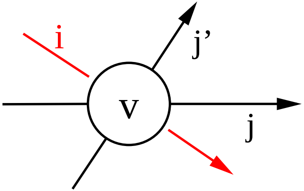
Train i arrives at a station with a delay.



What should a connecting train j do?

The delay management problem

Train i arrives at a station with a delay.



What should a connecting train j do?

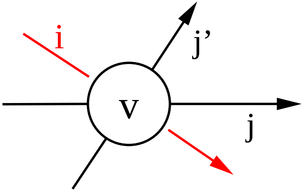
Wait

but cause further delays?

- for the passengers in train j
- for passengers who wait for train j
- for subsequent other vehicles

The delay management problem

Train i arrives at a station with a delay.



What should a connecting train j do?

Wait

but cause further delays?

- for the passengers in train j
- for passengers who wait for train j
- for subsequent other vehicles

depart on time

although passengers who wanted to transfer from train i to train j miss their connection?

Can optimization help?

In case of delayed trains (or buses), at least two decisions have to be made:

- wait for transferring passengers or depart on time?
- which train can go first if two trains are assigned to the same track?

Modeling delay management by integer programming

$$z_a = \begin{cases} 1 & \text{if transfer } a \text{ is maintained} \\ 0 & \text{otherwise} \end{cases} \qquad \eta_{ij} = \begin{cases} 1 & \text{if train } i \text{ goes before train } j \\ 0 & \text{otherwise} \end{cases}$$

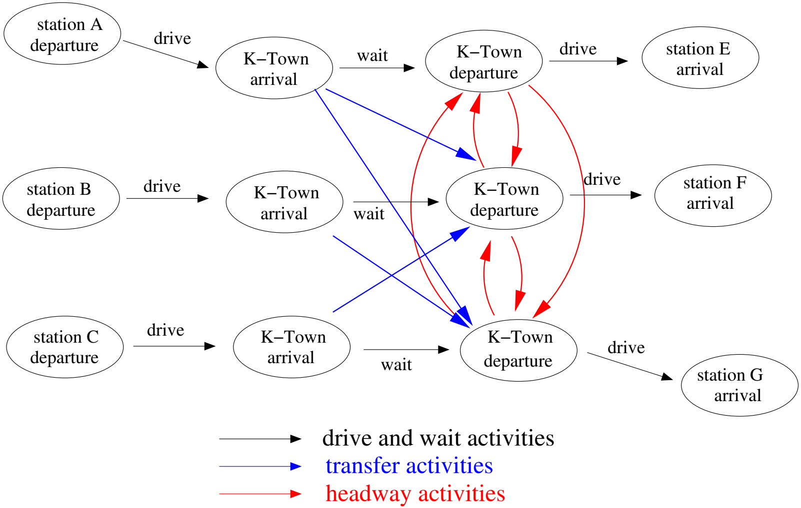
We also need to keep track of the delays:

$$x_i = \text{ disposition timetable for event } i$$

$\rightarrow$ To be able to compute z_a and η_{ij}
$\rightarrow$ Objective function: minimize sum of delays over all passengers

Propagating delays

Use event-activity network $(\mathcal{E}, \mathcal{A})$:



Delay management as integer program

$$\min \sum_{i \in \mathcal{E}} w_i x_i \quad + \sum_{a=(i,j) \in \mathcal{A}_{transfer}} w_a z_a T$$

$$\begin{array}{rrcl}
\text{s.t.} & x_i & \geq & \pi_i + d_i \quad \text{for all } i \\
& x_j - x_i & \geq & L_a \quad \text{for all } a = (i,j) \in \mathcal{A}_{wait} \cup \mathcal{A}_{drive} \\
& M z_a + x_j - x_i & \geq & L_a \quad \text{for all } a = (i,j) \in \mathcal{A}_{transfer} \\
& M \eta_{ij} + x_j - x_i & \geq & L_a \quad \text{for all } a = (i,j) \in \mathcal{A}_{head} \\
& \eta_{ij} + \eta_{ji} & = & 1 \quad \text{for all } i,j : a = (i,j) \in \mathcal{A}_{head} \\
& x_i \in \mathbb{N}^0 & , & z_a \in \{0,1\}
\end{array}$$

Surveys: Dollevoet, Huisman, Schöbel, Schmidt (2018), König (2020)

Many extensions

- The trickle-in effect Müller, Pätzold, Schöbel (2019) in a project funded by SWZ!
- ML-based rules for deciding about wait or not wait Bauer and Schöbel (2014)

Recently: Find *robust* timetables

- Classic methods: combine timetabling with delay management Grafe and Schöbel (2023), Grafe (2024)
- Using a ML-based oracle to evaluate public transport supplies Müller-Hannemann, Rückert, Schiewe, Schöbel (2022,2023)

Many extensions

- The trickle-in effect Müller, Pätzold, Schöbel (2019) in a project funded by SWZ!
- ML-based rules for deciding about wait or not wait Bauer and Schöbel (2014)

Recently: Find *robust* timetables

- Classic methods: combine timetabling with delay management Grafe and Schöbel (2023), Grafe (2024)
- Using a ML-based oracle to evaluate public transport supplies Müller-Hannemann, Rückert, Schiewe, Schöbel (2022,2023)

Data-based and model-based methods

Good models exist for delay management

- If a train starts with some delay, it arrives with some (easily to estimate) array
- However: Source delays are not known beforehand

Combine model-based knowledge with data-based knowledge! Bauer and Schöbel (2014)

Robust timetabling

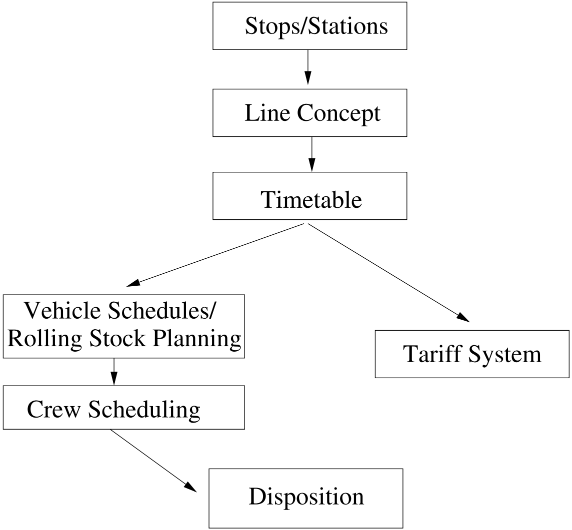
- Evaluate a line plan and timetable under various delay scenarios to estimate the robustness
- However, such an evaluation takes *way too* long to be used in optimization procedures

Replace this evaluation by a ML-based oracle and use this as black box for optimization.

Müller-Hannemann, Rückert, Schiewe, Schöbel (2022,2023)

Content of the talk

Our goal: Integrating three stages



Integrating the Planning Stages

So far, research is mostly focused on single planning stages.

Question: Does this lead to good solutions for the whole system?

Integrating the Planning Stages

So far, research is mostly focused on single planning stages.

Question: Does this lead to good solutions for the whole system?

Answer: No!

- The result of one stage may be a “bad” input for the next stage.
  Experiments with LinTim: Many line planning models generate instances for which not even a feasible timetable exists!

Integrating the Planning Stages

So far, research is mostly focused on single planning stages.

Question: Does this lead to good solutions for the whole system?

Answer: No!

- The result of one stage may be a “bad” input for the next stage.
  Experiments with LinTim: Many line planning models generate instances for which not even a feasible timetable exists!

- The objective used in a former stage is maybe not a good approximation for what we really want.
  Experiments with LinTim: The costs to be minimized in line planning do not meet the real costs after vehicle scheduling.

Integrating the Planning Stages

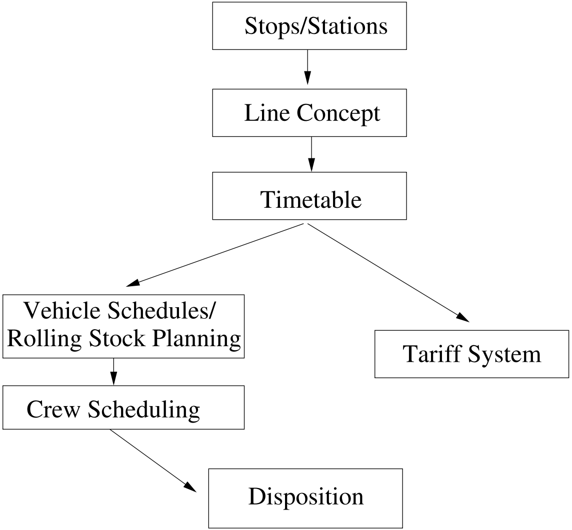
So far, research is mostly focused on single planning stages.

Question: Does this lead to good solutions for the whole system?

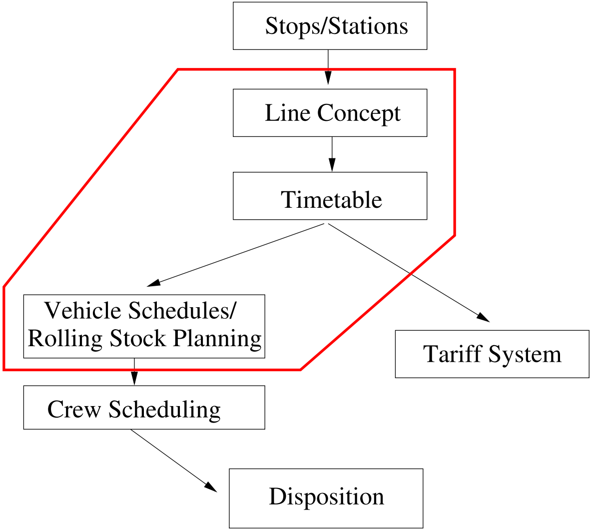
Answer: No!

- The result of one stage may be a "bad" input for the next stage.
  Experiments with LinTim: Many line planning models generate instances for which not even a feasible timetable exists!
- The objective used in a former stage is maybe not a good approximation for what we really want.
  Experiments with LinTim: The costs to be minimized in line planning do not meet the real costs after vehicle scheduling.
- An integrated solution is always as least as good as optimizing stage by stage.

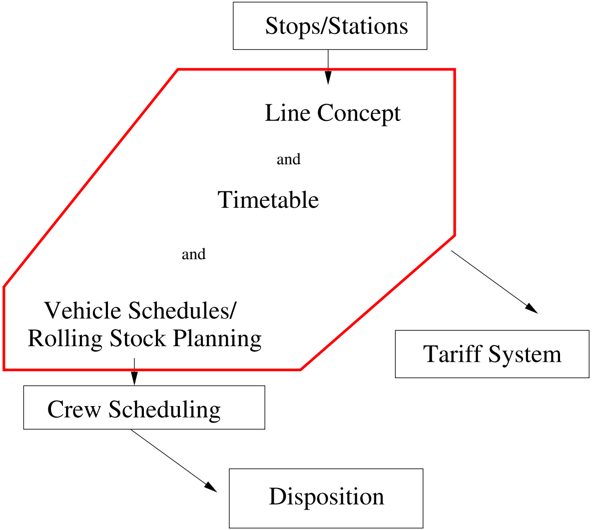
Our goal: Integrating three stages



Our goal: Integrating three stages



Our goal: Integrating three stages



Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

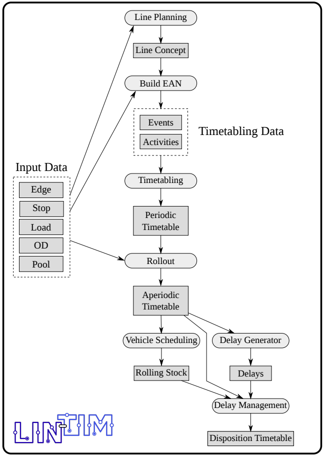
Academic **Open Source Library** for optimization in public transportation

for planning stops, lines, timetables, vehicle schedules, and for delay management.
since 2007, open source since 2017

LinTim

`https://www.lintim.net/`

LinTim: Open Source Library for public transport



Data sets:

- Toy example
- Lower Saxony (railway)
- Grid Network
- Metro in Athens
- Long-distance trains of Germany
- Göttingen Bus System
- more to come!

LinTim: Open Source Library for public transport

Team: Philine Schiewe, Anita Schöbel, Sven Jäger, and researchers from RPTU Kaiserslautern, University Stuttgart, University Passau, ZHAW Zürich, Fraunhofer Kaiserslautern, Fraunhofer Erlangen, and Deutsche Bahn.

LinTim: Open Source Library for public transport

Don't forget:

LinTim

https://www.lintim.net/

End of Commercial Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

Evaluating an LTS-Plan

What we look for:

- Line Plan
- Timetable
- Vehicle Schedule

$\Longrightarrow$ LTS-Plan

Evaluating an LTS-Plan

What we look for:

- Line Plan
- Timetable
- Vehicle Schedule

$\Longrightarrow$ LTS-Plan

Evaluation: We have two main goals $\rightarrow$ biobjective

Costs: Kilometers driven + Time driven + Number of vehicles

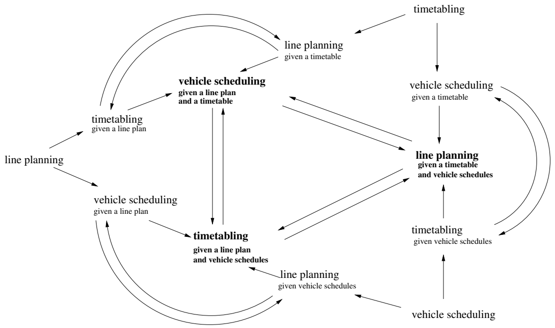
Perceived traveling time: Traveling time of all passengers + penalty for each transfer

Approaches for Integrated traffic planning

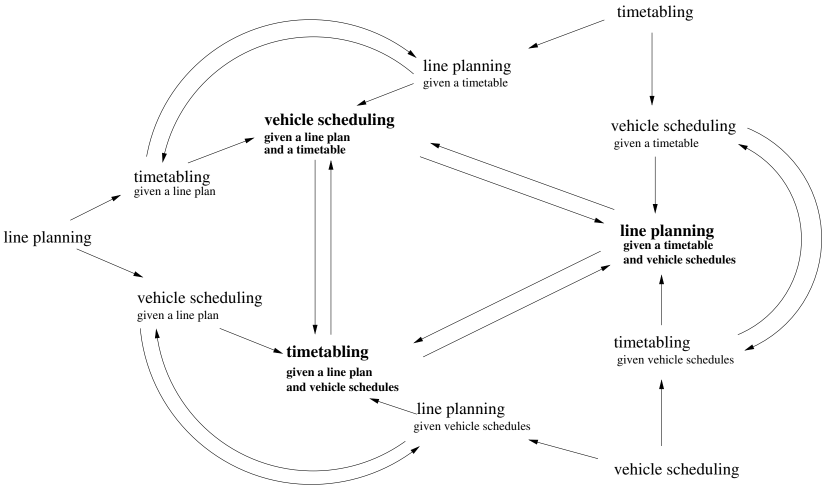
Exact approaches

- One very large IP model?
- Solvable by decomposition?
- Solvable in special cases?

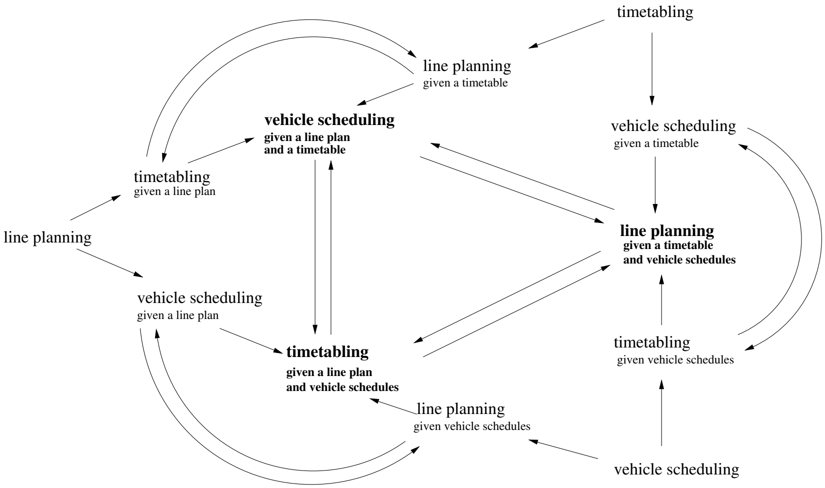
Heuristic approaches



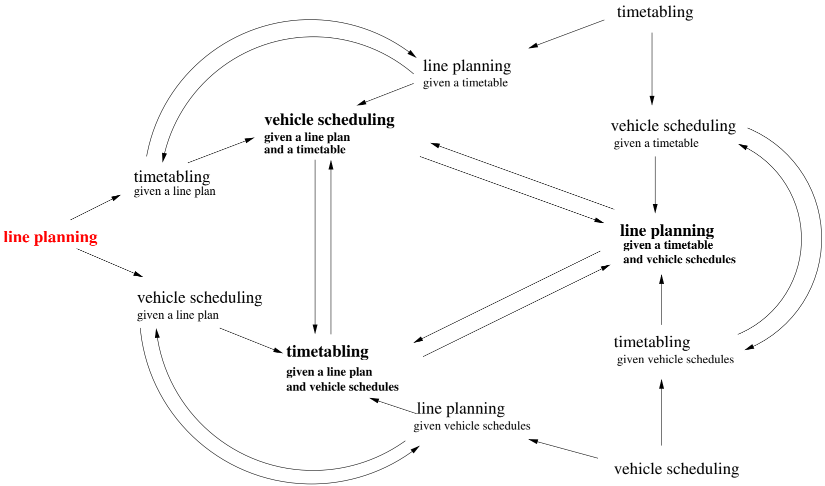
The Eigenmodel as heuristic approach



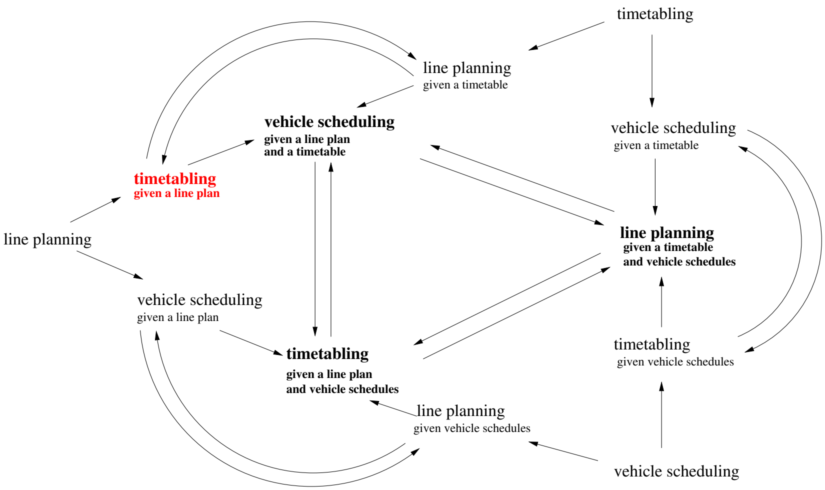
Classic approach



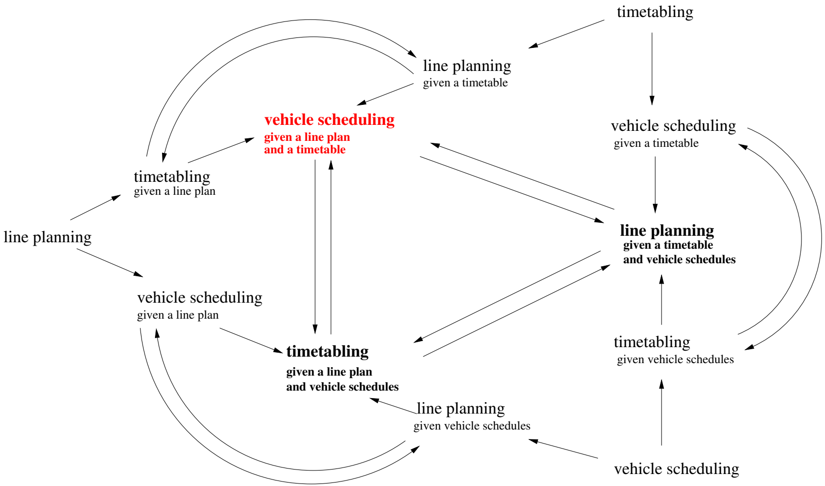
Classic approach



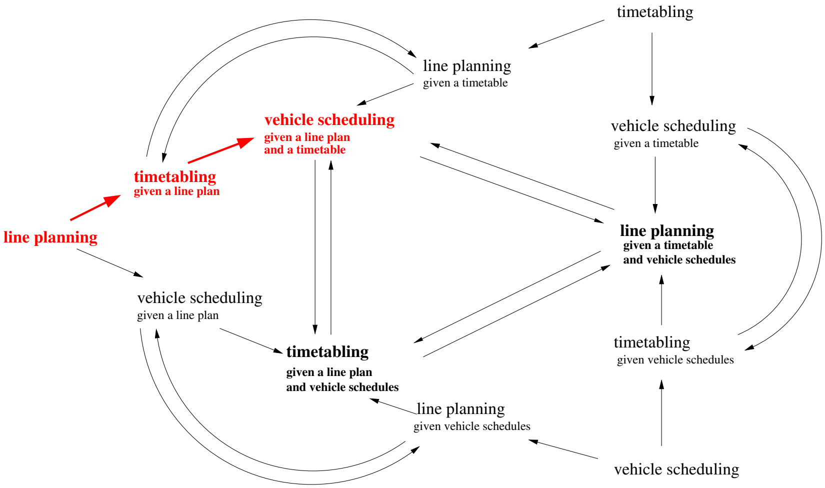
Classic approach



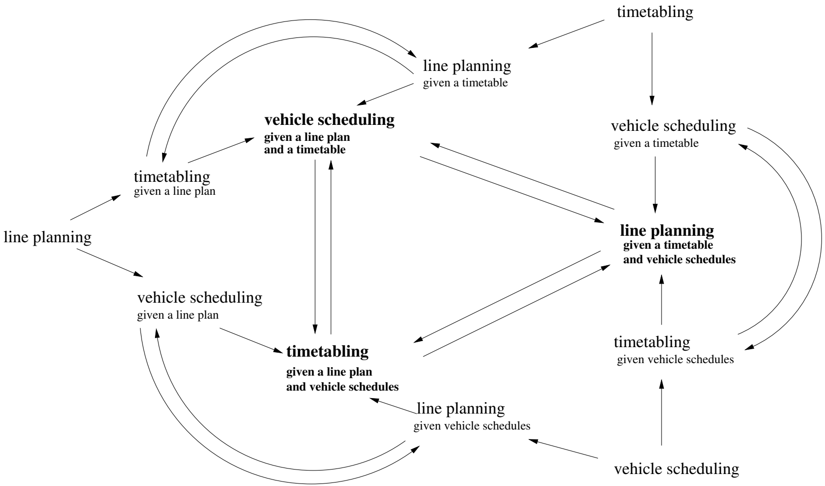
Classic approach



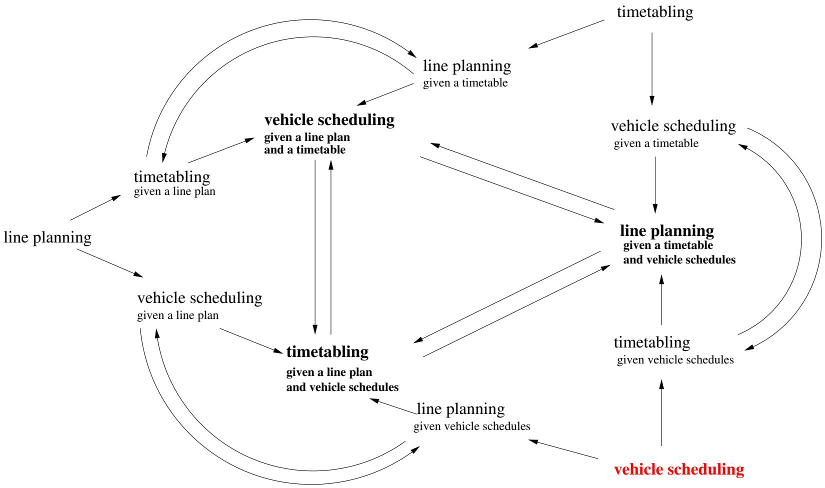
Classic approach



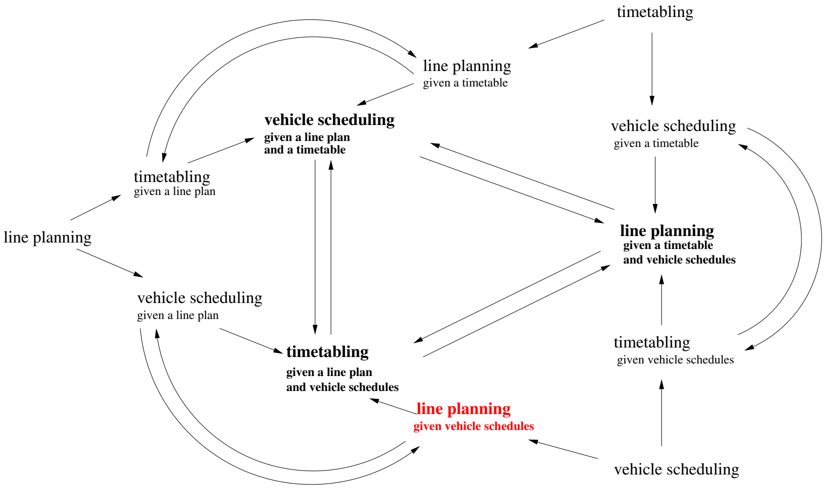
Why not starting in another way?



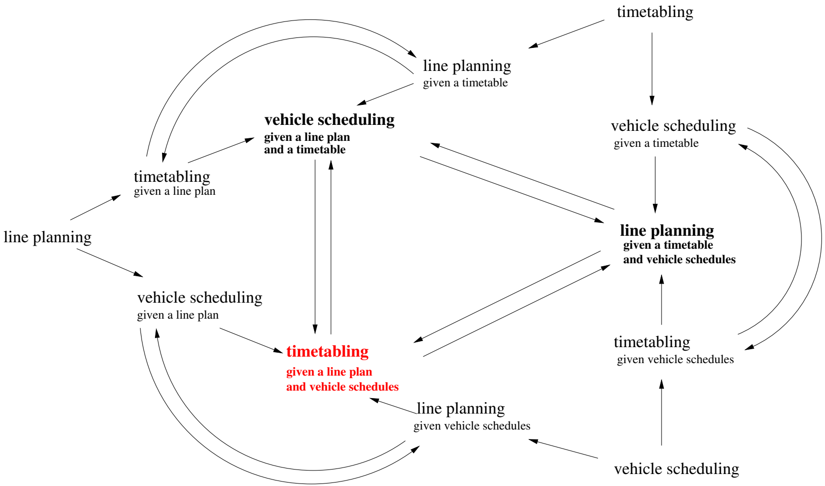
Why not starting in another way?



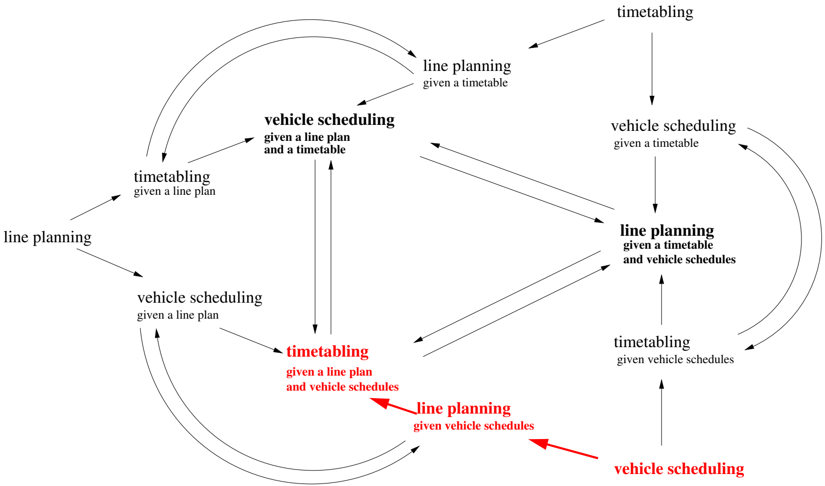
Why not starting in another way?



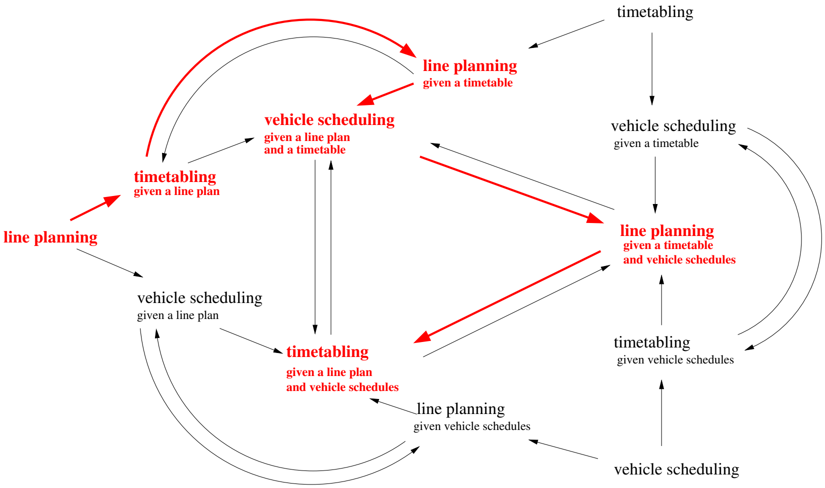
Why not starting in another way?



Why not starting in another way?



Why not an iterative improvement?



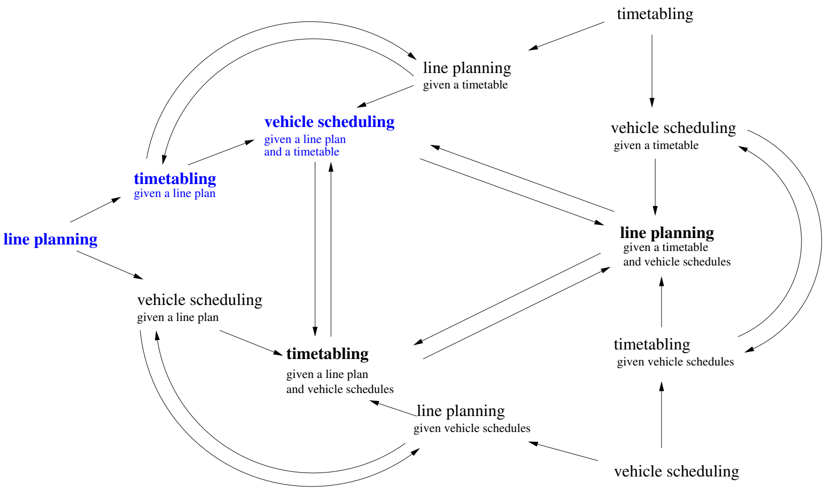
Exploiting the Eigenmodel

Properties of the Eigenmodel

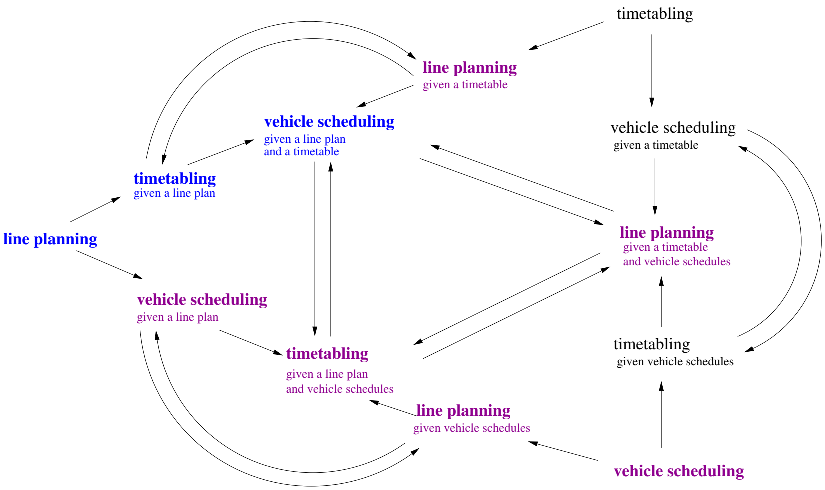
- Every path through the Eigenmodel represents a heuristic algorithm.
- The nodes of the Eigenmodel represent (new) challenging problems with interesting combinatorial structures.

'Eigenmodel'
since it describes the **own** (=eigen) subproblems of the model.

New problems



New problems



The math behind

Iterating through the Eigenmodel is blockwise coordinate descent.

The math behind

Iterating through the Eigenmodel is blockwise coordinate descent.

Algorithm Blockwise Coordinate Descent (BCD)
Input: Variable sets $I_1, \ldots, I_p \subseteq \{1, \ldots, n\}$, initial solution x.
Repeat
For $j := 1$ to p **do**

1. Fix all variables not in I_j and optimize the variables in I_J, let x^* be an optimal solution for them.
2. Set $x := (x^*, x_{-j})$

Until stopping criterion

Well known from continuous optimization, but never analyzed for discrete problems!

BCD for integer linear optimization Jäger and Schöbel, 2020

When can BCD be applied? If any of the two conditions holds:

- All p subproblems are bounded.
- The p subproblems of the first round of Algorithm BCD have optimal solutions.

BCD for integer linear optimization Jäger and Schöbel, 2020

When can BCD be applied? If any of the two conditions holds:

- All p subproblems are bounded.
- The p subproblems of the first round of Algorithm BCD have optimal solutions.

Does BCD converge? If Algorithm BCD is executable *and (P) is bounded*, then the sequence of objective function values converges and becomes constant (linear objective!).

$\Longrightarrow$ Algorithm BCD terminates.

BCD for integer linear optimization Jäger and Schöbel, 2020

When can BCD be applied? If any of the two conditions holds:

- All p subproblems are bounded.
- The p subproblems of the first round of Algorithm BCD have optimal solutions.

Does BCD converge? If Algorithm BCD is executable *and (P) is bounded*, then the sequence of objective function values converges and becomes constant (linear objective!).

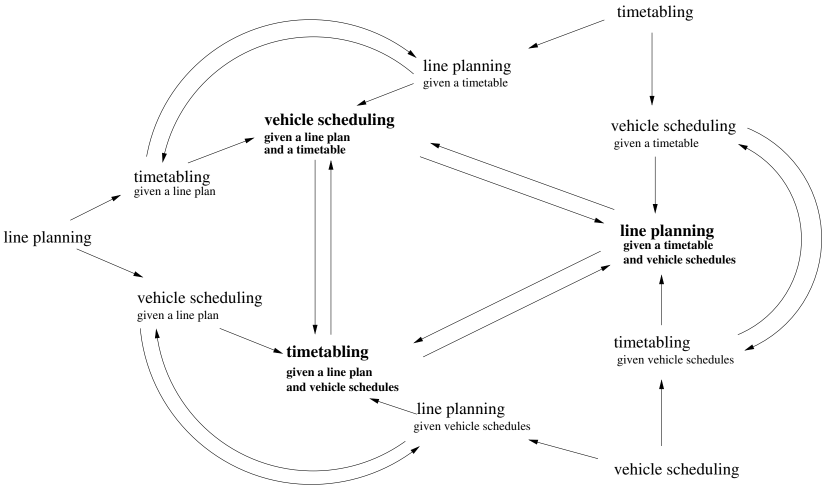
$\Longrightarrow$ Algorithm BCD terminates.

To what does it converge? If BCD terminates with a solution x, then:

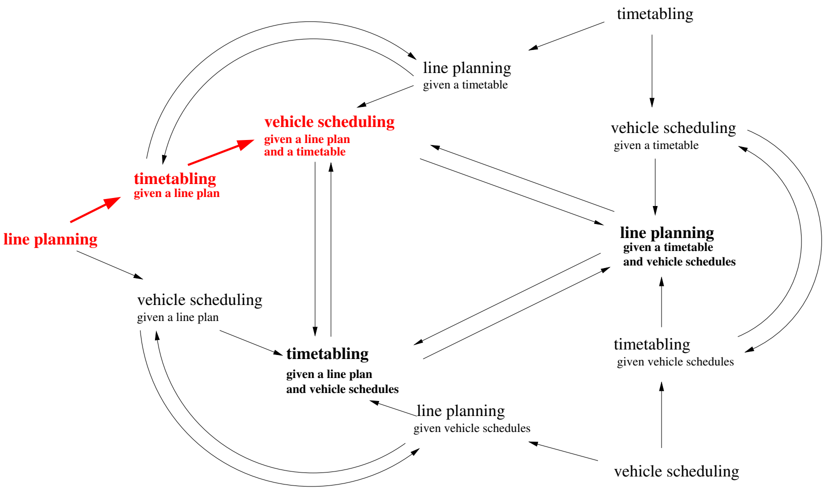
(i) x is blockwise optimal.

(ii) If G contains only one coupling constraint, x is Pareto optimal.

And it works!

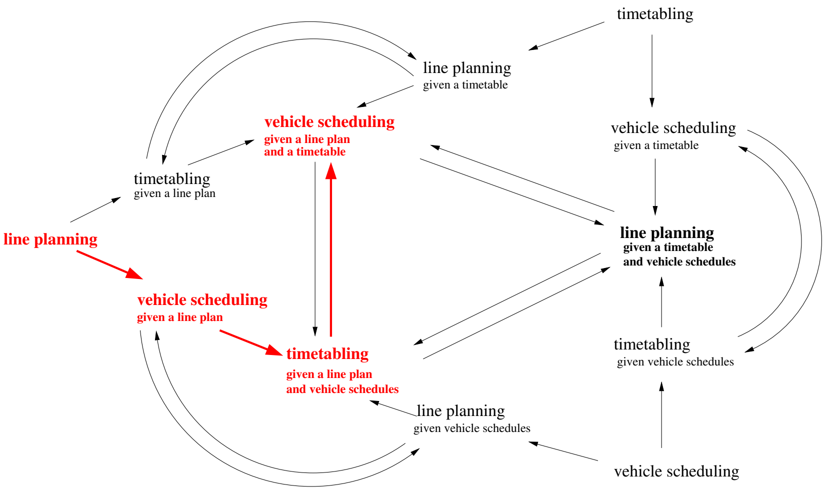

timetabling
line planning
given a timetable
vehicle scheduling
given a line plan
and a timetable
vehicle scheduling
given a timetable
timetabling
given a line plan
line planning
line planning
given a timetable
and vehicle schedules
vehicle scheduling
given a line plan
timetabling
given vehicle schedules
timetabling
given a line plan
and vehicle schedules
line planning
given vehicle schedules
vehicle scheduling

And it works!



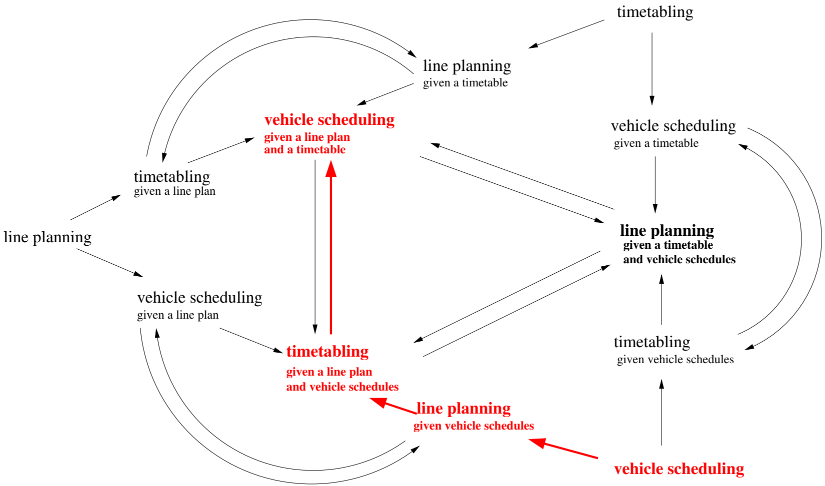
timetabling
line planning
given a timetable
vehicle scheduling
given a line plan
and a timetable
vehicle scheduling
given a timetable
timetabling
given a line plan
line planning
given a timetable
and vehicle schedules
line planning
vehicle scheduling
given a line plan
timetabling
given vehicle schedules
timetabling
given a line plan
and vehicle schedules
line planning
given vehicle schedules
vehicle scheduling

And it works!

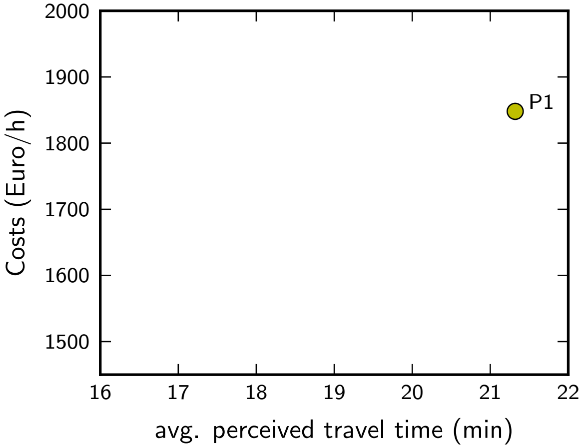


timetabling
line planning
given a timetable
vehicle scheduling
given a line plan
and a timetable
vehicle scheduling
given a timetable
timetabling
given a line plan
line planning
given a timetable
and vehicle schedules
line planning
vehicle scheduling
given a line plan
timetabling
given a line plan
and vehicle schedules
timetabling
given vehicle schedules
line planning
given vehicle schedules
vehicle scheduling

And it works!

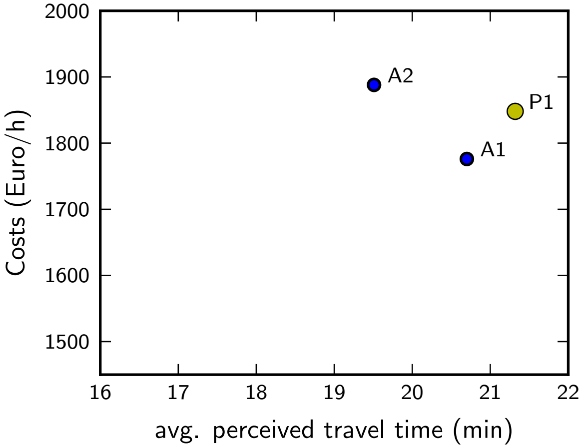

timetabling
line planning
given a timetable
vehicle scheduling
given a line plan
and a timetable
vehicle scheduling
given a timetable
timetabling
given a line plan
line planning
given a timetable
and vehicle schedules
line planning
vehicle scheduling
given a line plan
timetabling
given a line plan
and vehicle schedules
timetabling
given vehicle schedules
line planning
given vehicle schedules
vehicle scheduling

And it works!

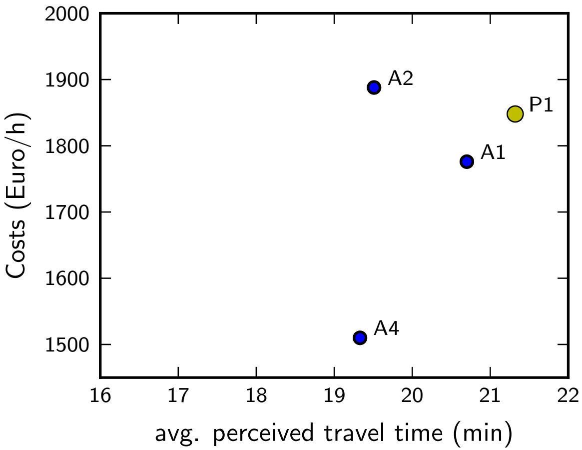


2000
1900
1800
1700
1600
1500
16
17
18
19
20
21
22
P1
Costs (Euro/h)
avg. perceived travel time (min)

And it works!

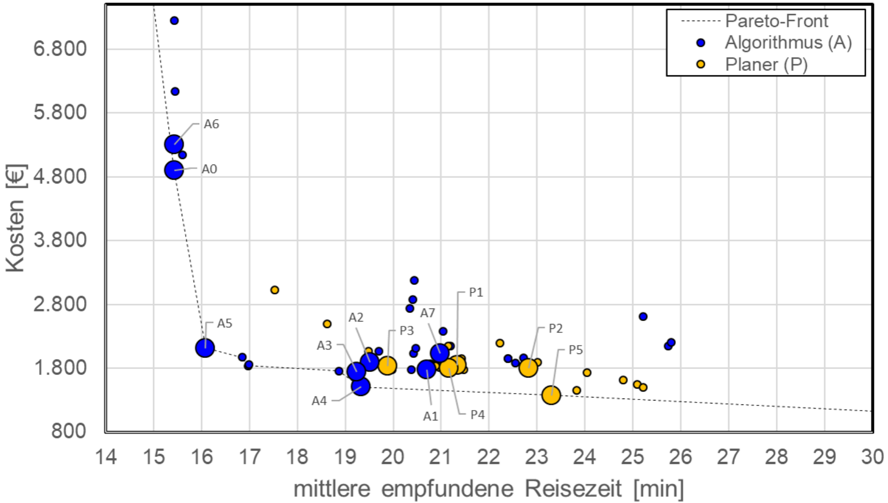

2000
1900
1800
1700
1600
1500
Costs (Euro/h)
A2
P1
A1
16
17
18
19
20
21
22
avg. perceived travel time (min)

And it works!



2000
1900
1800
1700
1600
1500
Costs (Euro/h)
A2
P1
A1
A4
16
17
18
19
20
21
22
avg. perceived travel time (min)

And it works!



Pareto-Front
Algorithmus (A)
Planer (P)
6.800
5.800
4.800
3.800
2.800
1.800
800
Kosten [€]
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
mittlere empfundene Reisezeit [min]
A6
A0
A5
A3
A2
A4
P3
A7
A1
P1
P4
P2
P5

Content of the talk

1. Towards sustainable mobility
2. Making public transport more attractive
   - Line Planning
   - Delay Management
   - Integrated planning
3. Improve the modes themselves
4. Multi-modal planning
5. The end

Sustainable mobility

Emissions of a city Juan Carlos Muñoz (2023) $=$

no. of inhabitants	·	trips per inhabitant	·	km per trip	·	energy per km	·	emissions per energy
family issue		life style		location problem		mode choice		engineering
not our business		home-office, leisure time		minimize travel distances		**make sustainable modes attractive**		**improve modes**

Improve the modes themselves

A lot of research has been done for using electric cars, also in public transport

Not so much known:

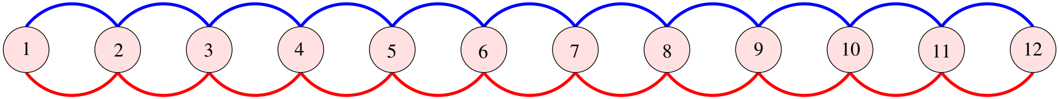
1. Skip-Stop
2. Regenerative energy
3. Reduce pollution from tires

Skip-stops problem

Idea: Juan Carlos Munoz, e.g., IFORS'23

On a line with high frequency:

- Split the line into two: a red and a blue line.
- Let each of the lines leave out some stops.

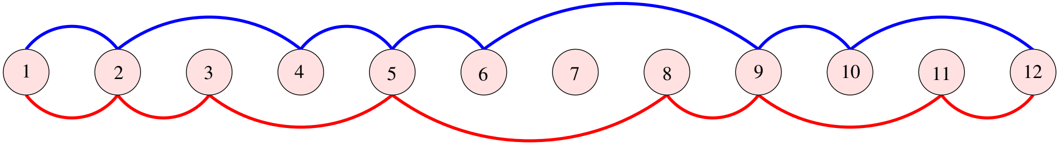


Skip-stops problem

Idea: Juan Carlos Munoz, e.g., IFORS'23

On a line with high frequency:

- Split the line into two: a red and a blue line.
- Let each of the lines leave out some stops.



Why is this sustainable?

- Main reason: The line gets faster (since stopping takes time)
  $\Longrightarrow$ We can have more trains to bring people into or out of the city center
- Also, transportation becomes faster and hence more attractive for some passengers
- Acceleration is the main factor for fuel consumption and emissions
  $\Longrightarrow$ Makes "transport/kilometer" more sustainable.

However: Some passengers will have to transfer or even have detours!

Why is this sustainable?

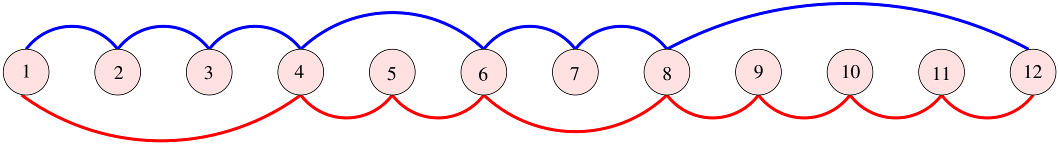
- Main reason: The line gets faster (since stopping takes time)
  $\Longrightarrow$ We can have more trains to bring people into or out of the city center
- Also, transportation becomes faster and hence more attractive for some passengers
- Acceleration is the main factor for fuel consumption and emissions
  $\Longrightarrow$ Makes “transport/kilometer” more sustainable.

However: Some passengers will have to transfer or even have detours!

Skip-stop Reicherz, Schöbel, Jäger (2024)

Characterize feasible patterns:

- No passenger has to transfer if and only if one line visits all stations
- No passenger has a detour if and only if the pattern is homogeneous
- Train travel times are minimal if and only if the pattern is interval-wise



Regenerative Energy

Regenerative Energy

Idea:

- While a train brakes it produces energy
- This energy is best used if it is transferred to a departing train directly

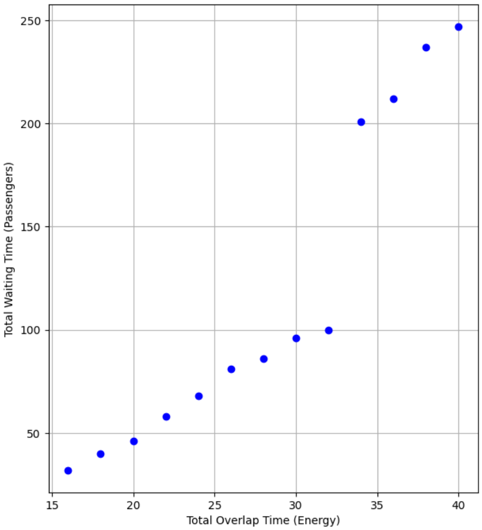
Question: How to design a timetable such that there is enough overlap between arriving and departing trains?

Challenge: From a passenger's perspective this is the worst that can happen!
exactly contradicting the *Basel solution*

Regenerative Energy Roth, Jäger, Schöbel (2024)

For one station

- Poly-time algorithm for maximizing regenerative energy
- NP-hardness for minimizing traveling time
- Case-study for bi-objective problem



Minimizing pollution from tires

Minimizing pollution from tires

Tires are important:

- For stability and duration of cars
  CDTire, ©by ITWM
- but are the largest source of pollution for electric cars
- 1/3 of all micro-plastic in the sea stems from tires

Minimizing pollution from tires

Goals:

1. Develop models for simulating abrasion and noise (dependent on the road surface, the driving style, the load, . . .
2. Use them for pollution-minimal routing, line planning Burger, Schiewe, Schöbel (2022)
3. Use them for simulating and optimizing the design of tires.

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

Commercial Break

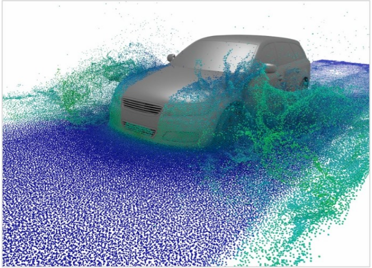
Commercial Break

Welcome at the Fraunhofer Institute for Industrial Mathematics

Welcome at the Fraunhofer Institute for Industrial Mathematics

We work at Modeling, Simulation, and Optimization

- with mostly continuous and some discrete methods
- using ML where appropriate (in particular in hybrid models)
- and are also interested in new technologies: quantum computing, next generation computing



to transfer results from university to real life
in material sciences, mobility, health, energy, production, insurances, ...

Welcome at the Fraunhofer Institute for Industrial Mathematics

Join us at KLAIM 2025!

KLAIM 2023

Kaiserslautern Applied and
Industrial Mathematics Days

organized jointly between RPTU und ITWM

Join us as colleague!

- we are 450 engaged researchers
- with a great working atmosphere
- and always look for new colleagues supporting our research.

End of Commercial Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

End of Break

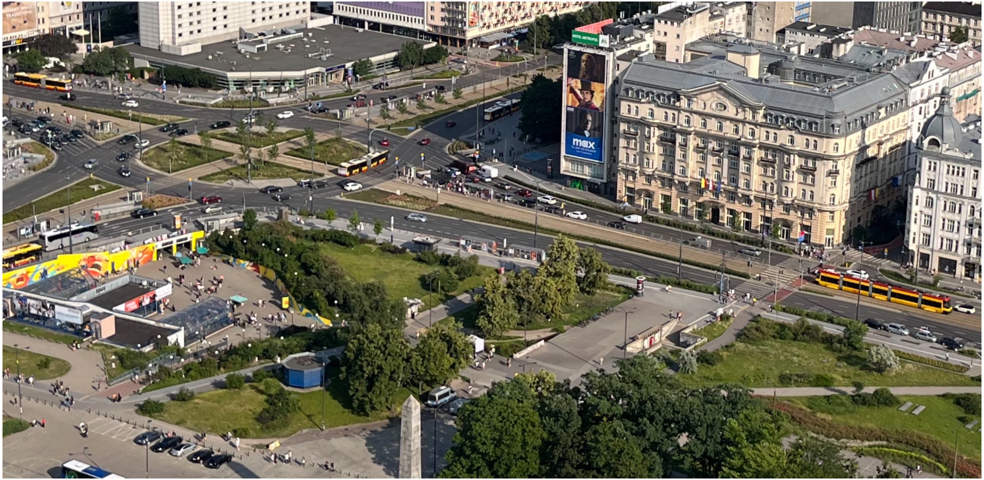
End of Break

Content of the talk

1. Towards sustainable mobility
2. Making public transport more attractive
   - Line Planning
   - Delay Management
   - Integrated planning
3. Improve the modes themselves
4. Multi-modal planning
5. The end

Sustainable mobility

Sustainable mobility



Sustainable mobility

Multi-objective and multi-modal planning

Given is a city and a demand matrix: from where to where wish people to travel?

Task: Determine the best transport modes to be installed in the city.

where we consider three goals:

- traveling times for the passengers
- the budget
- and CO_2 emissions and energy

Multi-objective and multi-modal planning

Given is a city and a demand matrix: from where to where wish people to travel?

Task: Determine the best transport modes to be installed in the city.

where we consider three goals:

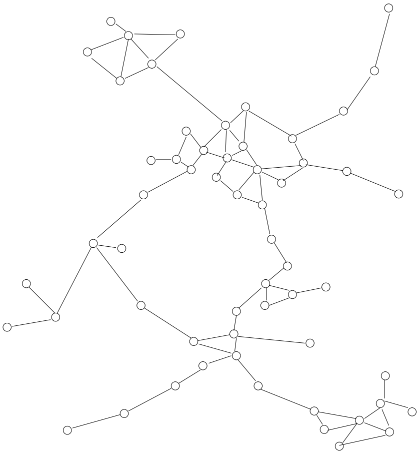
- traveling times for the passengers
- the budget
- and CO_2 emissions and energy

Questions:

- Do we need a metro?
- Where in the city should we offer regular bus transportation? With which lines?
- Where is shared mobility (ride pooling) more appropriate? With how many vehicles?
- To whom do we recommend to use the private car?

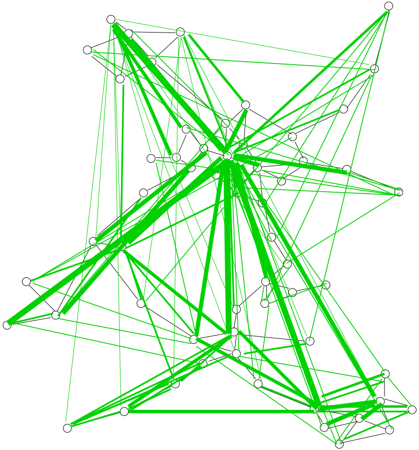
Illustration

Given: City und demand. Goal: transport modes



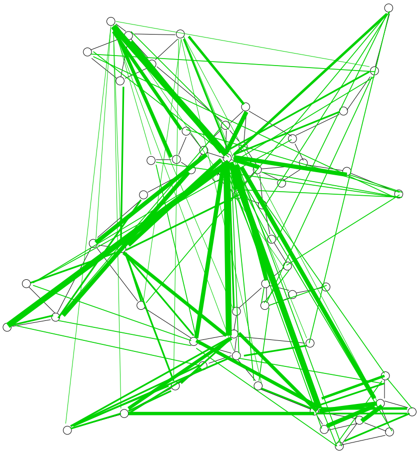
Illustration

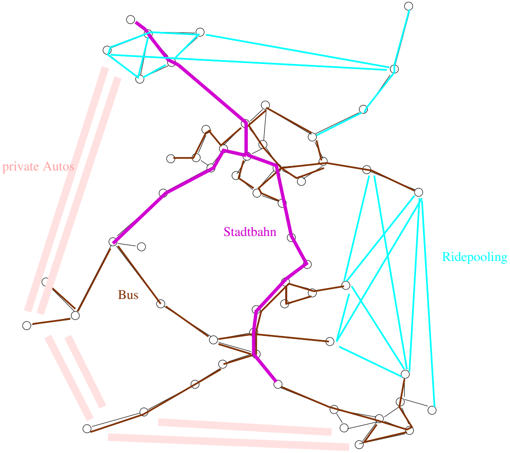
Given: City und demand. Goal: transport modes



Illustration

Given: City und demand. Goal: transport modes





Particularities

Multimodal planning

- Metro
- Bus
- DRT (ride pooling)
- Car

Multicriteria evaluation

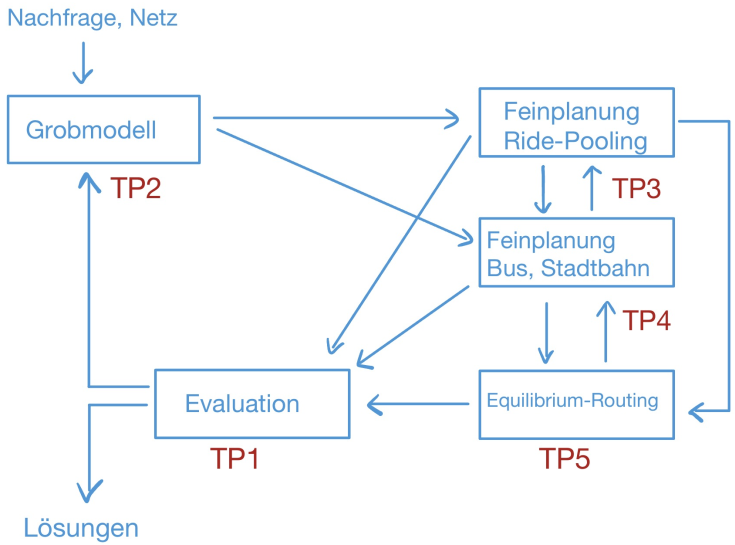
- Travel times
- budget needed
- CO_2 emissions, energy

Equilibrium-constraints

- to model the behavior of the passengers
- compute their traveling times including traffic jams

Not easy.

Modeling idea



The rough model

Idea: Determine capacities per mode per edge such that everybody can travel

neglecting:

- structure of lines or other transport modes
- equilibrium constraints
- costs that vary with the usage

The rough model

Input:

- Graph $G = (V, E)$
- Set of OD-pairs $\mathcal{OD} := \{d = (i, j) : \mathrm{W}_{i,j} > 0\}$
- Set of modes $\mathcal{M} = \{\mathrm{bus}, \mathrm{metro}, \mathrm{DRT}, \mathrm{car}\}$

We determine the units $y_{e,m}$ of infrastructure per mode and per edge such that everybody can travel.

A unit of infrastructure is

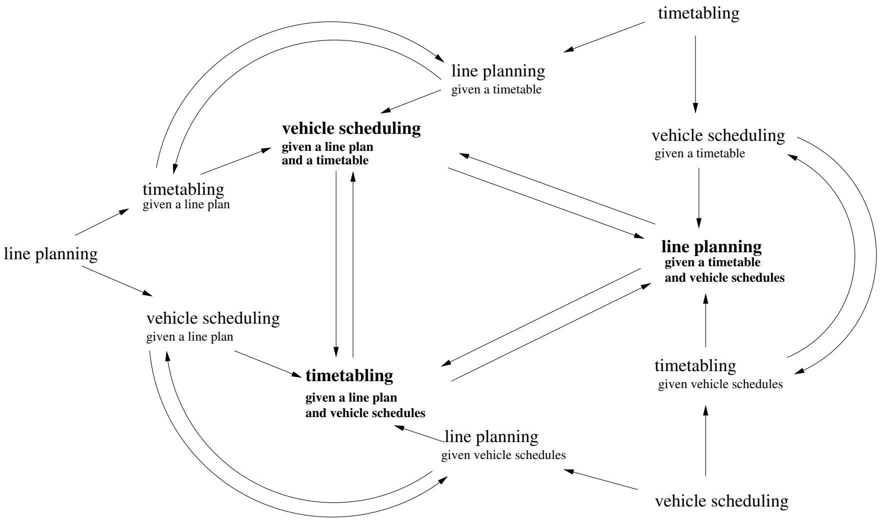
- for car transportation: a lane of a street
- for bus/metro transportation: a bus or a metro
- for DRT: a car

Take-Home Messages

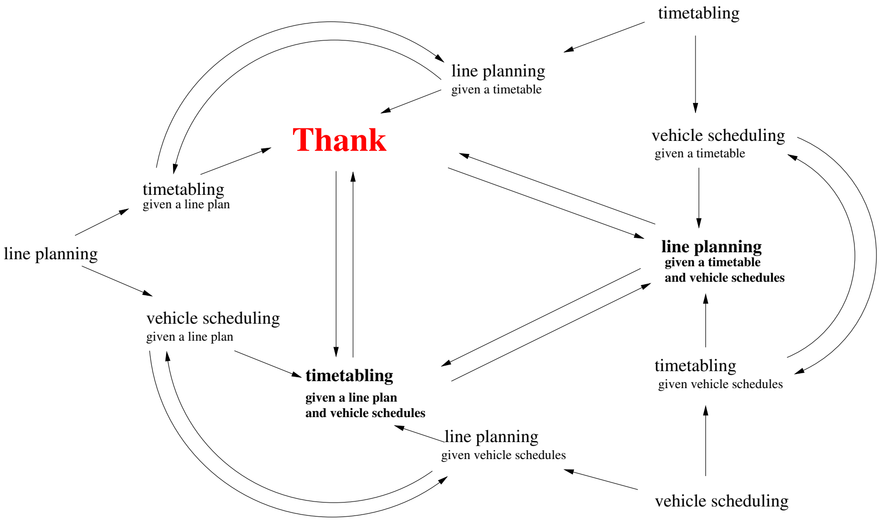
1. Simulation, Optimization, AI can help to make mobility more sustainable
   - Many cute problems wait for us!
     Skip stop problem, multi-period planning, locating places for shared bikes and scooters, edge orientation problem, ...
   - Considering different modes is a new and challenging topic.
2. If AI or classical optimization should be used depends on the problem, the goal, the availability of the data, the security needed.
3. Integration of problems
   - vertically along the planning stages
   - horizontally to handle different modes of transport

   should be considered instead of detailed optimization of single stages.

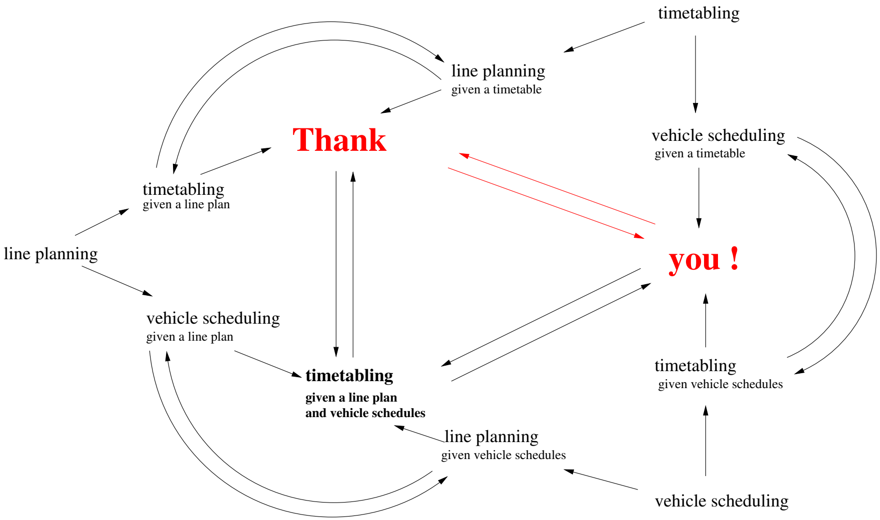
Coming back to the Eigenmodel



Coming back to the Eigenmodel



Coming back to the Eigenmodel



Coming back to the Eigenmodel