University of Paderborn

Optimization systems to support planning processes in traffic and transportation

Leena Suhl
DS&OR Lab
University of Paderborn

Aalto, Nov 29, 2016

University of Paderborn

- University of the Information Society
- ~20.000 students, ~250 professors
- Five Schools (Faculties):

I Faculty of Arts and Humanities
Department of English and American Studies, Department of Educational Science, Department of Protestant Theology, Department of German Studies and Comparative Literary Studies, History Department, Department of Social and Human Sciences, Department of Catholic Theology, Department of Art, Music, Textiles, Department of Media Studies, Department of Romance Languages

II Faculty of Business Administration and Economics
Department 1: Management, Department 2: Taxation, Accounting and Finance Department 3: Business Information Systems, Department 4: Economics, Department 5: Business and Human Resource Education, Department 6: Law

III Faculty of Science
Department of Physics, Department of Chemistry, Department of Sports and Health

IV Faculty of Mechanical Engineering
Sixteen professorships, four interdisciplinary research facilities

V Faculty of Computer Science, Electrical Engineering and Mathematics
Department of Electrical Engineering and Information Technology, Department of Computer Science, Department of Mathematics

DS&OR Lab Paderborn

- Decision Support and Operations Research Lab University of Paderborn (since 1995)
  - Optimization/simulation models and applications for traffic, transportation, logistics, production, supply chain management, infrastructure networks
  - Embedded in Decision Support Systems

- PACE – International Graduate School
  - Research projects with PhD candidates
  - Mathematical optimization in production and logistics processes
  - Joint projects with enterprises

PACE Paderborn Center for Advanced Studies

International Graduate School of Dynamic Intelligent Systems

Operations Research in Germany

- German OR Society: 1300 Members
  - President 2015-16 Leena Suhl
  - 15 working groups
  - International annual conference (in English)
    - 2015 Vienna, 2016 Hamburg, 2017 Berlin, 2018 Brussels
- Many OR professors have a chair for
  - Optimization in mathematics
  - Production management
  - Business information systems
  - Analytics
  - Controlling

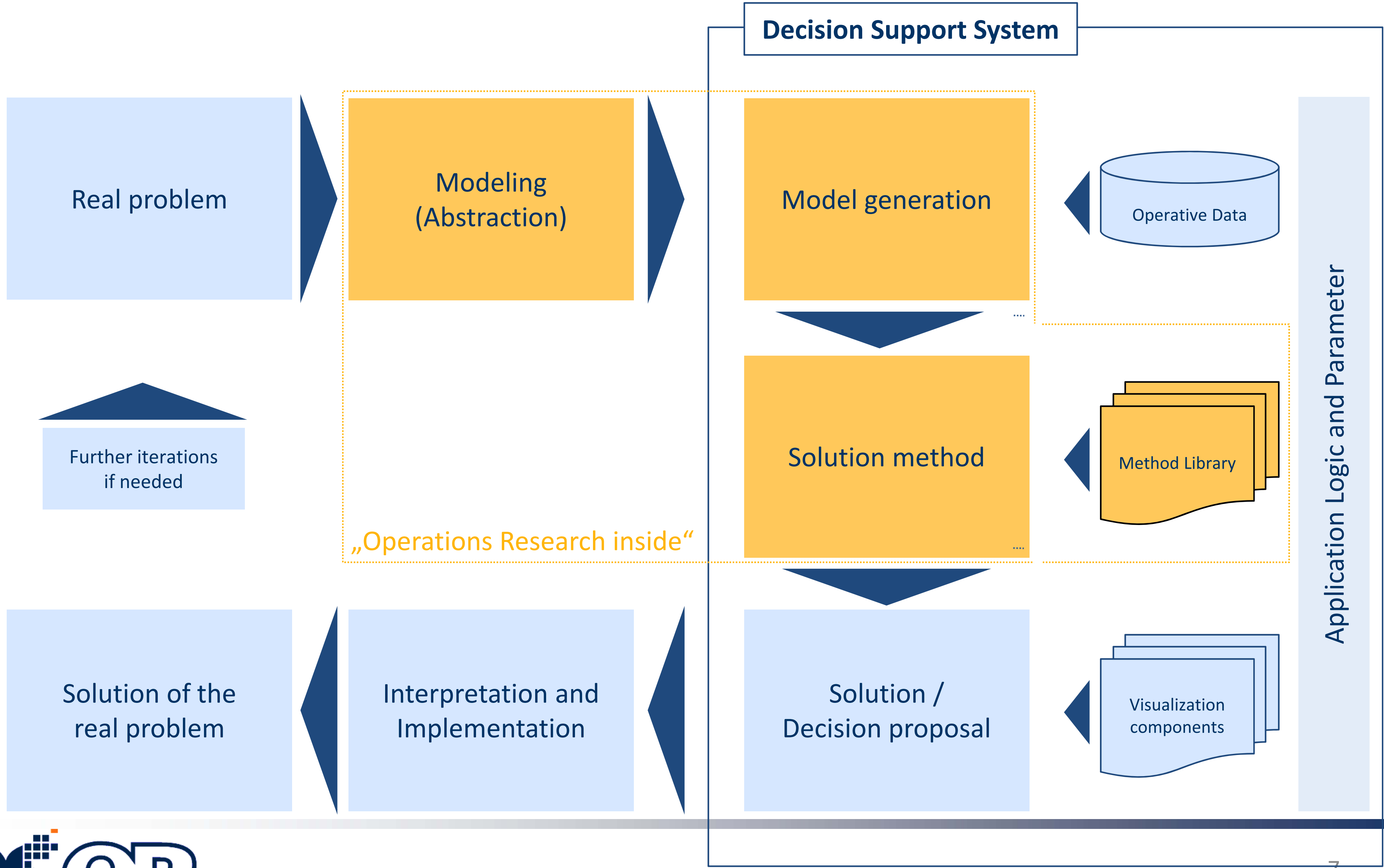
Agenda

- Optimization systems; Decision Support Systems
- Application areas
- Planning problems in public transport
- Integrated vehicle and crew scheduling
- Maintaining regularity
- Integrated crew scheduling and rostering

Typical Research Topics

- Business process analysis
- Modeling approach
- Solution methods
  - Optimization, (meta)heuristics, simulation
- Special aspects such as
  - Uncertainties
  - Missing data
  - Robustness
  - Dynamics => online optimization
  - Integration
  - Multiple criteria

Decision Support System



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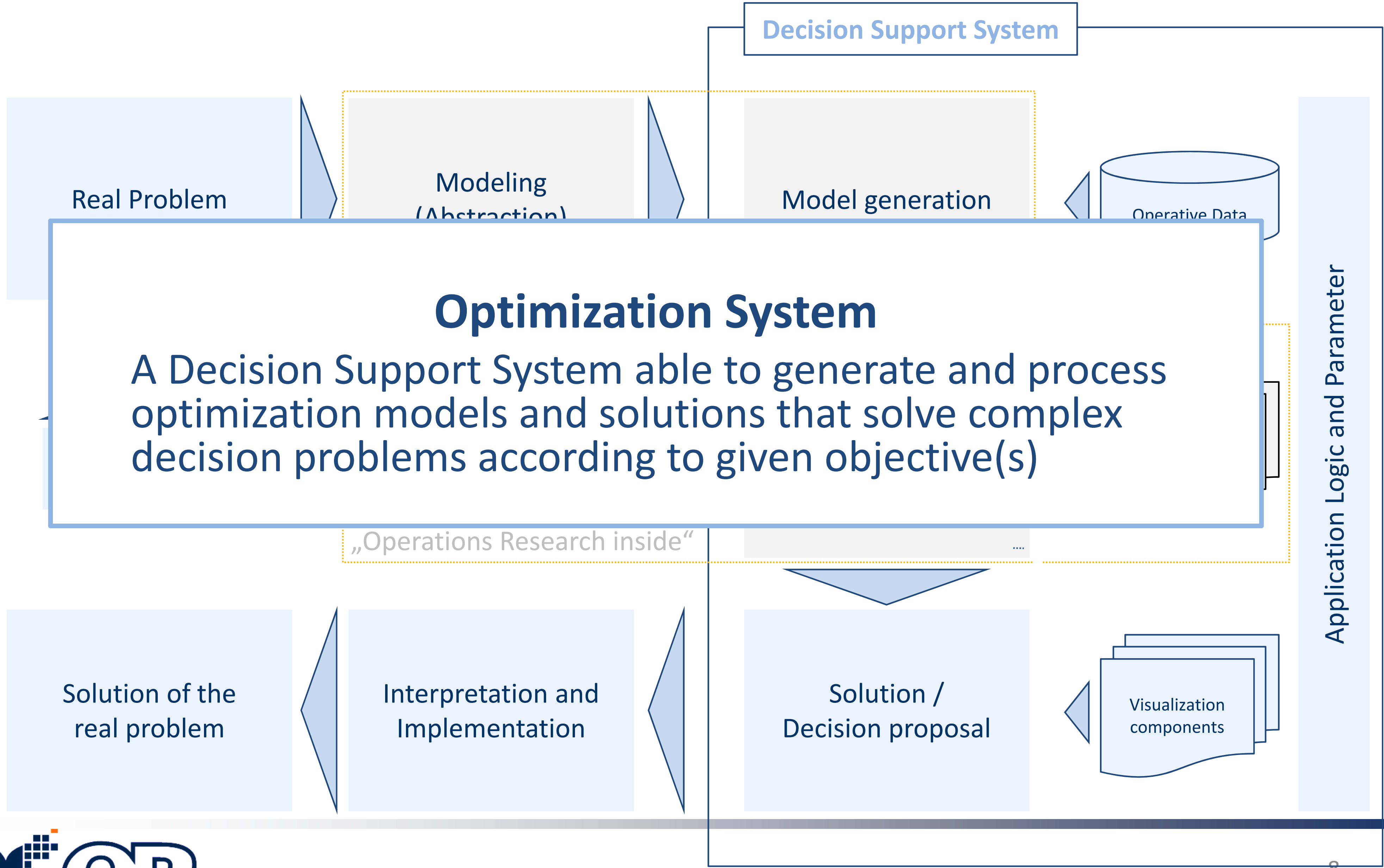
Optimization System



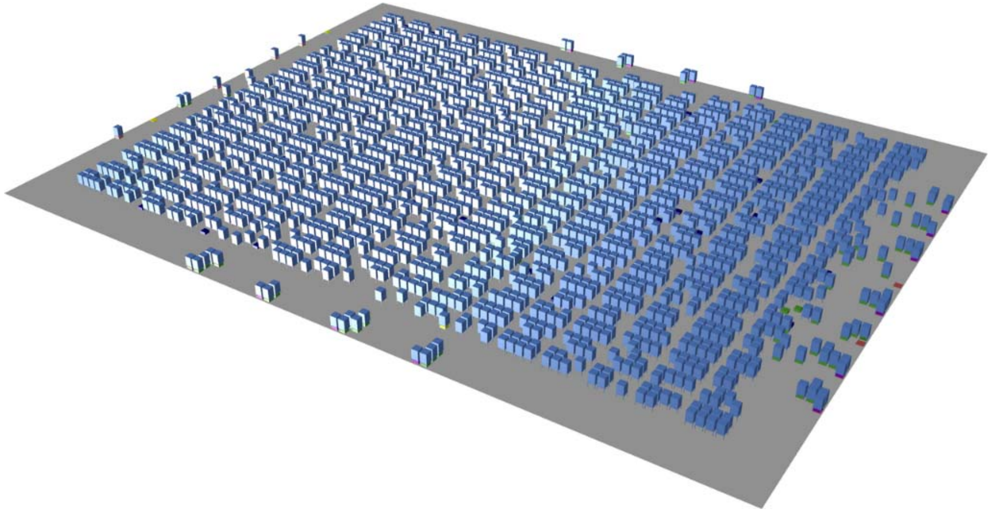
Optimization System

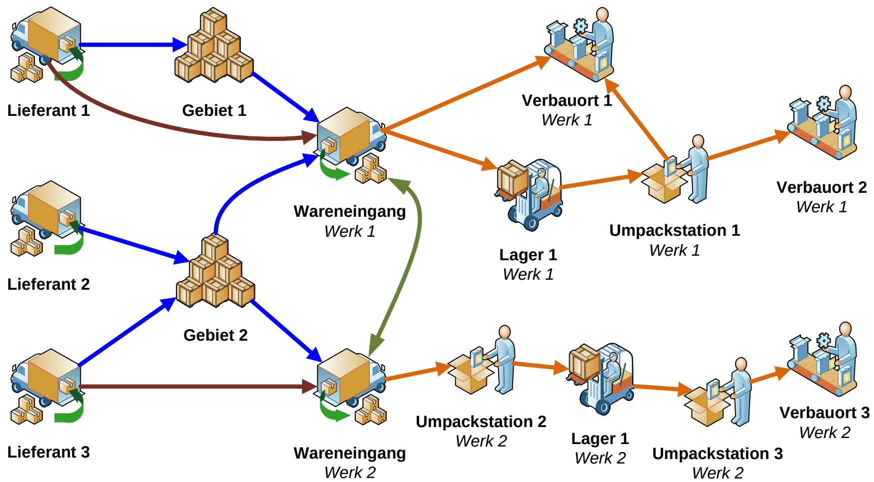
A Decision Support System able to generate and process optimization models and solutions that solve complex decision problems according to given objective(s)

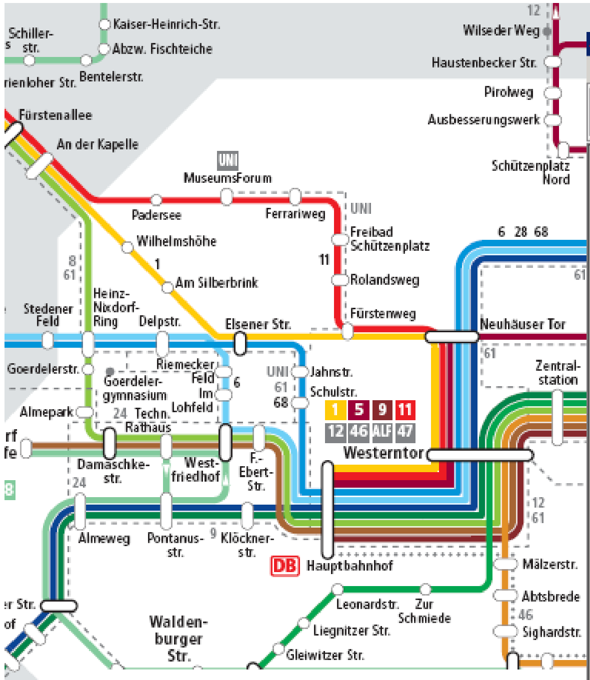
Some Optimization Applications

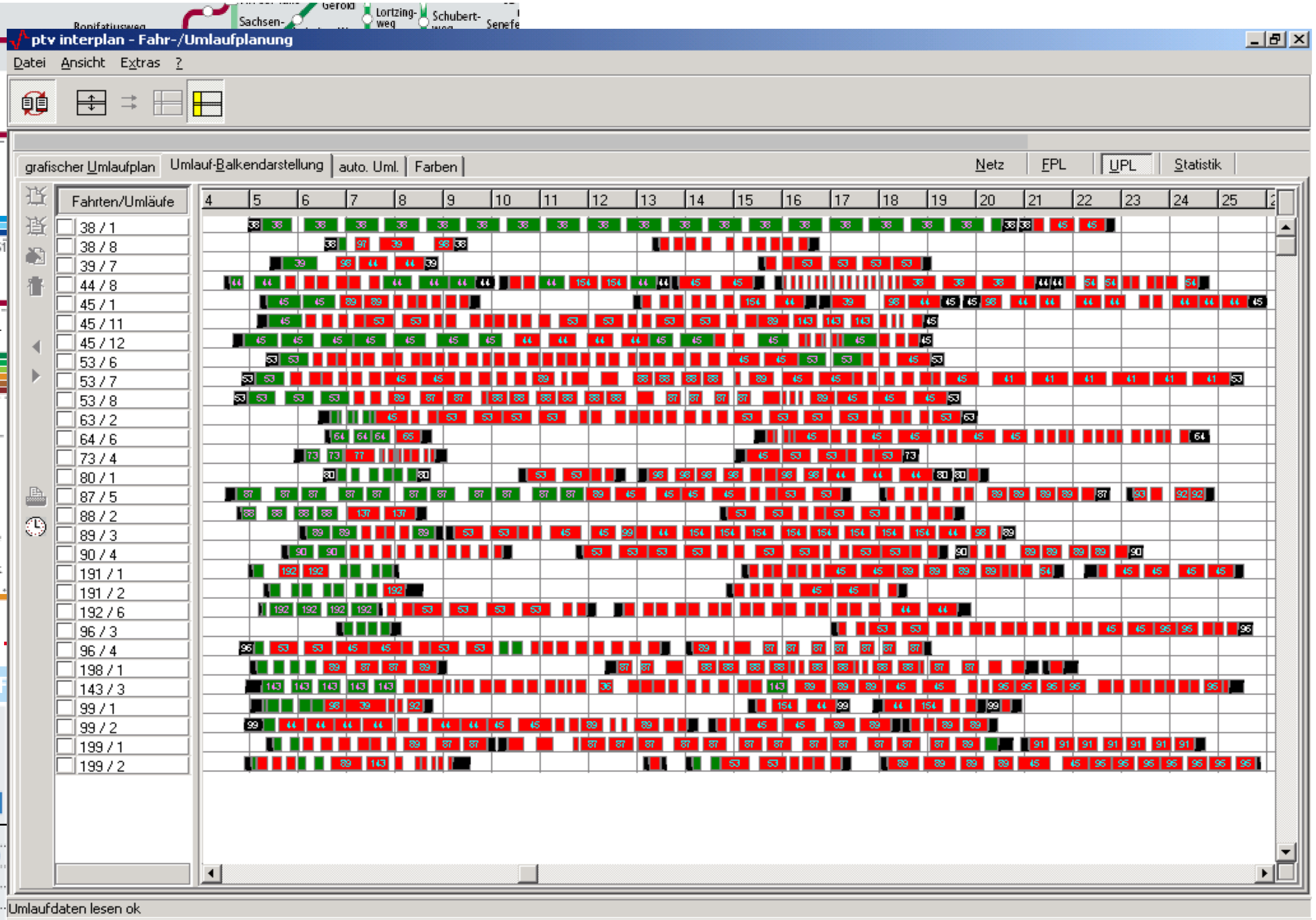
Focus: Efficient ressource utilization

- Vehicle routing and scheduling
- Production planning
- Production network optimization
- Inbound logistics optimization
- Crew scheduling
- Supply chain management
- Packing problems
- Home health care
- Water/Gas networks
- Mobile robot fulfillment systems









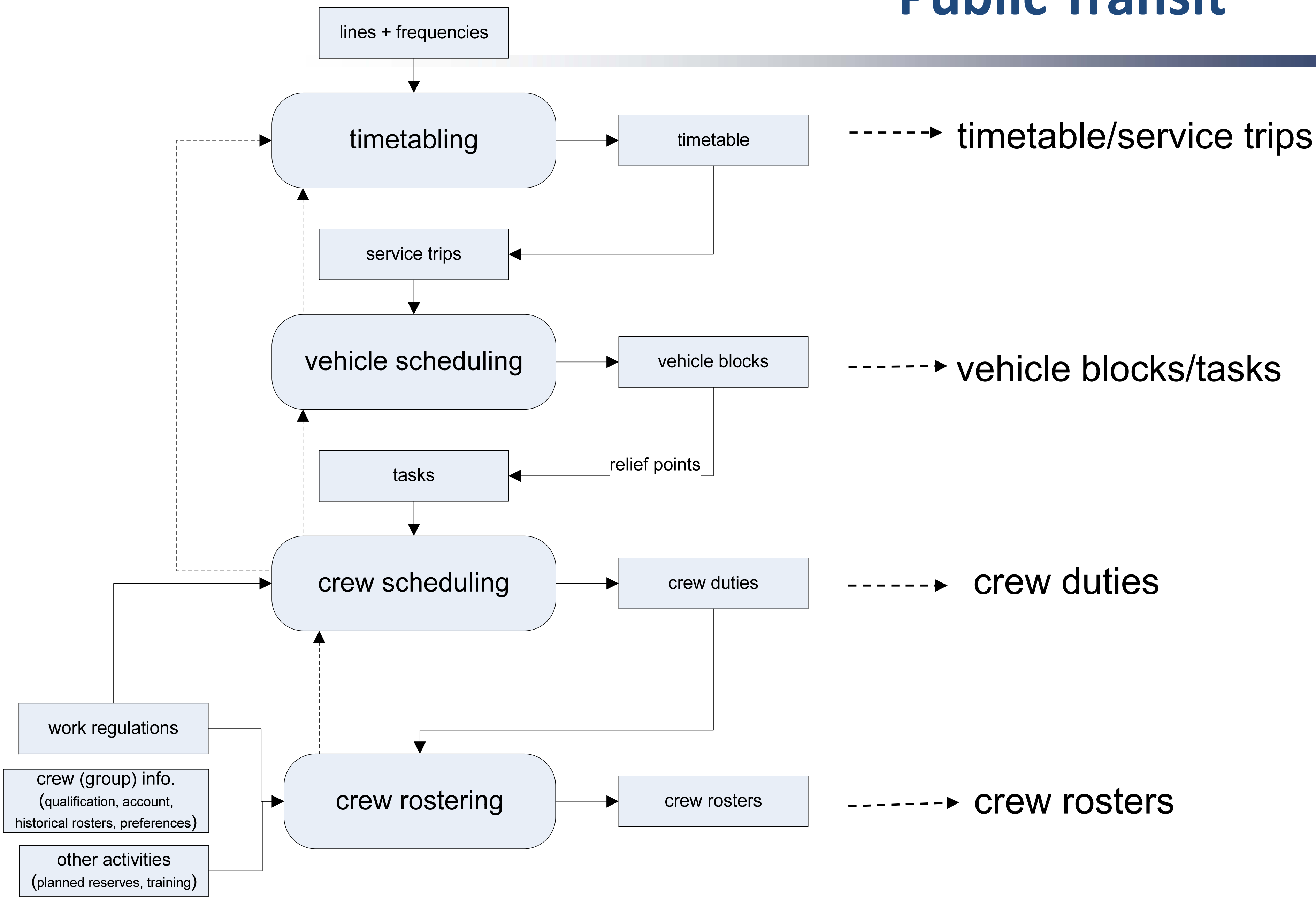
1 Hauptbahnhof → Schloß Neuhaus

MONTAG BIS F

	4 …	5 …	6… Uhr		11		7… Uhr 11		11													
Hauptbahnhof	45	32	02	32	38	00	17	32	47													
Westerntor	47	34	05	35	40	03	19	35	49													
Neuhäuser Tor	48	35	07	37	42	05	21	37	51													
Fürstenweg	49	36	08	38	42	06	21	38	51													
Elsener Straße	50	37	09	39	|	07	|	39														
Am Silberbrink	51	38	10	40	|	08	|	40	|	10	|	40	|	10	|	51	14	|	53	|	53	23
Wilhelmshöhe	52	39	11	41	|	09	|	41	|	11	|	41	|	11	|	52	15	|	54	|	54	24
An der Kapelle	53	40	13	43	48	11	27	43	57	13	27	43	57	13	27	53	16	27	55	27	55	25
Fürstenallee	54	41	14	44	49	12	28	44	58	14	28	44	58	14	28	54	17	28	55	28	55	25
Marienloher Straße	55	42	15	45	50	13	29	45	59	15	29	45	59	15	29	55	18	29	56	29	56	26
Schloß Neuhaus	56	43	16	46	51	14	30	46	00	16	30	46	00	16	30	56	19	30	57	30	57	27
Hatzfelder Platz	57	44	17	47	52	15	31	47	01	17	31	47	01	17	31	57	20	31	57	31	57	27
Waldlust	58	45	18	48		16		48		18		48		18		58	21		58		58	28
Adenauerring	59	46	19	49		17		49		19		49		19		59	22		59		59	29
Wilhelmsberg	00	47	20	50		18		50		20		50		20		00	23		00		00	30
Bahnkreuzung	01	48	21	51		19		51		21		51		21		01	24		01		01	31
Thunebrücke	02	49	22	52		20		52		22		52		22		02	25		01		01	31
Hauptwache	03	50	23	53		21		53		23		53		23		03	26		02		02	32
Salvatorstraße	04	51	24	54		22		54		24		54		24		04	27		03		03	33
Pionierweg	05	52	25	55		23		55		25		55		25		05	28		04		04	34
Infanterieweg	06	53	26	56		24		56		26		56		26		06	29		05		05	35

11 Linie 11 (Thuner Siedlung)

Planning Process in Public Transit



Decision Support for Public Transit: Some research problems

- Multi-depot VSP, several vehicle types
- Regularity of schedules
- Integrated vehicle and crew scheduling
- Integrated crew scheduling & rostering
- Cyclic crew scheduling
- Limited #line changes
- Maintenance routing
- Robust planning
- Stochasticity
- Decision support tools

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Vehicle scheduling for public transport

Simple VSP:

- Construct a collection of vehicle runs for a given timetable, so that trips can be linked only through vehicle connections at terminal stations
  - Minimize the number of vehicles needed
  - Min-cost network flow problem, easily solvable

Extensions:

- Deadheading
- Multiple depots
- Periodicity
- Multiple vehicle types
- Time windows
- Maintenance routing

1 Hauptbahnhof → Schloß Neuhaus → Sennelager

MONTAG BIS FREITAG

	4 ...	5 ...	6... Uhr			7... Uhr				8...-18... Uhr				19... Uhr			20... Uhr			21...-22...		23 ...
					11		11		11		11		11		11			11		11		
Hauptbahnhof	45	32	02	32	38	00	17	32	47	02	17	32	47	02	17	45	08	17	47	17	47	17
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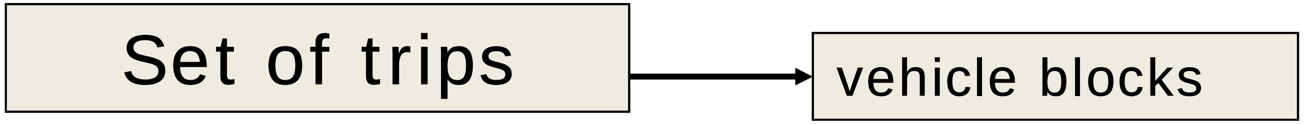
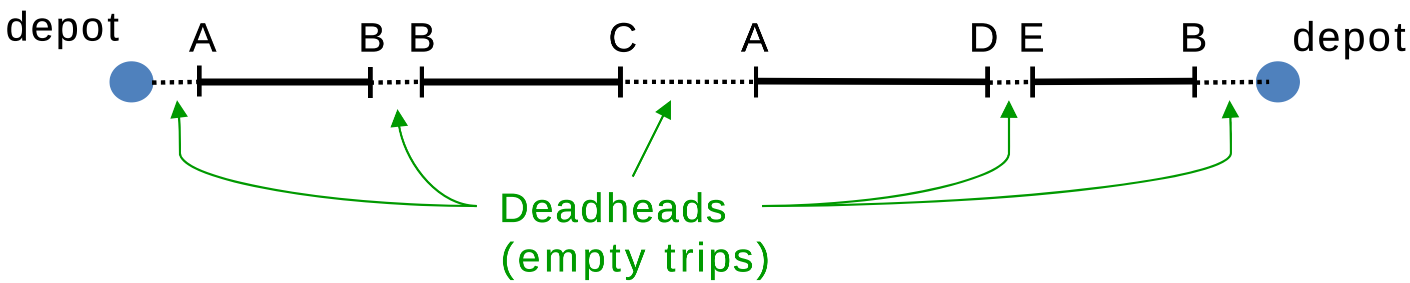
Infanterieweg	06	53	26	56		24		56		26		56		26		06	29		05		05	35

11 Linie 11 (Thuner Siedlung)

The Multi-Depot Vehicle Scheduling Problem (MDVSP)



Vehicle block:



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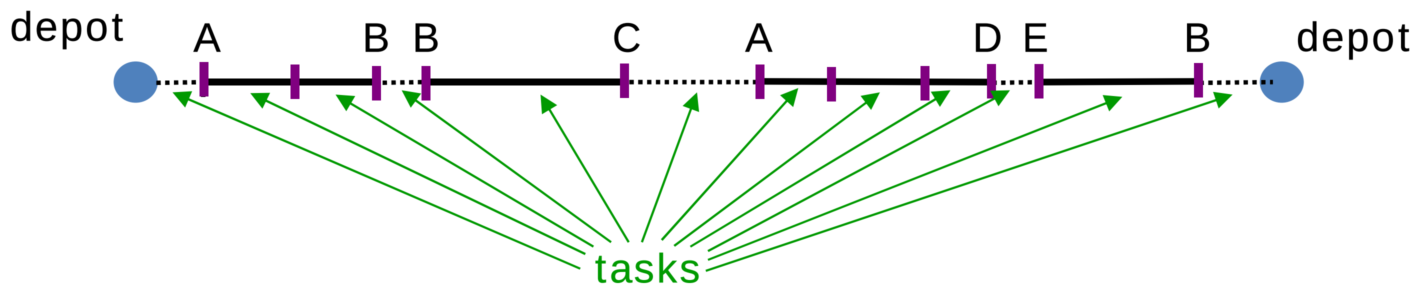
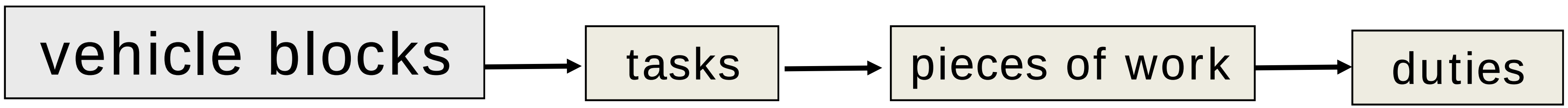
Crew Scheduling (after Vehicle Scheduling)

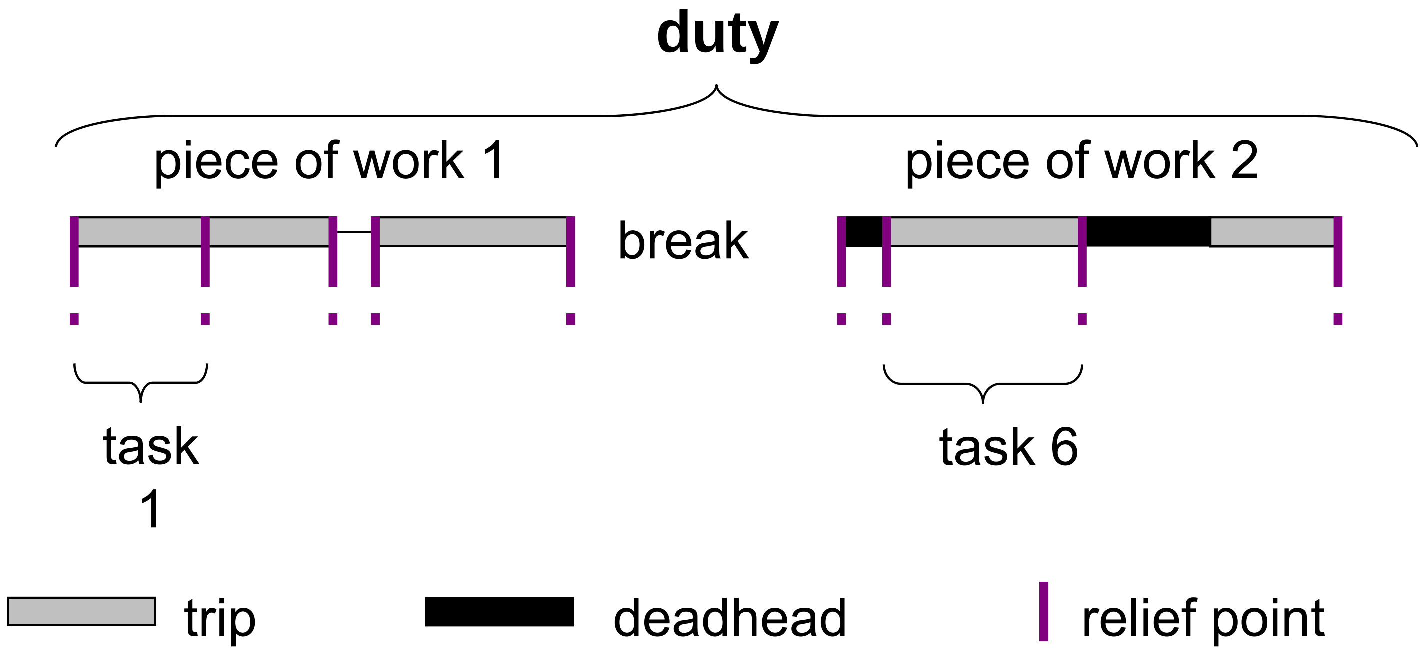


Relief point: location where a change of driver can occur

Task: portion of work between two consecutive relief points along a bus block

Crew Scheduling (after Vehicle Scheduling)





Consider: Piece of work related and duty related constraints

- Number of pieces, Min and max piece duration, min and max break duration, Min and max duty length, Min and max working time

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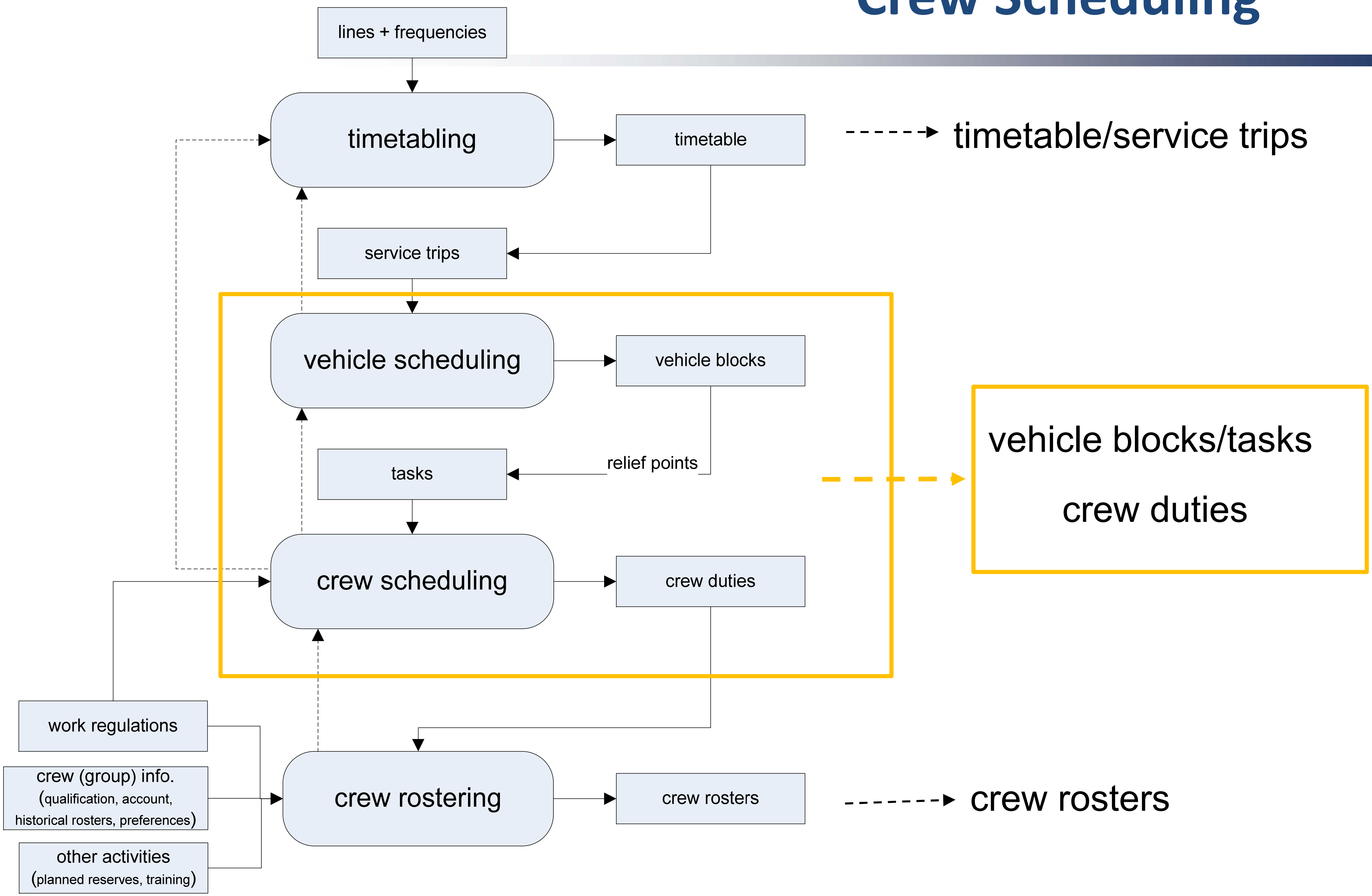
Integrated Vehicle and Crew Scheduling



Integrated Vehicle and Crew Scheduling

- Disadvantages of sequential planning
  - Deadheads are fixed through the VSP

  ➔ CSP may be unfeasible or not efficient

- Advantages of integration
  - Parallel consideration of VSP and CSP
  - All possible deadheads are available

  ➔ More degrees of freedom for the CSP

- But: Problem with integration
  - Fully integrated models are large and very difficult to solve

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Integrated Multi-Depot Vehicle and Crew Scheduling Problem (MDVCSP)

- **Given:** set of service trips of a timetable and set of relief points
- **Task:** find a set of vehicle blocks and crew duties such that
  - Vehicle and crew schedules are feasible
  - Vehicle and crew schedules are mutually compatible
  - Sum of vehicle and crew costs is minimized

- **Exact Formulation:** MDVSP + CSP + linking constraints
  - Compare with variable fixing heuristic

Basic Model Types

Models for the MDVSP

- Connection based flow modeling
- Time-space network flow modeling
  - Single commodity vs. Multi-commodity flow
- Set partitioning models

Set Partitioning Problem

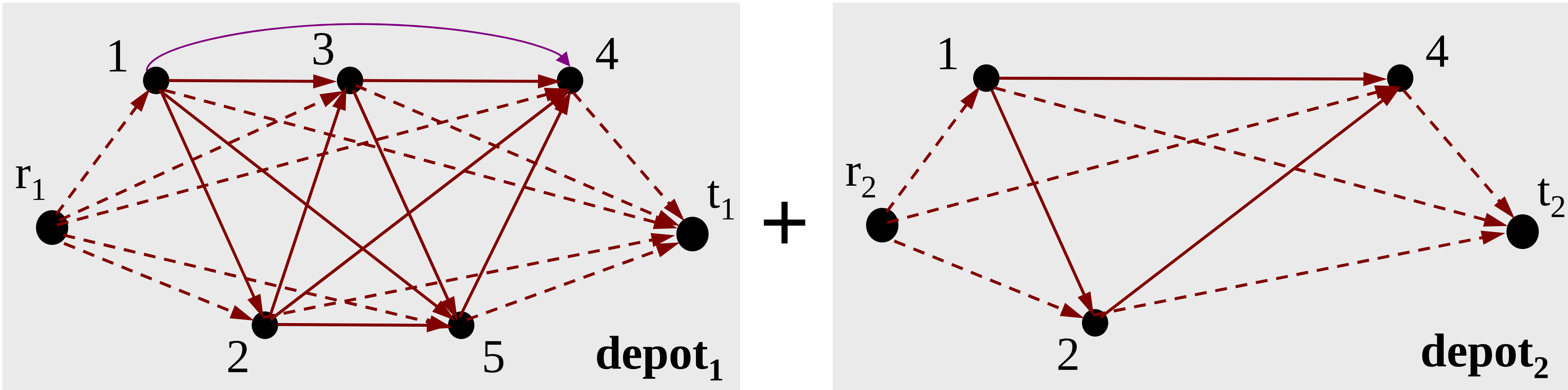
$$
\begin{array}{lllllllll}
\max & \delta_1 & +\delta_2 & +\delta_3 & +\delta_4 & +\delta_5, & & \\
s.t. & \delta_1 & +\delta_2 & & & & +\delta_6 & =1, \\
 & \delta_1 & & +\delta_3 & & +\delta_5 & +\delta_7 & =1, \\
 & & \delta_2 & & +\delta_4 & +\delta_5 & +\delta_8 & =1, \\
 & & & \delta_3 & & & +\delta_9 & =1, \\
 & \delta_1 & & & & & +\delta_{10} & =1, \\
 & & \delta_2 & & +\delta_4 & +\delta_5 & +\delta_{11} & =1, \\
\end{array}
$$

$$\delta_i \in \{0, 1\}, \text{ 1 to 11}$$

Models for the CSP

- Set partitioning models
- Time-space network flow modeling
  - Only for smaller problems
    (because of history-based restrictions)

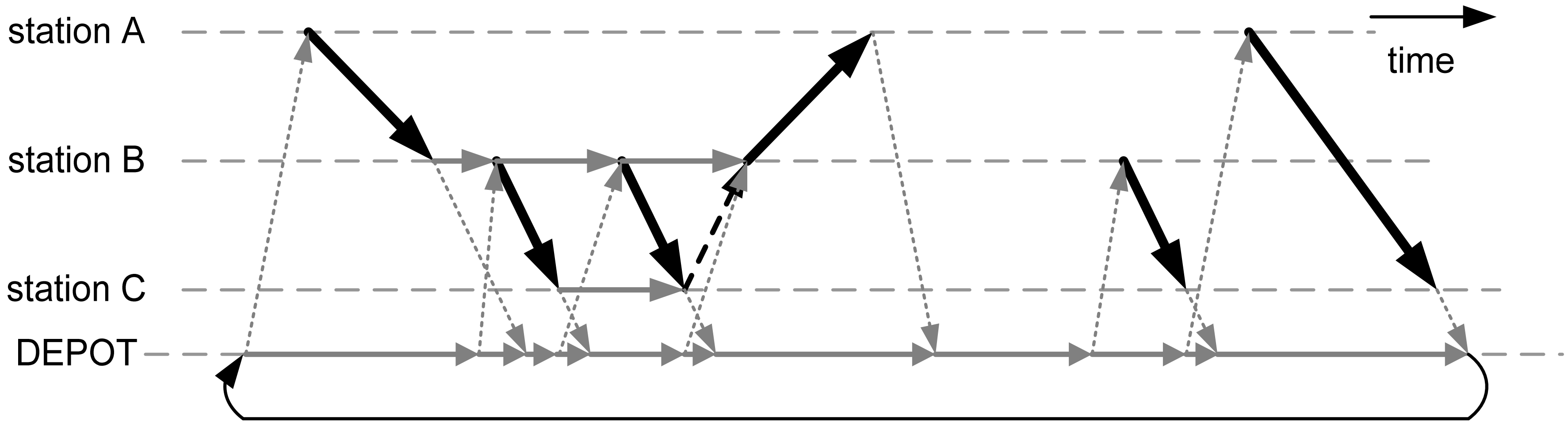
MDVSP: Connection Based Modeling (traditional)



- Nodes ⇔ Trips (n trips)
- Arc (i,j): Connection between trips i and j

arcs: ***O(n²)***

MDVSP: Time-Space Network Modeling



- Nodes ⇔ Points in time-space; Arcs ⇔ trips or waiting
- #arcs: ***O(nm)***
  - n trips; m stations: Note that m<<n !!
- Works well for the MDVSP
- Size can be drastically reduced through aggregation of arcs

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Crew Scheduling: Set Partitioning Model

- Complex working time rules
  => need to follow the path of each crew member

Set partitioning

Set Partitioning Problem

$$
\begin{aligned}
\max\quad & \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5, \\
s.t.\quad & \delta_1 + \delta_2 + \delta_6 = 1, \\
& \delta_1 + \delta_3 + \delta_5 + \delta_7 = 1, \\
& \delta_2 + \delta_4 + \delta_5 + \delta_8 = 1, \\
& \delta_3 + \delta_9 = 1, \\
& \delta_1 + \delta_{10} = 1, \\
& \delta_2 + \delta_4 + \delta_5 + \delta_{11} = 1, \\
& \delta_i \in \{0, 1\},\ 1 \text{ to } 11
\end{aligned}
$$

- 1) Generate a large amount of feasible duties
  - For example with resource constrained shortest path (RCSP) formulation
- 2) Use integer programming formulation:
  - Possible duties are expressed as columns of the coefficient matrix indicating which trips are covered by the duty
  - 0/1 Variable x_j indicates if crew schedule j is chosen or not
  - Constraints require that each trip is covered

MDVCSP: Connection-based Formulation

Edge connecting task i and j with vehicle from depot d

equals 1 if duty k in depot d is selected

D – set of all depots
N – set of all tasks
N^d – set of all tasks of depot d
A^{sd} – set of all short edges of depot d
A^{ld} – set of all long edges of depot d
y_{ij} – edge connecting task i and j

$$\min \sum_{d \in D} \sum_{(i,j) \in A^d} c_{ij}^d y_{ij}^d + \sum_{d \in D} \sum_{k \in K^d} f_k^d x_k^d$$

Vehicle scheduling

$$\sum_{d \in D} \sum_{\{j:(i,j) \in A^d\}} y_{ij}^d = 1 \qquad \forall i \in N$$

$$\sum_{d \in D} \sum_{\{i:(i,j) \in A^d\}} y_{ij}^d = 1 \qquad \forall j \in N$$

$$\sum_{\{i:(i,j) \in A^d\}} y_{ij}^d = \sum_{\{i:(j,i) \in A^d\}} y_{ji}^d \qquad \forall d \in D, \forall i \in N^d$$

Crew scheduling

$$\sum_{\{j:(i,j) \in A^d\}} y_{ij}^d = \sum_{k \in K^d(i)} x_k^d \qquad \forall d \in D, \forall i \in N^d$$

Linking constraints

$$y_{ij}^d = \sum_{k \in K^d(i,j)} x_k^d \qquad \forall d \in D, \forall (i,j) \in A^{sd}$$

$$y_{it^d}^d + \sum_{\{j:(i,j) \in A^{ld}\}} y_{ij}^d = \sum_{k \in K^d(i,t^d)} x_k^d \qquad \forall d \in D, \forall i \in N^d$$

$$y_{r^d j}^d + \sum_{\{i:(i,j) \in A^{ld}\}} y_{ij}^d = \sum_{k \in K^d(r^d,j)} x_k^d \qquad \forall d \in D, \forall i \in N^d$$

$$x_k^d, y_{ij}^d \in \{0,1\} \quad \forall d \in D, \forall k \in K^d, \forall (i,j) \in A^d$$

Huisman et al. 2005

MDVCSP: Time-Space Network Formulation

vehicle costs of arc (i,j) in depot d

flow on arc (i,j) in depot d

costs of duty k in depot d

D – set of all depots
A^d – set of productive arcs depot d
y^d_{ij} – edge connecting task i and j
t – trip
V^d - set of nodes

$$\min \sum_{d \in D} \sum_{(i,j) \in A^d} c^d_{ij} y^d_{ij} + \sum_{d \in D} \sum_{k \in K^d} f^d_k x^d_k$$

equals 1 if duty k in depot d is selected

s. t.:

$$\sum_{\{i:(i,j) \in A^d\}} y^d_{ij} = \sum_{\{i:(i,j) \in A^d\}} y^d_{ji} \qquad \forall d \in D, \forall j \in V^d$$

$$\sum_{d \in D} \sum_{(i,j) \in A^d(t)} y^d_{ij} = 1 \qquad \forall t \in T$$

Vehicle scheduling

$$\sum_{k \in K^d(i,j)} x^d_k = y^d_{ij} \qquad \forall d \in D, \forall (i,j) \in A^d$$

$$x^d_k \in \{0,1\} \qquad \forall d \in D, \forall k \in K^d$$

Crew scheduling
+
Linking

$$0 \le y^d_{ij} \le u^d_{ij} \qquad \forall d \in D, \forall (i,j) \in A^d$$

$$y^d_{ij} \text{ integer } \forall d \in D, \forall (i,j) \in A^d$$

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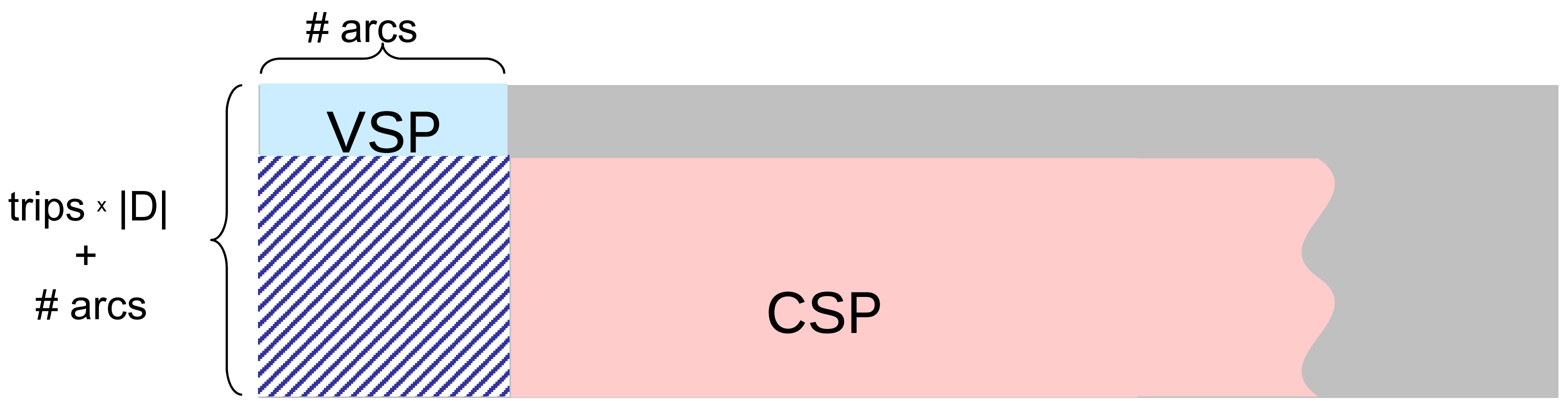
Suhl, Steinzen et al. 2010

Comparison of TSN with Connection-based Formulation

- TSN: More compact formulation; smaller network
  MIP is smaller and easier to solve



#arcs\#trips	100	200	400	800
Connection-based network	17800	69500	273000	1075000
Time-space network	3000	6500	13800	27900
% of conn-based	16,9	9,3	5,1	2,6

Avg. results for Huisman 2005 test set, 10 instances per group

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Solution using the TSN formulation

Column generation in combination with Lagrangean relaxation

Solve MDVSP and CSP sequentially

duties = columns of CSP model

while *duties* ≠ ∅ or no termination criteria satisfied

- Add *duties* to MDVCSP
- ↓
- Compute dual multipliers by solving Lagrangean dual problem with current set of columns
- ↓
- Delete duties with high positive reduced costs
- ↓
- *duties* = Generate new negative reduced cost columns

↓

Find integer solution

Approach:
Standard MIP-Solver
Network optimizer
Heuristics
Duty generation alg.

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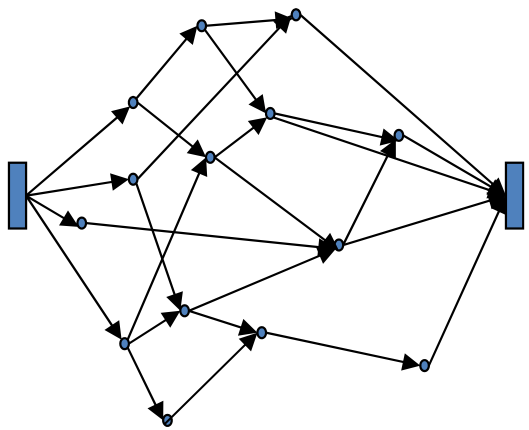
Modeling the Column Generation Pricing Problem

- In the column generation phase, we need to generate duties with negative reduced costs
  - a very complex problem with huge degree of freedom
- Usually formulated as a resource constrained shortest path problem (RCSP)
- Define network G(N,A)
  - nodes N: relief points, source, sink
  - arcs A: tasks, task connections (e.g. breaks, deadheads, sign-on/off)
- Duty constraints and piece of work related constraints have to be considered



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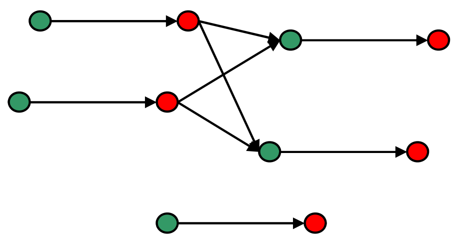
Network Models for a Decomposed Pricing Problem

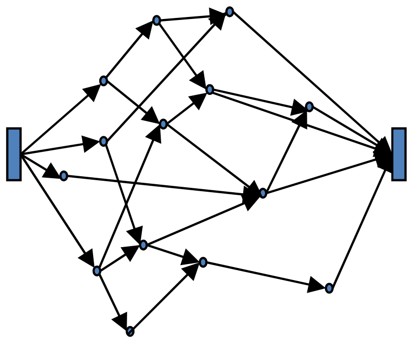
Piece generation network



pieces of work

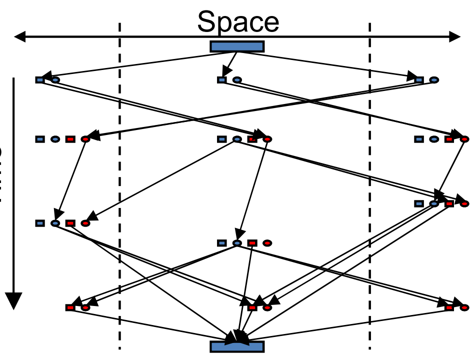
pieces of work

connection-based duty generation network (Freling et al. 1997, 2003)



network size: O(#tasks^4)

aggregated time-space duty generation network (Steinzen/Suhl 2011)



network size: O(#tasks^2)

Computational Results
Duty Types with two pieces of work, four depots

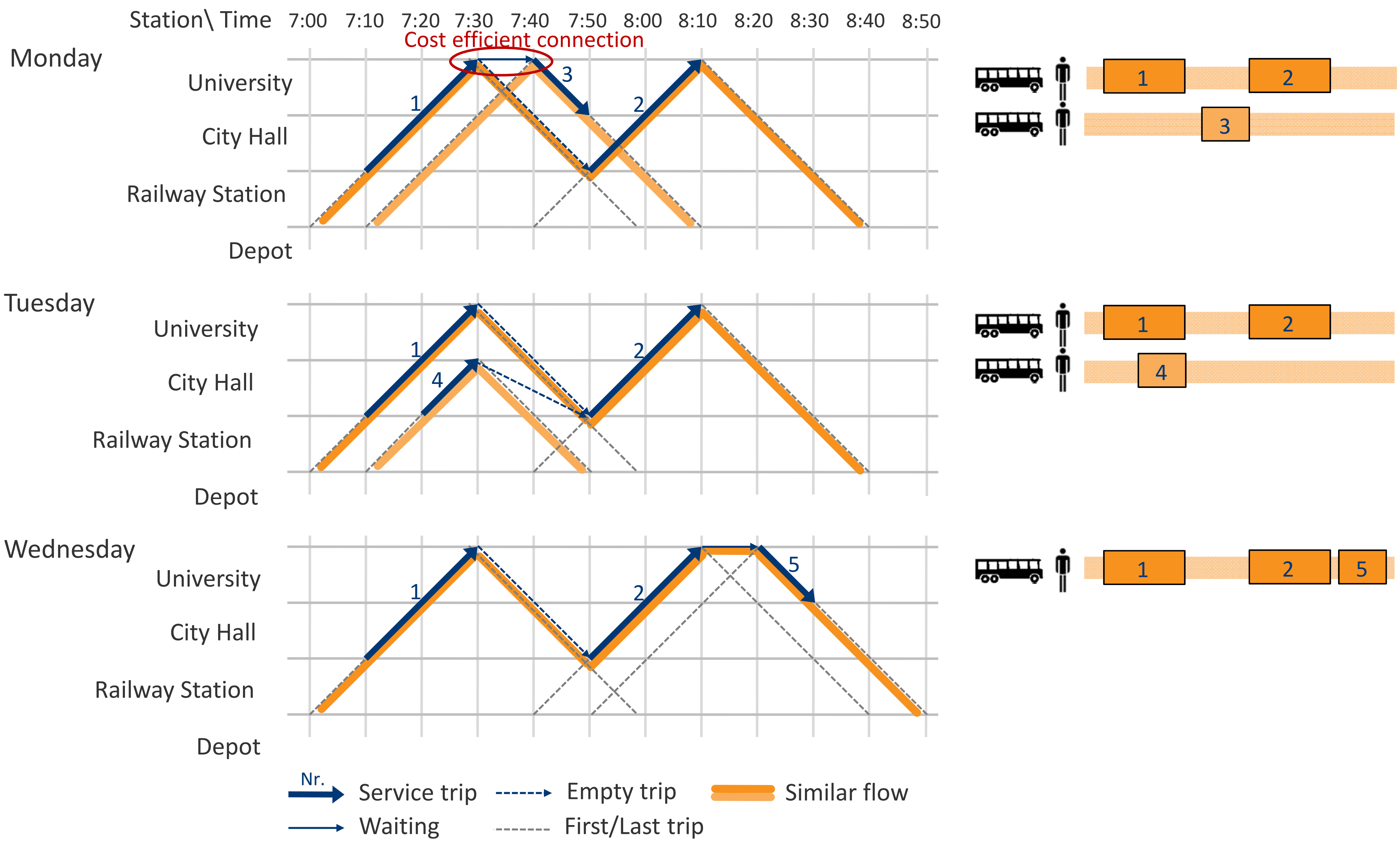
trips	80	100	160	200
#col.gen. iterations	15.3	19.2	23.5	24.9
cpu total (hh:min)	00:06	00:13	00:27	01:15
#blocks	9.2	11.0	14.8	18.4
#duties	19.7	23.1	32.6	39.3
Time-Space Network Integrated approach total	**28.9**	**34.1**	**47.2**	**57.7**
Conn.-based integrated total	**29.6**	**36.2**	**49.5**	**60.4**
Sequential approach total	**35.0**	**40.9**	**53.6**	**65.5**

5 duty types with ≤2 pieces of work, 4 depots (Huisman)

Regularity in Vehicle Schedules

- In a timetable, regular trips are offered every day
- Further individual trips occur irregularly
  - Interest groups, events, school classes etc.
- Many public transit providers prefer as regular vehicle (crew) schedules as possible
- Research question:
- How to achieve/measure regularity in vehicle schedules?

Example


Station\ Time
7:00
7:10
7:20
7:30
7:40
7:50
8:00
8:10
8:20
8:30
8:40
8:50
Cost efficient connection
Monday
University
City Hall
Railway Station
Depot
1
2
3
Tuesday
University
City Hall
Railway Station
Depot
1
2
4
Wednesday
University
City Hall
Railway Station
Depot
1
2
5
Nr.
Service trip
Waiting
Empty trip
First/Last trip
Similar flow

Generation of regular schedules

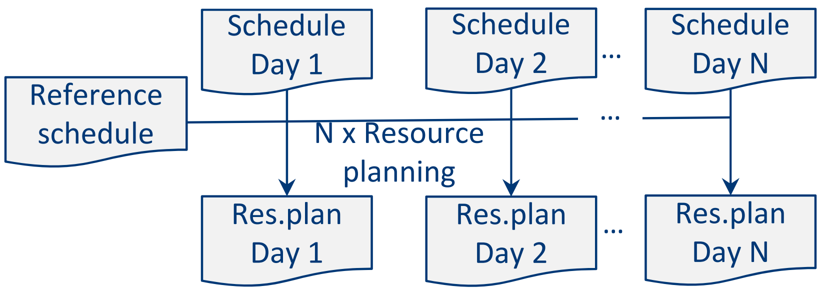
Basic concepts

Daily Regularity (Reference)

Input:
- Regular trips
- Irregular trips on one day

Goal:
- Reference schedule

Find a schedule that is similar to the reference schedule

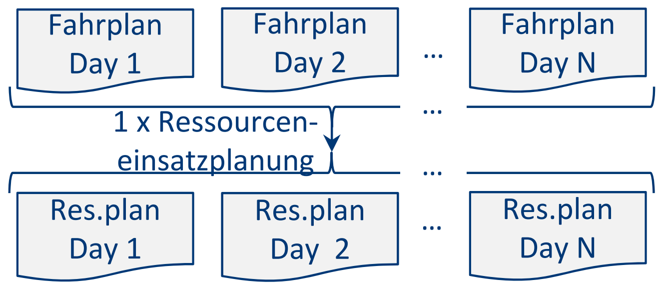


[+] less complex problem
[-] Similarity depends on the reference plan

Regularity over Several Days (Pattern)

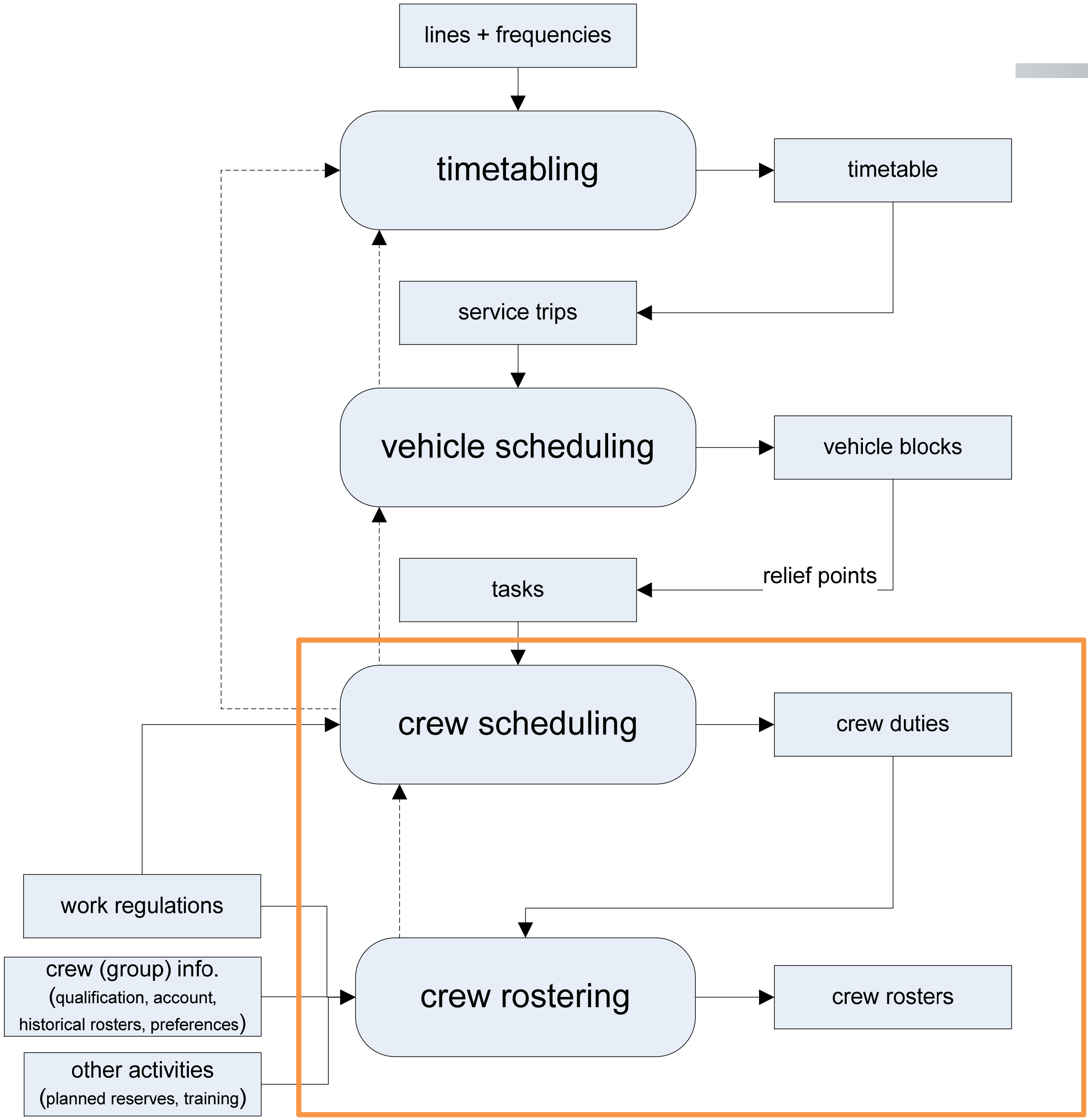
Input:
- Regular trips
- Irregular trips of all days

Goal: Find patterns that can be used on several days



[-] Higher problem complexity
[+] Similarity is not limited by reference schedule

Planning Process in Public Transit Networks



Crew rostering problem

- Assign all possible activities to crews, including crew duties, planned reserves, days-off etc. for a given planning period
- Complex work regulations should be held
- Fairness among all drivers
- Preferences of drivers
- Fixed activities (fixed in previous planning period, leaves)

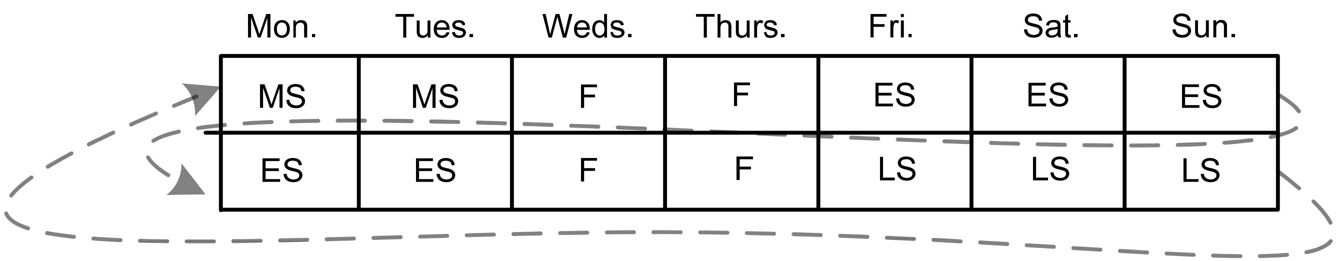
Crew rostering steps:

- Days-off
- Shifts
- Duties

The Crew Rostering Problem in Public Transit

Cyclic and non-cyclic crew rostering

- Cyclic crew rostering problem (CCR)
  - considers days of the week
  - A roster is generated for a group of drivers
  - Preferences are considered for a day of the week
  - Popular and unpopular duties as well as the days-off and weekends-off are evenly distributed
  - Shortcomings:
    - not flexible enough to respond to changes in traffic (special events)



	Mon.	Tues.	Weds.	Thurs.	Fri.	Sat.	Sun.	Mon.	Tues.	Weds.	Thurs.	Fri.	Sat.	Sun.
d1	MS	MS	F	F	ES	ES	ES							
d2	ES	ES	F	F	LS	LS	LS							

ES: early shift
MS: midday shift
LS: late shift
F: day off

The Crew Rostering Problem in Public Transit

Cyclic and non-cyclic crew rostering

- Non-cyclic crew rostering problem (NCCR)
  - considers calendar dates
  - A roster is generated for each driver
  - Preferences can be specifically defined for a calendar date
  - Real traffic schedule every calendar date is considered

Solution:
Exact solver
Column generation
Simulated annealing
Multiobj. metaheur.

	26.06	27.06	28.06	29.06	30.06	01.07	02.07	03.07	04.07	05.07	06.07	07.07	08.07	09.07
d1	MS	MS	F	F	F	ES	ES	ES	ES	F	F	LS	LS	LS
d2	ES	ES	MS	MS	MS	F	F	MS	MS	MS	MS	ES	F	F

ES: early shift
MS: midday shift
LS: late shift
F: day off

Optimization model

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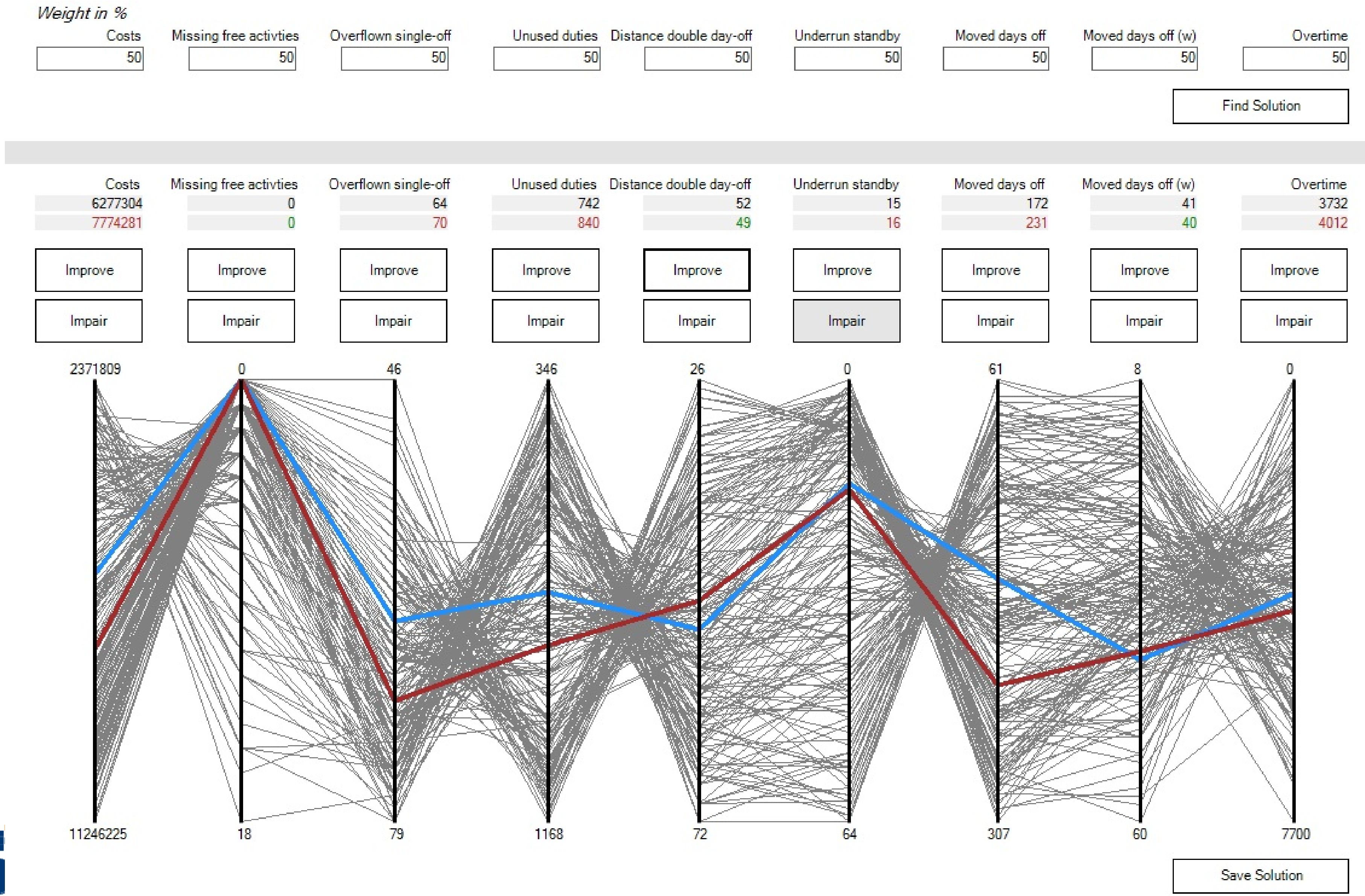
Cyclic and non-cyclic crew rostering

Computational results (sequential vs. Integrated)

Instance	Unassigned duties (%)		Unassigned days (%)	
	Sequential approach	Integrated approach	Sequential approach	Integrated approach
48-75-6	1.4	0.3	3.9	0
52-73-6	0.5	0	0.2	0
52-75-6	0.5	0	0.4	0
9-238-11 (CCR)	6.3	1.5	3	0.3
393-45-37	8.6	4.4	0.8	0
392-45-37	16.9	11.1	0.9	0
397-40-37	9	3.8	0.8	0
96-70-8	11.7	6.3	2.6	0
87-70-8	4	0.2	3.7	0
89-70-8	7.0	1.77	3.9	0
221-45-30	4.1	0	2.9	0
214-45-34	4.2	0.53	2.9	0
211-45-34	4.9	5.5	3.5	0
629-46-26	0.24	0.06	0.04	0
606-70-26	0.57	0.037	0.05	0
607-70-26	6.3	0.29	0.03	0

Decision Support for Crew Rostering

Rota scheduling: computational results with multi-objective metaheuristics



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Conclusion

- Requirements from enterprises often imply challenging research problems for which no solutions exist yet
- In the optimization area, resulting new models and methods improve the state-of-the-art and can be published in scientific research journals
- Simultaneously the results have significant practical influence
  - New models and methods make high cost savings possible
- Working with practical problems and data often takes lot of time
- Such time aspects should be appreciated in universities
  - Not just counting publications, but also impact in practice

Thank you very much for your attention

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