# Time-dependent ambulance allocation considering data-driven empirically required coverage

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# Outline

1. Motivation
2. Basic idea and models
3. Data driven optimization model for tactical ambulance planning
4. A real world EMS planning problem in the city of Bochum
5. Conclusions and Outlook

# Motivation

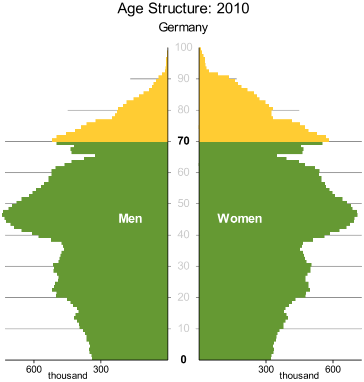
- Aging population


- Age class of $70+$ causes 50 % of ambulance operations
- EMS demand increases

source: Statistisches Bundesamt 2013

# Motivation

- Aging population





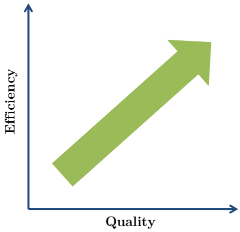
- Age class of $70+$ causes 50 % of ambulance operations
- EMS demand increases

source: Statistisches Bundesamt 2013

# Motivation

1. Access to emergency medical services (EMS) is crucial
2. Ensuring optimal supply quality
   - Short arrival time
   - Coverage of entire demand area
   - High degree of achievement

   ⟹ Dependent on location and number of ambulances
3. Efficiency
   - Reduction of fixed costs (avoid overcapacity)
   - Utilization of ambulances



# Quality criteria and objectives

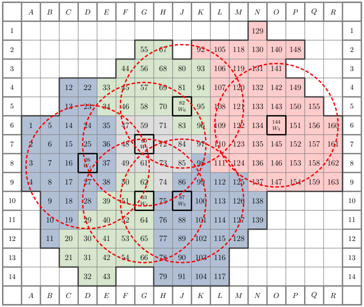
Evaluation of emergency medical services (objective of EMS provider):

- Degree of achievement (ex post):

$$\frac{\#\text{ operations within a time standard } T}{\#\text{ total number of operations}}$$

Objectives in literature (ex ante):

- single coverage models
- double coverage models
- busy fraction models
- queue models
- hypercube models



# Optimal quality in emergency medical services

Research project: 2 years (work in progress)

Stiftung Zukunft NRW

Stadt Bochum
Feuerwehr und Rettungsdienst

**Focus**:

- Analysis of required resources for EMS
- Analysis of time-dependent demand and speed fluctuations for EMS
- Tactical and strategic planning horizon
- Stochastic influences, uncertain parameters (demand, speed)

**Goal**:

- Dynamic (and robust) optimization model

$\Longrightarrow$ IT-based decision support tool for local EMS providers

# Decision support tool

## Decision support

| Optimization | Simulation | Forecast |
| --- | --- | --- |
| location, allocation and resource planning | degree of achievement, resources, utilization | trends, development |
| empirical demand, required/adequate coverage | evaluations | population, experts |

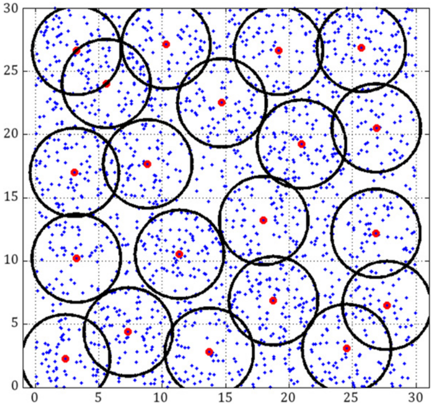
# Decision support tool

## Decision support

| Optimization | Simulation | Forecast |
|---|---|---|
| location, allocation and resource planning | degree of achievement, resources, utilization | trends, development |
| empirical demand, required/adequate coverage | evaluations | population, experts |

# Basic covering location models

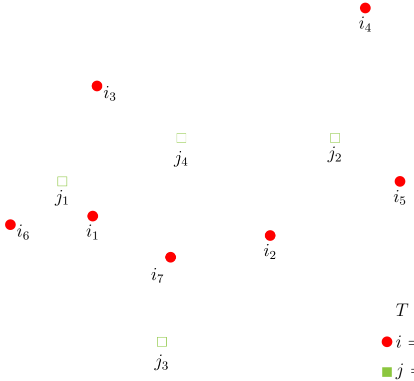
**Idea:** Demand nodes $i$ have to be covered within a time standard $T$




source: Zarandi et al. 2011–The large scale maximal covering location problem; page 1565

# Set Covering Problem (SCP)

Toregas et al. 1971




$T$ = response time

● $i$ = demand node $i \in I$

■ $j$ = vehicle location $x_j = 1$, $j \in J$

□ $j$ = vehicle location $x_j = 0$, $j \in J$

$$\mathcal{N}_i := \{j \in J \mid t_{ij} \leq T\}$$

# Set Covering Problem (SCP)

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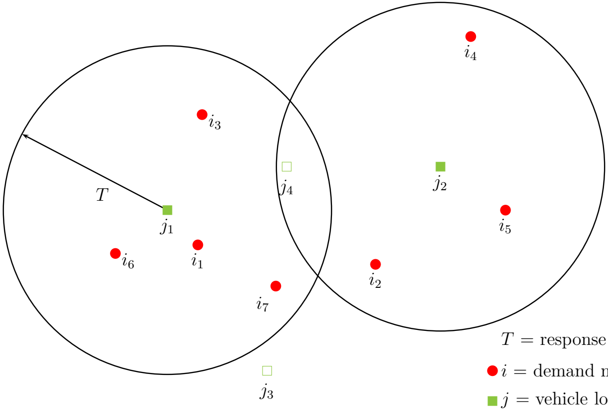


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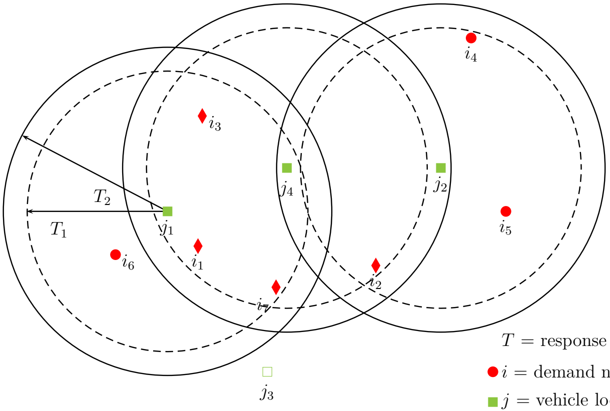
# Double Standard Model (DSM)

## Gendreau et al. 1997




$T$ = response time

$i$ = demand node $i \in I$

$j$ = vehicle location $x_j = 1$, $j \in J$

$j$ = vehicle location $x_j = 0$, $j \in J$

$$\mathcal{N}_i^{T_\ell} := \{j \in J \mid t_{ij} \leq T_\ell,\, \ell \in \{1,2\}\}$$

# Double Standard Model (DSM)

Gendreau et al. 1997

$$\max \quad \sum_{i \in I} d_i x_i^2$$

$$\text{s.t.} \quad \sum_{j \in \mathcal{N}_i^{T_2}} y_j \geq 1 \qquad \forall i \in I$$

$$\sum_{i \in I} d_i x_i^1 \geq \alpha \sum_{i \in I} d_i$$

$$x_i^1 \geq x_i^2 \qquad \forall i \in I$$

$$\sum_{j \in \mathcal{N}_i^{T_1}} y_j \geq x_i^1 + x_i^2 \qquad \forall i \in I$$

$$\sum_{j \in J} y_j = p$$

$$x_i^1, x_i^2 \in \{0,1\} \qquad \forall i \in I$$

$$y_j \in \mathbb{N}_0 \qquad \forall j \in J$$

- $d_i$: demand at node $i$
- $\mathcal{N}_i^{T_\ell} := \{j \in J \mid t_{ij} \leq T_\ell\}$
  $T_1 < T_2$
- $p$: number of ambulances
  (fleet size)

$$x_i^k = \begin{cases} 1, & \text{if demand node } i \text{ is covered } k \in \{1,2\} \text{ times} \\ 0, & \text{else.} \end{cases}$$

$y_j$: number of ambulances at node $j$

# Double Standard Model (DSM)

Gendreau et al. 1997 — Limitations: (1) static consideration (2) fixed double coverage

$$\max \sum_{i\in I} \boldsymbol{d}_i \boldsymbol{x}_i^2$$

$$\text{s. t.} \quad \sum_{j\in\mathcal{N}_i^{T_2}} y_j \geq 1 \qquad \forall i \in I$$

$$\sum_{i\in I} \boldsymbol{d}_i x_i^1 \geq \alpha \sum_{i\in I} \boldsymbol{d}_i$$

$$x_i^1 \geq \boldsymbol{x}_i^2 \qquad \forall i \in I$$

$$\sum_{j\in\mathcal{N}_i^{T_1}} y_j \geq x_i^1 + \boldsymbol{x}_i^2 \qquad \forall i \in I$$

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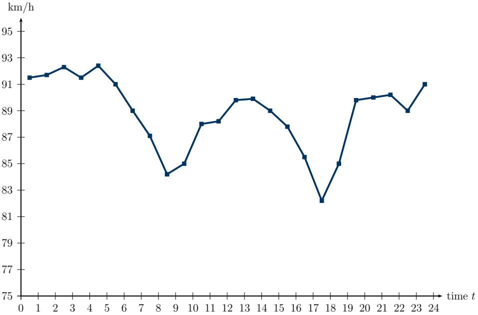
# Extensions of the Double Standard Model

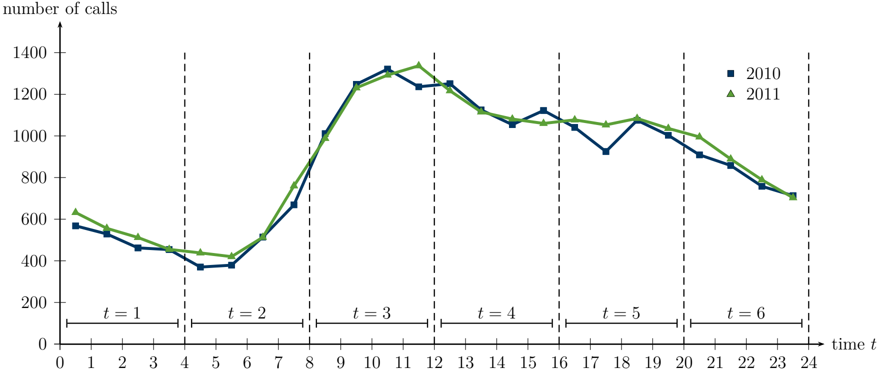
## Time-dependent parameter: speed




- Time-dependent speed on (city-)motorways (example of the city of Vienna)

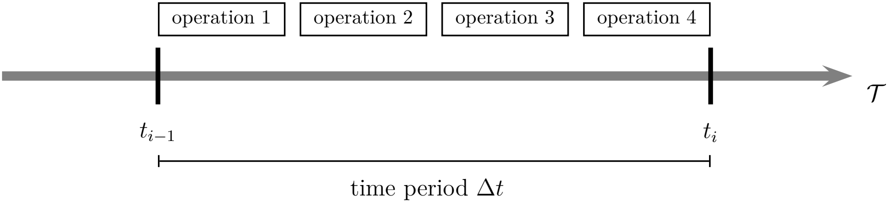
  Source: Kritzinger et al. (2011)

# Time-dependent parameter: demand




$\Longrightarrow$ Dynamic considerations required

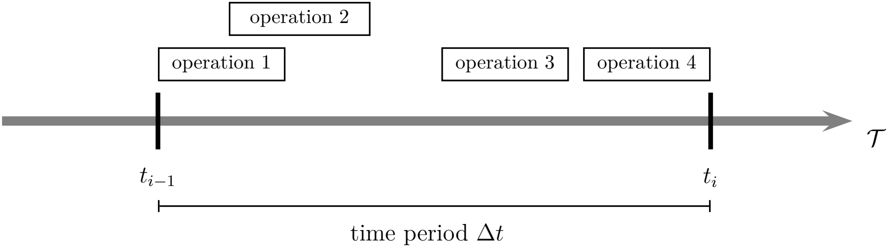
# Time-dependent parameter: degree of required coverage




$\xi$ : number of ambulances, $X$ : number of parallel operations

$$P(\{X \leq \xi\}) \geq \beta \quad (= 0.95)$$

# Time-dependent parameter: degree of required coverage

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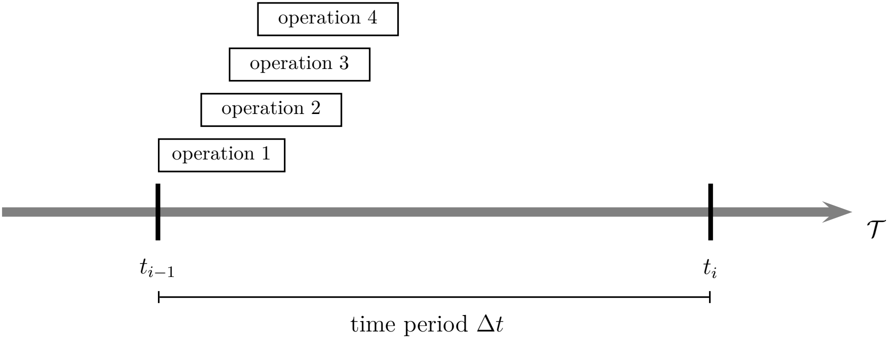



$\xi$ : number of ambulances, $X$ : number of parallel operations

$$P(\{X \leq \xi\}) \geq \beta \quad (= 0.95)$$

# Extensions of the Double Standard Model

**Existing:**

- **Speed** is time-dependent and location-dependent
- Empirical investigation (e.g. Schmid/Doerner 2010; Degel et al. 2014)

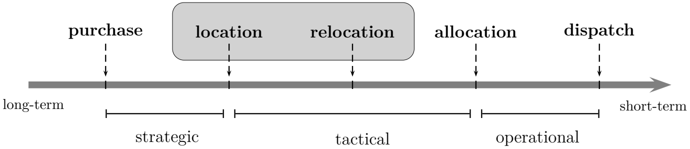
# Extensions of the Double Standard Model

**Existing:**

- **Speed** is time-dependent and location-dependent
- Empirical investigation (e.g. Schmid/Doerner 2010; Degel et al. 2014)

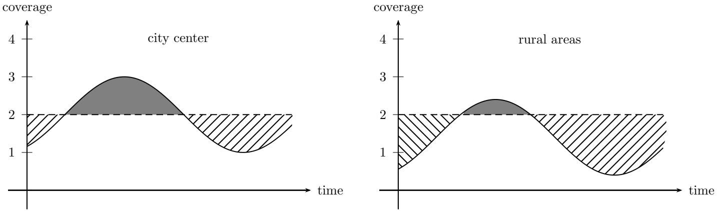
**Additional:**

- Time- and location-dependent **demand**
- **Empirically required coverage** for each demand node/period
- **Additional and flexible** ambulance stations
- **Dynamic** and **flexible allocation** of ambulances to stations



# New optimization approach

## Objectives (1)



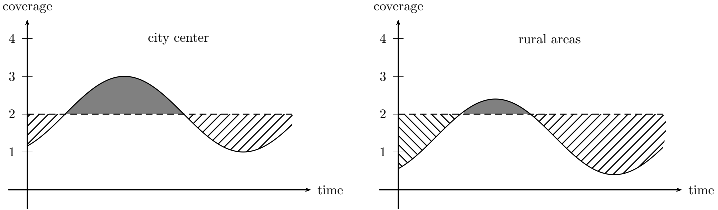

- Observed: differences between required and actual coverage
- Maximize the empirically required coverage:

$$x_{it}^{k} := \begin{cases} 1, & \text{if demand node } i \text{ is coverd } k\text{-times in period } t, \\ 0, & \text{overwise.} \end{cases}$$

- $k = \mathrm{e}(it)$ is determined empirically ($\leftarrow$ parallel operations)

# New optimization approach

## Objectives (1)




- Observed: differences between required and actual coverage
- Maximize the empirically required coverage: $x_{it}^{\mathrm{e}(it)} \in \{0, 1\}$

$$\max \quad \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} d_{it} x_{it}^{\mathrm{e}(it)}$$

- $k = \mathrm{e}(it)$ is determined empirically ($\leftarrow$ parallel operations)

# New optimization approach

## Objectives (2)

- Relocations due to variations of demand/speed (penalty costs)
- Utilization of flexible ambulance stations (penalty costs)

$$\min \quad \sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{J}} \sum_{j\in\mathcal{J}} u_{ijt}$$

$$\min \quad \sum_{t\in\mathcal{T}} \sum_{j\in\mathcal{F}} y_{jt}$$

$$y_{Dt} = p - p_t \qquad \forall t \in \mathcal{T}$$

$$y_{jt} + \sum_{i\in\mathcal{J}\cup\{D\}} u_{ij(t+1)} - \sum_{i\in\mathcal{J}\cup\{D\}} u_{ji(t+1)} = y_{j(t+1)} \qquad \forall j \in \mathcal{J}\cup\{D\}, \forall t \in \mathcal{T}\setminus\{T\}$$

$$y_{jT} + \sum_{i\in\mathcal{J}\cup\{D\}} u_{ij1} - \sum_{i\in\mathcal{J}\cup\{D\}} u_{ji1} = y_{j1} \qquad \forall j \in \mathcal{J}\cup\{D\}$$

$$u_{ijt} \in \{0,1\} \qquad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}\cup\{D\}, \forall t \in \mathcal{T}$$

$$y_{jt} \in \mathbb{N}_0 \qquad \forall j \in \mathcal{J}, \forall t \in \mathcal{T}$$

$$\vdots$$

# New optimization approach

## Constraints

- covering constraints
- location constraints
- relocation constraints
- allocation constraints
- demand constraints

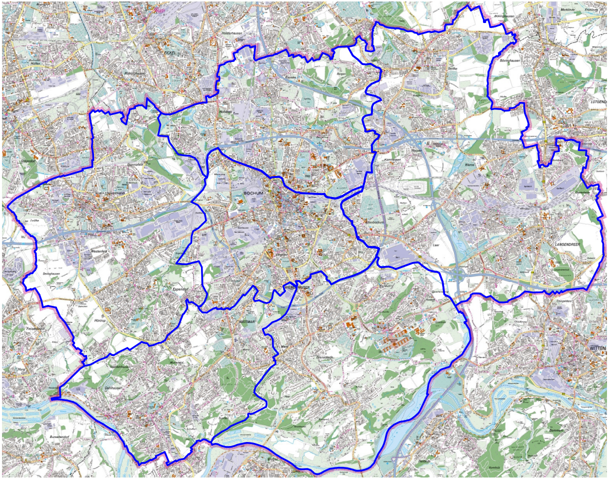
# Bochum

Coordinates

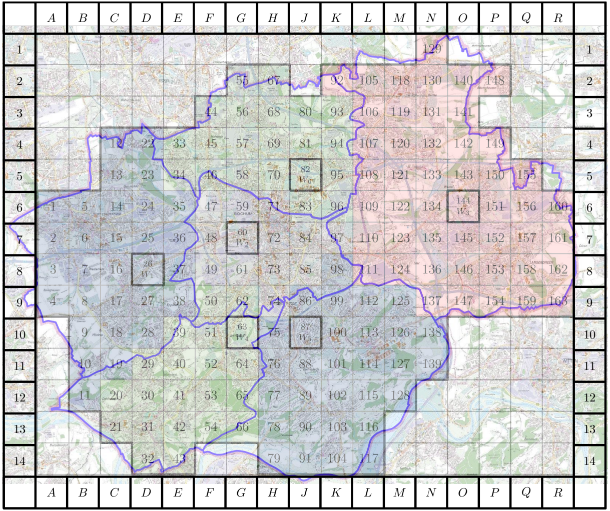
$51^\circ\,28'\,55''N \quad 7^\circ\,12'\,57''E$

- 16th biggest city in Germany
- Area: 145.4 $km^2$ (56.1 sq mi)
- Population: ca. 375,000
- Population density: 2,577$/km^2$
- Services: about 21,000 operations per year
- Services per 1,000 inhabitants per year: about 56 operations
- **14** ambulances

# The city area of Bochum



# The city area of Bochum



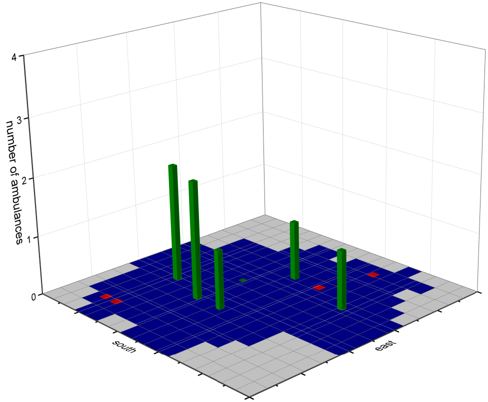
# The city area of Bochum

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | 129 | | | | | 1 |
| 2 | | | | | | | 55 | 67 | | 92 | 105 | 118 | 130 | 140 | 148 | | | 2 |
| 3 | | | | | | 44 | 56 | 68 | 80 | 93 | 106 | 119 | 131 | 141 | | | | 3 |
| 4 | | | 12 | 22 | 33 | 45 | 57 | 69 | 81 | 94 | 107 | 120 | 132 | 142 | 149 | | | 4 |
| 5 | | | 13 | 23 | 34 | 46 | 58 | 70 | 82 $W_6$ | 95 | 108 | 121 | 133 | 143 | 150 | 155 | | 5 |
| 6 | 1 | 5 | 14 | 24 | 35 | 47 | 59 | 71 | 83 | 96 | 109 | 122 | 134 | 144 $W_3$ | 151 | 156 | 160 | 6 |
| 7 | 2 | 6 | 15 | 25 | 36 | 48 | 60 $W_2$ | 72 | 84 | 97 | 110 | 123 | 135 | 145 | 152 | 157 | 161 | 7 |
| 8 | 3 | 7 | 16 | 24 $W_1$ | 37 | 49 | 61 | 73 | 85 | 98 | 111 | 124 | 136 | 146 | 153 | 158 | 162 | 8 |
| 9 | 4 | 8 | 17 | 27 | 38 | 50 | 62 | 74 | 86 | 99 | 112 | 125 | 137 | 147 | 154 | 159 | 163 | 9 |
| 10 | | 9 | 18 | 28 | 39 | 51 | 63 $W_4$ | 75 | 87 $W_5$ | 100 | 113 | 126 | 138 | | | | | 10 |
| 11 | | 10 | 19 | 29 | 40 | 52 | 64 | 76 | 88 | 101 | 114 | 127 | 139 | | | | | 11 |
| 12 | | 11 | 20 | 30 | 41 | 53 | 65 | 77 | 89 | 102 | 115 | 128 | | | | | | 12 |
| 13 | | | 21 | 31 | 42 | 54 | 66 | 78 | 90 | 103 | 116 | | | | | | | 13 |
| 14 | | | | 32 | 43 | | | 79 | 91 | 104 | 117 | | | | | | | 14 |
| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |

# Model results

## Usage of flexible ambulance stations and relocations

Period $t = 1$, number of ambulances $7$

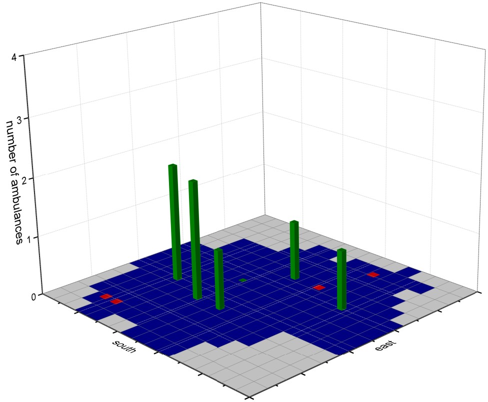



main stations, flexible stations

# Model results

Usage of flexible ambulance stations and relocations

Period $t = 2$, number of ambulances $7$

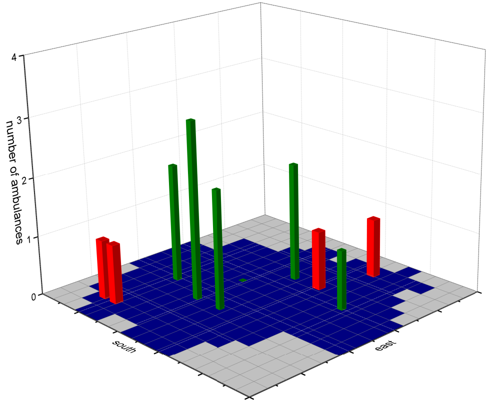



■ main stations, ■ flexible stations

# Model results

## Usage of flexible ambulance stations and relocations

Period $t = 3$, number of ambulances $14$

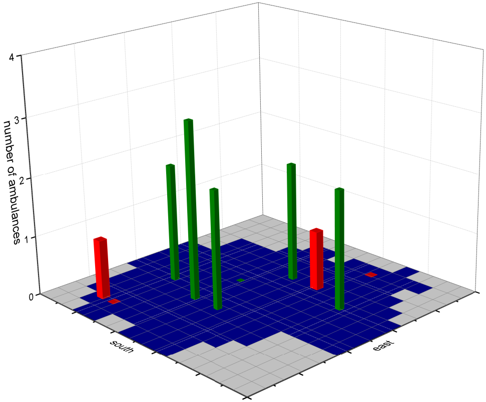



main stations, flexible stations

# Model results

## Usage of flexible ambulance stations and relocations

Period $t = 4$, number of ambulances $13$

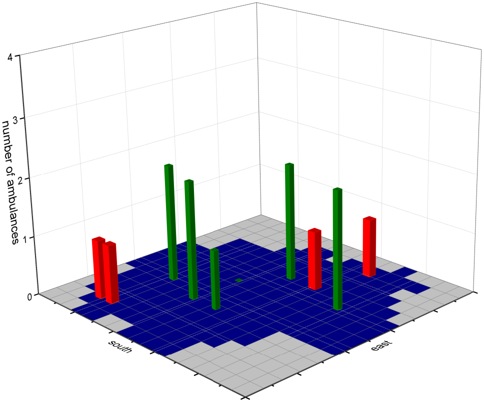



main stations, flexible stations

# Model results

## Usage of flexible ambulance stations and relocations

Period $t = 5$, number of ambulances $13$

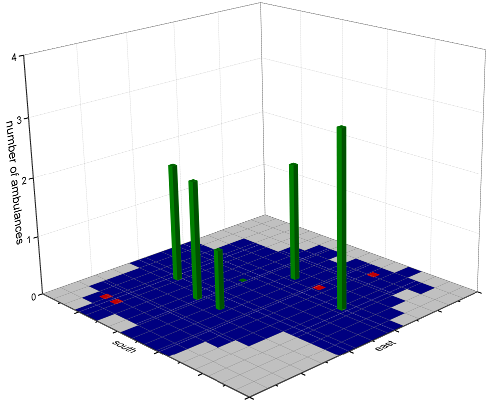



main stations, flexible stations

# Model results

## Usage of flexible ambulance stations and relocations

Period $t = 6$, number of ambulances $10$




main stations, flexible stations

# Model results

## Difference between resulting and required degree of coverage (period 8-12 a.m.)

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | −2 | | | | | 1 |
| 2 | | | | | | | −2 | −1 | | −1 | −2 | −2 | −2 | −2 | −2 | | | 2 |
| 3 | | | | | | −2 | −1 | −1 | −1 | −1 | −1 | −2 | 2 | 2 | | | | 3 |
| 4 | | | −2 | −2 | −2 | 3 | 3 | 3 | −1 | −1 | −1 | 3 | 2 | 2 | 2 | | | 4 |
| 5 | | | 1 | 1 | 5 | 3 | 3 | 3 | 3 | −1 | 3 | 3 | 2 | 2 | 2 | 2 | | 5 |
| 6 | −2 | 1 | 1 | 5 | 5 | 5 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 6 |
| 7 | 1 | 1 | 1 | 5 | 5 | 5 | 6 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 7 |
| 8 | 1 | 1 | 1 | 5 | 6 | 5 | 6 | 4 | 4 | 4 | −1 | 2 | 2 | 2 | 2 | 2 | −2 | 8 |
| 9 | 1 | 1 | 1 | 2 | 6 | 7 | 7 | 3 | 4 | 0 | −1 | −1 | 2 | 2 | 2 | −2 | −2 | 9 |
| 10 | | 1 | 1 | 2 | 2 | 7 | 4 | 4 | 0 | 0 | −1 | −1 | −2 | | | | | 10 |
| 11 | | −2 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | −1 | −1 | −2 | | | | | 11 |
| 12 | | −2 | −2 | −2 | −1 | −1 | 0 | 0 | 0 | −1 | −1 | −2 | | | | | | 12 |
| 13 | | | −2 | −2 | −2 | −1 | −1 | 0 | −1 | −1 | −2 | | | | | | | 13 |
| 14 | | | | −2 | −2 | | | −2 | −2 | −2 | −2 | | | | | | | 14 |
| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |

status quo

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | −1 | | | | | 1 |
| 2 | | | | | | | −2 | 0 | | 2 | 0 | 0 | −1 | −1 | −1 | | | 2 |
| 3 | | | | | | −2 | 0 | 0 | 2 | 2 | 2 | 0 | 2 | 1 | | | | 3 |
| 4 | | | −2 | −2 | −2 | 0 | 0 | 1 | 1 | 2 | 2 | 4 | 2 | 2 | 0 | | | 4 |
| 5 | | | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 4 | 4 | 2 | 1 | 0 | 0 | | 5 |
| 6 | −2 | 0 | 0 | 0 | 0 | 1 | −1 | 0 | 1 | 1 | 3 | 3 | 1 | 1 | 0 | 0 | 0 | 6 |
| 7 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 2 | 2 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 7 |
| 8 | 0 | 0 | 0 | 0 | 2 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | −2 | 8 |
| 9 | 0 | 0 | 0 | 2 | 2 | 4 | 4 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | −2 | −2 | 9 |
| 10 | | 1 | 2 | 4 | 3 | 4 | 2 | 2 | 2 | 2 | 0 | 0 | −2 | | | | | 10 |
| 11 | | 0 | 2 | 4 | 4 | 3 | 2 | 2 | 2 | 2 | 0 | 0 | −2 | | | | | 11 |
| 12 | | 0 | 0 | 0 | 2 | 2 | 3 | 2 | 2 | 0 | 0 | −2 | | | | | | 12 |
| 13 | | | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | −2 | | | | | | | 13 |
| 14 | | | | 0 | 0 | | | −2 | −2 | −2 | −2 | | | | | | | 14 |
| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |

max double coverage

# Model results

## Difference between resulting and required degree of coverage (period 8-12 a.m.)

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | −2 | | | | | 1 |
| 2 | | | | | | | −2 | −1 | | −1 | −2 | −2 | −2 | −2 | −2 | | | 2 |
| 3 | | | | | | −2 | −1 | −1 | −1 | −1 | −1 | −2 | 2 | 2 | | | | 3 |
| 4 | | | −2 | −2 | −2 | 3 | 3 | 3 | −1 | −1 | −1 | 3 | 2 | 2 | 2 | | | 4 |
| 5 | | | 1 | 1 | 5 | 3 | 3 | 3 | 3 | −1 | 3 | 3 | 2 | 2 | 2 | 2 | | 5 |
| 6 | −2 | 1 | 1 | 5 | 5 | 5 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 6 |
| 7 | 1 | 1 | 1 | 5 | 5 | 5 | 6 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 7 |
| 8 | 1 | 1 | 1 | 5 | 6 | 5 | 6 | 4 | 4 | 4 | −1 | 2 | 2 | 2 | 2 | 2 | −2 | 8 |
| 9 | 1 | 1 | 1 | 2 | 6 | 7 | 7 | 3 | 4 | 0 | −1 | −1 | 2 | 2 | 2 | −2 | −2 | 9 |
| 10 | | 1 | 1 | 2 | 2 | 7 | 4 | 4 | 0 | 0 | −1 | −1 | −2 | | | | | 10 |
| 11 | | −2 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | −1 | −1 | −2 | | | | | 11 |
| 12 | | −2 | −2 | −2 | −1 | −1 | 0 | 0 | 0 | −1 | −1 | −2 | | | | | | 12 |
| 13 | | | −2 | −2 | −2 | −1 | −1 | 0 | −1 | −1 | −2 | | | | | | | 13 |
| 14 | | | | −2 | −2 | | | −2 | −2 | −2 | −2 | | | | | | | 14 |
| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |

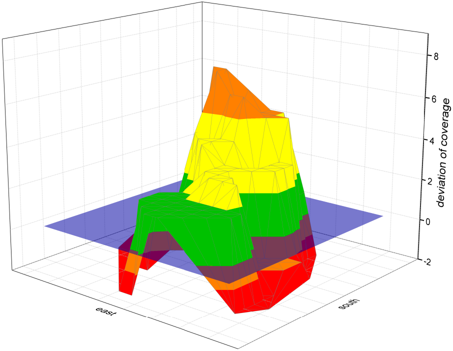
status quo

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | −1 | | | | | 1 |
| 2 | | | | | | | −2 | 1 | | 3 | 0 | 0 | −1 | −1 | −1 | | | 2 |
| 3 | | | | | | −2 | 1 | 1 | 3 | 3 | 3 | 0 | 2 | 1 | | | | 3 |
| 4 | | | −2 | −2 | −2 | 1 | 1 | 2 | 2 | 3 | 3 | 5 | 2 | 2 | 0 | | | 4 |
| 5 | | | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 2 | 5 | 5 | 2 | 1 | 0 | 0 | | 5 |
| 6 | −2 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 2 | 2 | 4 | 4 | 1 | 1 | 0 | 0 | 0 | 6 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 3 | 3 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 7 |
| 8 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 3 | 3 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | −2 | 8 |
| 9 | 0 | 0 | 0 | 1 | 1 | 3 | 3 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | −2 | −2 | 9 |
| 10 | | 1 | 2 | 3 | 2 | 3 | 1 | 1 | 1 | 1 | 0 | 0 | −2 | | | | | 10 |
| 11 | | 0 | 2 | 3 | 3 | 2 | 1 | 1 | 1 | 1 | 0 | 0 | −2 | | | | | 11 |
| 12 | | 0 | 0 | 0 | 1 | 1 | 2 | 1 | 1 | 0 | 0 | −2 | | | | | | 12 |
| 13 | | | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | −2 | | | | | | | 13 |
| 14 | | | | 0 | 0 | | | −2 | −2 | −2 | −2 | | | | | | | 14 |
| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | Q | R | |

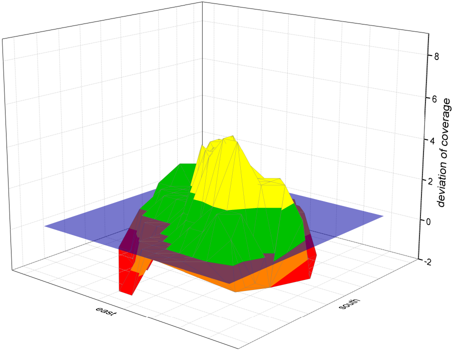
max empirically required coverage

# Coverage level

## Difference to empirically required coverage (period 8-12 a.m.)




current allocation



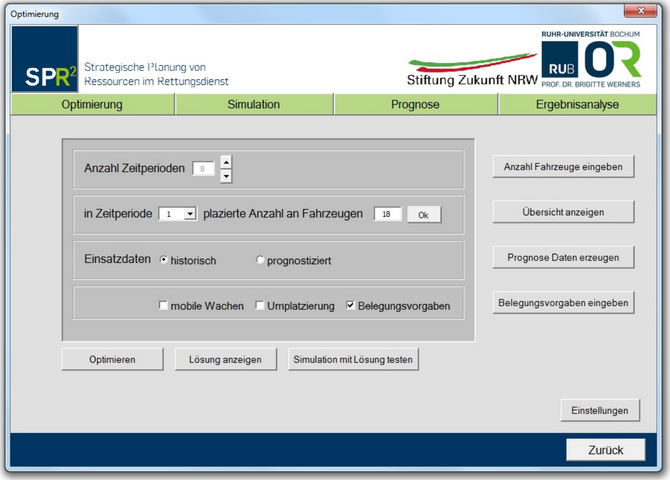

optimal allocation

# Integration in a Decision Support Tool

## Main Menu

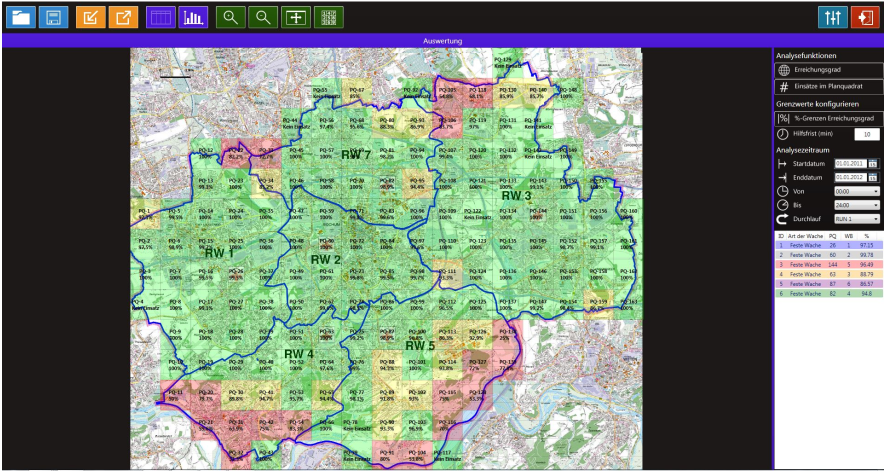
# Integration in a Decision Support Tool

## Input Parameters



# Integration in a Decision Support Tool

## Extensive analyses – real-world performance measures



# Conclusions and outlook

## Improvements & further research

- Quality improvements:
  - Consideration of flexible ambulance stations is recommended
  - More suitable coverage according to empirical demands
- Efficiency of resource utilization:
  - Reduced number of ambulances
  - Constant quality with cost reduction
  - Higher quality with equal costs
- Integration of uncertainties (demand, driving speed)
  - Robust Uncertain Set Covering Problem (considers uncertainty in driving speed)
- Evaluation of the solution with a discrete event simulation

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# Optimization model

## Objectives

- maximize the demand which get the required coverage

$$\max \quad \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} d_{it} x_{it}^{\mathrm{e}(it)}$$

- avoid relocations

$$\min \quad \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{J}} \sum_{j \in \mathcal{J}} u_{ijt}$$

- avoid the use of flexible EMS stations

$$\min \quad \sum_{t \in \mathcal{T}} \sum_{j \in \mathcal{F}} y_{jt}$$

# Optimization model

- location/covering constraints

$$\sum_{j \in \mathcal{N}_{it}^2} y_{jt} \geq 1 \qquad \forall i \in \mathcal{I}, \forall t \in \mathcal{T}$$

$$\sum_{j \in \mathcal{N}_{it}^1} y_{jt} \geq \sum_{k=1}^{p} x_{it}^k \qquad \forall i \in \mathcal{I}, \forall t \in \mathcal{T}$$

$$x_{it}^{(k-1)} \geq x_{it}^k \qquad \forall i \in \mathcal{I}, \forall t \in \mathcal{T}, k = 2, \ldots, p$$

$$\sum_{j \in \mathcal{J}} y_{jt} \leq p_t \qquad \forall t \in \mathcal{T}$$

# Optimization model

- relocation constraints

$$y_{Dt} = p - p_t \qquad \forall t \in \mathcal{T}$$

$$y_{jt} + \sum_{i \in \mathcal{J} \cup \{D\}} u_{ij(t+1)} - \sum_{i \in \mathcal{J} \cup \{D\}} u_{ji(t+1)} = y_{j(t+1)} \qquad \forall j \in \mathcal{J} \cup \{D\}, \forall t \in \mathcal{T} \setminus \{T\}$$

$$y_{jT} + \sum_{i \in \mathcal{J} \cup \{D\}} u_{ij1} - \sum_{i \in \mathcal{J} \cup \{D\}} u_{ji1} = y_{j1} \qquad \forall j \in \mathcal{J} \cup \{D\}$$

$$\sum_{i \in \mathcal{J}} u_{iDt} \leq |p_{(t-1)} - p_t| \qquad \forall t \in \mathcal{T} \setminus \{1\}$$

$$\sum_{j \in \mathcal{J}} u_{Djt} \leq |p_{(t-1)} - p_t| \qquad \forall t \in \mathcal{T} \setminus \{1\}$$

$$\sum_{i \in \mathcal{J}} u_{iD1} \leq |p_T - p_1|$$

$$\sum_{j \in \mathcal{J}} u_{Dj1} \leq |p_T - p_1|$$

# Optimization model

- demand constraints

$$\sum_{i \in \mathcal{I}} d_{it} x_{it}^1 \geq \alpha \sum_{i \in \mathcal{I}} d_{it} \qquad \forall t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{I}} d_{it} \leq c \sum_{j \in \mathcal{J}} y_{jt} \qquad \forall t \in \mathcal{T}$$

- site capacity constraints

$$y_{jt} \leq \rho_j \qquad \forall j \in \mathcal{J}, \forall t \in \mathcal{T}$$

$$y_{jT} = 0 \qquad \forall j \in \mathcal{F}$$

- variable domain

$$x_{it}^k \in \{0, 1\} \qquad \forall i \in \mathcal{I}, k = 1, \ldots, p, \forall t \in \mathcal{T}$$

$$y_{jt} \in \{0, 1, \ldots, p\} \subset \mathbb{N}_0 \qquad \forall j \in \mathcal{J}, \forall t \in \mathcal{T}$$

$$u_{ijt} \in \{0, 1, \ldots, p\} \subset \mathbb{N}_0 \qquad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \forall t \in \mathcal{T}$$