Health Care Logistics
Health Care Logistics

Appointment planning
Health Care Logistics

Waiting time in the practice

<table>
<thead>
<tr>
<th>Waiting Time</th>
<th>Percentage of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>No waiting</td>
<td>0%</td>
</tr>
<tr>
<td>up to 15 min</td>
<td>20%</td>
</tr>
<tr>
<td>up to 30 min</td>
<td>40%</td>
</tr>
<tr>
<td>up to 60 min</td>
<td>20%</td>
</tr>
<tr>
<td>up to 2 hr</td>
<td>10%</td>
</tr>
<tr>
<td>over 2 hr</td>
<td>0%</td>
</tr>
</tbody>
</table>

Waiting time for an appointment

<table>
<thead>
<tr>
<th>Waiting Time</th>
<th>Percentage of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>No waiting</td>
<td>0%</td>
</tr>
<tr>
<td>up to 15 min</td>
<td>0%</td>
</tr>
<tr>
<td>up to 30 min</td>
<td>10%</td>
</tr>
<tr>
<td>up to 60 min</td>
<td>20%</td>
</tr>
<tr>
<td>up to 2 hr</td>
<td>30%</td>
</tr>
<tr>
<td>over 2 hr</td>
<td>40%</td>
</tr>
</tbody>
</table>

A Queuing System

- Arrival Rate ($\lambda$)
- Average Wait in Queue ($W_q$)
- Average Number in Queue ($L_q$)
- Service Rate ($\mu$)
- Departure

Appointment planning

Data from the “Versichertenbefragung der Kassenärztlichen Bundesvereinigung 2013”

Institute of Operations Research
Discrete Optimization and Logistics
dol.ior.kit.edu

Stefan Nickel
Process Improvement in Hospitals: A Case Study in a Radiology Department

Anne Zander
Development of efficient Appointments Systemes
Health Care Logistics

- Appointment planning
- Emergency medical services
Health Care Logistics

Institute of Operations Research
Discrete Optimization and Logistics
dol.ior.kit.edu

Melanie Reuter


Patient Transport

Ambulance Location and Relocation

Emergency medical services
Health Care Logistics

- Appointment planning
- Patient transportation
- Emergency medical services
Health Care Logistics

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Stefan Nickel

Patient transportation
Health Care Logistics

- Home health care
- Patient transportation
- Emergency medical services
- Appointment planning
Health Care Logistics

Home health care

Research Center for Information Technology
www.fzi.de

Jacqueline Wirnitzer
Patient-based nurse rostering and tour planning in home care

<table>
<thead>
<tr>
<th>Pfleger</th>
<th>Schicht</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pfleger 1</td>
<td>Schicht 1</td>
<td>Tour 4</td>
<td>Tour 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pfleger 2</td>
<td>Schicht 1</td>
<td>Tour 12</td>
<td>Tour 14</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pfleger 3</td>
<td>Schicht 2</td>
<td>Tour 5</td>
<td>Tour 10</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Patient 1
Patient 4
Patient 2
Patient 8
Health Care Logistics

- Hospital layout planning and evaluation
- Home health care
- Patient transportation
- Emergency medical services
- Appointment planning
Health Care Logistics

Hospital layout planning and evaluation

Research Center for Information Technology
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Jacqueline Wirnitzer
Prevention of bottlenecks in hospital layouts through simulation modeling

Institute of Operations Research
Discrete Optimization and Logistics
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Ines Arnolds
Hospital layout planning: combining simulation and optimization

Jacqueline Wirnitzer
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Ines Arnolds
Hospital layout planning: combining simulation and optimization

Input data

Deterministic parameters
Stochastic parameters

Optimization model
Optimal solution
Simulation model
Feedback

Kulkarni (2012)
Health Care Logistics

Hospital layout planning and evaluation

Home health care

Patient transportation

Emergency medical services

Appointment planning
An Iterative Simulation-Optimization Approach for Hospital Layout Planning

Stefan Nickel, Ines Arnolds
Outline

- Motivation and research questions
- Literature
- Methodology
- Models
- Preliminary results
- Summary and next steps
Motivation

- Holistic view
  - Logistics
    - Patient and personnel flow
  - Architecture
    - Experience
    - Design aspects
    - Legal regulations
  - Operations Research
    - Mathematical models
    - Simulation

- Influence on daily operations, e.g. patient transportation
  - Short distances
  - Process efficiency
  - Quality of treatment and economic efficiency
Motivation

Compare and improve the performance and robustness of hospital layouts for various scenarios.

Studying factors by DES, which are hard to integrate in mathematical models or heuristics for hospital layout planning.

Combination of
- Mathematical optimization and
- Discrete event simulation

Extrinsic configuration
- Control, capacity and number of elevators,
- Personnel elevators,
- Personnel shifts and schedules for breaks.

Stochastic influences
- Clinical pathways,
- Means and speed of transportation,
- Patient arrival rates,
- Service durations.
Research questions

- How to implement a generic simulation model?
- How do identified KPIs affect different patient types?
- How to implement a feedback loop: optimization – simulation?
- What are relevant KPIs for a hospital layout?
- How to measure the quality and performance of the approach?
Outline

- Motivation and research questions
- Literature
- Methodology
- Models
- Preliminary results
- Summary and next steps
## Literature

### Hospital layout planning


### Simulation-optimization


Kulkarni, K., J. Venkateswaran. 2012: „Stochastic Job Shop Scheduling using Hybrid Simulation and Optimization Approaches“. *International Simulation Conference of India*. 
Outline

- Motivation and research questions
- Literature
- Methodology
- Models
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- Summary and next steps
Methodology

Combining simulation and optimization

Non-iterative models
- Models interact just once
- Running either simulation or optimization first
- Using preliminary results to obtain final solution from other model

Iterative models
- Models interact multiple times
- Until stopping criterion is met
Methodology

- Iterative optimization and simulation

---

Kulkarni (2012)
Outline

- Motivation and research questions
- Literature
- Methodology

Models
- Quadratic assignment problem
- Discrete event simulation

Preliminary results

Summary and next steps
Iterative simulation-optimization approach

- Objective: Robust hospital layout with short travel distances and times
- Assumption: Worse objective function value under uncertainty
  - DES: Additional patient arrivals with uncertain pathways

Implementation: AnyLogic

Based on Acar (2009)
Models: Quadratic assignment problem (QAP)

\[
\min Z = \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk} d_{rl} y_{jr} y_{kl} \quad \text{Minimize total travel distance} \tag{1}
\]

s.t.

\[
\sum_{r=1}^{m} y_{jr} = 1 \quad \text{Each department assigned to one room} \quad \forall j \in \{1, \ldots, m\} \tag{2}
\]

\[
\sum_{j=1}^{m} y_{jr} = 1 \quad \text{Each room assigned to one department} \quad \forall r \in \{1, \ldots, m\} \tag{3}
\]

\[
y_{jr} \in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\} \tag{4}
\]

- **Parameters:**
  - \( f_{jk} \) | flow between departments \( j \) and \( k \)
  - \( d_{rl} \) | distance between rooms \( r \) and \( l \)

- **Decision Variables:**
  - \( y_{jr} \) | \[
  \begin{cases} 
  1, & \text{if department } j \text{ is assigned to room } r \\
  0, & \text{otherwise}
  \end{cases}
  \]
Models: Quadratic assignment problem (QAP)

\[
\min Z = \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk} d_{rl} y_{jr} y_{kl} + \sum_{n} N_n Z_n
\]

\[
\text{Penalty: Feedback from simulation}
\]

\[
\text{s.t. } \sum_{r=1}^{m} y_{jr} = 1 \quad \forall j \in \{1, \ldots, m\}
\]

\[
\sum_{j=1}^{m} y_{jr} = 1 \quad \forall r \in \{1, \ldots, m\}
\]

\[
y_{jr} \in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\}
\]

- **Parameters:**

  
  \[
  N_n \mid \text{impact of uncertainty found by simulation for candidate solution } n
  \]

- **Decision Variables:**

  
  \[
  Z_n \mid \text{binary variable for incorporating cost of uncertainty for candidate solution } n:
  \begin{cases}
  1, & \text{if layout currently considered by QAP was suggested in a previous iteration} \\
  0, & \text{otherwise}
  \end{cases}
  \]
Models: Quadratic assignment problem (QAP)

Example: Influence of penalty $N_n$

- DES solution value for 2\textsuperscript{nd} deterministic layout
- Best found QAP layout in 2\textsuperscript{nd} iteration
- DES solution value for 1\textsuperscript{st} deterministic layout
- Best found QAP layout in 1\textsuperscript{st} iteration

Permutation (assignment)
Models: Quadratic assignment problem (QAP)

\[
\begin{align*}
\min Z &= \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk}d_{rl}y_{jr}y_{kl} + \sum_{n} N_n Z_n \\
\text{s.t. } \sum_{r=1}^{m} y_{jr} &= 1 \quad \forall j \in \{1, \ldots, m\} \\
\sum_{j=1}^{m} y_{jr} &= 1 \quad \forall r \in \{1, \ldots, m\} \\
\quad y_{jr} &\in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\}
\end{align*}
\]

Determine decision variables \( Z_n \)

\[
\sum_{j} \sum_{r} (2T_{n,jr}y_{jr} - y_{jr} - T_{n,jr}) \leq Z_n - 1 \quad \forall n \in \{1, \ldots, I\}
\]

\[
\sum_{j} \sum_{r} (2T_{n,jr}y_{jr} - y_{jr} - T_{n,jr}) \geq M(Z_n - 1) \quad \forall n \in \{1, \ldots, I\}
\]

Parameters:

\[
\begin{array}{c|c}
T_{n,jr} & 1, \text{ if binary variable } y_{jr} \text{ in candidate solution } n \text{ is } 1 \\
0, \text{ otherwise} \\
I & \# \text{ iterations}
\end{array}
\]

\[28.11.2013\]
Models: Quadratic assignment problem (QAP)

\[
\min Z = \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk} d_{rl} y_{jr} y_{kl} + \sum_{n} N_n Z_n
\]  

(1)

\[
s.t. \quad \sum_{r=1}^{m} y_{jr} = 1 \quad \forall j \in \{1, \ldots, m\}  
\]

(2)

\[
\sum_{j=1}^{m} y_{jr} = 1 \quad \forall r \in \{1, \ldots, m\}  
\]

(3)

\[
y_{jr} \in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\}  
\]

(4)

\[
\sum_{j} \sum_{r} (2T_{n,jr} y_{jr} - y_{jr} - T_{n,jr}) \leq Z_n - 1 \quad \forall n \in \{1, \ldots, I\}  
\]

(5)

\[
\sum_{j} \sum_{r} (2T_{n,jr} y_{jr} - y_{jr} - T_{n,jr}) \geq M(Z_n - 1) \quad \forall n \in \{1, \ldots, I\}  
\]

(6)

\[
Z \leq Q_{\min} \quad \text{Min. cost of QAP} \leq \text{best found solution of DES}  
\]  

(7)

- Parameters: \( Q_{\min} \mid \text{minimum total cost obtained so far from simulation} \)
Models: Quadratic assignment problem (QAP)

- Example: Influence of $Q_{\text{min}}$

![Graph](chart.png)

- Permutation (assignment)

- $Z_{\text{QAP}}$

- $Z_{\text{DES}}$

- $Q_{\text{min}}$

- $Q_{\text{min}}$

- $Z_{\text{QAP}}$

- $Z_{\text{DES}}$
Model: Discrete event simulation (DES)

- Parameters
  - 3 patient types: Walking, wheelchair, bed
  - Individual speed per patient type
  - Individual weights for elevator usage per patient type
  - Arrival rates per patient type
  - Transition probabilities
Outline

- Motivation and research questions
- Literature
- Methodology
- Models

Preliminary results
- Simulation-optimization approach
- Focusing on elevators in DES model

Summary and next steps
Preliminary results: Simulation-optimization approach

Setting

- Layout: One floor: 6 rooms and entry/exit
- Randomly generated flow matrix
- Random transition probabilities

![Diagram of a hospital floor layout with 6 rooms and an entry/exit point]
Preliminary results: Simulation-optimization approach

Performance measures

- DES solution value for 1st deterministic layout
- Improvement under uncertain data
- DES solution value for robust layout
- Deterioration under deterministic data
- Best found QAP layout in last iteration (robust layout)
- Best found QAP layout in 1st iteration

Performance measures:
- $Z_{QAP}$
- $Z_{DES}$
Preliminary results: Simulation-optimization approach

Higher improvement than deterioration

Deterioration under deterministic data
Improvement under uncertain data

% Additional patients with uncertain pathways

-5,00% -4,00% -3,00% -2,00% -1,00% 0,00% 1,00% 2,00% 3,00% 4,00% 5,00% 6,00% 7,00%

10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

Deterioration/Improvement
Preliminary results:
Focusing on elevators in DES model

Setting

- Layout: 4 different layouts where locations of wards, surgical units and functional departments are interchanged
- Elevators: Varying number vs. capacities of elevators
- # Replications: 10 replications for each scenario

20 departments on 4 floors

1st floor

2nd floor

3rd floor

4th floor
Preliminary results:
Focusing on elevators in DES model

Sensitivity analysis

Average total waiting time for elevator
Preliminary results:
Focusing on elevators in DES model

- Layout 1
- Layout 2
- Layout 3
- Layout 4

<table>
<thead>
<tr>
<th>Layout</th>
<th>Average waiting time for elevator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layout 1</td>
<td>40 sec</td>
</tr>
<tr>
<td>Layout 2</td>
<td>50 sec</td>
</tr>
<tr>
<td>Layout 3</td>
<td>55 sec</td>
</tr>
<tr>
<td>Layout 4</td>
<td>60 sec</td>
</tr>
</tbody>
</table>

Sensitivity analysis
Outline

- Motivation and research questions
- Literature
- Methodology
- Models
- Preliminary results
- Summary and next steps
Summary

- Robust hospital layout via simulation-optimization approach

For people in charge of hospital planning (architects, hospital managers, and engineers)

- Improved operational processes, e.g. more efficient transport of patients and material

Decision support tool

Patient satisfaction and economic efficiency

Considering the dynamic environment

Working quality and staff satisfaction

- Additional patients
- Uncertain pathways (changing diseases, courses of diseases as well as treatment methods)

Utilize working time more effectively and efficiently
Next steps

- Modify QAP to solve larger instances
  - Practically relevant constraints
  - Symmetry breaking constraints

- DES model: Measurement of other relevant KPI’s
  - Travel times
  - Personnel: Travel distances/times with/without patients
  - Fair layout: Regarding KPI’s for different patient types
  - …

- Tests on real-world data
  - Flow data
  - Transition matrices and transition probabilities
An Iterative Simulation-Optimization Approach for Hospital Layout Planning

Stefan Nickel, Ines Arnolds
Backup
Hospital layout planning: Example
Methodology

- Iterative optimization and simulation-based optimization

**Input Parameters**

- Deterministic parameters
- Stochastic parameters

**Optimization model**

**Simulation model**

- Objective value
- Decision variables

**Meta-heuristic based improvement**

**Feedback**

Kulkarni (2012)
Hybrid models

- Non-iterative optimization and simulation

![Diagram showing hybrid models]

- **Input parameters**
  - Deterministic parameters
  - Stochastic parameters

- **Optimization (MIP) model**
  - Delay and non-delay solutions

- **Simulation model**
  - Optimal decision variables
  - Non-delay solutions by default

- Interval estimates on objective value

Kulkarni (2012)
Hybrid models

- Non-iterative simulation-based optimization and optimization

![Diagram of hybrid models]

- Input Parameters
  - Simulation model
  - Objective value
  - Decision variables
  - Meta-heuristic based optimization model
    - Initial Solution
  - Optimization (MIP) model
    - Optimum

Deterministic parameters

Kulkarni (2012)
Hybrid models

- Iterative simulation-based Optimization

![Diagram](image)

Kulkarni (2012)
Models: Quadratic assignment problem (QAP)

\[
\begin{align*}
\min Z &= \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk} d_{rl} y_{jr} y_{kl} + \sum_{n} N_n Z_n \\
\text{s.t.} \quad \sum_{r=1}^{m} y_{jr} &= 1 \quad \forall j \in \{1, \ldots, m\} \quad (2) \\
\sum_{j=1}^{m} y_{jr} &= 1 \quad \forall r \in \{1, \ldots, m\} \quad (3) \\
y_{jr} &\in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\} \quad (4) \\
\sum_{j} \sum_{r} (2T_{n,jr} y_{jr} - y_{jr} - T_{n,jr}) &\leq Z_n - 1 \quad \forall n \in \{1, \ldots, I\} \quad (5)
\end{align*}
\]

- Parameters:
  - \(T_{n,jr}\) \(= \begin{cases} 
1, & \text{if binary variable } y_{jr} \text{ in candidate solution } n \text{ is 1} \\
0, & \text{otherwise}
\end{cases}\)
  - \(I\) \# iterations

\((T_{n,jr} = y_{jr} \ \forall \ j, r) \Rightarrow (Z_n = 1)\)
Models: Quadratic assignment problem (QAP)

\[
\min Z = \sum_{j=1}^{m} \sum_{k=1}^{m} \sum_{l=1}^{m} \sum_{r=1}^{m} f_{jk} d_{rl} y_{jr} y_{kl} + \sum_{n} N_n Z_n
\]  \hspace{1cm} (1)

s.t. \[ \sum_{r=1}^{m} y_{jr} = 1 \quad \forall j \in \{1, \ldots, m\} \] \hspace{1cm} (2)

\[ \sum_{j=1}^{m} y_{jr} = 1 \quad \forall r \in \{1, \ldots, m\} \] \hspace{1cm} (3)

\[ y_{jr} \in \{0, 1\} \quad \forall j, r \in \{1, \ldots, m\} \] \hspace{1cm} (4)

\[ \sum_{j} \sum_{r} (2T_{njr} y_{jr} - y_{jr} - T_{njr}) \leq Z_n - 1 \quad \forall n \in \{1, \ldots, I\} \] \hspace{1cm} (5)

\[ \sum_{j} \sum_{r} (2T_{njr} y_{jr} - y_{jr} - T_{njr}) \geq M(Z_n - 1) \quad \forall n \in \{1, \ldots, I\} \] \hspace{1cm} (6)

\[(\exists \ T_{njr} \neq y_{jr}) \Rightarrow (Z_n = 0)\]
Model: Discrete event simulation (DES)

- **Parameters**
  - 3 patient types: Walking, wheelchair, bed
  - Individual speed per patient type
  - Individual weights for elevator usage per patient type
  - Arrival rates per patient type
  - Transition probabilities
  - 20 departments on 4 floors:
    - Fixed
      - Entrance
    - Variable
      - 3 surgical units, laboratory
      - 4 functional departments
      - 12 wards