Electric Bus Fleet Mileage Maximization | Marius Madsen | Prof. Dr.-Ing. Marc Gennat

Hochschule Niederrhein
University of Applied Sciences
SWK E²

1st IAEE Online Conference

Electric Bus Fleet Mileage Maximization with a Given Schedule Using Integer Programming

SWK E² - Institute for Energy Technology and Energy Management

Marius Madsen | Prof. Dr.-Ing. Marc Gennat

SWK E² - Institute of Energy Technology and Energy Management

SWK E²: Institute at Hochschule Niederrhein in Krefeld (NRW)

Founding

- 2012 as competence centre
- 2017 transformation into an institute

Involved faculties

- Industrial Engineering
- Mechanical and Process Engineering
- Electrical Engineering

Agenda

- **Introduction**
- Modeling
- Problem Formulation and Constraints
- Approach 1: Heuristic
- Approach 2: Integer Linear Programming
- Comparison
- Economic Analysis
- Results
- Summary and Outlook

Introduction

In Krefeld, public transport is based on trams and **diesel buses**

- 12 meter buses: 2.15 mio. km/a
- 18 meter buses: 2.25 mio. km/a

Local **emissions** by diesel buses → Electric buses

Electric buses economical?

Introduction

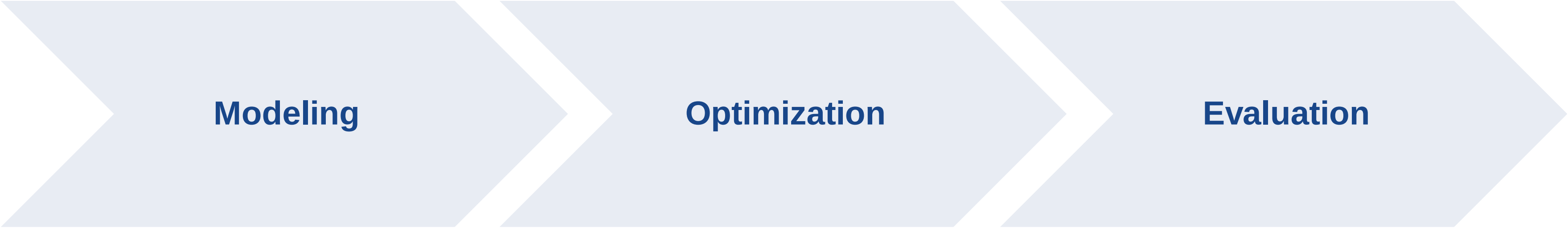
State of the art: Electric buses are **not yet economically** usable [9]

- **Capital investments** are **higher** than for diesel buses [4]
    - High impact of battery costs
- **Mileage-related costs** are **lower** than costs of diesel buses [3,9]

Object of investigation: Economic **re-evaluation** after…

- **maximizing** the **electric** driven **mileage** and
- **minimizing** of **battery capacity** when using electric buses.

Method:



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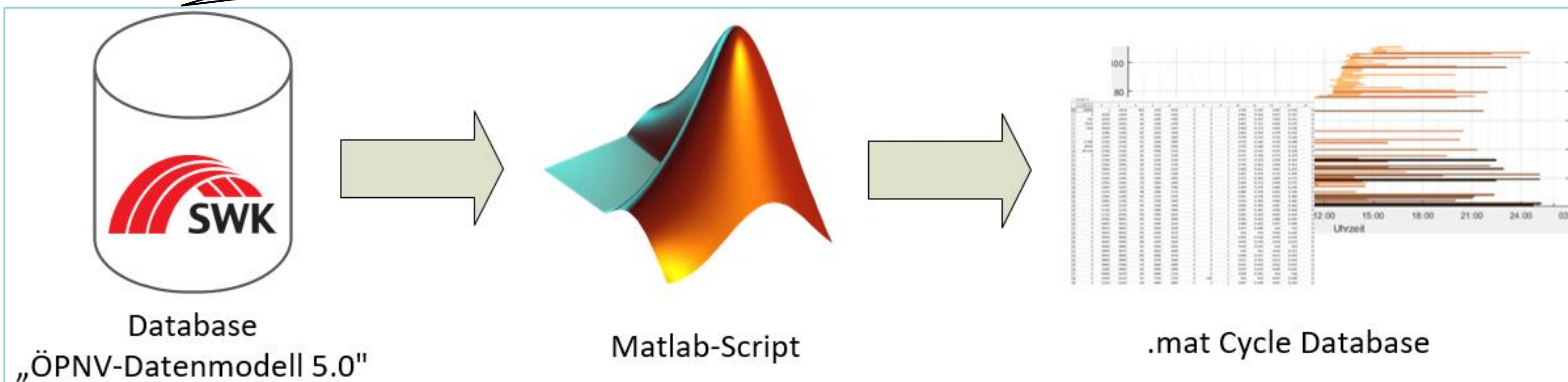
Modeling
Data Basis

Local transport company SWK Mobil GmbH organizes cycle information, according to the **standard interface „ÖPNV-Datenmodell 5.0“.** [11]

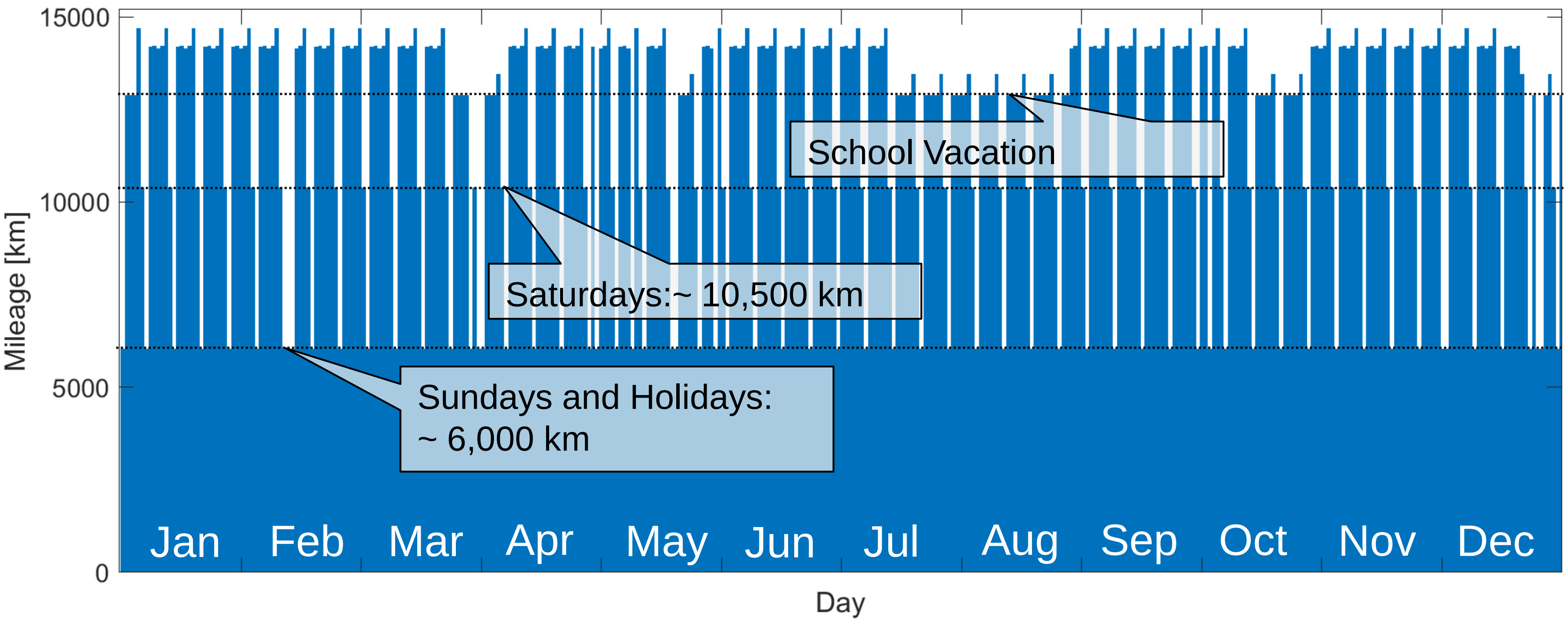


Matlab-Script was created to **import** the database, to **arrange** and **save** the **cycles** for each **day** type.

Result is the data basis for analysis, optimization and simulation

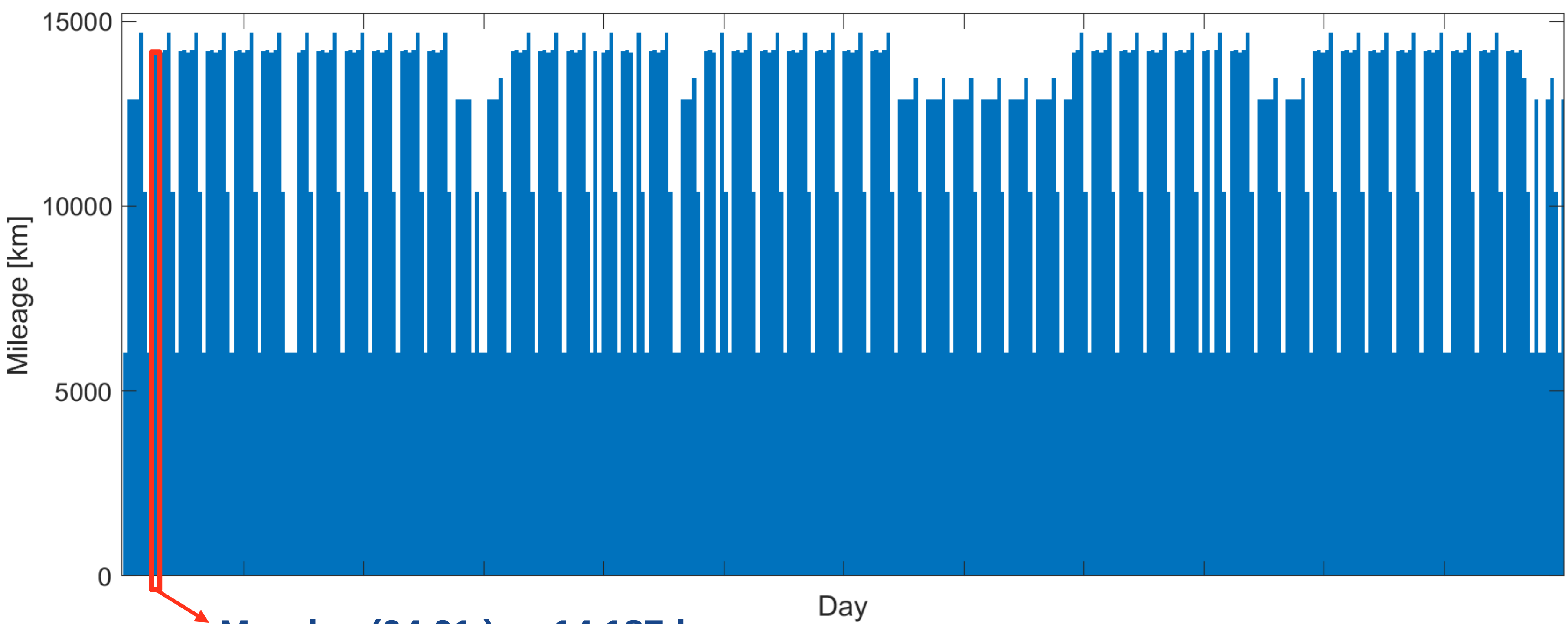
Modeling
Cycle Database

Cycle database as **sum of all cycle mileage** per day of the year:



Modeling
Mileage per Day

Cycle database as **sum of all cycle mileage** per day of the year:



Monday (04.01.): 14,187 km

- Standard buses: 6,237 km
- Articulated buses: 7,950 km → **Example on next slide**

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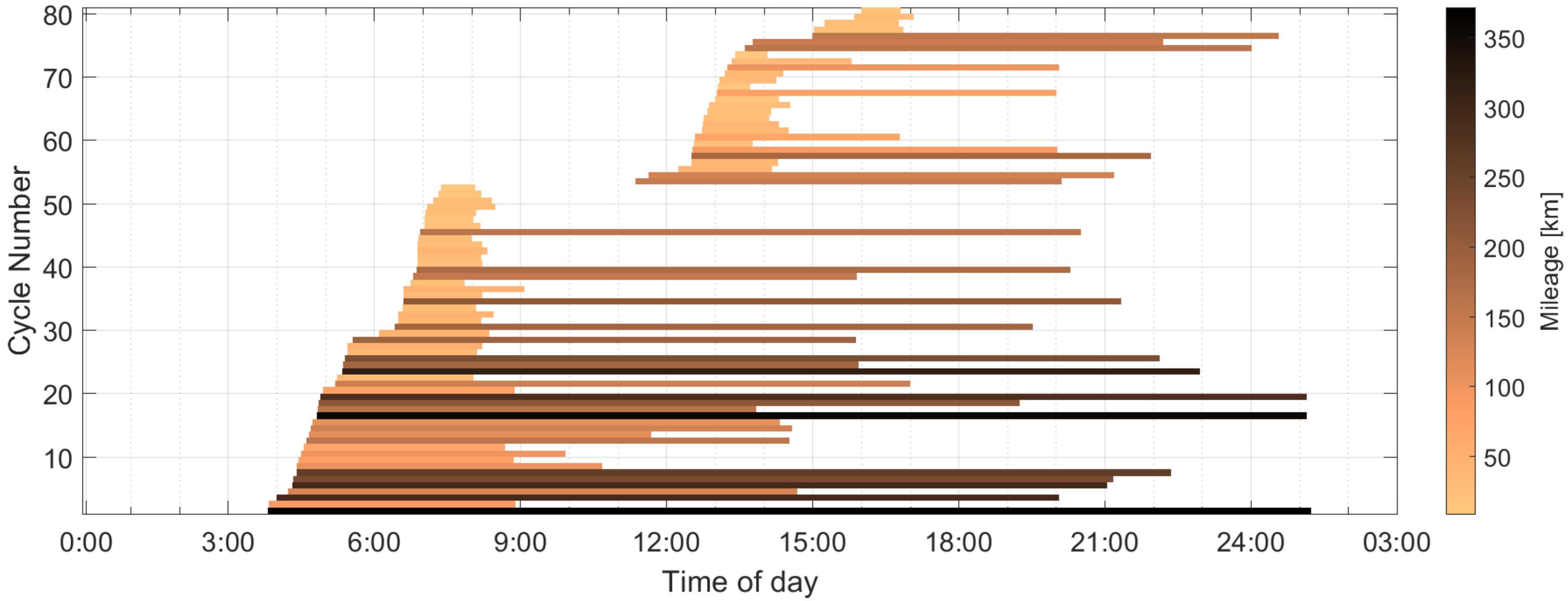
Modeling
Analysis of the Modeled Cycles

Example:

Articulated buses (18 meters) | Day type: (non-school-holidays) **Monday |** Sum: 7,950 km

Total number of (articulated bus) **cycles: 81**



→ **Not all cycles** take place **at the same time**

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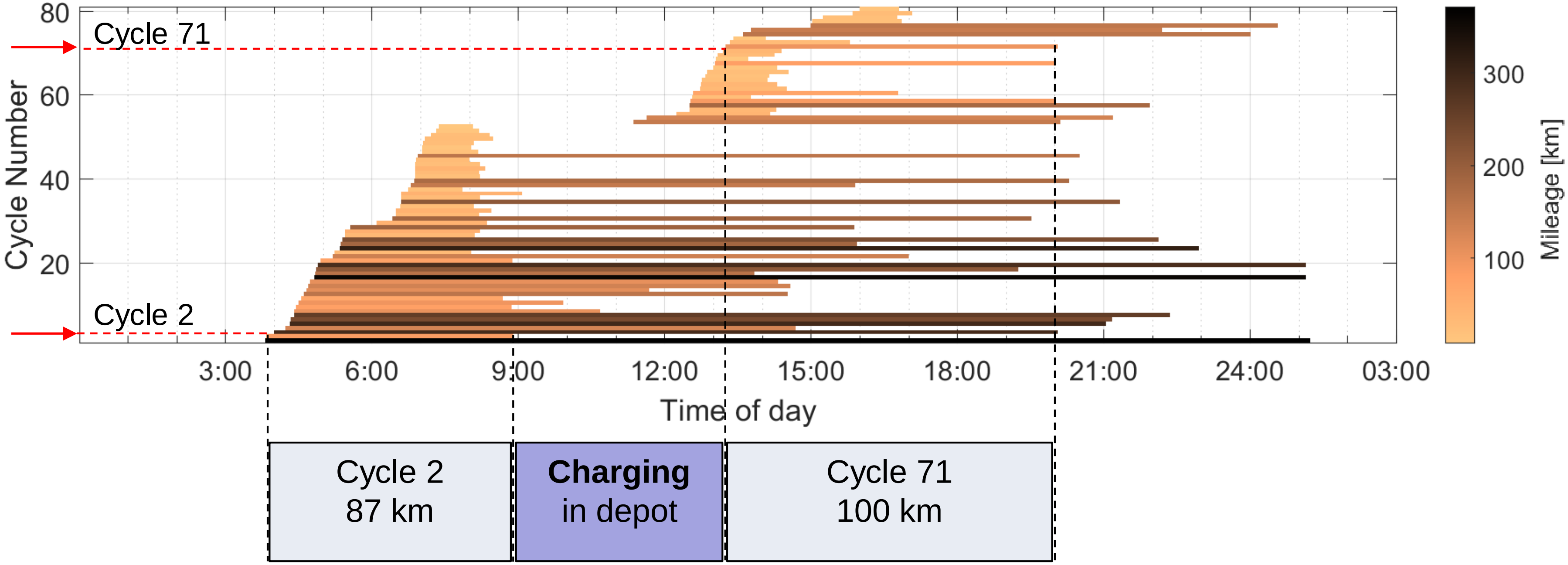
Modeling
Mileage per Day

Example:

Articulated buses (18 meters) | Day type: (non-school-holidays) **Monday**



In this example: Electric driven mileage is **187 km** with a **100 km battery** (approx.)

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Problem Formulation and Constraints
Combination of Cycles

Base Case: A bus can travel…

- **a long cycle**, or
- **several short cycles** in a row.
  → This allows intermediate **recharging** in depot

Additional Constraints: The **energy requirements** of the individual cycles **vary,** depending on: **Bus type**, **weather**, **battery** design, **cycle specifications**.

Problem Formulation and Constraints
Combination of Cycles

- **Maximum of three bus operations per day and bus** due to time overlaps

$$n_{comb} = \prod_{j=1}^{|B|} \sum_{i=1}^{n_{e,max}=3} \binom{|U| - j + 1}{i}$$

- For ten 18-meter buses, this results in more than $\mathrm{n}_{comb} = \mathbf{10^{48}}$ **combinations**
- **Challenge:** Development of approaches to combine the cycles with the target
  - Minimized battery capacity
  - Maximized electrically mileage

    …in a reasonable time

- **Comparison of approaches**
  - Heuristic
  - Integer linear programming

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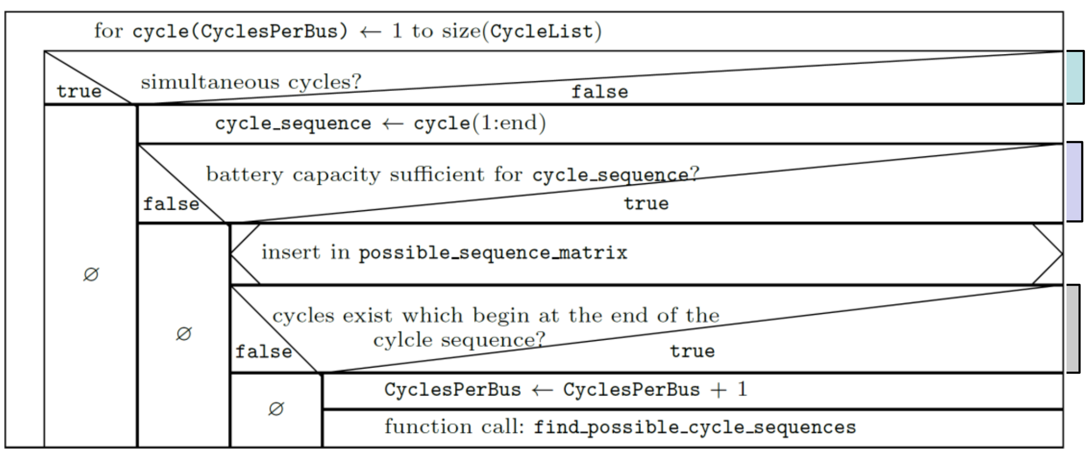
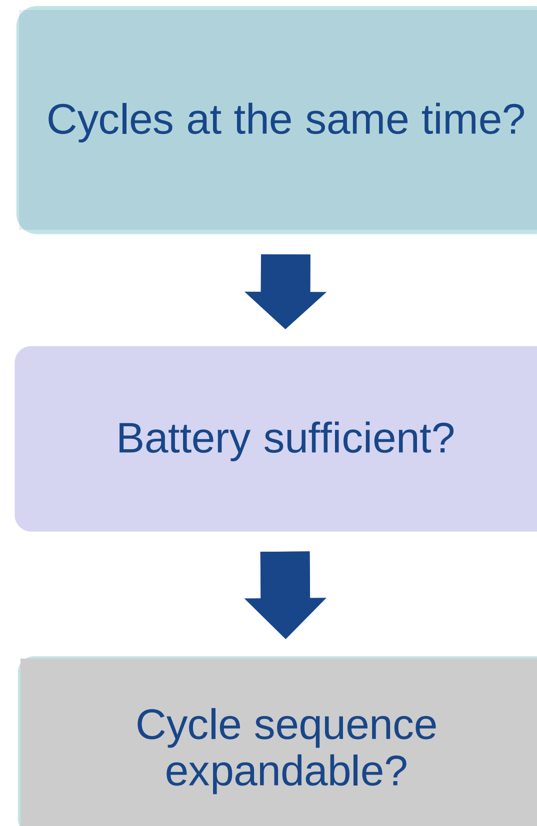
Heuristic
Maximization of Electric Mileage

- The first part is to **find** and **select** possible **combinations** of cycles.
- The required **heating** and **cooling** capacity and the **possible charging time** between the cycles is considered.





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Integer Linear Programming
Target Function

Formulation of objective function:

$$\max_{x} \ c^T x \qquad \text{subject to} \qquad A_i \cdot x \leq d_i \qquad \forall\, i \in \{1, \ldots, |d|\},$$

Decision vector $\boldsymbol{x}$ with length $|x| = |U| \cdot |B|$ ist

$$x^T = (\underbrace{x_{u=1}\ x_{u=2} \cdots x_{u=|U|}}_{b=1} \quad \underbrace{x_{u=1}\ x_{u=2} \cdots x_{u=|U|}}_{b=2} \quad \underbrace{x_{u=1}\ x_{u=2} \cdots x_{u=|U|}}_{b=3})$$

Vector $\boldsymbol{c}$ ($|c| = |x|$) includes **cycle lengths** of the circulations for all electric buses.

$$c^T = (\underbrace{s_{u=1}\ s_{u=2} \cdots s_{u=|U|}}_{b=1} \quad \underbrace{s_{u=1}\ s_{u=2} \cdots s_{u=|U|}}_{b=2} \quad \underbrace{s_{u=1}\ s_{u=2} \cdots s_{u=|U|}}_{b=3})$$

Integer Linear Programming
1. Constraint

Each Cycle can be used by a maximum of **one** electric **bus**:

$$\sum_{b=1}^{|B|} x_{(b-1)\,|U|+u} \leq 1 \quad \forall\, u \in U$$

Constrains of the linear program:

$$A_i \cdot x \leq d_i$$

Formulation of the constraint for the linear Program:

$$\qquad b=1 \qquad\qquad b=2 \qquad\qquad b=3$$

$$A_1 = \begin{pmatrix} \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 \\ 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 \\ 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 \\ 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} \end{pmatrix} \qquad d_1 = \begin{pmatrix} \mathbf{1} \\ \mathbf{1} \\ \mathbf{1} \\ \mathbf{1} \end{pmatrix}$$

Integer Linear Programming

2. Constraint

A bus may **not** make **more than one cycle** at the **same time**:

$$t_{start}, e_{i,b} \geq t_{end}, e_{i-1,b} + \Delta t \quad \forall\, i \in [2, |e_b|] \qquad \forall\, b \in B$$

Constrains of the linear program:

$$A_i \cdot x \leq d_i$$

Example: Time overlap of cycle 1 and 3:

$$\begin{array}{cccc} & b=1 & b=2 & b=3 \end{array}$$

$$A_2 = \begin{pmatrix} \mathbf{1} & 0 & \mathbf{1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & 0 & \mathbf{1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{1} & 0 & \mathbf{1} & 0 \end{pmatrix} \qquad d_2 = \begin{pmatrix} \mathbf{1} \\ \mathbf{1} \\ \mathbf{1} \end{pmatrix}$$

Integer Linear Programming
3. Constraint

Traction **batteries** must **always** be charged **between >0% and ≤100%**. Intermediate charges are only allowed in the depot between cycles.

$$\delta \leq \mathrm{SoC}_{b,t} \leq 1 \quad \forall\, b \in B, \qquad t \in \{1, \ldots, 1440\}$$

Constraints of the linear program:

$$A_i \cdot x \leq d_i$$

Example: Avoiding of the cycle combinations 1, 2 and 4 for all buses:

$$\begin{matrix} & b=1 & b=2 & b=3 \end{matrix}$$

$$A_3 = \begin{pmatrix} \mathbf{1} & \mathbf{1} & 0 & \mathbf{1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & \mathbf{1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & \mathbf{1} \end{pmatrix} \qquad d_3 = \begin{pmatrix} \mathbf{2} \\ \mathbf{2} \\ \mathbf{2} \end{pmatrix}$$

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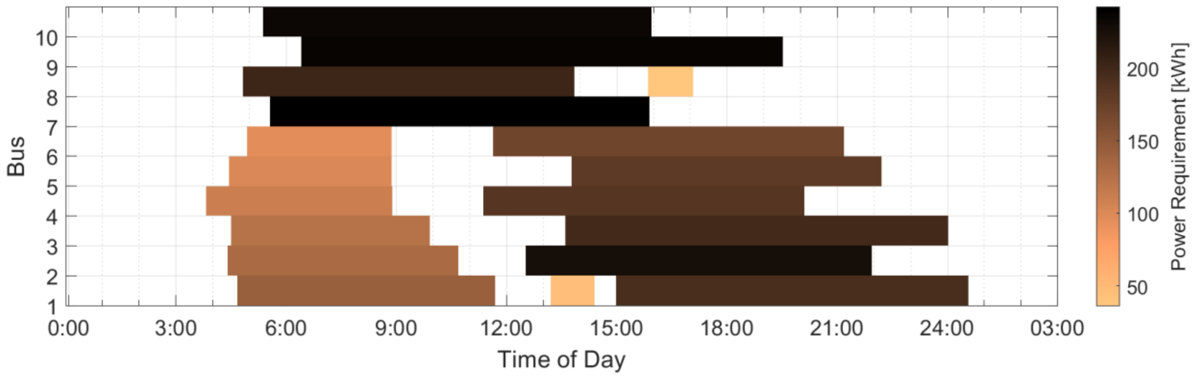
Comparison

Example Results | 10 Buses | 250 kWh Battery



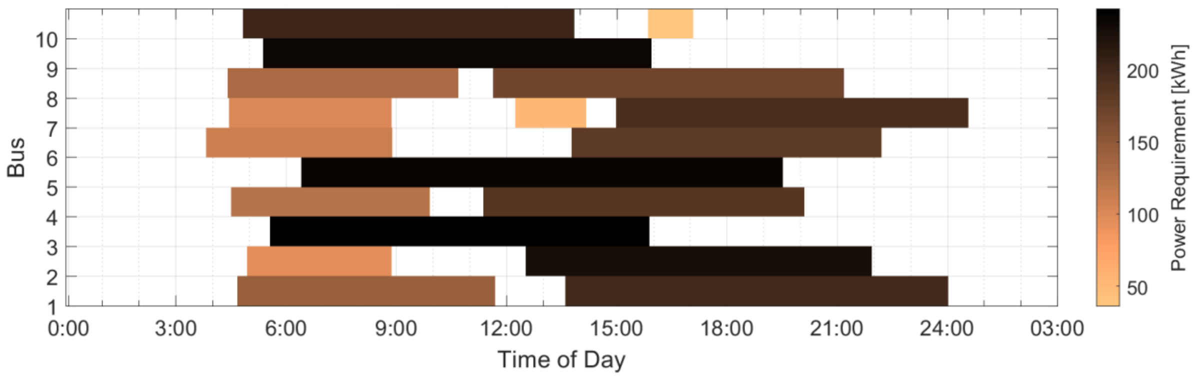
Heuristic

Computing Time:

- 0.05 s

Determined Total Distance

- 2271.7 km



Integer Linear Programming

Computing Time:

- Gurobi [2] : 1.48 s
- Intlinprog [6]: 49587.23 s

Determined Total Distance

- 2277.28 km

- Heuristic **deviates** of **0.25%** but has significantly **shorter computing time**
- For further consideration the heuristic is used

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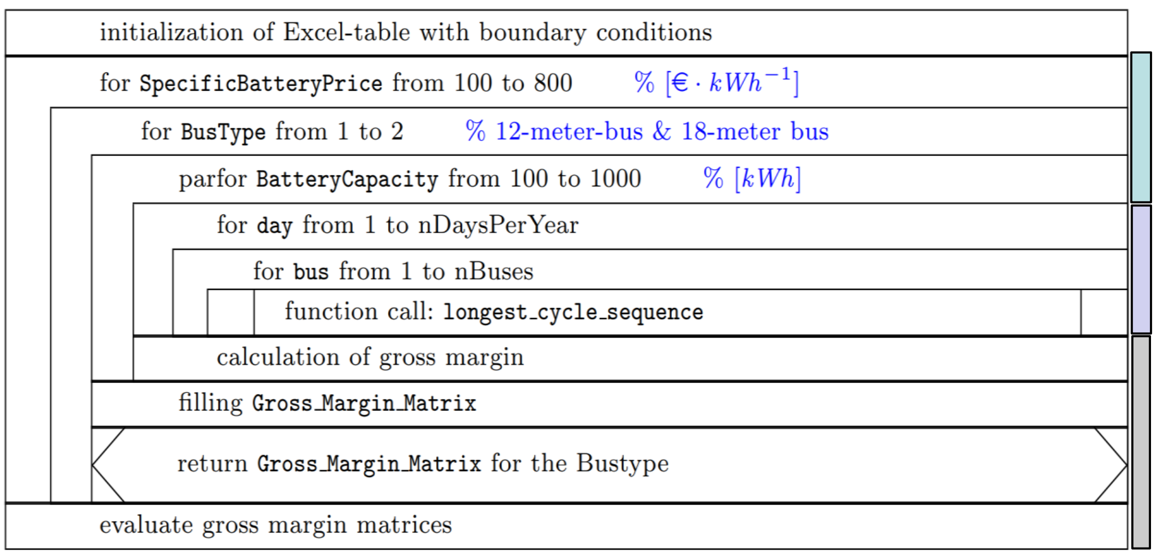
Economic Analysis
Variation of the Input Parameters

Extension of the **heuristic**
- to determine cost efficiency for different conditions
- to view an entire year



Variation of parameters
- Specific battery price
- Bus type
- Battery capacity

Iterate
- Days of a year
- Quantity of electric buses

Calculate
- Gross margin for each iteration

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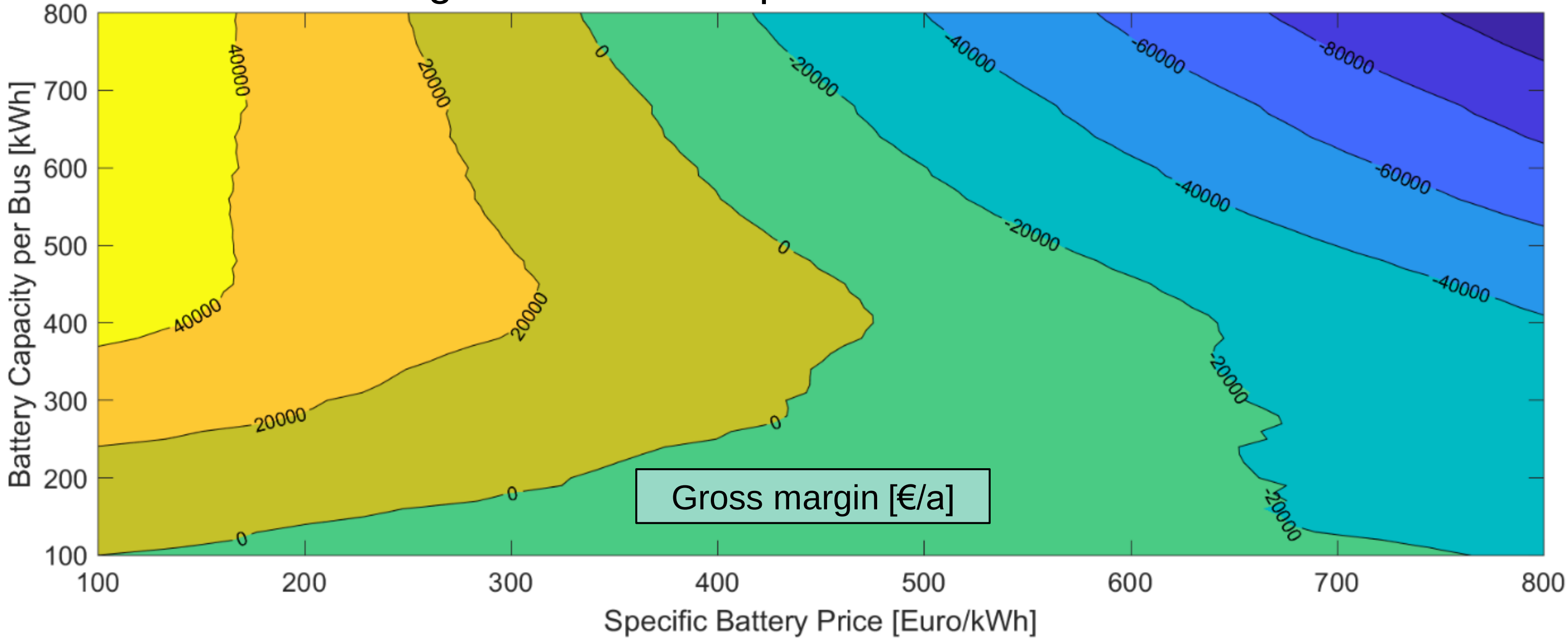
Economic Analysis

Results of Maximizing Electrical Operating Kilometers

Gross margin Matrix: Example for 5 18-meter buses



- 18-meter buses can be used economically in Krefeld if the specific battery price falls below € **480 / kWh**
  - Current battery **cell** price: 97 € / kWh [1]
  - Current battery pack price: 600 - 1000 € / kWh [5, 7, 10]

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Summary and Outlook

Summary

- Optimal cycle allocations **can be determined using linear optimization**
- However, due to the computing time, the **algorithm is more usable**
- In Krefeld, electric buses can be used economically if the specific battery prices fall **below 480 € / kWh**.

Outlook

- Further Potential: Breaking up and optimizing the cycles
- Intelligent charging management (electricity prices, control energy, charging load distribution)
- Impact of CO_2 pricing

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Gladly ask questions and make comments!

Thank you for your attention!

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Appendix

Appendix
Parameters

Boundary Conditions

- charging: power, efficiency, start time
- power demand (traction, besides consumption, heating, cooling)
- desired temperature
- year temperature history
- depreciation periods
- level of investment
- specific weight of battery & passengers
- government subsidies
- energy prices: electricity & diesel
- timetable planning & cycles
- classification of day types to calendar days

→

Optimization Method

- identify the most suitable cycles per day and bus
- vary the battery specification of the bus types
- vary the number of the buses per types

→

Results

economically optimal:

- number of 12-meter electric buses
- number of 18-meter electric buses
- battery capacity of the 12-meter electric buses
- battery capacity of the 18-meter electric buses

Appendix
Opportunity Charging vs. Overnight Charging

Overnight Charging: The full charging of the batteries in the night in the depot

- High flexibility of the bus
- High weight of the battery
- Range problem

Opportunity Charging: Charging the batteries in between stops at the cycle

- Smaller battery
- Investments in charging stations
- No range problem
- The charging times are important which must be respected

[8]

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