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# Methods to improve computing times in linear energy system optimization models

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DLR – German Aerospace Center, Institute of Engineering Thermodynamics

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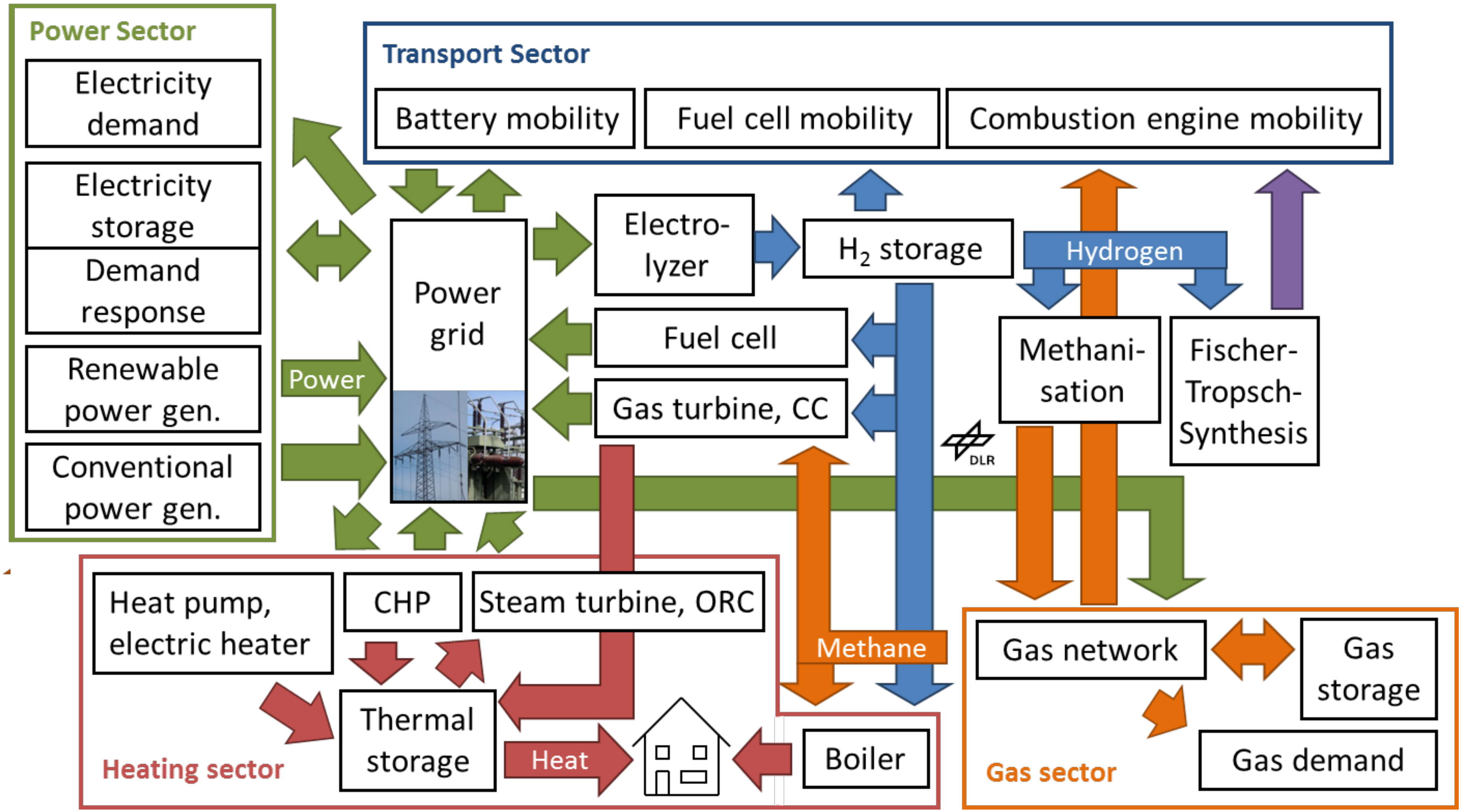
A PROJECT BY

GAMS · TU berlin · HLRS · JÜLICH FORSCHUNGSZENTRUM · DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center · ZIB

# Background: energy systems analysis




Ongoing transformation drastically increases complexity of the energy system

# REMix energy system model

BEAM-ME

Complexity is reflected by state-of-the-art energy system models

**Input**

**Climate and weather data, techno-economic technology parameter, scenario data**

DLR

***REMix Energy System Model***

**Energy Data Analysis Tool *REMix-EnDAT***

**Calculation of RE technology potentials, as well as hourly profiles of power demand and RE power generation**

**Energy System Optimization Model *REMix-OptiMo***

**Least-cost composition and hourly operation of the power system, determined by linear optimization**

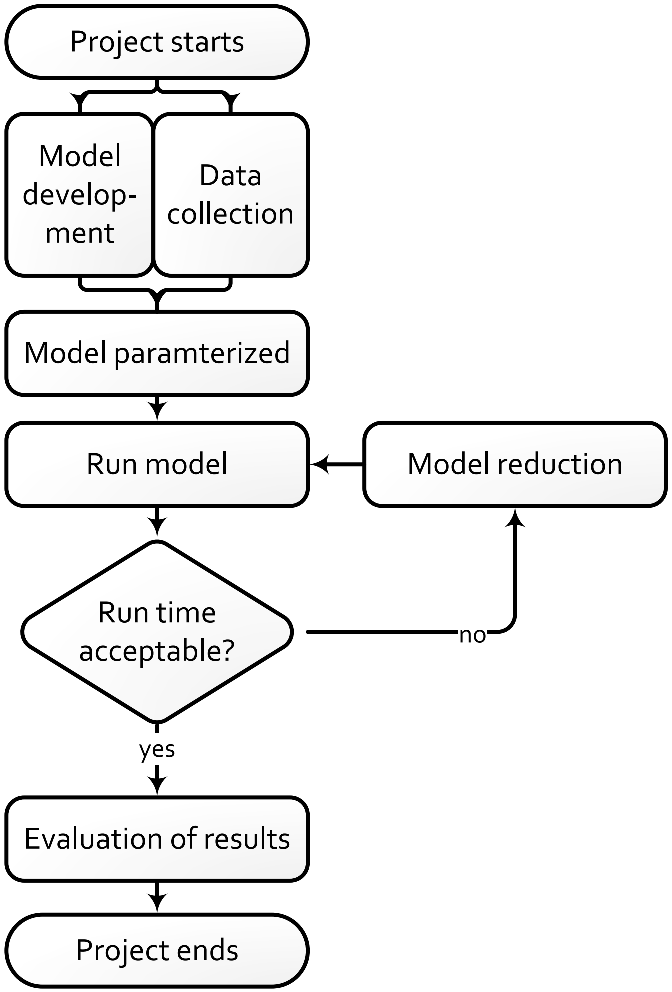
**Minimize $C_{system} = \sum c_j x_j$**

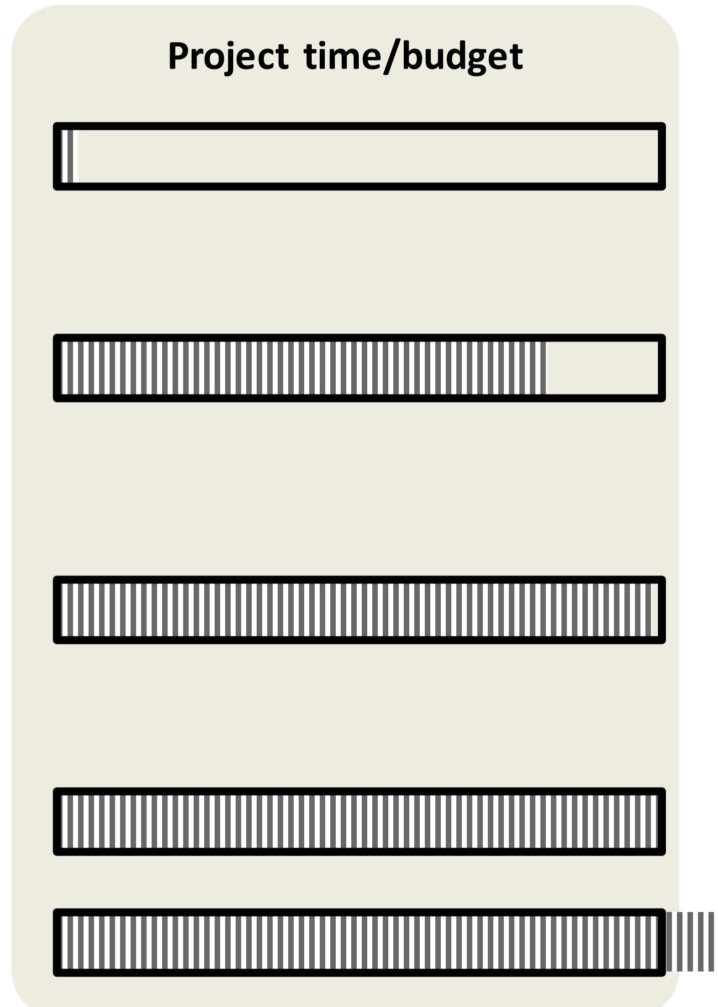
**Output**

**Hourly system operation, system costs, $CO_2$ emissions, construction of new assets**

- Deterministic linear optimization model realized in GAMS
- Assessment of investment and hourly system dispatch during one year

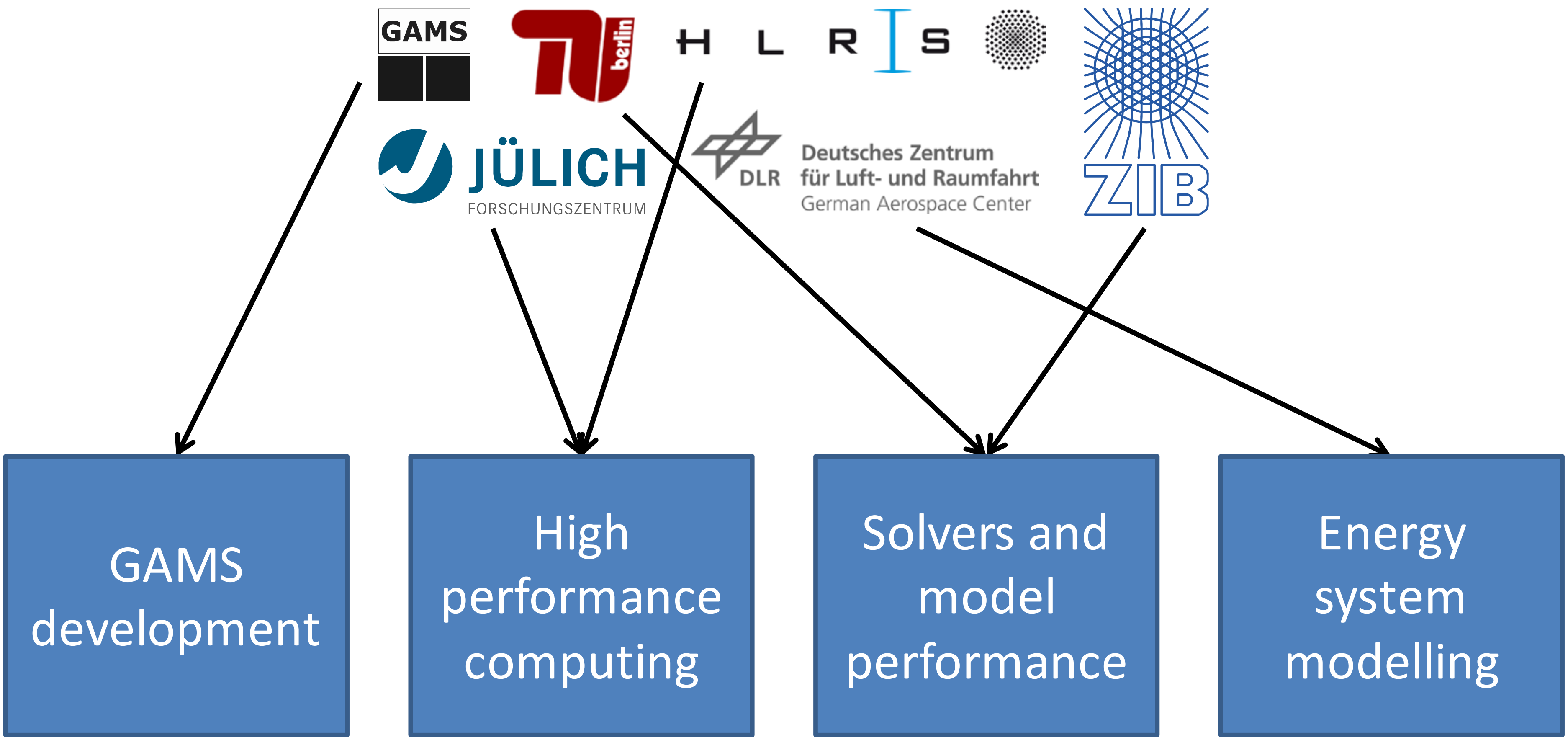
# Motivation


Project starts
Model develop-ment
Data collection
Model paramterized
Run model
Model reduction
Run time acceptable?
no
yes
Evaluation of results
Project ends


Project time/budget

# Project consortium



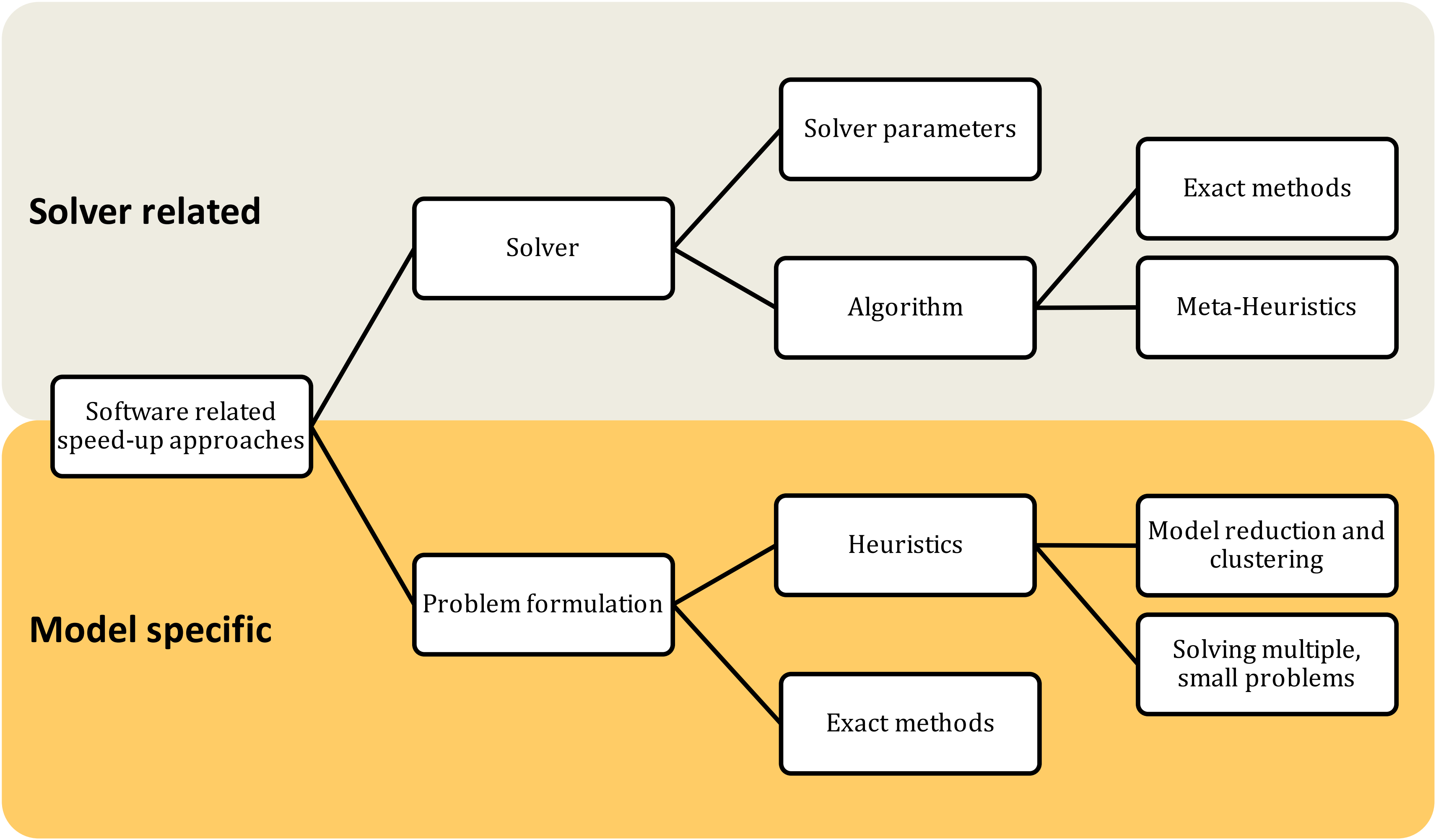


# Idea and scope of BEAM-ME

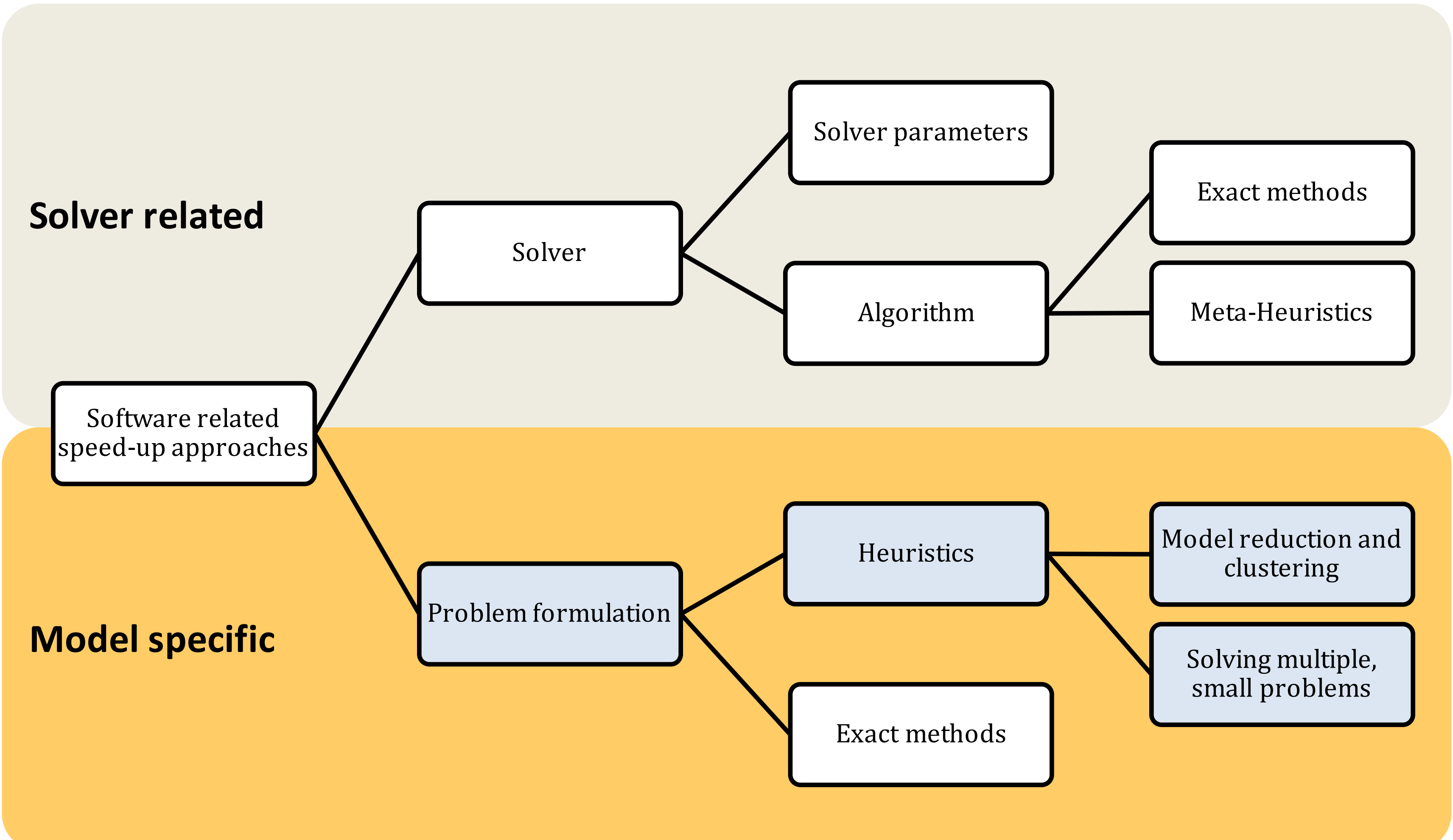
Reduction of solution times urgently needed to enable the reflection of energy system complexity in state-of-the-art models

- Evaluation of different approaches to reduce model solution times
  - Increased modelling efficiency
  - Higher computing power
- Implementation of selected approaches into REMix
- Assessment of the transferability to other models
- Definition of best-practice strategies

# Software related speed-up strategies



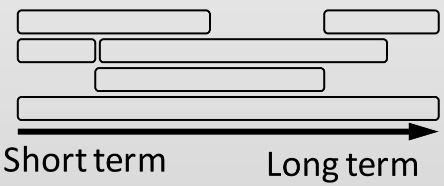
# Modification of the problem formulation



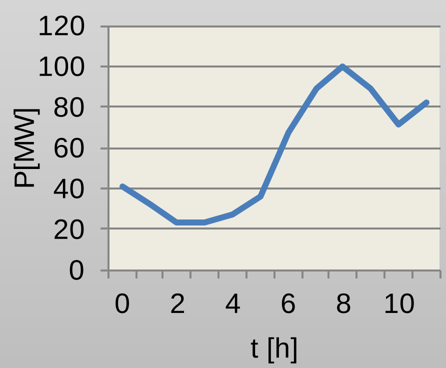
# Typical energy system model dimensions

## Time

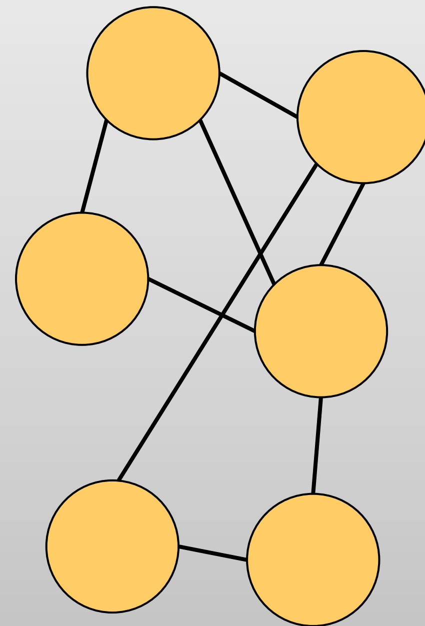
Investment horizon



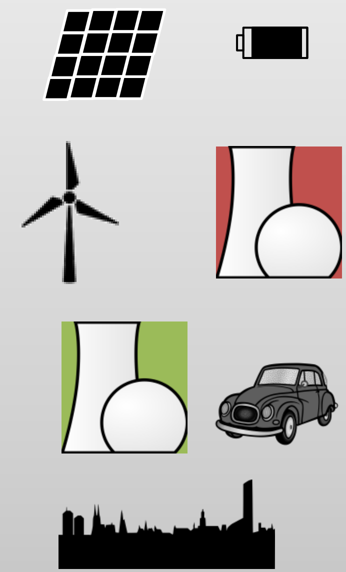

Operation horizon



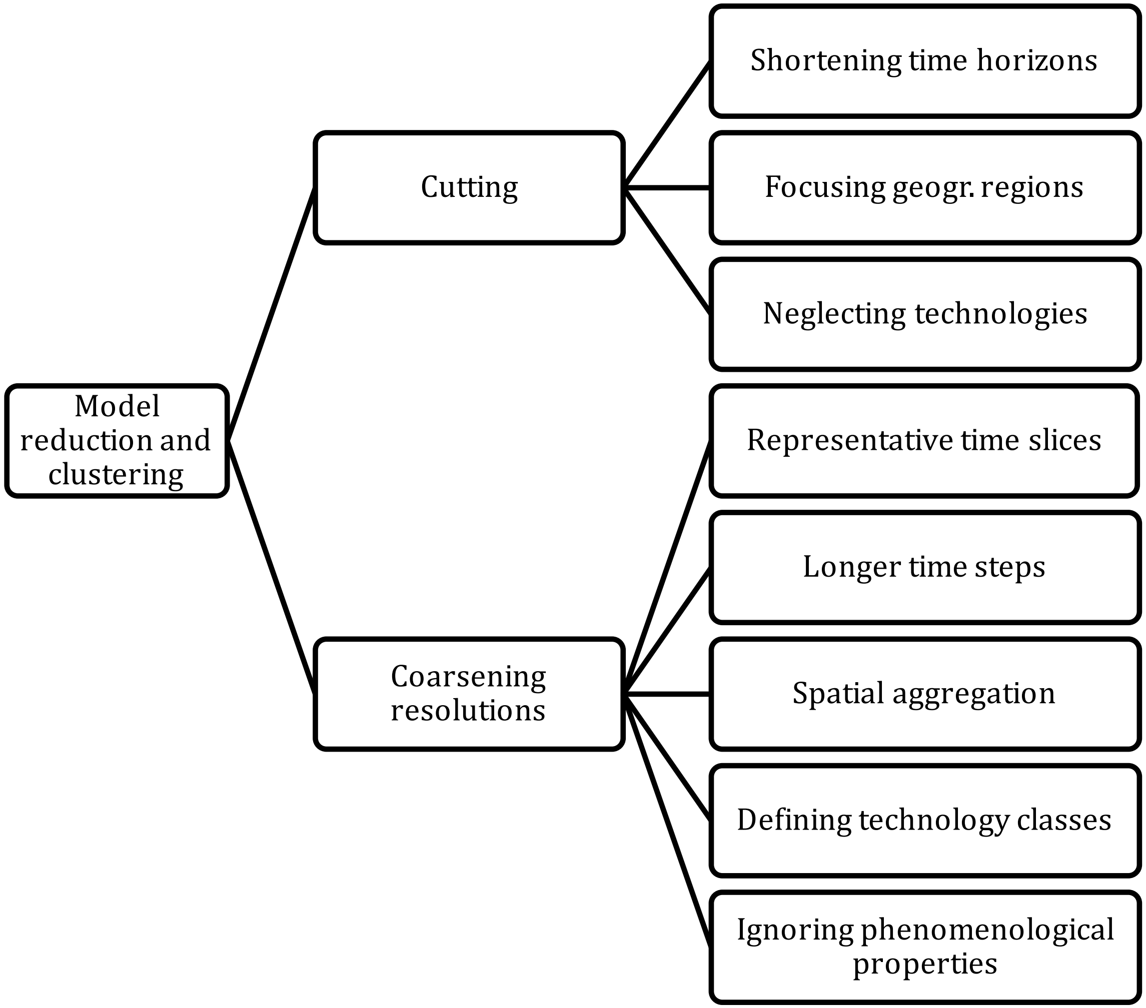

## Space

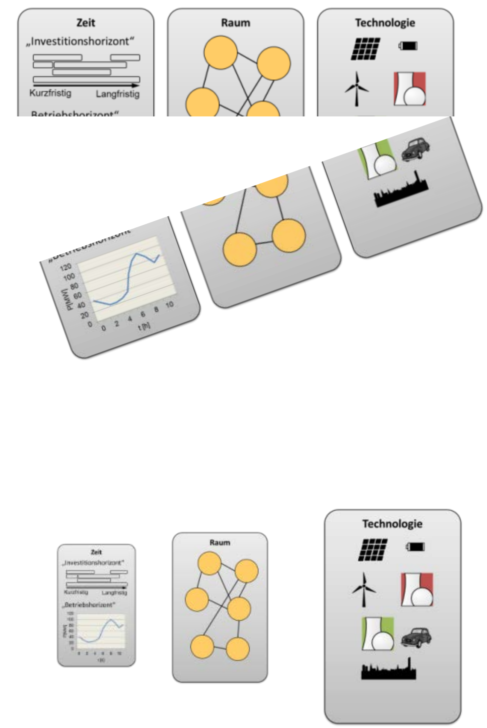


## Technology



# Heuristics: reduction and clustering (I)



# Spatial aggregation (I)

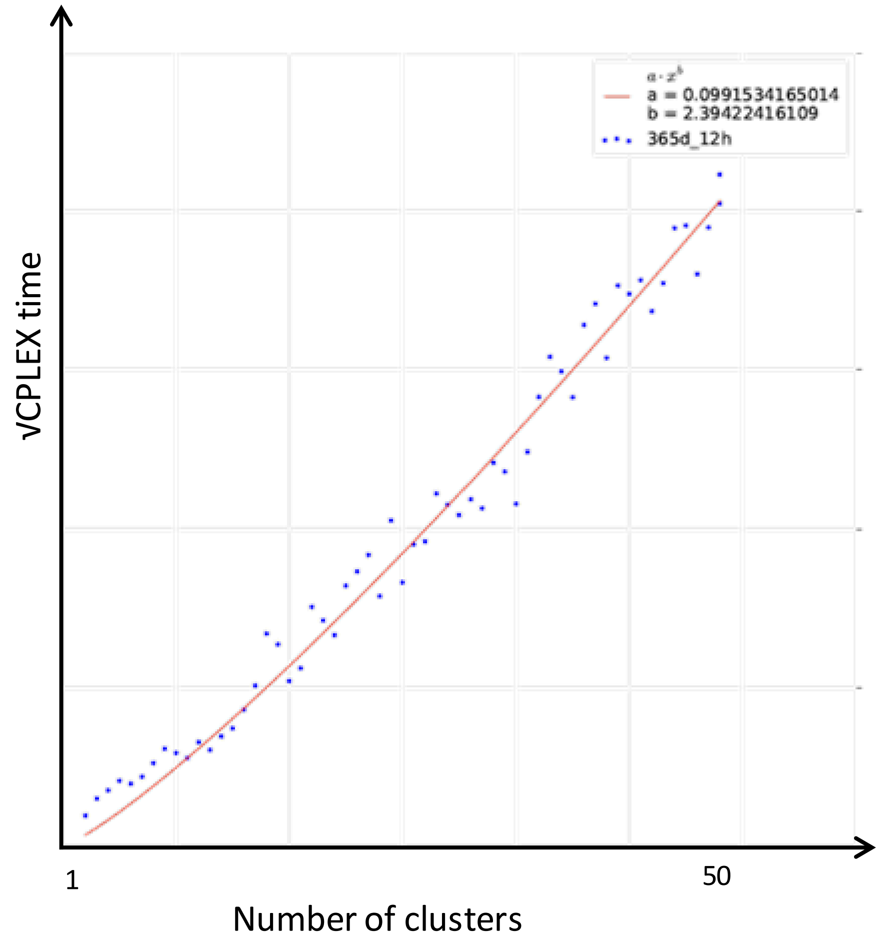
## Idea and implementation

- 2 Reference models:
  - Germany 500 regions
  - Europe 50 regions
- Aggregation of regions using spectral clustering
- Criterion: Δ of marginal costs for power supply

4 clusters

58 clusters

## Impact on CPLEX time (50 regions model)




Reference: Metzdorf, J.: "Development and implementation of a spatial clustering approach using a transmission grid energy system model", University Stuttgart, 2016
Brodbeck, S.: "Evaluierung konzeptioneller Beschleunigungsstrategien für optimierende Energiesystemmodelle", University Stuttgart, 2017

# Spatial aggregation (II)

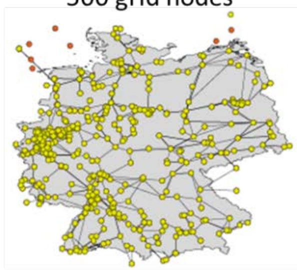
## **Impact on solution** (500 regions model)

| Number of clusters | 1 | 18 | 30 | 75 | 100 | 499 |
|---|---|---|---|---|---|---|
| System costs [M€] | 751 | 839 | 843 | 869 | 926 | 968 |
| Lignite power [TWh] | 13.12 | 10.69 | 10.44 | 10.29 | 9.23 | 8.88 |
| Coal power [TWh] | 7.44 | 9.85 | 9.66 | 10.11 | 10.39 | 9.86 |

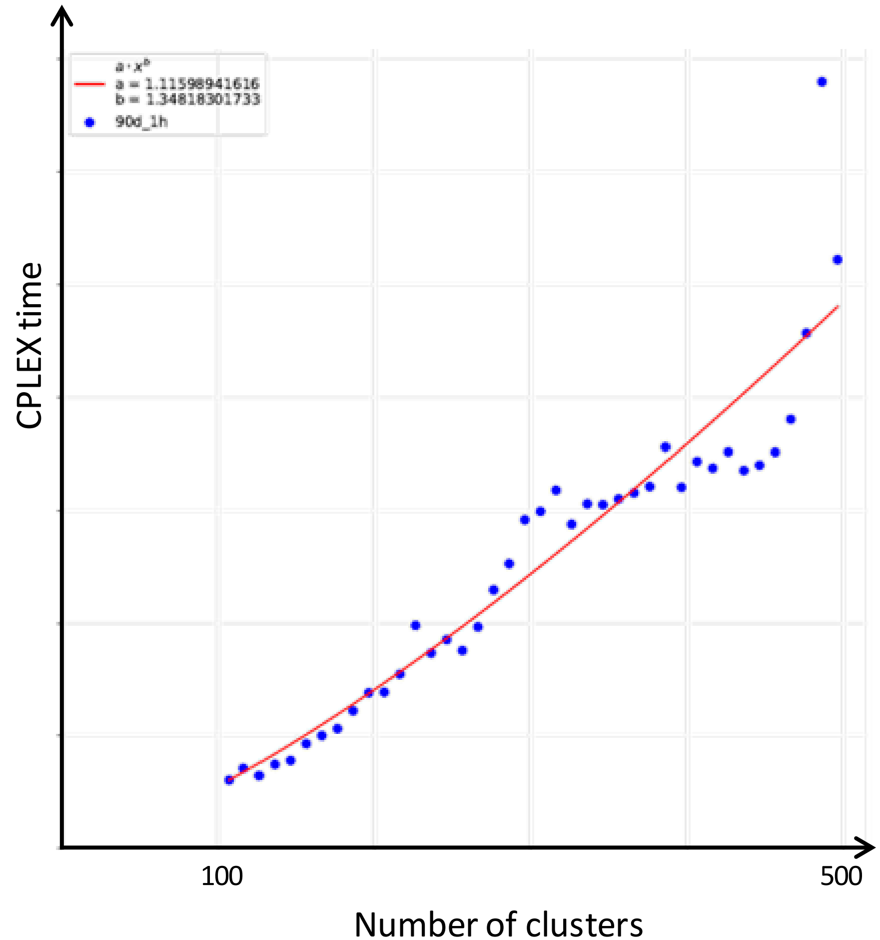
6 clusters

50 clusters

500 grid nodes



## **Impact on CPLEX time** (500 regions model)

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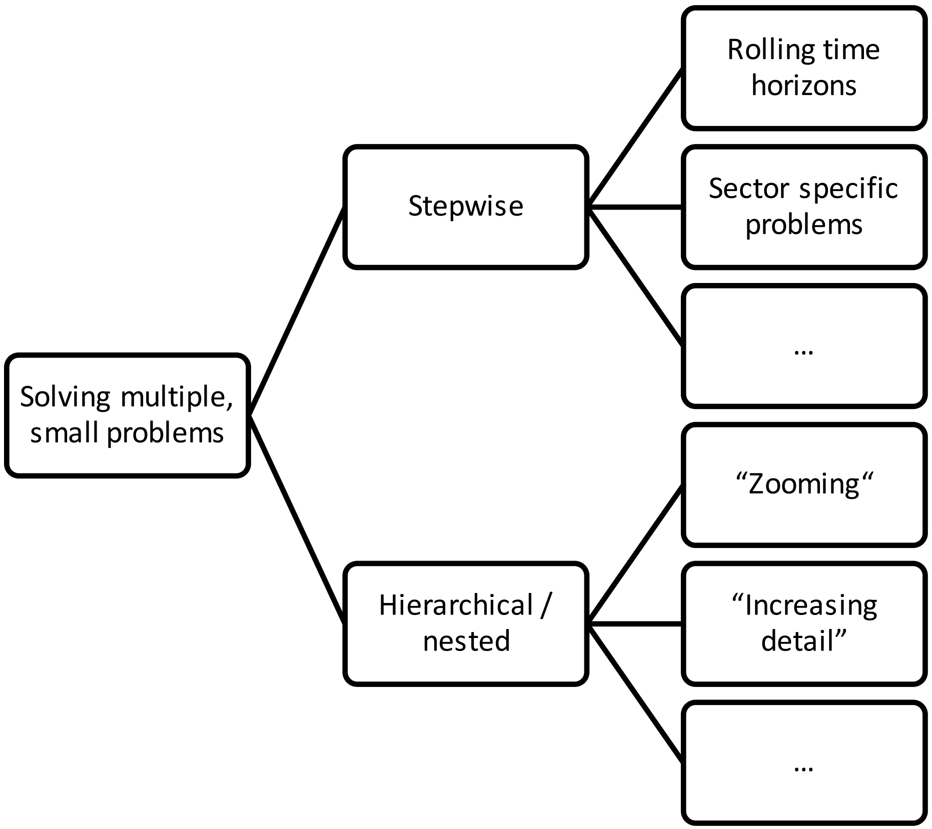
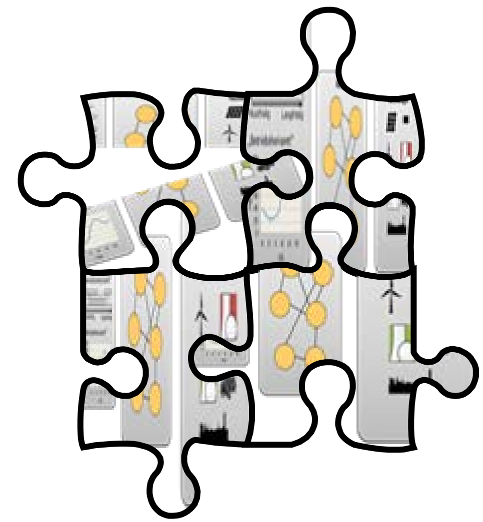
# Heuristics: reduction and clustering (II)



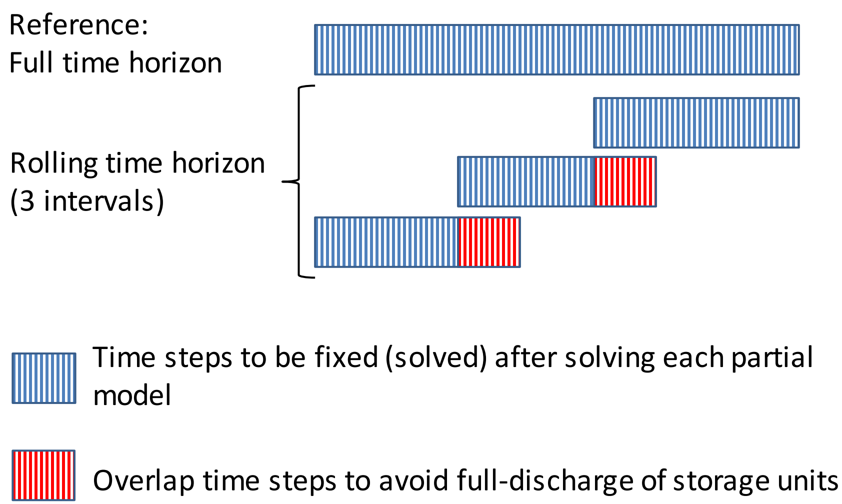



# Rolling horizon dispatch

BEAM-ME

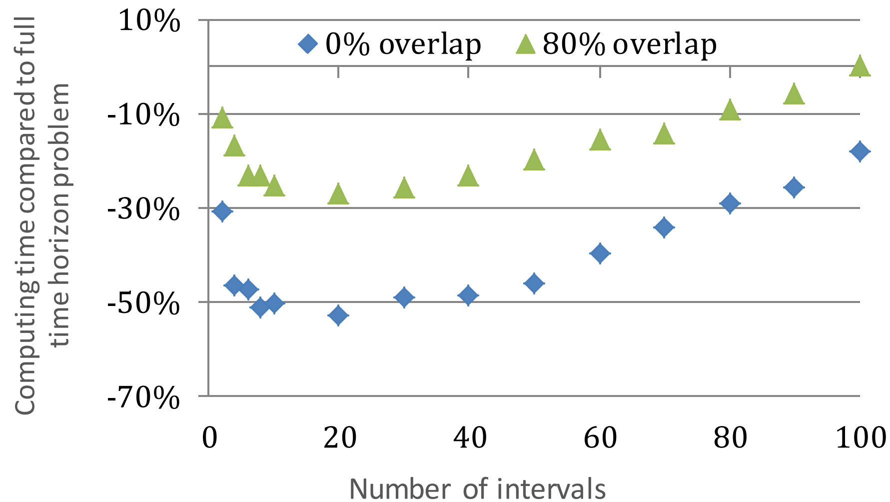
## Idea and implementation

- Splitting of the optimisation time horizon into several *intervals*, using different *overlaps*
- Test influence of *intervals* and *overlaps* w.r.t. computing time and solutions accuracy (e.g. deviation in system costs, $CO_2$ emissions)
- time steps to be fixed after solving an interval




## Results (medium-size ESMs)

- Reduction of computing times up to 53%



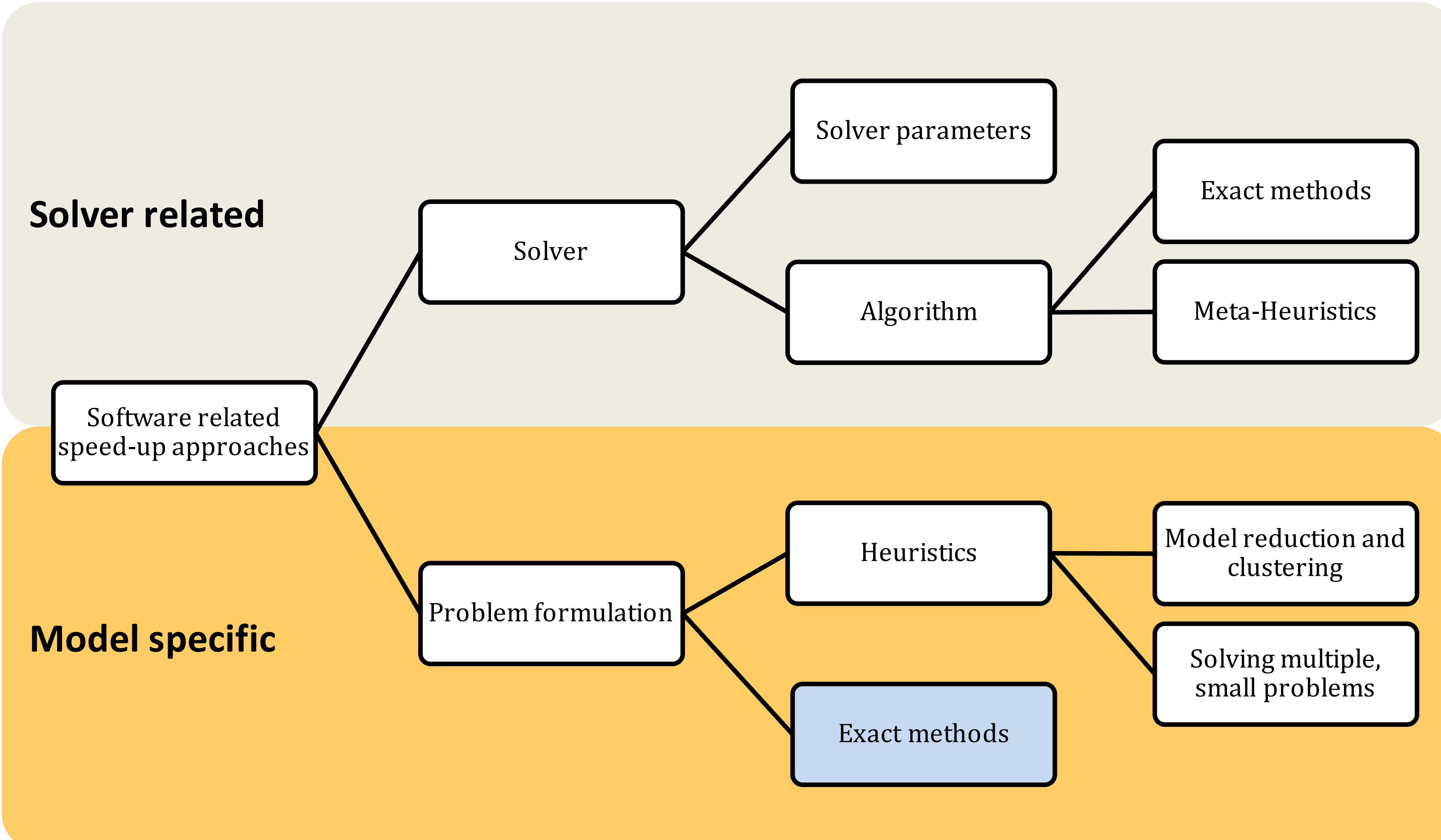

- Deviation of objective value usually <1%

| Overlap-size [%] | 2 | 4 | 6 | 8 | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.13 | 0.98 | 1.02 | 1.03 | 1.48 | 1.69 | 2.30 | 2.76 | 2.90 | 3.19 |
| 20 | 0.09 | 0.06 | 0.24 | 0.28 | 0.32 | 0.59 | 1.02 | 1.17 | 1.46 | 1.54 |
| 40 | 0.10 | 0.05 | 0.07 | 0.10 | 0.12 | 0.28 | 0.47 | 0.64 | 0.78 | 0.81 |
| 60 | 0.03 | 0.04 | 0.06 | 0.08 | 0.10 | 0.21 | 0.34 | 0.52 | 0.54 | 0.58 |
| 80 | 0.02 | 0.04 | 0.05 | 0.07 | 0.09 | 0.19 | 0.30 | 0.38 | 0.56 | 0.61 |
| 100 | 0.02 | 0.03 | 0.05 | 0.06 | 0.07 | 0.18 | 0.28 | 0.30 | 0.48 | 0.54 |

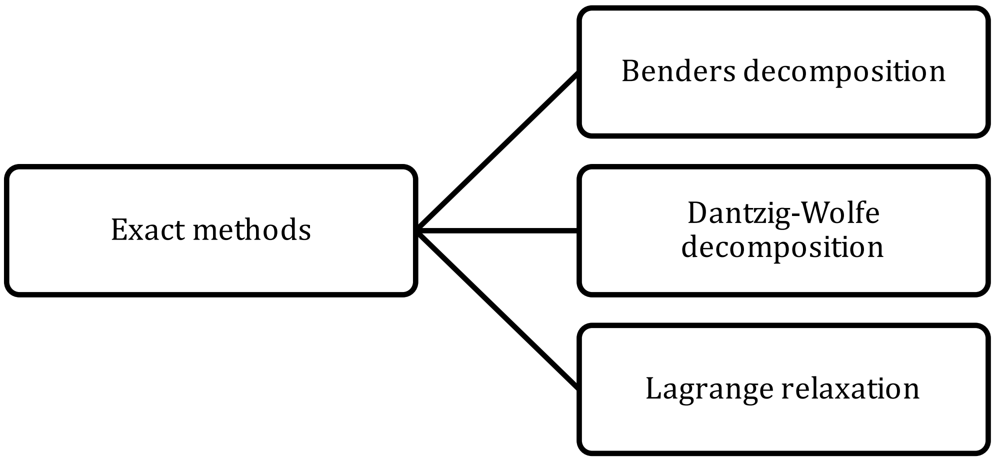
Number of intervals

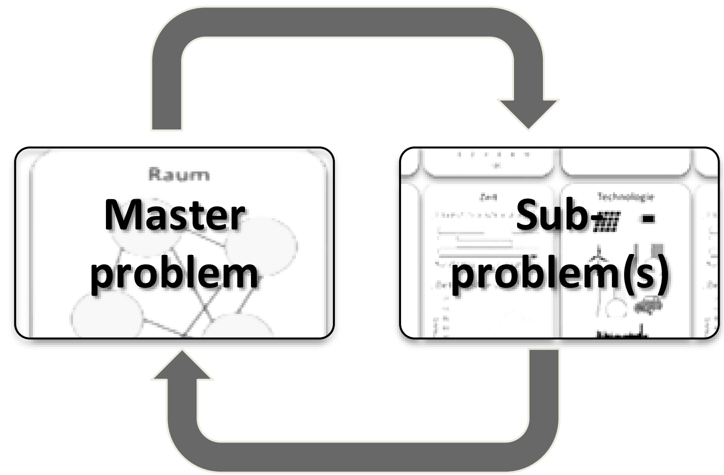

References:
Schreck, S: "Implementation and Analysis of a Rolling Horizon Approach for the Energy System Model REMix", University Stuttgart, 2016

# Categorization of speed-up approaches



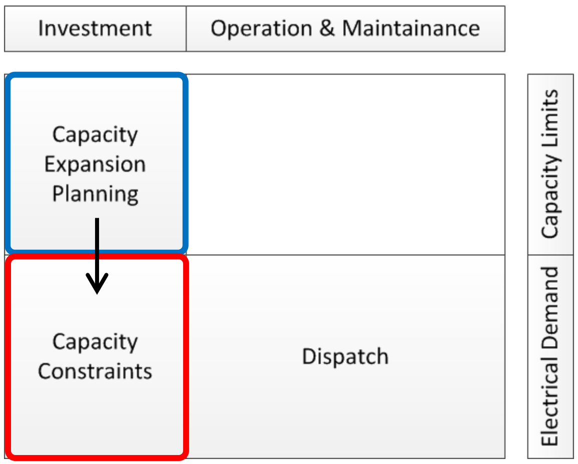
# Exact methods



# Benders decomposition

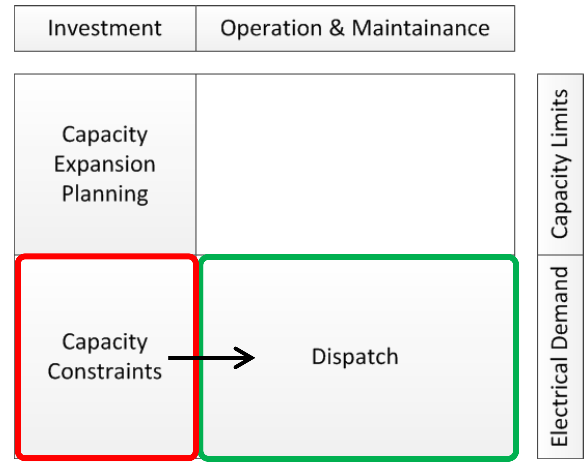
**Optimization of power plant capacities**
based on expected future costs




$$\min c \cdot x \quad A \cdot x \leq b$$ $+$ $\theta$

Future costs of subproblems

**Optimization of power plant dispatch**
based on given power plant capacities




$$\min c \cdot x \quad A \cdot x \leq b$$

Actual costs of subproblems

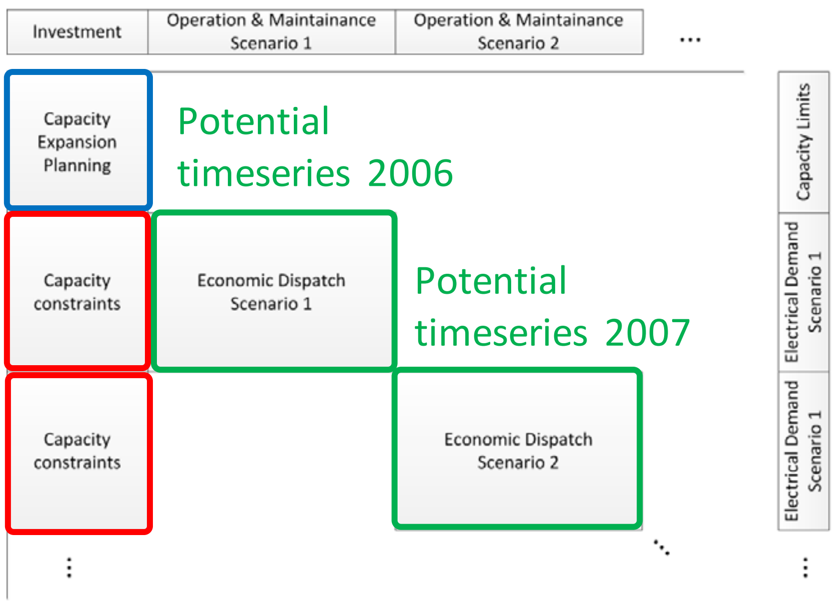
Information about actual costs of the subproblems improves new estimation of future costs (optimality cuts)

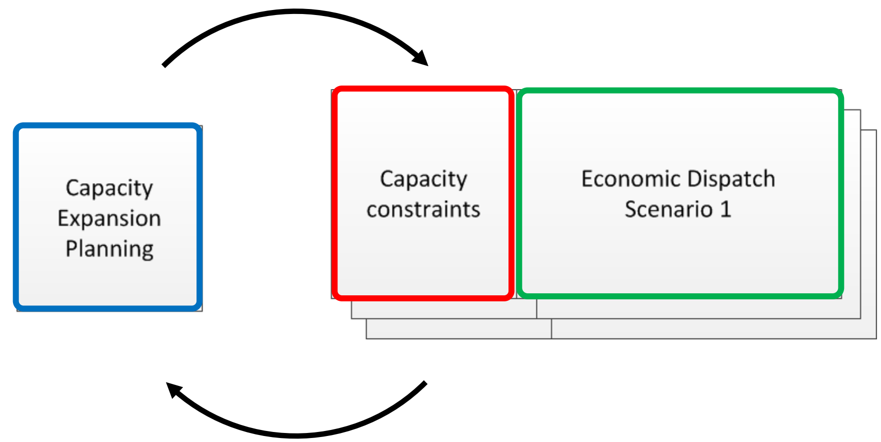
# Stochastic optimization and Benders

BEAM-ME

Stochastic optimization leads to large LP structures (**deterministic equivalent**)

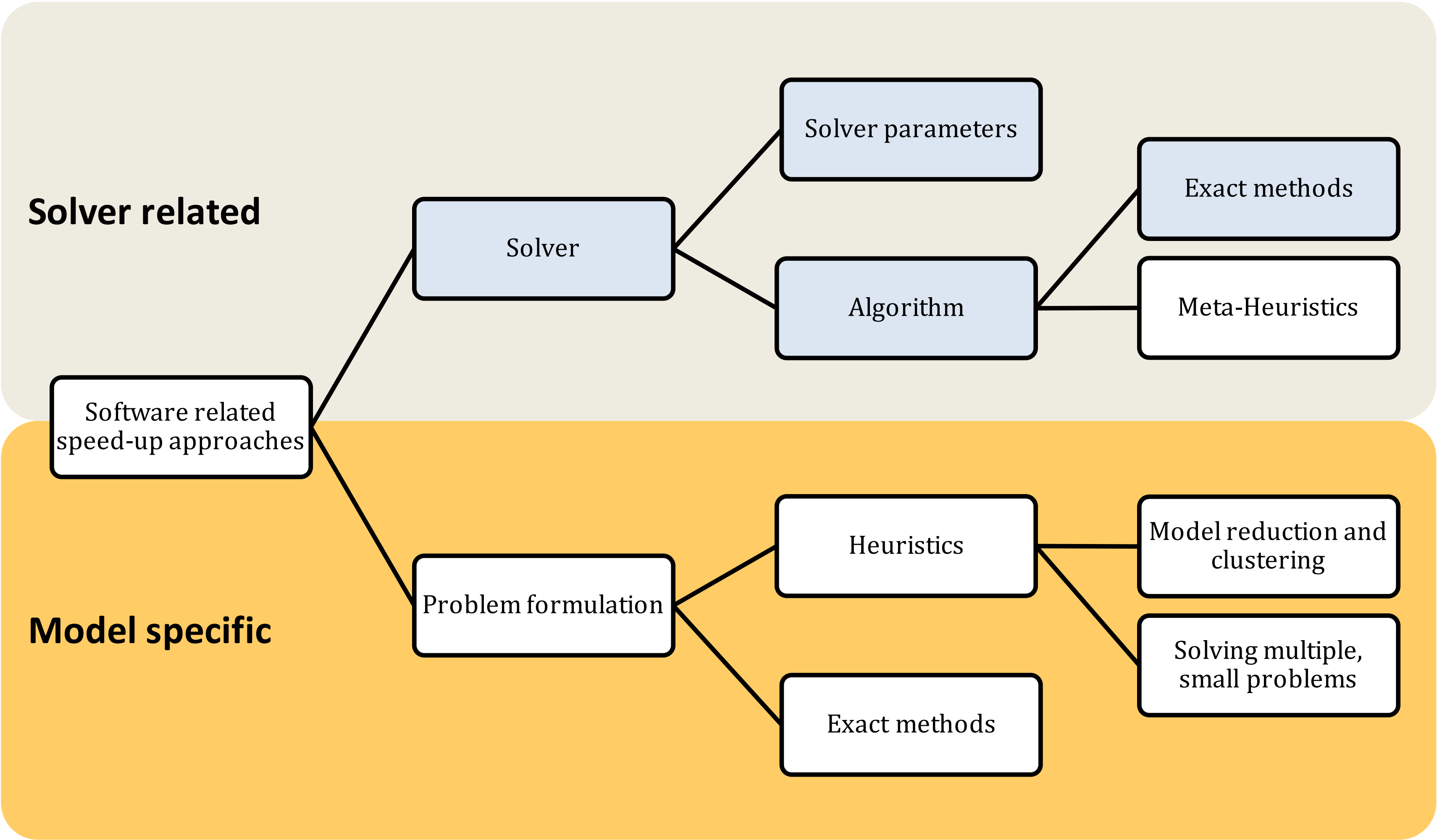
LP structure of stochastic optimization can be **decomposed**



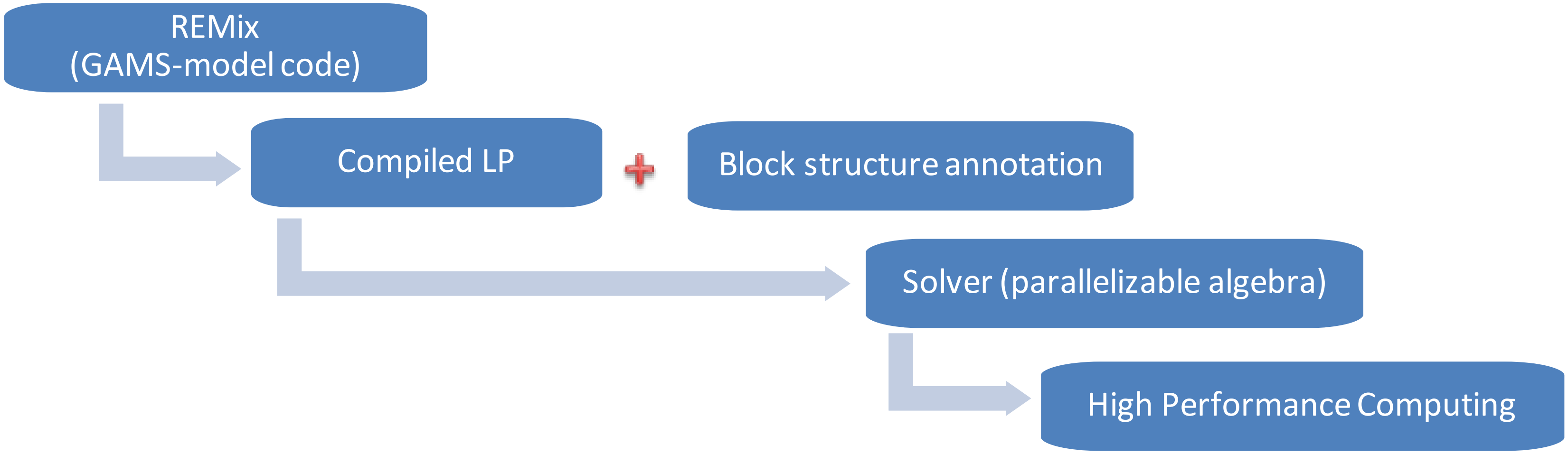

- Subproblems can be solved in parallel
- RAM limitations can be avoided (individual generation of subproblems)
- Convergence of masterproblem can be improved methodologically (trust-regions, asynchronous masterproblem, GUSS for GAMS-formulated models)

# Solver-related model speed-up



# Algorithms and solvers – Starting point

- Energy system models mostly use CPLEX or GUROBI
- For our use cases, interior point method is preferable compared to Simplex
- Cross-Over increases computing time dramatically, but is not always needed
- There are potentially effective implementations of interior point methods, which are suitable for parallelization, exploiting a certain block structure of the problem
- Aim: application of a parallelizable solver that is callable in GAMS
- Using the knowledge about the problem‘s structure for parallelization



# Enhancement and application of PIPS-IPM

- Extension of an existing solver instead of new development
- Enhancement of PIPS-IPM
  - Extension to handle LPs with both linking variables and constraints (ZIB/TU Berlin)
  - Development of a link between GAMS and PIPS-IPM (GAMS)
  - Consideration of requirements of high performance computers (ZIB/GAMS/HLRS/JRC)
- Annotation of REMix model to communicate block structure
  - Application of the *stage* functionality to assign variables and constraints to blocks (DLR/GAMS)

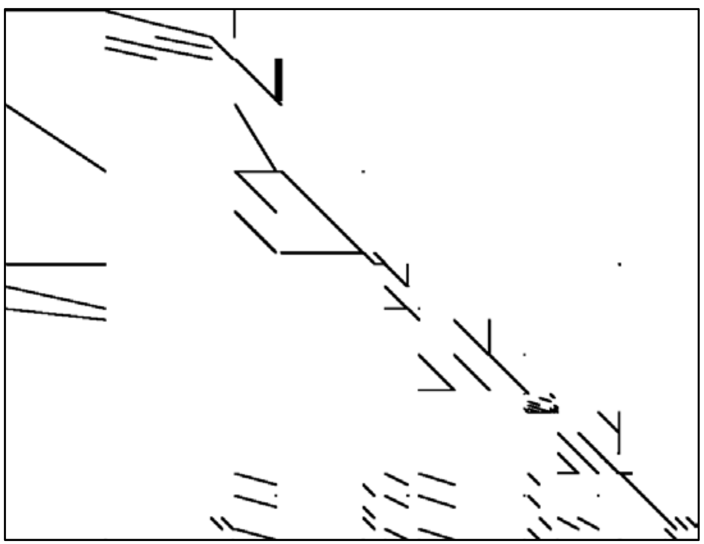
# Block structure required by PIPS-IPM

**Extension** of the general formulation of a linear program

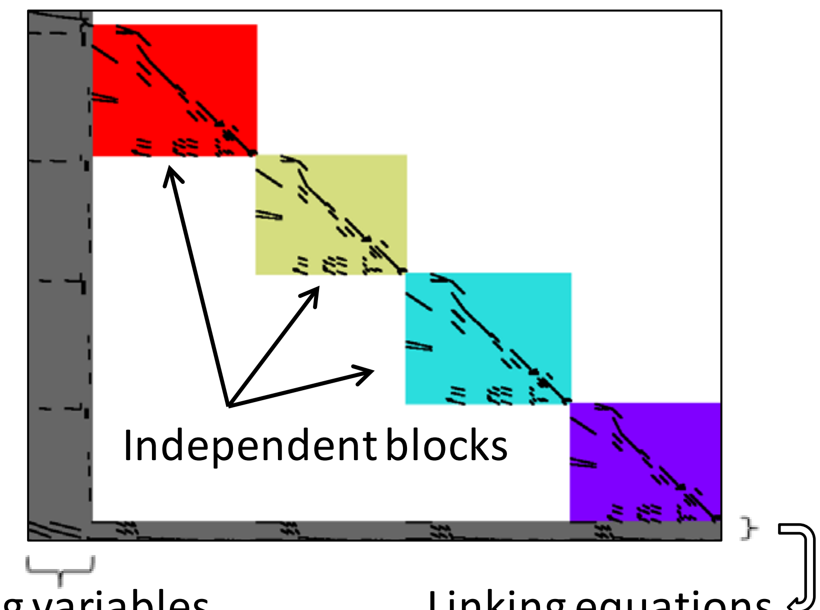
$$\begin{aligned} \min \quad & c^T x \\ \text{s.t.} \quad & Ax = b \end{aligned} \quad \longrightarrow$$

$$\begin{array}{lllllll} \min & c^T x & & & & & \\ \text{s.t.} & T_0 x_0 & & & & = h_0 & (eq_0) \\ & T_1 x_0 & + W_1 x_1 & & & = h_1 & (eq_1) \\ & T_2 x_0 & + & W_2 x_2 & & = h_2 & (eq_2) \\ & \vdots & & & \ddots & \vdots & \\ & T_N x_0 & + & & W_N x_N & = h_N & (eq_N) \\ & F_0 x_0 & + F_1 x_1 & + F_2 x_2 \;\cdots & F_N x_N & = h_{N+1}, & (eq_{N+1}) \end{array}$$

Matrix of **non-zero entries** of REMix LP



Permuted matrix revealing **block structure**



# Transferability of speed-up strategies

- Project includes funding for 6 external partners
  - Selection made on a list of model criteria
  - Model modifications have to be implemented with our support
  - Evaluation of the transferability of speed-up strategies

- Selected institutes in first tender
  - Institute of Energy Economics at the University of Cologne
  - Danish Technical University, Management Engineering

# Summary and Conclusions

- Detailed evaluation of the impact of model aggregation has high value
  → systematic benchmark of speed-capability and error estimation
- Text-book decomposition approaches not necessarily helpful
  → decomposition requires very profound knowledge of the model
  → new development required
- Application of high performance computing requires substantial preparation
  → identification of block structures, linking variables, linking constraints…
  → still work in progress within BEAM-ME
- Strategies promising for REMix will be tested in other models as well
- Results to be summarized in a best-practice guide for energy system models

# Outlook

- Special session on BEAM-ME at the OR 2017 conference in Berlin:
  **“Implementation of acceleration strategies from mathematics and computational sciences for optimizing energy system models”**
- Focus on model annotation, PIPS-IPM extension and GAMS/PIPS-link
- Contributions:
  - M. Wetzel et al. „Getting linear optimising energy system models ready for High Performance Computing”
  - D. Rehfeldt et al. „Optimizing large-scale linear energy problems with block diagonal structure by using parallel interior-point methods”
  - F. Fiand et al. „High Performance Computing with GAMS “
  - T. Breuer et al. „High Performance Computing for Energy System Modelling”
- See you in Berlin (6-8 September 2017)!

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