Supported by:
Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Next generation energy modelling –

Benefits of applying parallel optimization and high performance computing

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Frieder Borggrefe

System Analysis and Technology Assessment
DLR - German Aerospace Center
Stuttgart

Modelling Smart Grids 2017
26.10.2017, Prague

A PROJECT BY

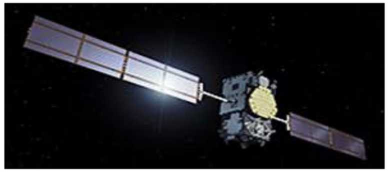
GAMS
TU berlin
HLRS
JÜLICH FORSCHUNGSZENTRUM
DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center
ZIB

Agenda

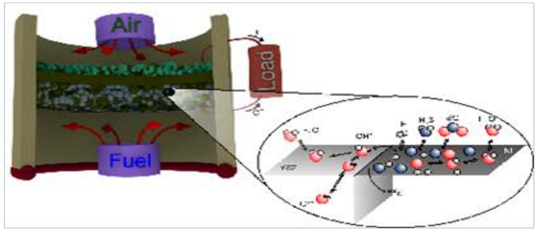
1. Introduction – energy system Modelling and constraints
2. The project BEAM-ME
3. Decomposition
4. Model annotation and PIPS-IPM

It is not all about rocket science in DLR…

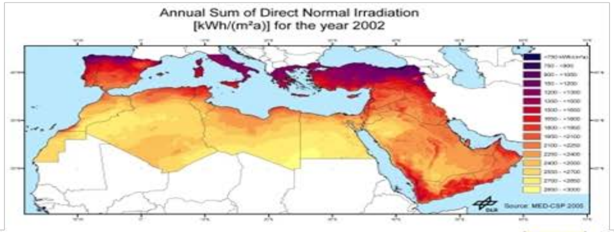
DLR

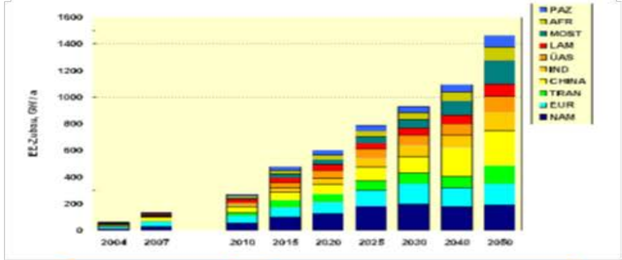


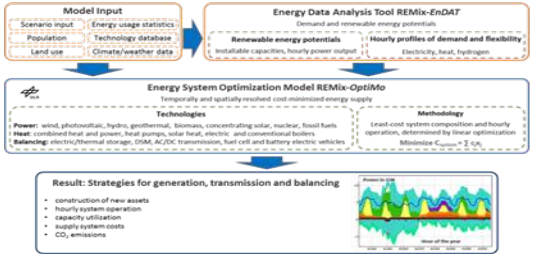
Institute of Engineering Thermodynamics



Systems Analysis and Technology Assessment







Model Input
- Scenario input
- Energy usage statistics
- Population
- Technology database
- Land use
- Climate/weather data

Energy Data Analysis Tool REMix-*EnDAT*

Demand and renewable energy potentials

- **Renewable energy potentials**: Installable capacities, hourly power output
- **Hourly profiles of demand and flexibility**: Electricity, heat, hydrogen

Energy System Optimization Model REMix-*OptiMo*

Temporally and spatially resolved cost-minimized energy supply

Technologies

Power: wind, photovoltaic, hydro, geothermal, biomass, concentrating solar, nuclear, fossil fuels
Heat: combined heat and power, heat pumps, solar heat, electric and conventional boilers
Balancing: electric/thermal storage, DSM, AC/DC transmission, fuel cell and battery electric vehicles

Methodology

Least-cost system composition and hourly operation, determined by linear optimization

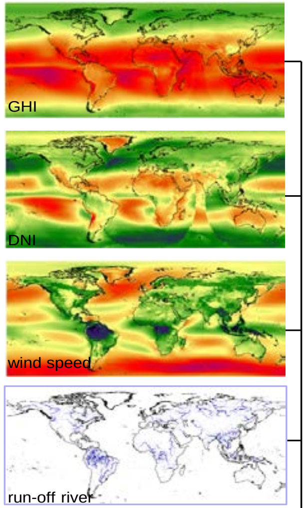
Minimize $C_{system} = \sum c_i x_i$

Result: Strategies for generation, transmission and balancing

- construction of new assets
- hourly system operation
- capacity utilization
- supply system costs
- CO_2 emissions

DLR Energy System Model REMix

Installed capacities and power generation profiles from renewables



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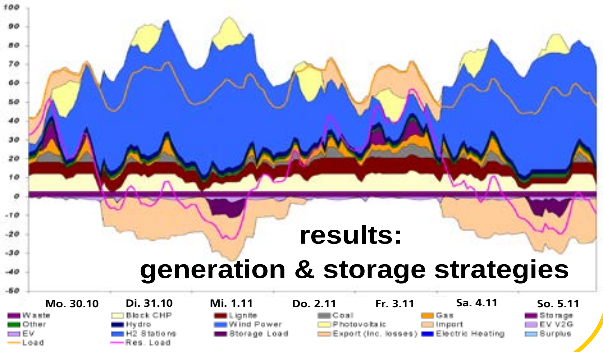
HVDC lines
long-range power exchange and imports

Transmission grid
based on current European AC grid

Scenario analysis with model REMix

cost minimised supply in temporal & spatial resolution

model



results: generation & storage strategies

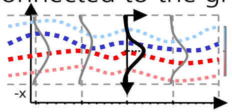
Electricity demand

Heat demand

Flexible operation of CHP with:
- heat storages
- peak boiler & electric heaters

Electric vehicles (EV)

BEV/hybrids: charging strategies, hourly battery capacities of the fleet connected to the grid



FCEV: flexible on-site H_2 generation

Conventional generation
nuclear, coal, gas power plants

Storages
pumped hydro
compressed air
hydrogen

Demand side management
industry & households, increases system efficiency

DLR Energy System Model REMix

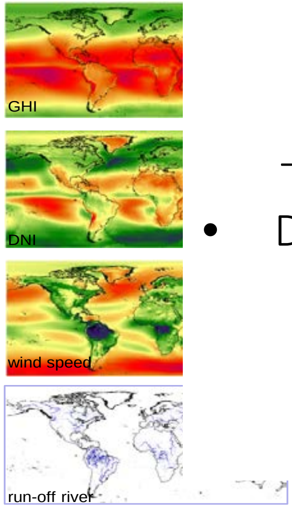
Energy system models:

- Simulate
  - policy and technology choices
  - influence on future energy demand and supply, and investments

-> are mostly used in an exploratory manner

- Depend on external assumptions/boundary conditions:
  - Development of economic activities,
  - demographic development,
  - or energy prices on world markets.

Installed capacities and power generation profile renew



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HVDC lines
long-range power
exchange and imports

Transmission grid
based on current European
AC grid

Electricity demand

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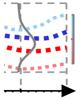


generation
nuclear, coal,
gas power plants

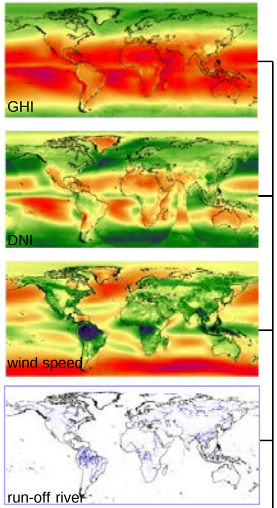
pumped hydro
compressed air
hydrogen

management
industry & households,
increases system efficiency

FCEV: flexible on-site H_2
generation

The Energy System Model REMix

Installed capacities and power generation profiles from renewables



....

HVDC lines
long-range power exchange and imports

Transmission grid
based on current European AC grid

$$\min \; c^T \lambda$$

$$\text{s.t.} \quad A \lambda \geq \tilde{b}$$

Electricity demand

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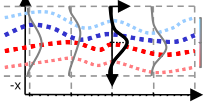

FCEV: flexible on-site H_2 generation

Conventional generation
nuclear, coal, gas power plants

Storages
pumped hydro
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hydrogen

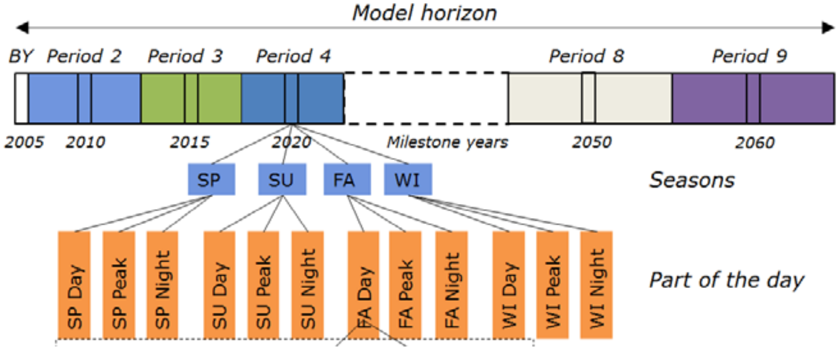
Demand side management
industry & households, increases system efficiency

Requirements for Energy System Models Increase

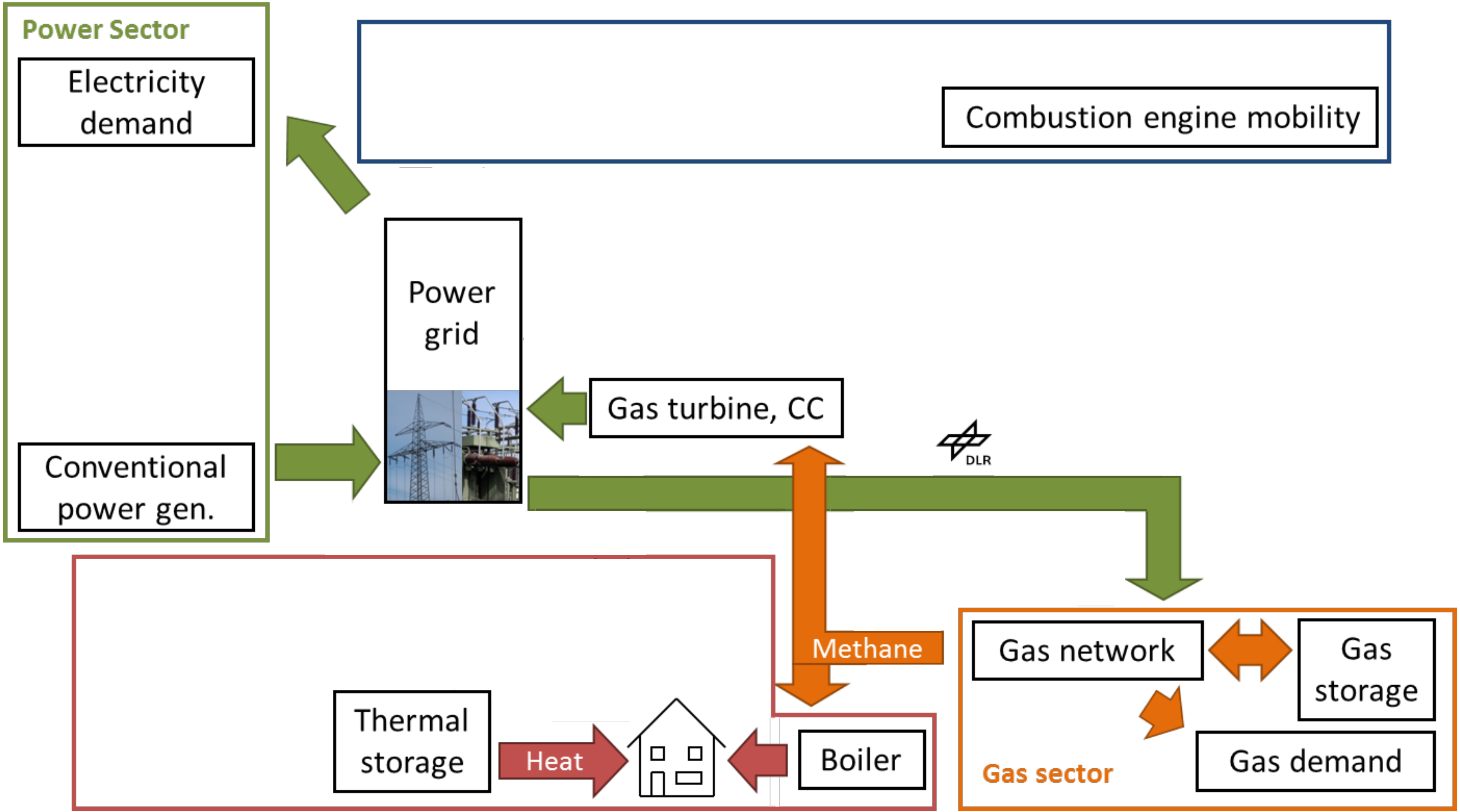
Modelling comes at a cost:

- Small number of time steps
- Or small number of regions
- Or small number of technologies

JRC Times model:



Energy Sector Integration



Power Sector

Electricity demand

Conventional power gen.

Power grid

Combustion engine mobility

Gas turbine, CC

Methane

Gas network

Gas storage

Gas demand

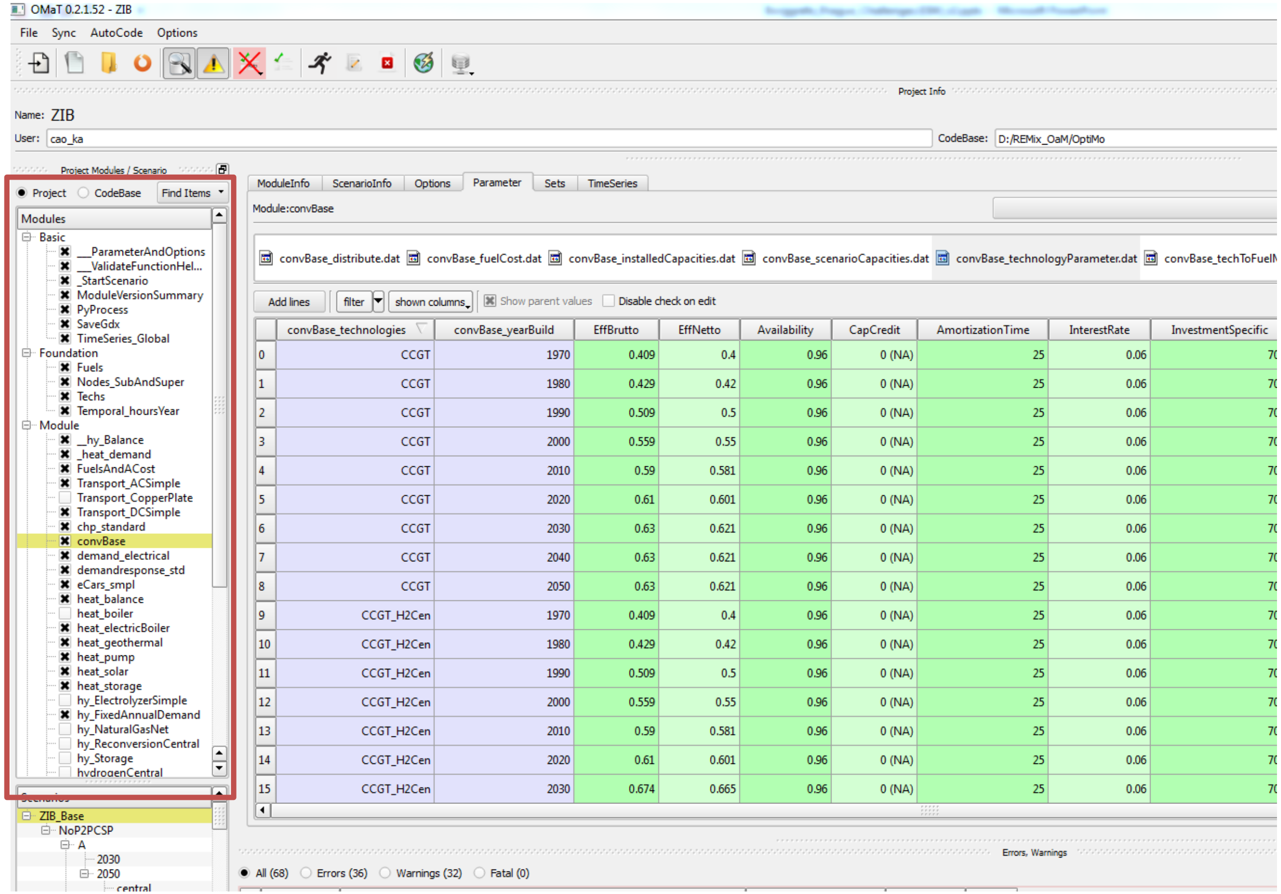
Gas sector

Thermal storage

Heat

Boiler

The Energy System Model REMix



Name: ZIB

User: cao_ka

CodeBase: D:/REMix_OaM/OptiMo

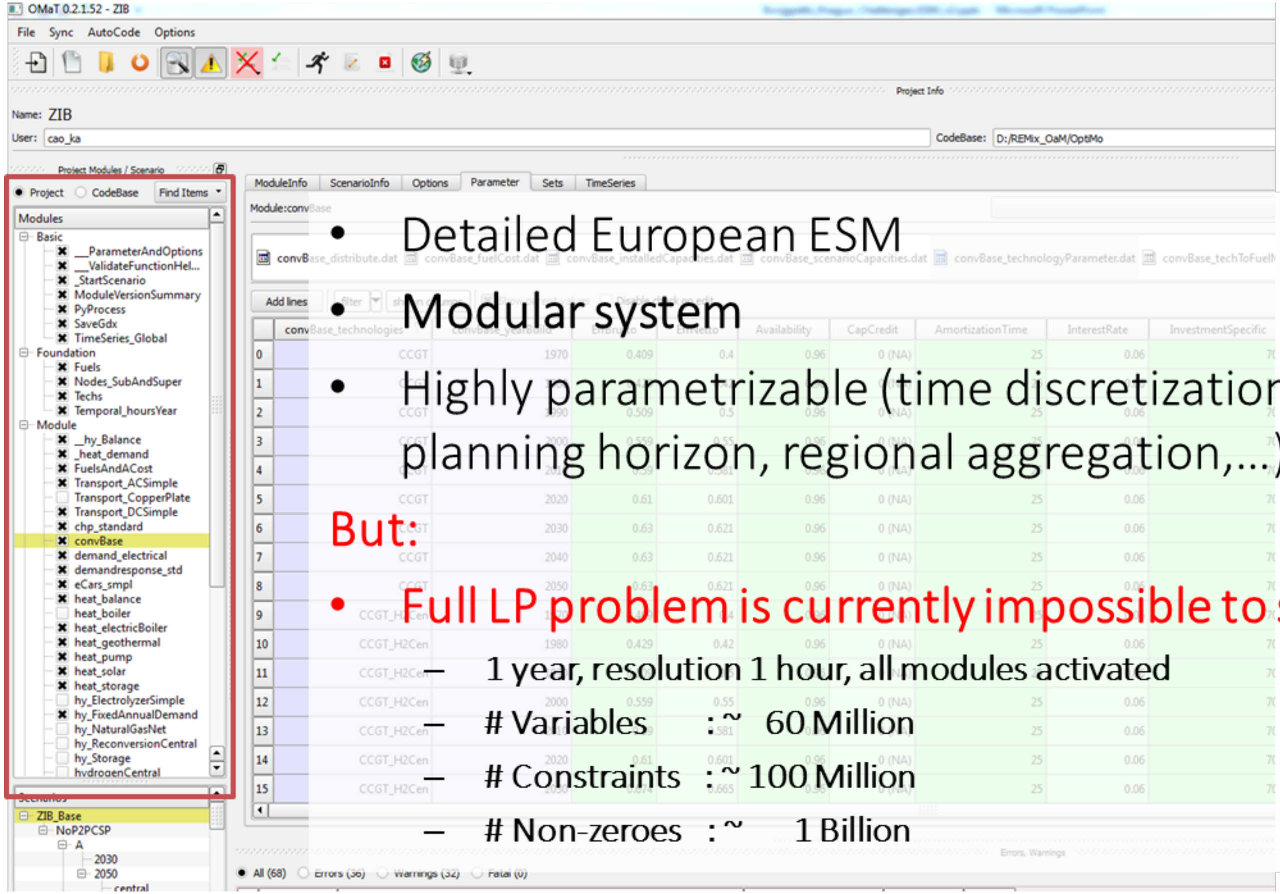
Module:convBase

Modules
- Basic
  - ☒ __ParameterAndOptions
  - ☒ __ValidateFunctionHel...
  - ☒ _StartScenario
  - ☒ ModuleVersionSummary
  - ☒ PyProcess
  - ☒ SaveGdx
  - ☒ TimeSeries_Global
- Foundation
  - ☒ Fuels
  - ☒ Nodes_SubAndSuper
  - ☒ Techs
  - ☒ Temporal_hoursYear
- Module
  - ☒ __hy_Balance
  - ☒ _heat_demand
  - ☒ FuelsAndACost
  - ☒ Transport_ACSimple
  - ☐ Transport_CopperPlate
  - ☒ Transport_DCSimple
  - ☒ chp_standard
  - ☒ convBase
  - ☒ demand_electrical
  - ☒ demandresponse_std
  - ☒ eCars_smpl
  - ☒ heat_balance
  - ☐ heat_boiler
  - ☒ heat_electricBoiler
  - ☒ heat_geothermal
  - ☒ heat_pump
  - ☒ heat_solar
  - ☒ heat_storage
  - ☐ hy_ElectrolyzerSimple
  - ☒ hy_FixedAnnualDemand
  - ☐ hy_NaturalGasNet
  - ☐ hy_ReconversionCentral
  - ☐ hy_Storage
  - ☐ hydrogenCentral

Scenarios
- ZIB_Base
  - NoP2PCSP
    - A
      - 2030
      - 2050
        - central

	convBase_technologies	convBase_yearBuild	EffBrutto	EffNetto	Availability	CapCredit	AmortizationTime	InterestRate	InvestmentSpecific
0	CCGT	1970	0.409	0.4	0.96	0 (NA)	25	0.06	70
1	CCGT	1980	0.429	0.42	0.96	0 (NA)	25	0.06	70
2	CCGT	1990	0.509	0.5	0.96	0 (NA)	25	0.06	70
3	CCGT	2000	0.559	0.55	0.96	0 (NA)	25	0.06	70
4	CCGT	2010	0.59	0.581	0.96	0 (NA)	25	0.06	70
5	CCGT	2020	0.61	0.601	0.96	0 (NA)	25	0.06	70
6	CCGT	2030	0.63	0.621	0.96	0 (NA)	25	0.06	70
7	CCGT	2040	0.63	0.621	0.96	0 (NA)	25	0.06	70
8	CCGT	2050	0.63	0.621	0.96	0 (NA)	25	0.06	70
9	CCGT_H2Cen	1970	0.409	0.4	0.96	0 (NA)	25	0.06	70
10	CCGT_H2Cen	1980	0.429	0.42	0.96	0 (NA)	25	0.06	70
11	CCGT_H2Cen	1990	0.509	0.5	0.96	0 (NA)	25	0.06	70
12	CCGT_H2Cen	2000	0.559	0.55	0.96	0 (NA)	25	0.06	70
13	CCGT_H2Cen	2010	0.59	0.581	0.96	0 (NA)	25	0.06	70
14	CCGT_H2Cen	2020	0.61	0.601	0.96	0 (NA)	25	0.06	70
15	CCGT_H2Cen	2030	0.674	0.665	0.96	0 (NA)	25	0.06	70

The Energy System Model REMix



Name: ZIB
User: cao_ka
CodeBase: D:/REMix_OaM/OptiMo

- Detailed European ESM
- Modular system
- Highly parametrizable (time discretization, planning horizon, regional aggregation,...)

But:

- Full LP problem is currently impossible to solve:
  - 1 year, resolution 1 hour, all modules activated
  - # Variables : ~ 60 Million
  - # Constraints : ~ 100 Million
  - # Non-zeroes : ~ 1 Billion

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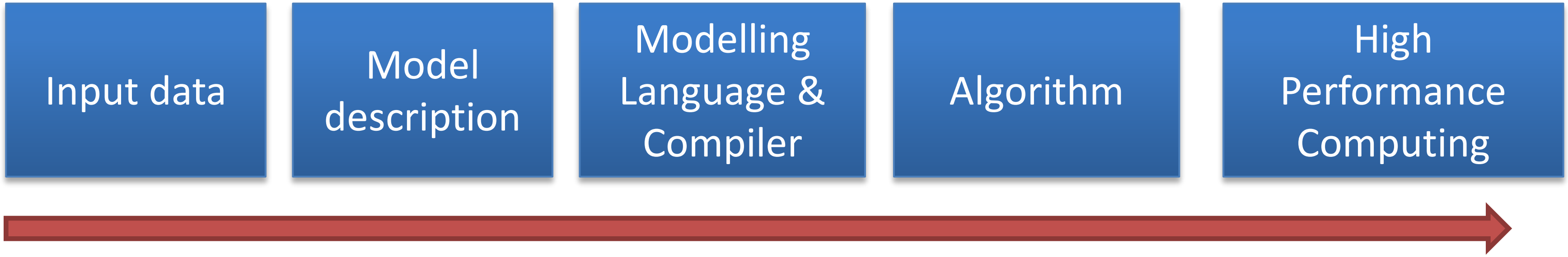
Idea and scope of BEAM-ME

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

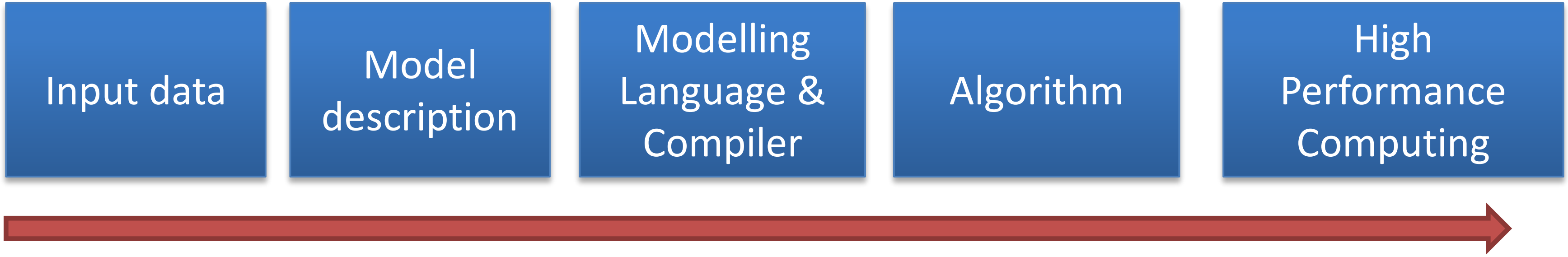
BEAM-ME: Optimizing performance of ESM



- Input data
- Model description
- Modelling Language & Compiler
- Algorithm
- High Performance Computing

BEAM-ME: Optimizing performance of ESM

BEAM-ME



Input data

Model description

Modelling Language & Compiler

Algorithm

High Performance Computing

Energy System Modeling

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Modelling Language

GAMS

Solver Development

ZIB

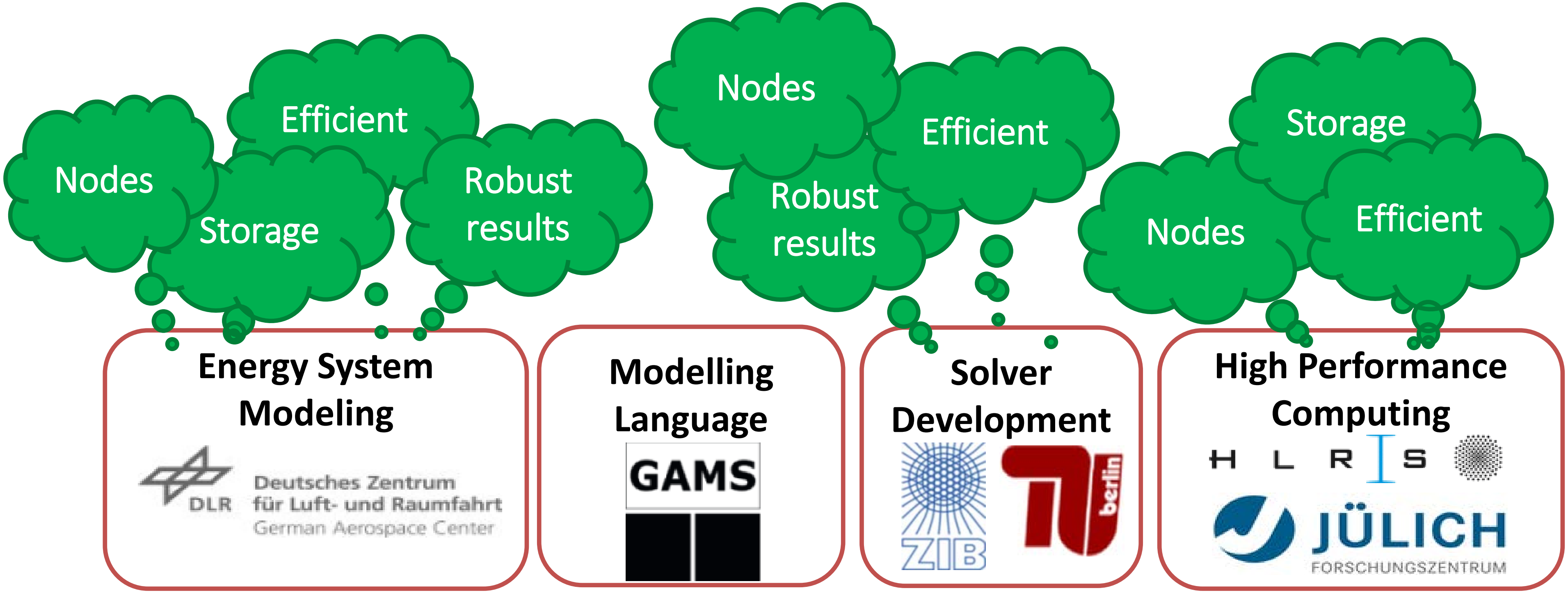
TU berlin

High Performance Computing

HLRS

JÜLICH
FORSCHUNGSZENTRUM

Nodes! Nodes? Nodes !? - Challenge: Common language



Nodes
Efficient
Storage
Robust results

Energy System Modeling

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Nodes
Robust results
Efficient

Modelling Language

GAMS

Solver Development

ZIB

Storage
Nodes
Efficient

High Performance Computing

HLRS

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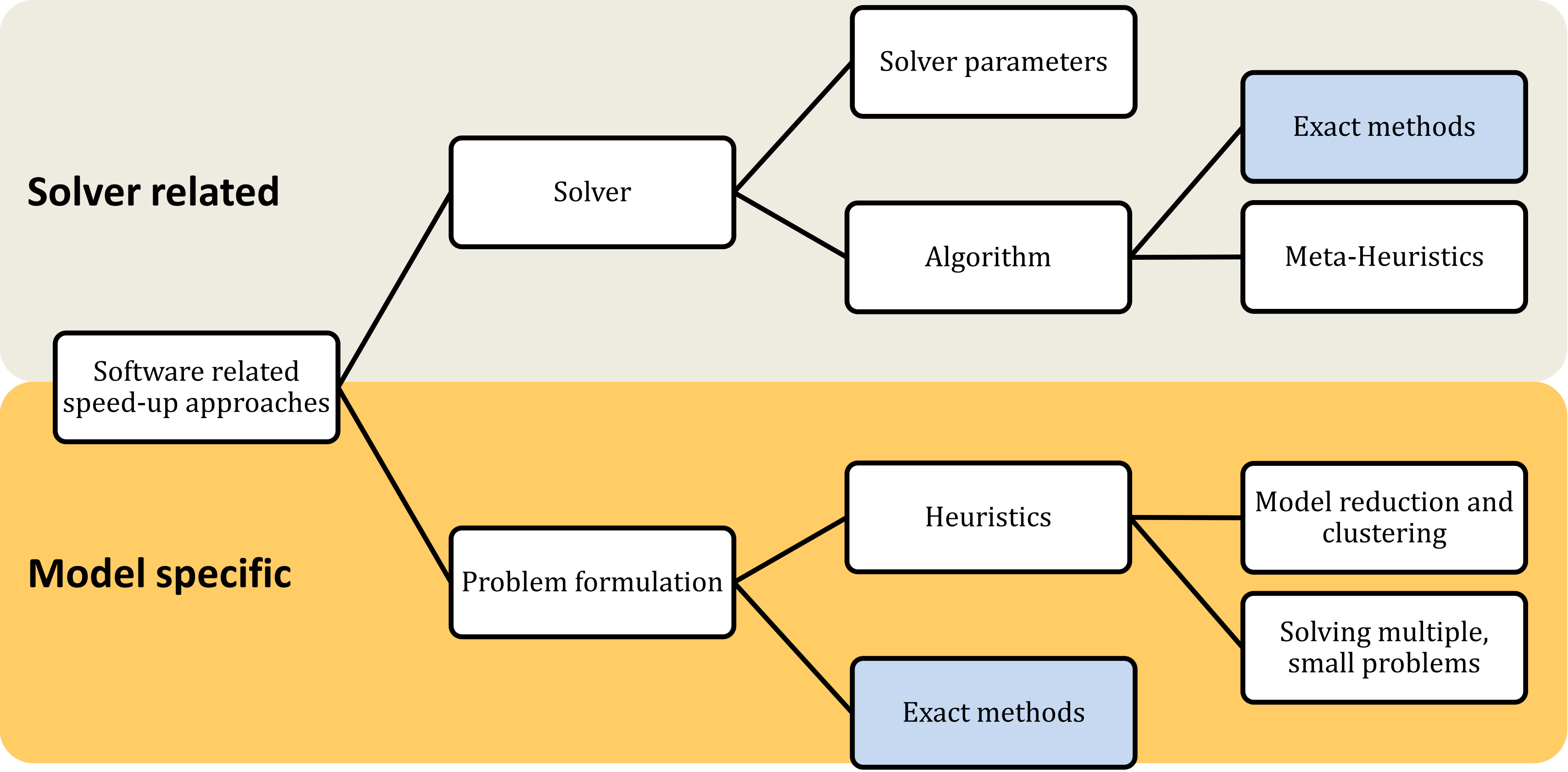
Categorization of speed-up approaches



Solver related

Model specific

Software related speed-up approaches

Solver

Solver parameters

Algorithm

Exact methods

Meta-Heuristics

Problem formulation

Heuristics

Exact methods

Model reduction and clustering

Solving multiple, small problems

Benders decomposition in capacity expansion and economic dispatch

Benders decomposition for two-stage stochastic optimization

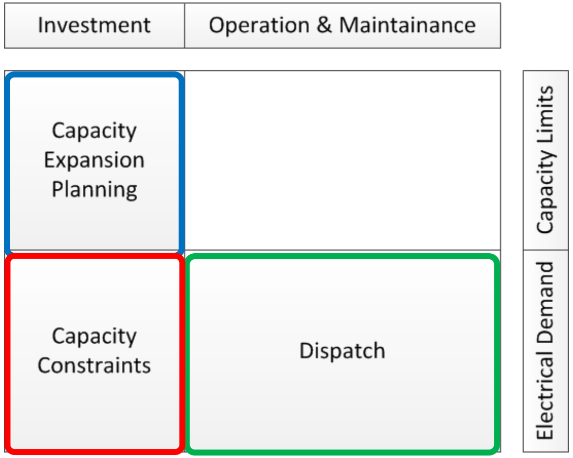
Investment -> Master problem:

- Decide now which capacities should be expanded

Dispatch -> Sub problem:

- Decide later on economic dispatch to satisfy electrical demand with capacities given by master problem

Mathematical formulation in LP table



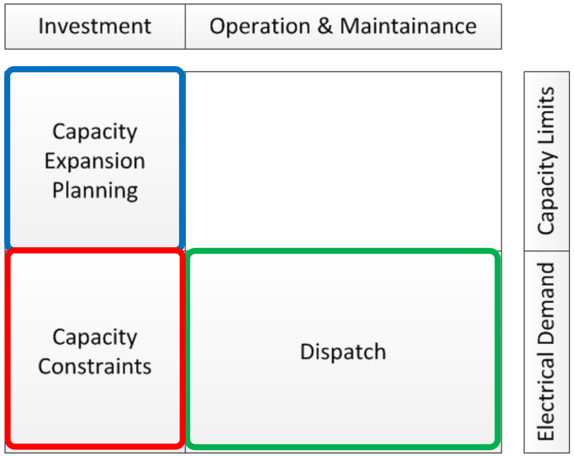
1st Stage:
Capacity expansion – Installed capacities

2nd Stage:
Dispatch – Generation variables

Linking variables:
Installed capacities, connecting the capacity expansion problem and the dispatch problem

Deterministic vs. Benders Decomposition

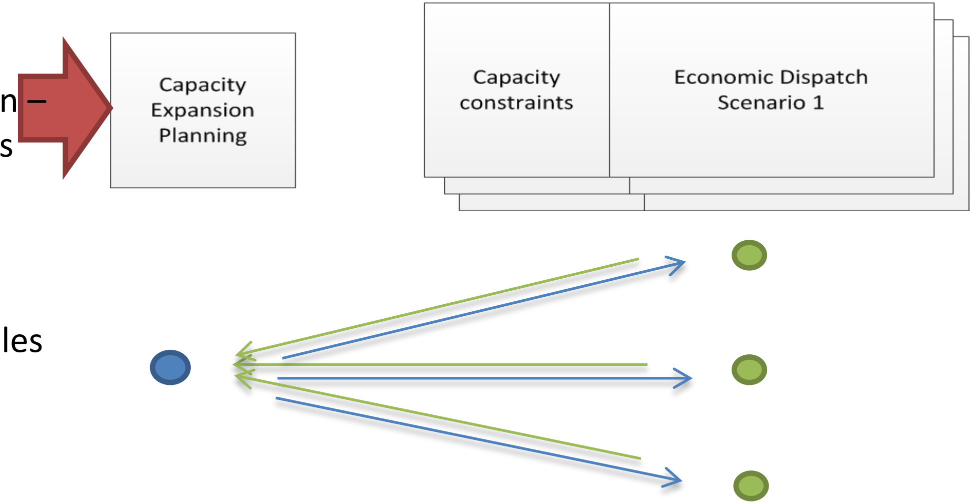
Deterministic Model



1st Stage:
Capacity expansion –
Installed capacities

2nd Stage:
Dispatch –
Generation variables

Benders Decomposition

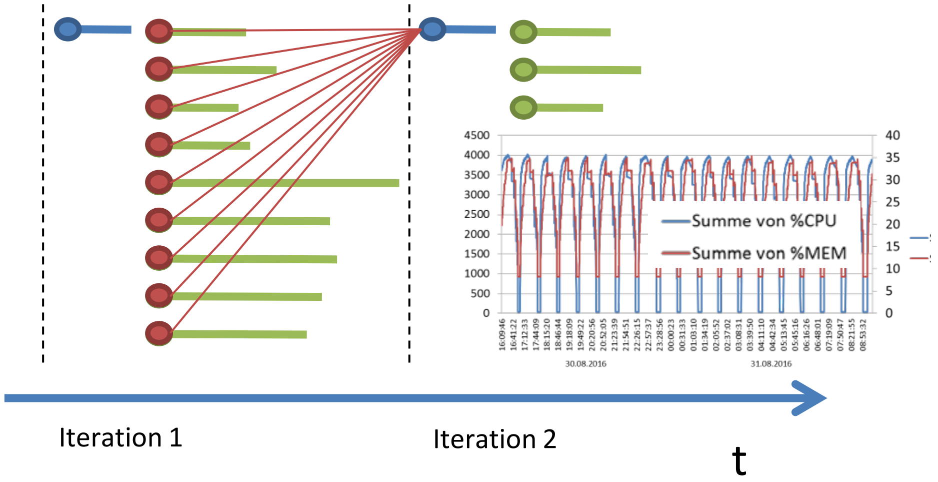


- Size of LP increases with number of scenarios, solved by SIMPLEX / Barrier
- **Out of memory** for typical REMix problems with scenario dimension

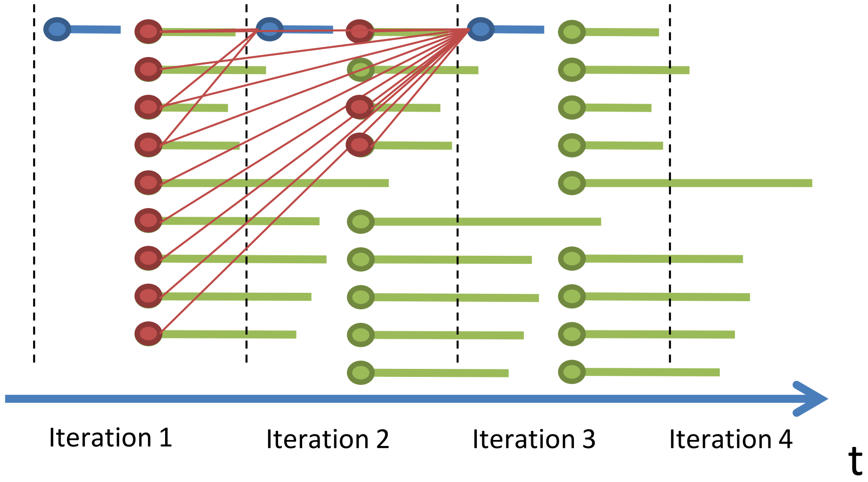
- Subproblems can be **solved in parallel**
- Memory demand **scales** with number of parallel solve processes

Challenges 3: Efficient use of ressources

Synchronous Model



Asynchronous Model



Input data

Model description

Modelling, Language & Compiler

Mathematical Optimization

High Performance Computing

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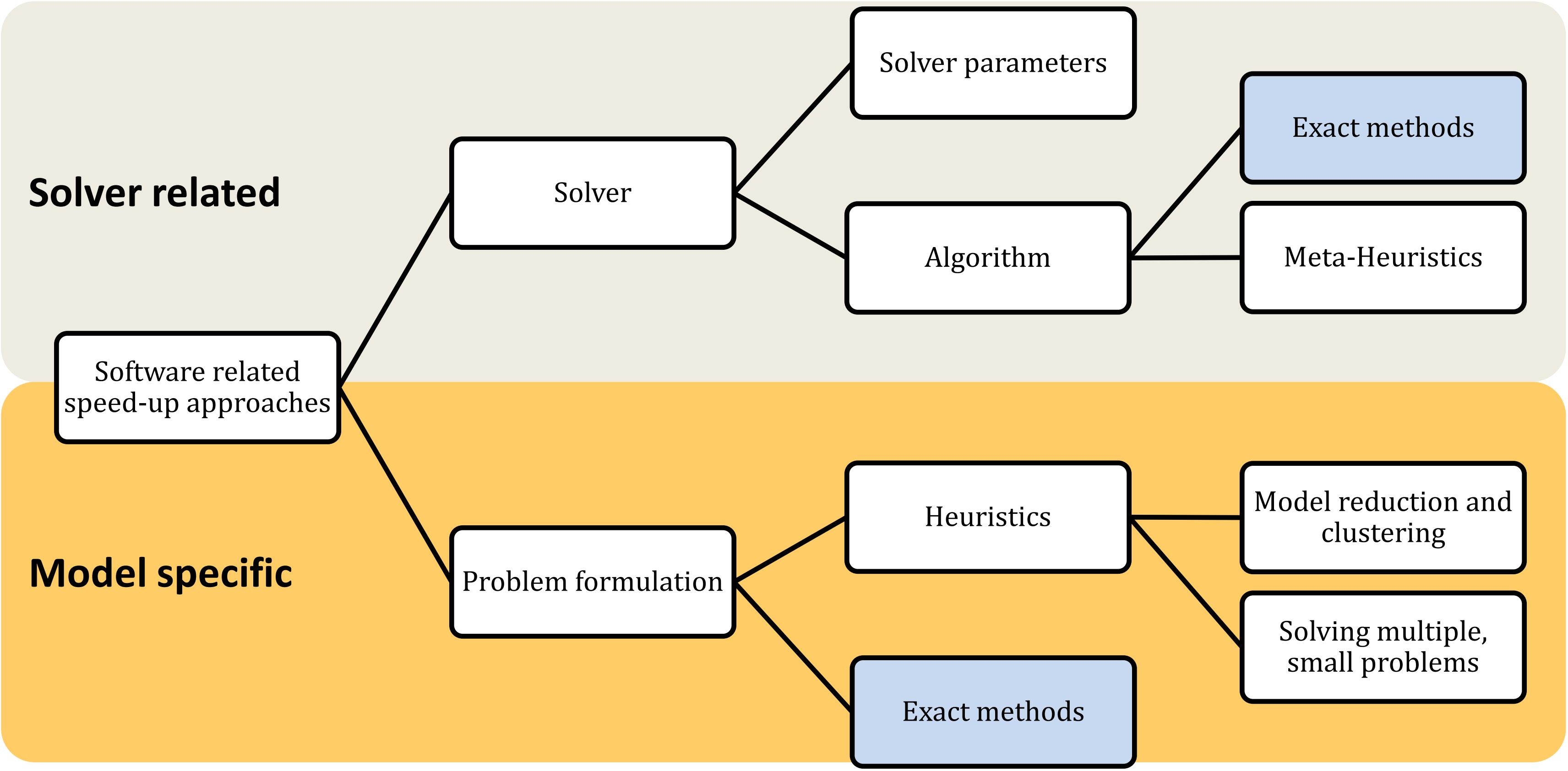


Challenges: Scalable Implementation

Input data

Model description

Modelling Language & Compiler

Mathematical Optimization

High Performance Computing

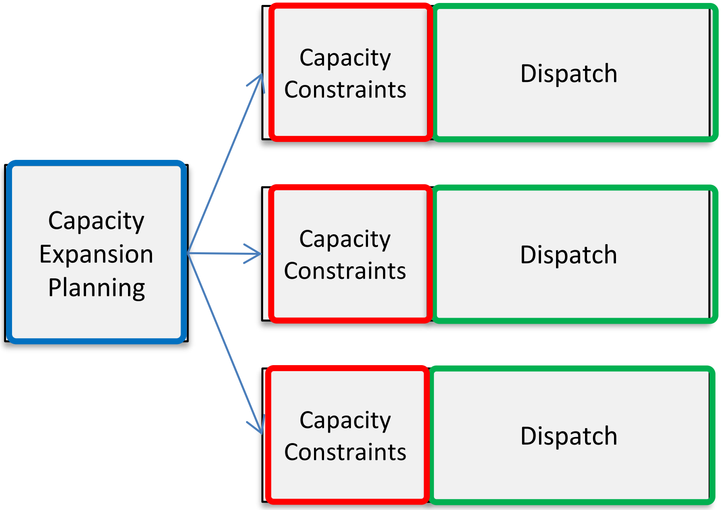
IBM Blue Gene/Q @ JSC:
28,672 nodes / 458,752 cores

- Efficient HPC implementation
- Benchmarking and profiling
- Distributed storage for large ESMs
- Apply new concepts for assigning tasks to cores

CRAY XC40 @ HLRS:
3,944 nodes / 94,656 cores

Application of stochastic PIPS solver

Decomposition Approach


Capacity Expansion Planning

Capacity Constraints

Dispatch

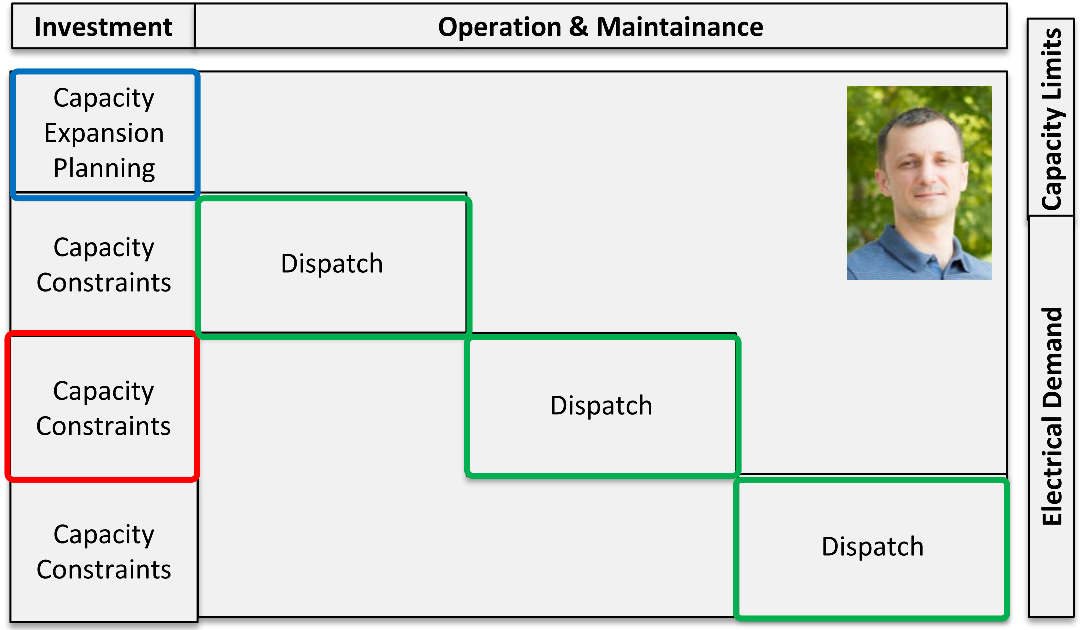
Capacity Constraints

Dispatch

Capacity Constraints

Dispatch

PIPS-Solver (Argonne National Lab)


Investment

Operation & Maintainance

Capacity Expansion Planning

Capacity Constraints

Dispatch

Capacity Constraints

Dispatch

Capacity Constraints

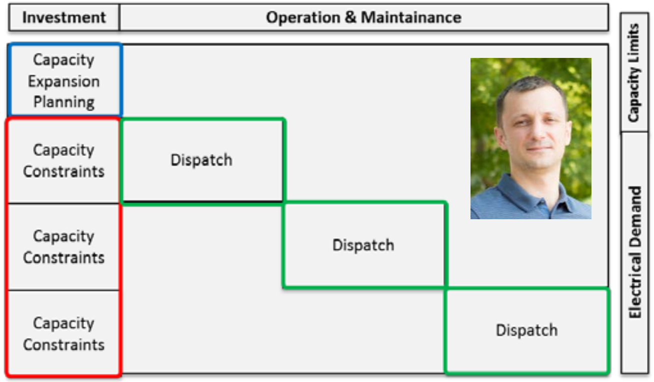
Dispatch

Capacity Limits

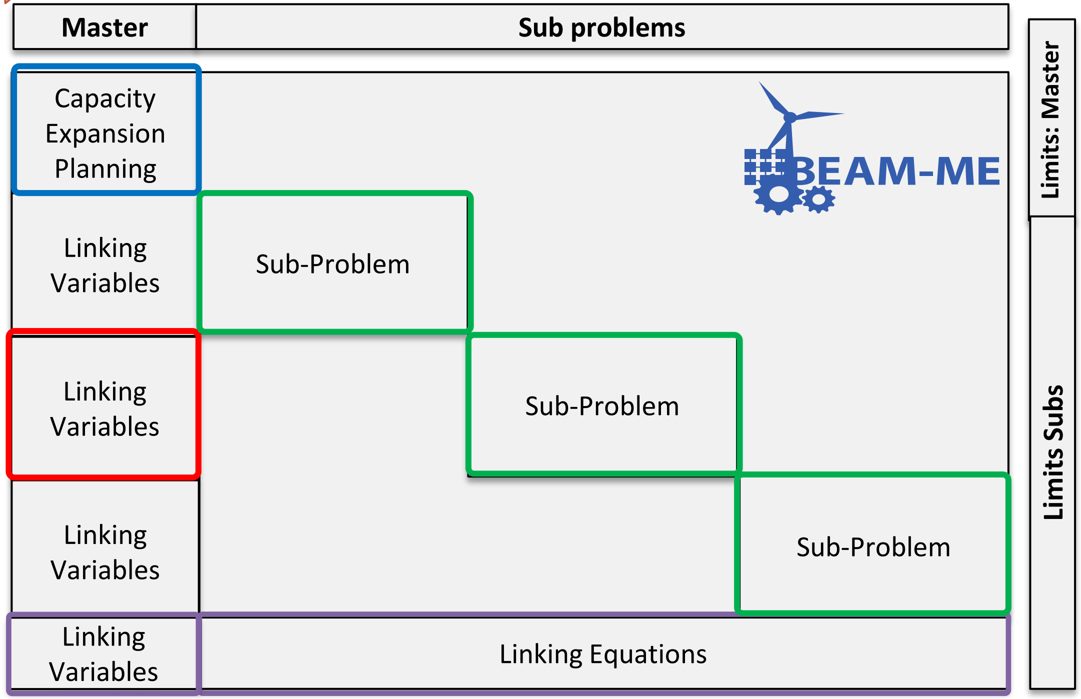
Electrical Demand

Within BEAM-ME adaptation of PIPS-Solver to PIPS IPM

PIPS-Solver

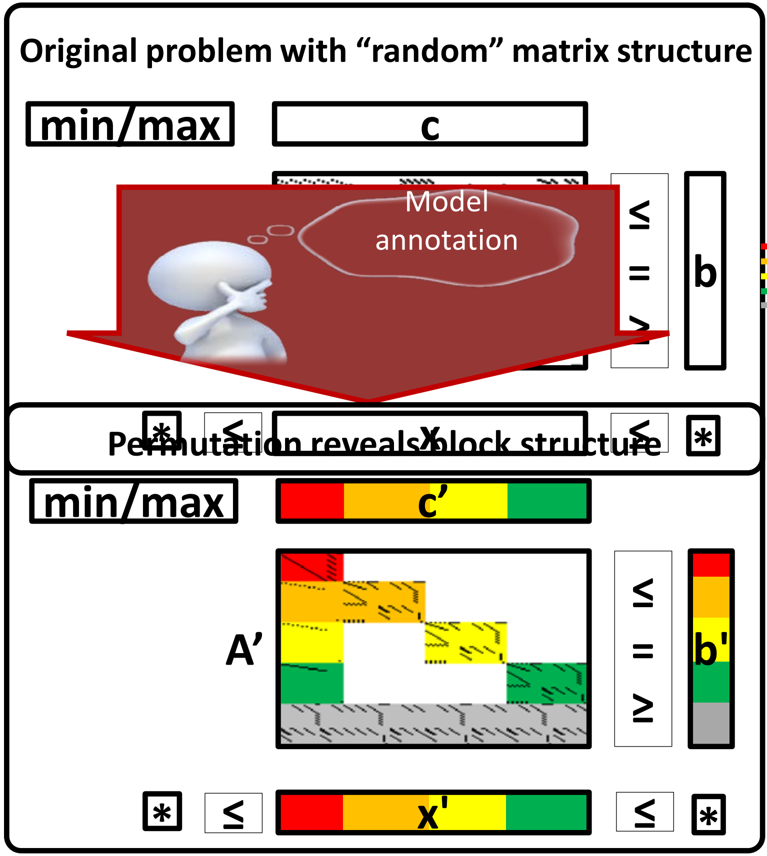


New PIPS-IPM-Solver under development

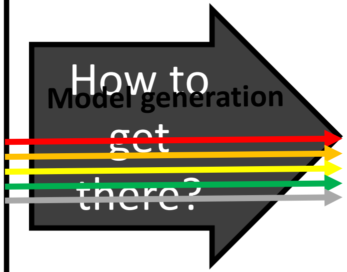


- New developed PIPS-IPM can be used for non stochastic models
- PIPS-IPM will also bring benefits to stochastic Modelling

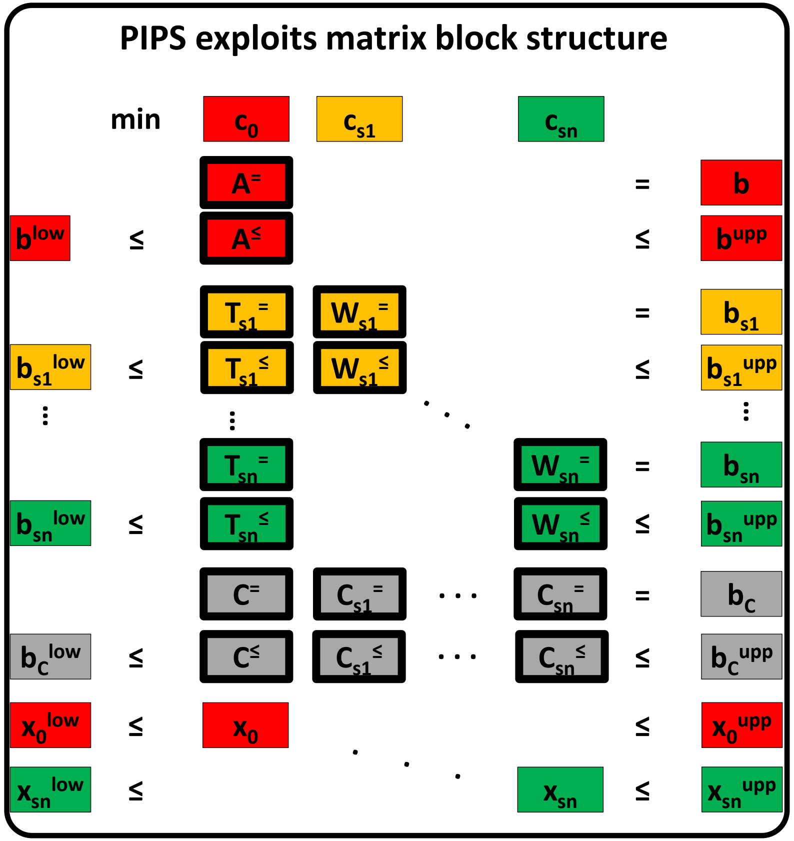
Original problem with “random” matrix structure



Permutation reveals block structure

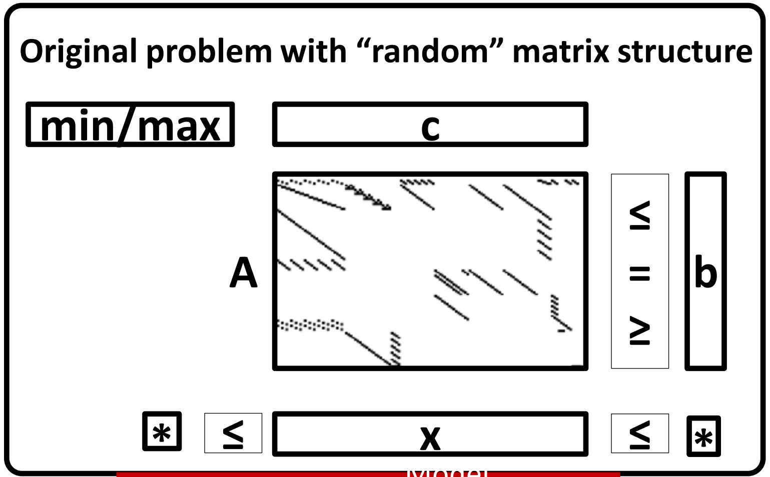


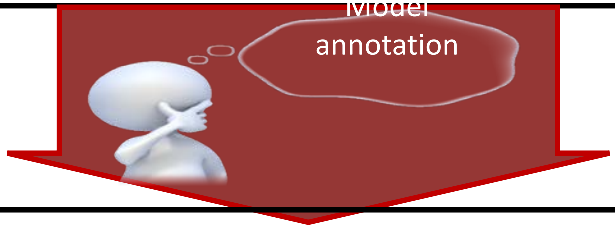
PIPS exploits matrix block structure



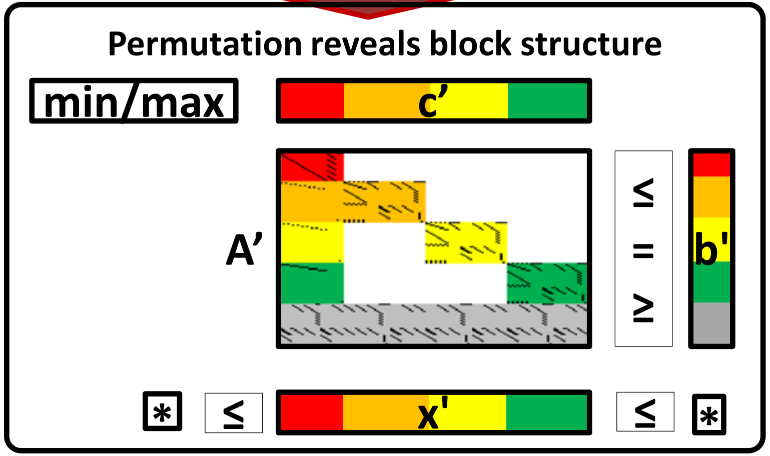
$$\begin{array}{cccccccc}
 & \min & c_0 & c_{s1} & & c_{sn} & & \\
 & & A^{=} & & & & = & b \\
b^{low} & \leq & A^{\leq} & & & & \leq & b^{upp} \\
 & & T_{s1}^{=} & W_{s1}^{=} & & & = & b_{s1} \\
b_{s1}^{low} & \leq & T_{s1}^{\leq} & W_{s1}^{\leq} & & & \leq & b_{s1}^{upp} \\
\vdots & & \vdots & & \ddots & & & \vdots \\
 & & T_{sn}^{=} & & & W_{sn}^{=} & = & b_{sn} \\
b_{sn}^{low} & \leq & T_{sn}^{\leq} & & & W_{sn}^{\leq} & \leq & b_{sn}^{upp} \\
 & & C^{=} & C_{s1}^{=} & \cdots & C_{sn}^{=} & = & b_C \\
b_C^{low} & \leq & C^{\leq} & C_{s1}^{\leq} & \cdots & C_{sn}^{\leq} & \leq & b_C^{upp} \\
x_0^{low} & \leq & x_0 & & & & \leq & x_0^{upp} \\
x_{sn}^{low} & \leq & & & \ddots & x_{sn} & \leq & x_{sn}^{upp}
\end{array}$$

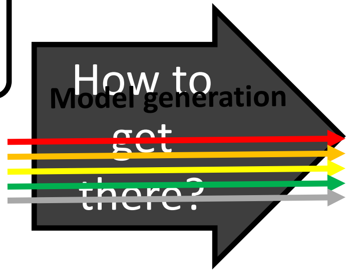
Original problem with "random" matrix structure



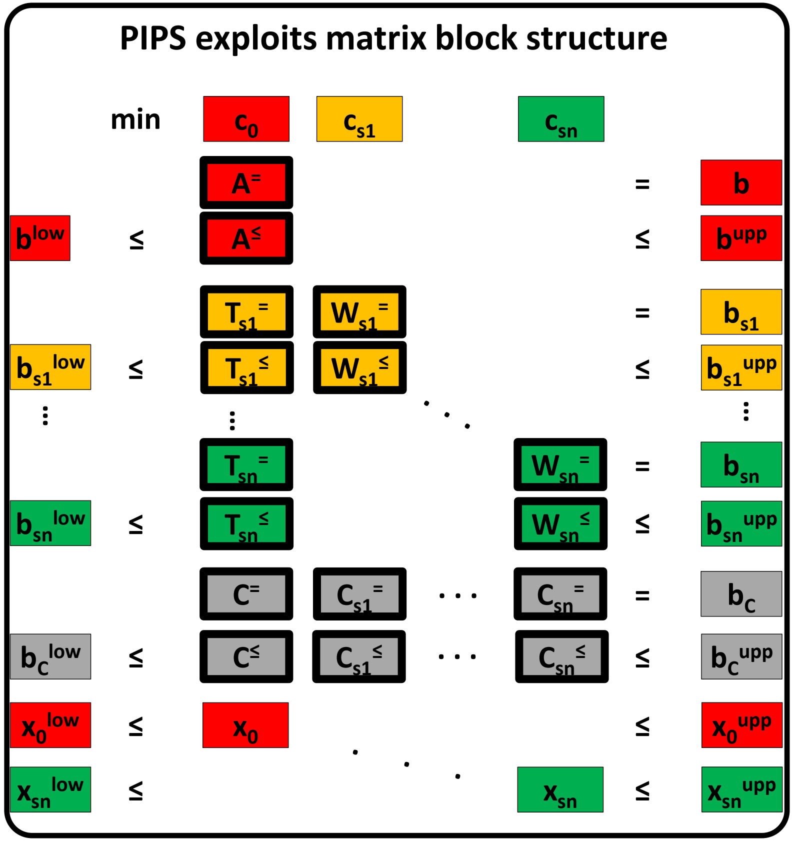


Permutation reveals block structure

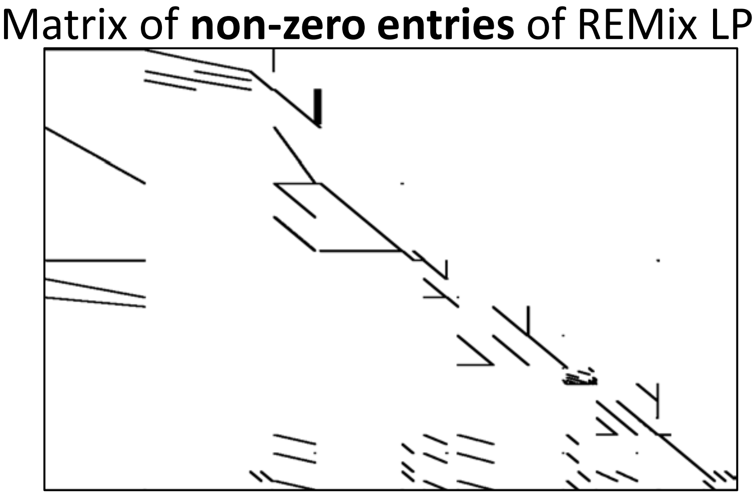


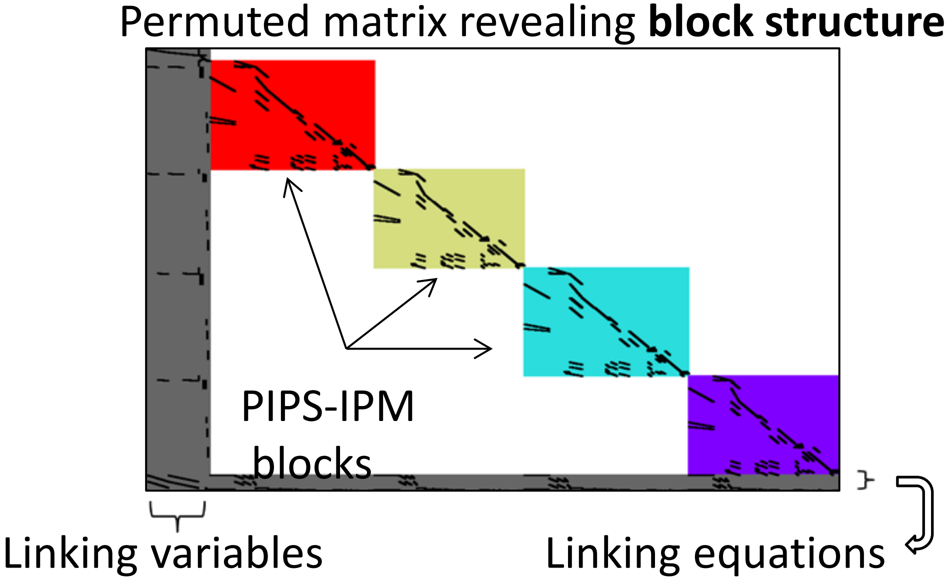


PIPS exploits matrix block structure



GAMS Annotation for PIPS-IPM





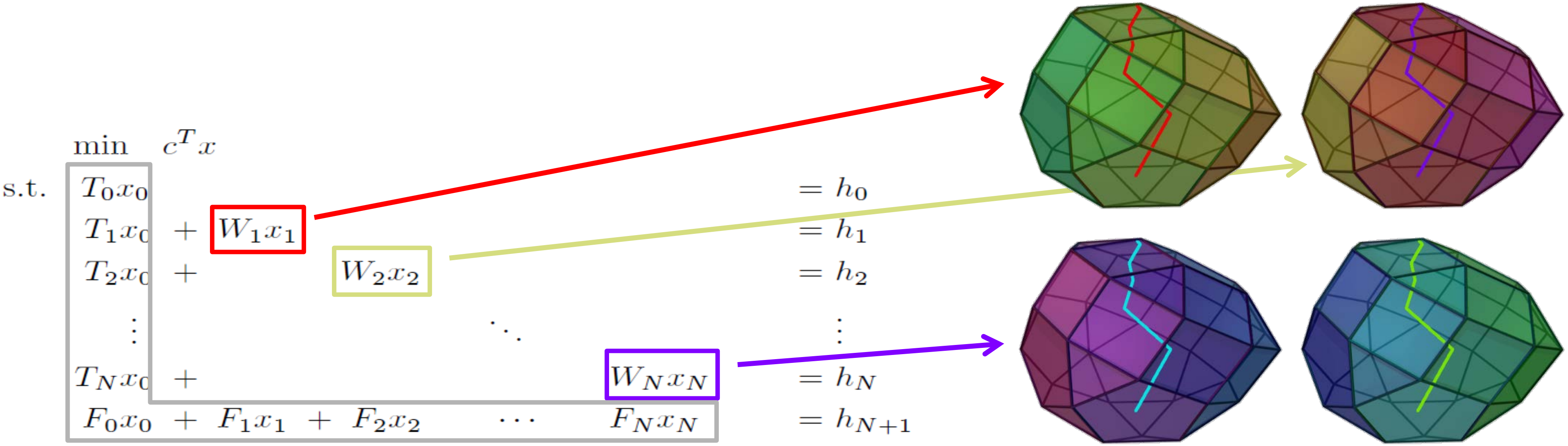
Annotation can be implemented directly in GAMS

Modellers provide knowledge about problem and decompositions

Introducing PIPS-IPM

Parallel Interior Point Solver – Interior Point Method (PIPS-IPM)

- Petra et al. 2014: *“Real-Time Stochastic Optimization of Complex Energy Systems on High-Performance Computers”*
- Wind feed-in planning in electrical power systems under uncertainty

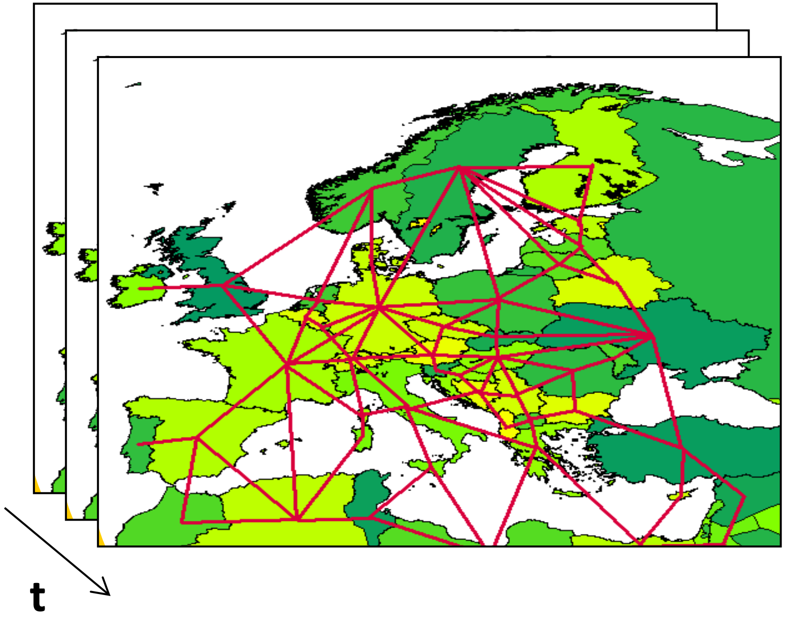


$$
\begin{array}{lllllll}
\min & c^T x & & & & & \\
\text{s.t.} & T_0 x_0 & & & & & = h_0 \\
 & T_1 x_0 & + \boxed{W_1 x_1} & & & & = h_1 \\
 & T_2 x_0 & + & \boxed{W_2 x_2} & & & = h_2 \\
 & \vdots & & & \ddots & & \vdots \\
 & T_N x_0 & + & & & \boxed{W_N x_N} & = h_N \\
 & F_0 x_0 & + F_1 x_1 & +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

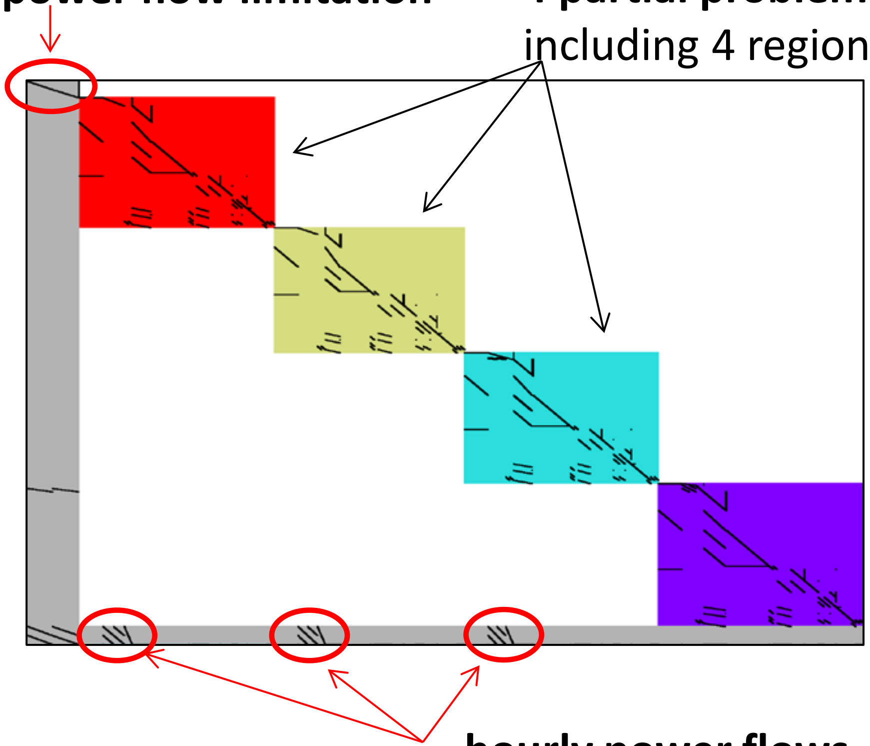
→ **OR 2017:** D. Rehfeldt *„Optimizing large-scale linear energy problems with block diagonal structure by using parallel interior-point methods“*

Decomposition by region I

Linking by region: electricity transports, fuel transports, global constraints (CO_2)



Temporal dimension of transport decisions leads to the largest number of linking variables



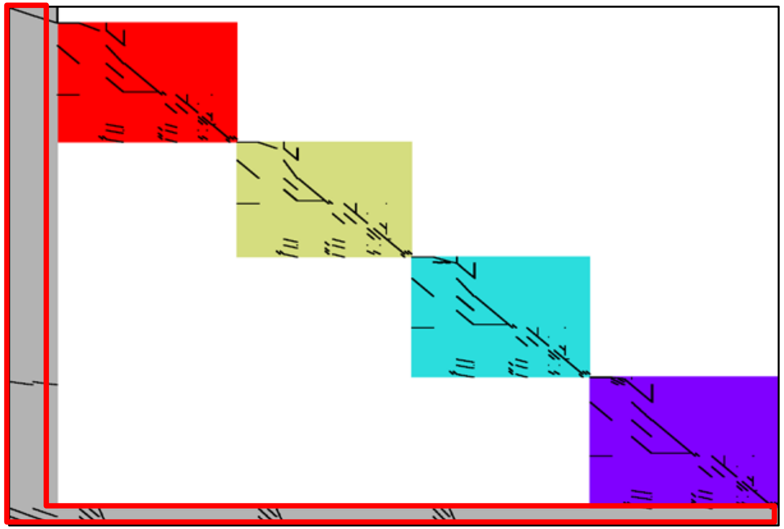
power flow limitation

4 partial problems including 4 regions

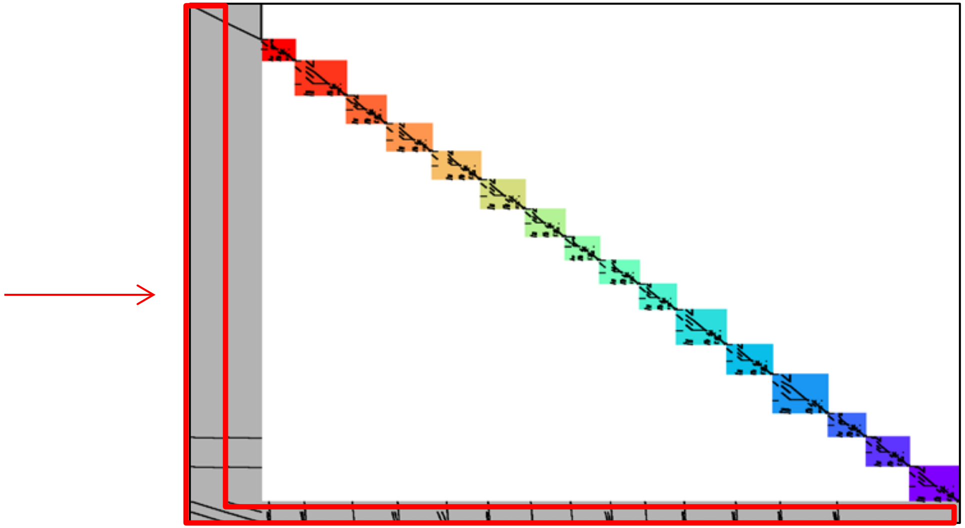
hourly power flows between regionblocks

Decomposition by region II

4 partial problems
including 4 regions



16 partial problems
including 1 region

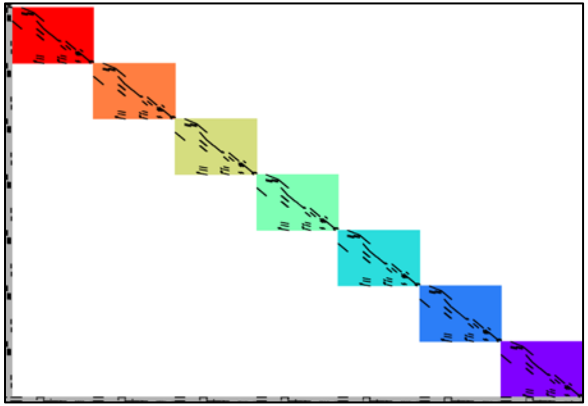


low increase in linking variables and constraints due to **sparsely connected regions**

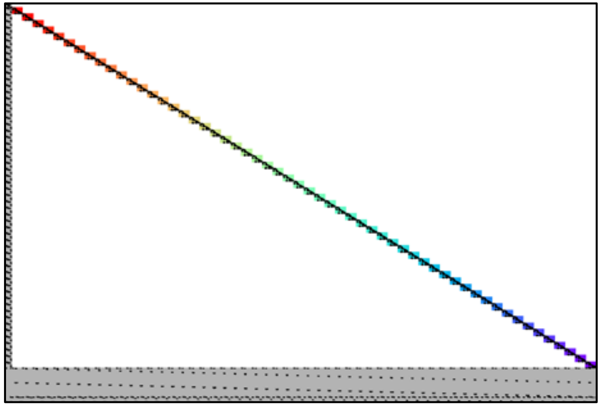
Target: Find **maximum number** of regionblocks of **similar size** which are **sparely linked** to other regionblocks

Decomposition by time

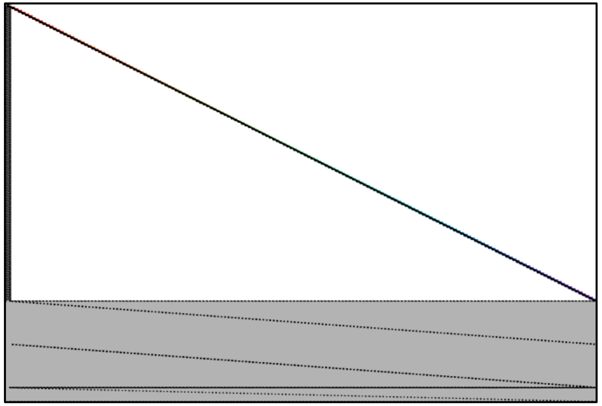
7 partial problems
including 24 time steps



56 partial problems
including 3 time steps



168 partial problems
including 1 time step



1 out of 24 storage constraints linking

3 out of 8 storage constraints linking

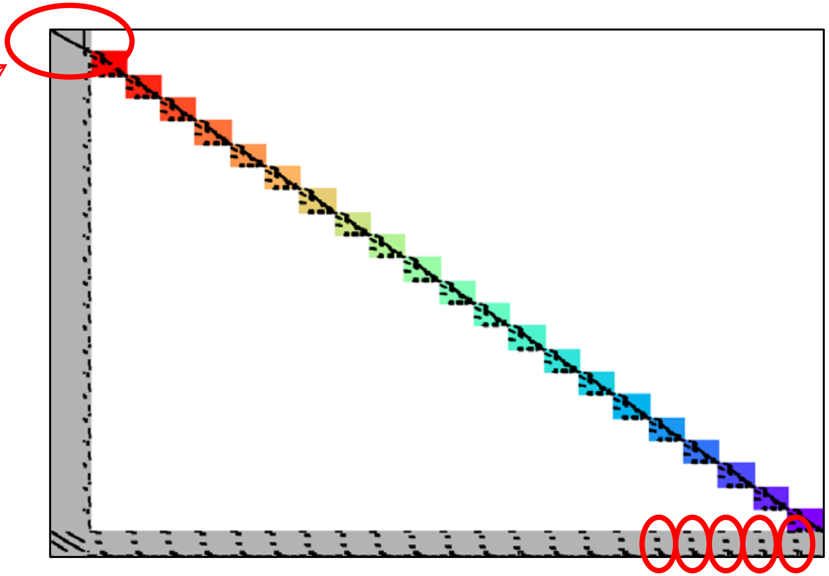
Every storage constraint linking

Target: Find good **trade-off** between **number of time blocks** and **number of linking constraints**

M. Wetzel et al. (DLR) Getting Energy System Models ready for HPC 07 Sept 2017 32

Evaluation of Annotations

Decomposition by **time and region** can be applied at the same time



power flow limitation from spatial decomposition

Linking to previous time step from temporal decomposition

All previously shown annotation plots describe exactly the **same ESM problem**

→ **Systematic evaluation** of promising annotations required

Current state and challenges

Current state of extended PIPS-IPM for BEAM-ME test problems:

- sequentially 10 times slower than CPLEX 12.7.1.0 (latest version) barrier.
- can solve problems with few (< 1000) linking constraints and variables faster than CPLEX (multi-threaded) when enough CPU-cores can be used (on several compute nodes).
- biggest problem solved so far has > 10 million variables and constraints

Current challenges:

- LPs with many (>10000) linking constraints and variables hard to solve due to factorization of large dense matrix in solving process

Challenges

- How to cut the model to allow for efficient application of solvers?
- How can PIPS-IPM use salient features of the problem?
- Identify options for „model tuning“ that work?

- algorithmic and implementation improvements, e.g. (parallel, structure-preserving) preprocessing, scaling, adaptation of interior-point algorithm
- handle dense (symmetric indefinite) matrix more efficiently:
  - try GPUs (e.g., MAGMA, cuSolver) for problems with not too many (< 10000) linking constraints and variables
  - try distributed linear algebra (e.g., Elemental, DPLASMA) for bigger problems

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Benchmark: PIPS-IPM and PIPS must beat SIMPLEX in the first place

Outlook: What can we do with more efficient models?

- Model new markets and market design
- Increase sparcial and temporal resolution
- Answer new questions
  - Improved market analysis
  - Regional potential of specific technologies
- Address uncertainty with stochastic models
  - Exploring solution space
  - Identifying tipping points between subsities
- Modelling sectors and sector integration