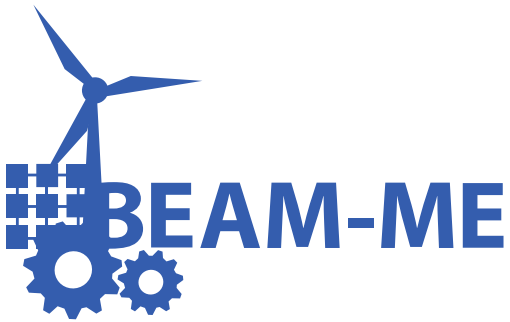

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Solving Large-Scale GAMS Models on HPC platforms

INFORMS 2019

Michael Bussieck

GAMS Software GmbH

BEAM-ME: An Interdisciplinary Approach

BEAM-ME

Energy System Modeling → **Modeling Language** → **Solver Development** → **High Performance Computing**

Deutsches Zentrum für Luft- und Raumfahrt (DLR) German Aerospace Center

GAMS

ZIB, TU Berlin

HLRS, JÜLICH FORSCHUNGSZENTRUM

Goal: *Implementation of acceleration strategies from mathematics and computational sciences for optimizing* ***energy system models*** *(ESM)*

Model Experiment: Apply and test new solution approaches

UNIVERSITÄT DUISBURG ESSEN

ewi Energiewirtschaftliches Institut an der Universität zu Köln
Energiemärkte erforschen – Entscheidungen verbessern.

PAUL SCHERRER INSTITUT PSI

DTU Technical University of Denmark

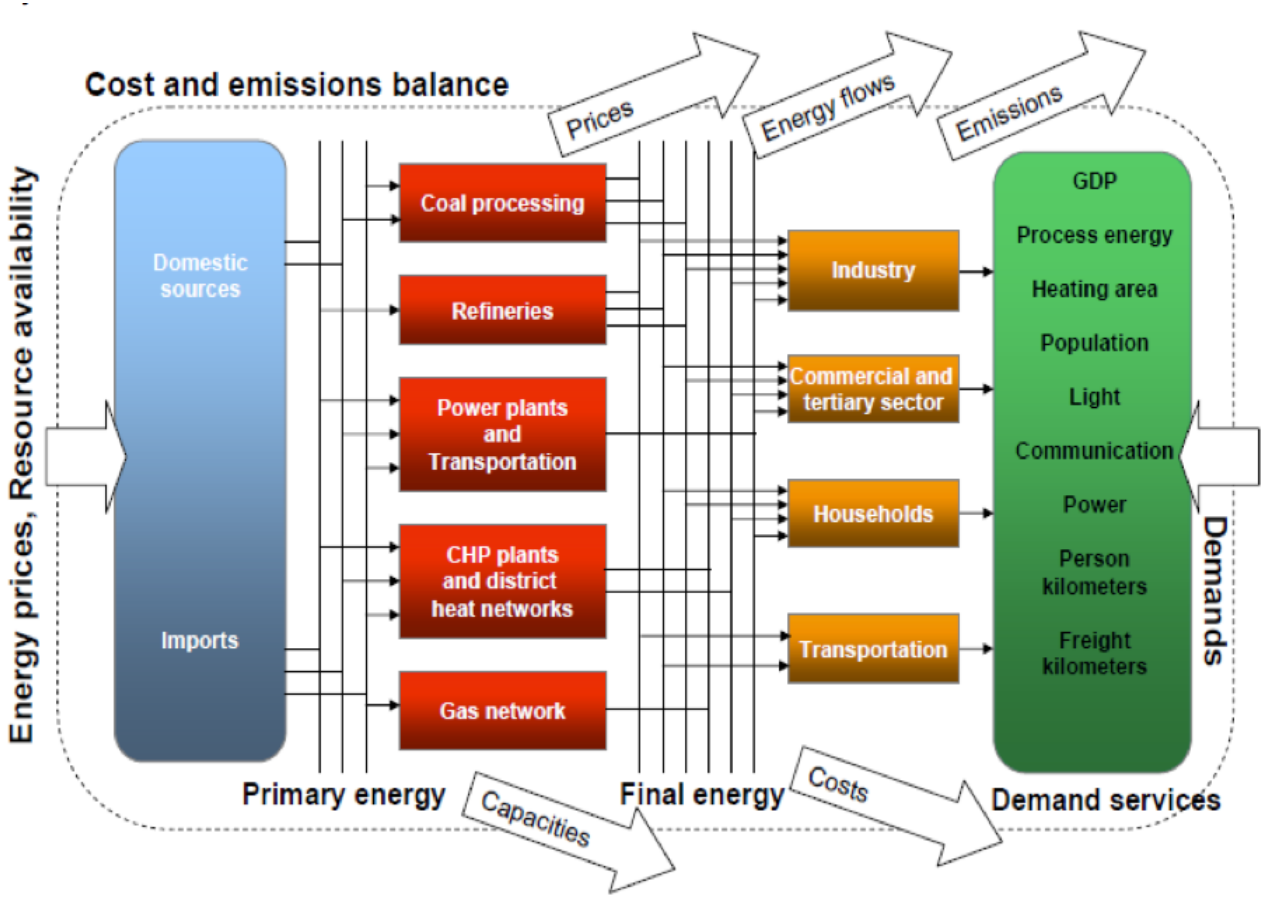
KIT Karlsruher Institut für Technologie

TECHNISCHE UNIVERSITÄT DRESDEN

ESM Principles

Model Ingredients:

- Technologies/Processes
  - Transform commodities into other commodities (e.g. fuel → electricity+emissions)
- Commodities
  - Commodity is produced or consumed by a process (e.g. fuels, electricity, emission, money)
- **Time**
- **Region**
- Policies
  - Minimum share of renewable energy
  - Maximum amount of (GHG) emissions
  - Minimum level of energy security
  - …



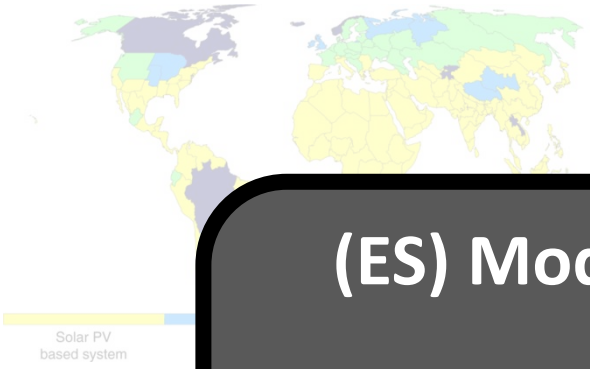
→The *mathematical*, *economic* and *engineering* relationships between these energy *producers* and *consumers* are basis of the ESM.

Building Elaborate (ES) Models

- **Significant investment!**
  - E.g. MARKAL/TIMES (Energy Technology Systems Analysis Program (ETSAP) of International Energy Agency (IEA))
    - Development & maintenance effort
      - ~10 person years
    - Lifetime of 20+ years
      - TIMES started ~1997, MARKAL ~1978)
    - Large user base
      - TIMES is used by ~200 research teams in more than 50 countries)
  - E.g. REMix (German Aerospace Center (DLR))
    - Start year: 2006
    - #PhD Thesis: 13 (6 in progress)
    - Person years (devel/use): 10-20
    - Maintenance: 1 PY/a
    - #Users: 11
    - #Developers: 4
    - #IT/UI Maintenance 0.25 PY/a

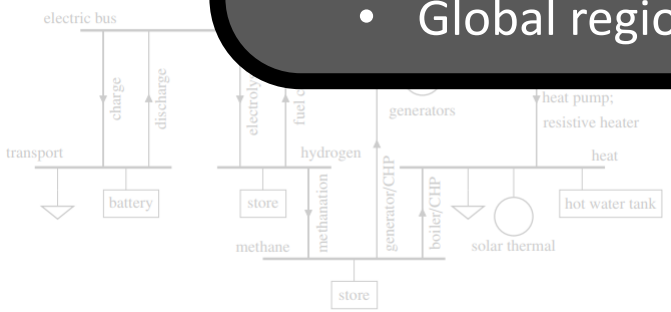
Trends in energy system models

Focus on global energy systems



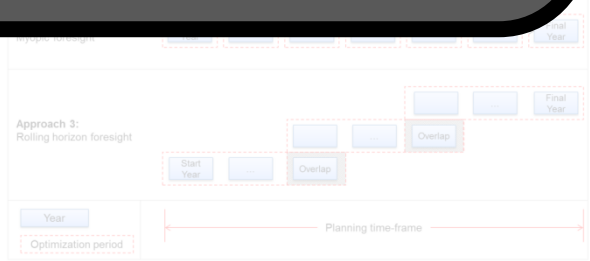
Bogdanov et al
towards sustai

Sector int



Brown et al., 2018, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system

Higher granularity of regions



Fichter, 2018, Long-term Capacity Expansion Planning with Variable Renewable Energies

(ES) Models challenge algorithms

Citius, altius, fortius (faster, higher, stronger)

- Level of granularity
- Time horizon
- Global regions

GAMS/PIPS-IPM, a new Hope?

BEAM-ME

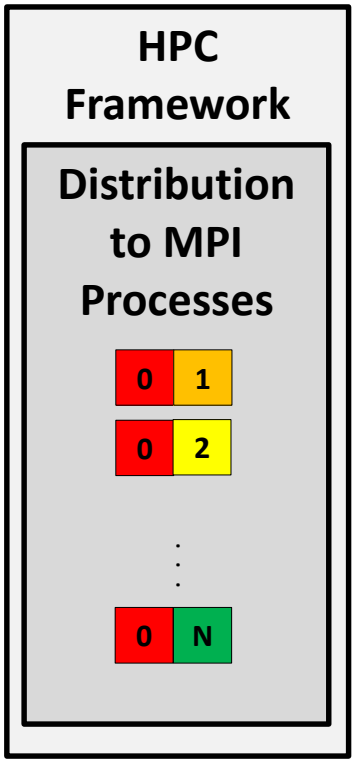
PIPS-IPM (a brief overview):

- Parallel interior-point solver for LPs (und QPs) from *stochastic* energy models
- Exploit **block structure** when solving Central Path equation system
- Main developers: Cosmin Petra
- Significant Extensions of PIPS-IPM (by ZIB, Daniel Rehfeldt, …)
  - Linking constraints
  - (structure preserving) Presolve
  - (structure preserving) Scaling
  - …

GAMS/PIPS-IPM[1,2]

Consider LP with block-diagonal structure, linking constraints, and linking variables (the kind of problem we want to solve):

$$
\begin{aligned}
\min \quad & \sum_{i=0}^{N} c_i^T x_i \\
\text{s.t.} \quad & T_0 x_0 = b \\
& T_1 x_0 + W_1 x_1 = h_1 \\
& T_2 x_0 + W_2 x_2 = h_2 \\
& \vdots \qquad\qquad \ddots \qquad\qquad \vdots \\
& T_N x_0 + W_N x_N = h_N \\
& F_0 x_0 + F_1 x_1 + F_2 x_2 \cdots F_N x_N = g
\end{aligned}
$$



- Block diagonal structure allows parallelization of linear algebra within PIPS-IPM
- Solve *N* systems of linear equations in parallel instead of one huge system

[1] Petra et al. 2014: *"Real-Time Stochastic Optimization of Complex Energy Systems on High-Performance Computers"*

[2] Breuer et al. 2017: *"Optimizing Large-Scale Linear Energy System Problems with Block Diagonal Structure by Using Parallel Interior-Point Methods."*

GAMS/PIPS-IPM Workflow (Comparison)

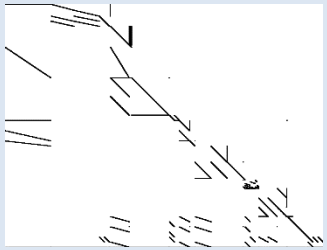
BEAM-ME

Model

$$\min c^T x$$
$$Ax = b$$
$$l \leq x \leq u$$

model generation

General purpose LP solver

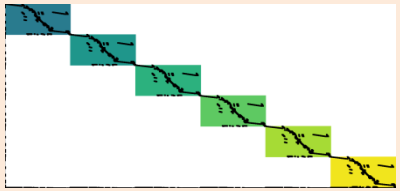


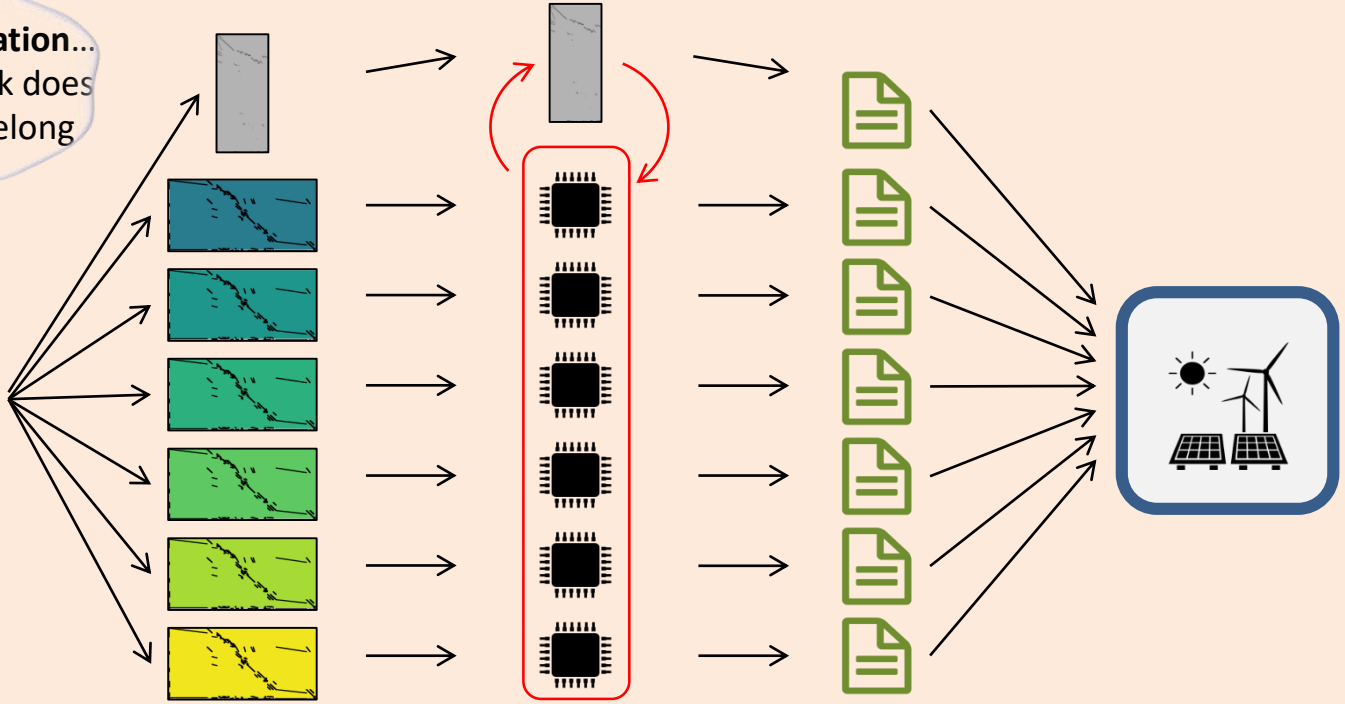
non-zero plot

optimization results

Model annotation…
To which block does variable x belong

model generation





block structure **split and distribute** **parallel solve** **merge** **optimization results**

GAMS/PIPS-IPM Workflow (Comparison)

BEAM-ME

Model

$$\min c^T x$$
$$Ax = b$$
$$l \leq x \leq u$$

model generation

General purpose LP solver

non-zero plot

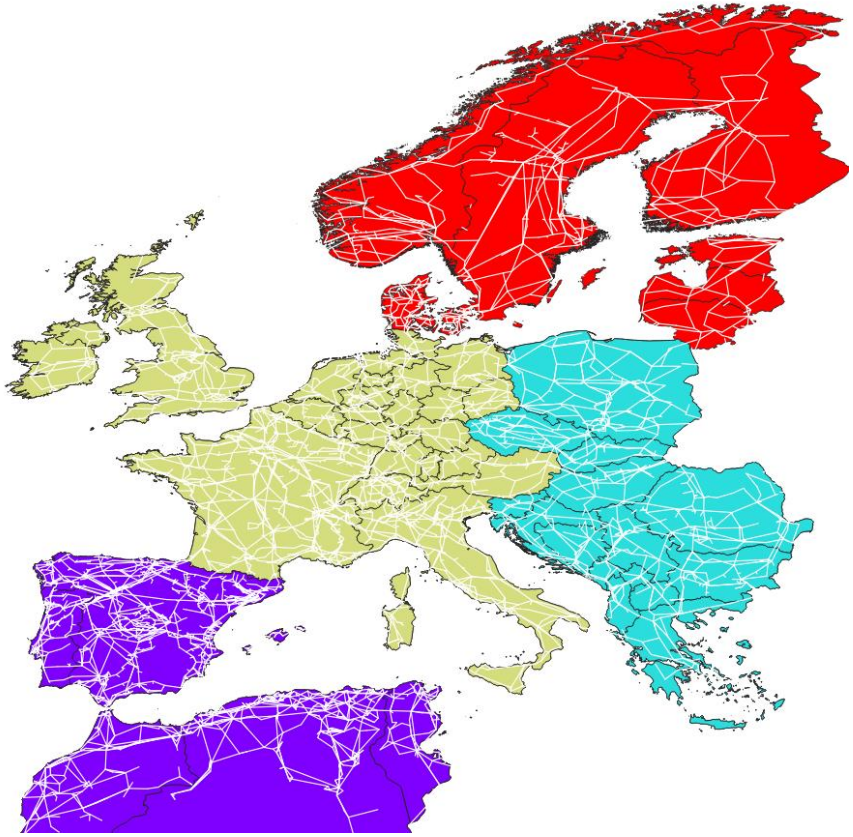
optimization results

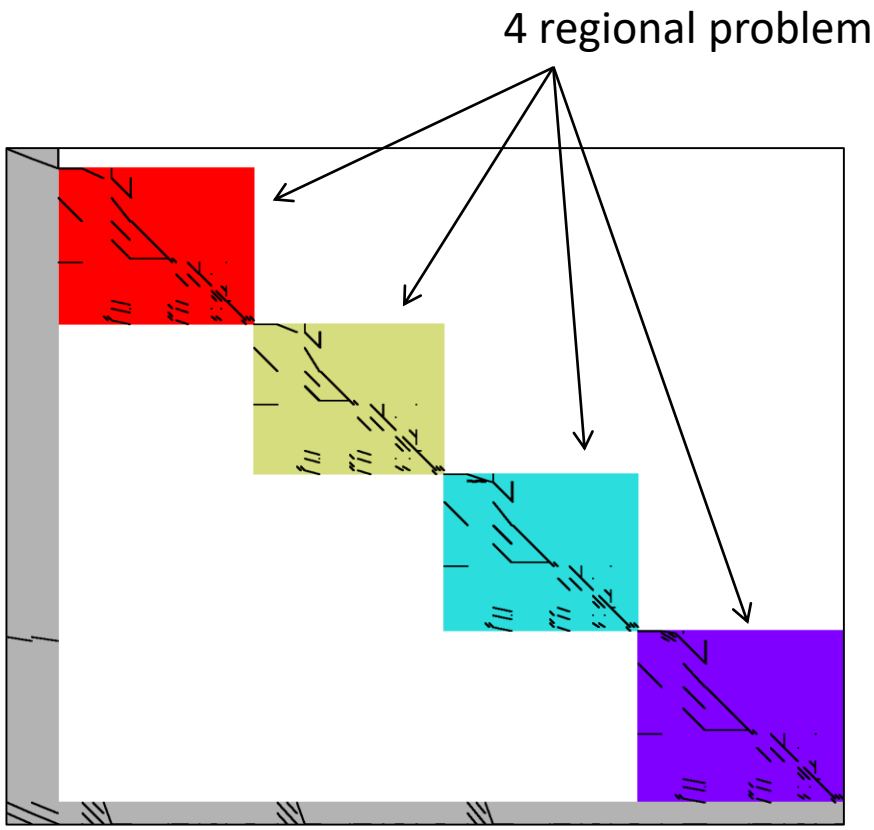
Model annotation…
To which block does variable X belong

Parallel model generation (work in progress)

block structure | **split and distribute** | **parallel solve** | **merge** | **optimization results**

Spatial Annotation



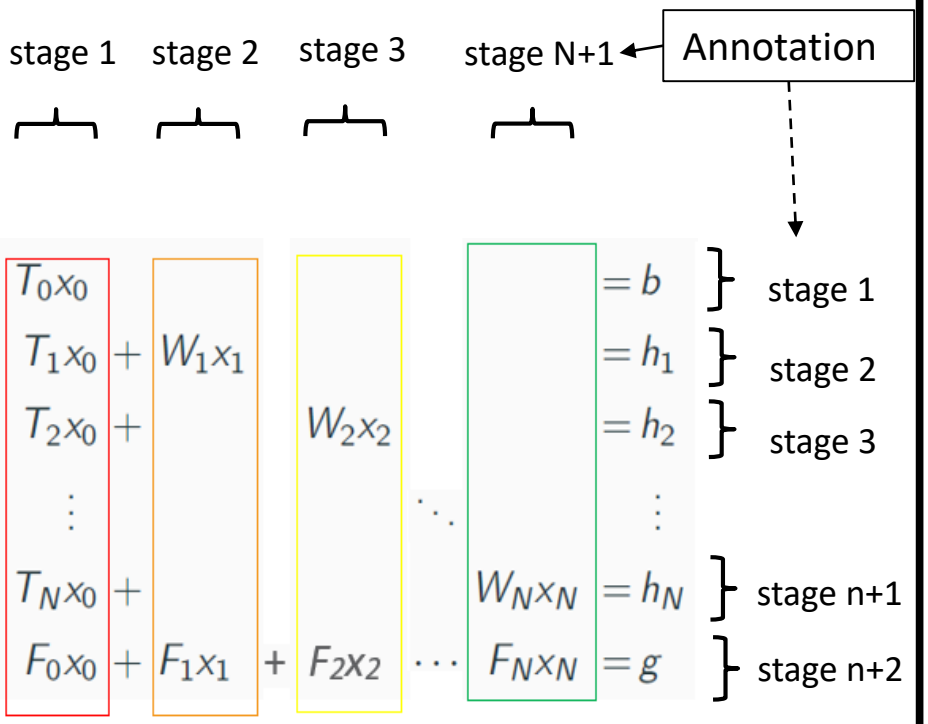


Linking elements scale with transmission lines and time steps

GAMS/PIPS-IPM cont.

Model Annotation by **.stage** attribute

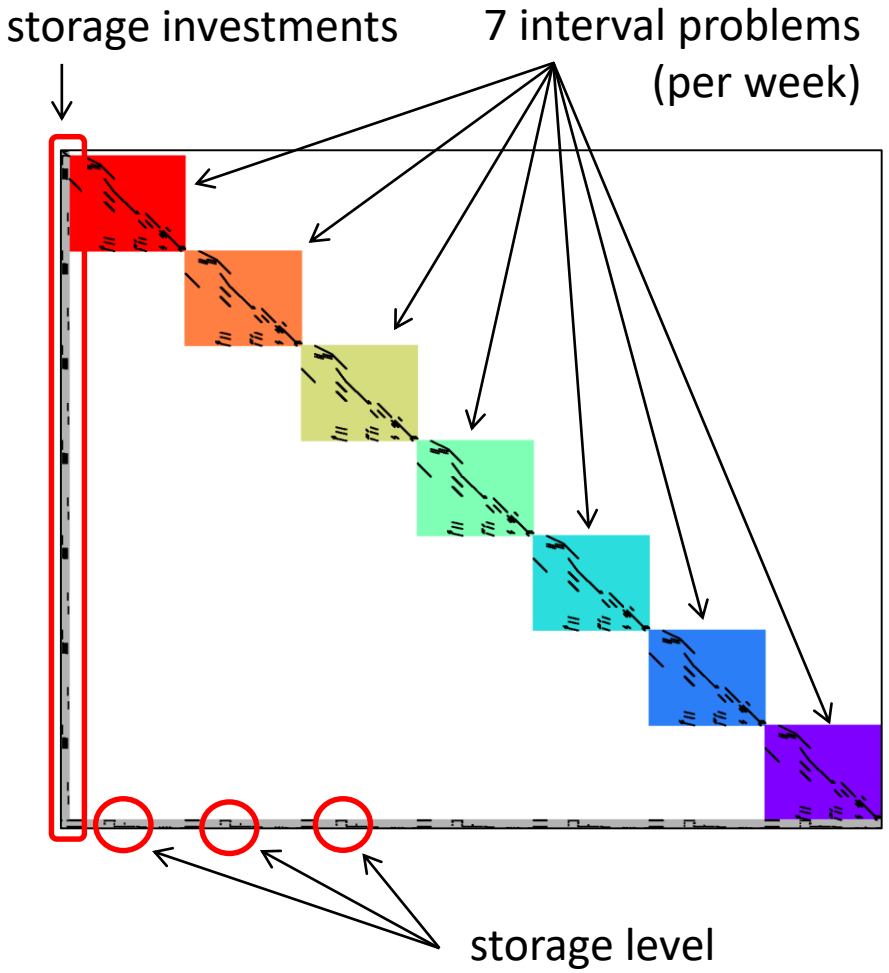
Matrix structure required by PIPS API



Exemplary (spatial) Annotation for SIMPLE energy system model

```
Set rr          'regions                    '
    p           'plants                     '
    s           'storages                   '
    tt          'time steps                 '
    net(rr,rr)  'transmission links         '
    rp(rr,p)    'region to plant mapping'
    rs(rr,s)    'region to strg  mapping'
;
[...]
* linking variables
FLOW.stage(t,net(rr1,rr2))         = 1;
LINK_ADD_CAP.stage(net(rr1,rr2)) = 1;
[...]
* Block variables
POWER.stage(t,rp(rr,p))            = ord(rr)+1;
STORAGE_INFLOW.stage(t,rs(rr,s)) = ord(rr)+1;
STORAGE_OUTFLOW.stage(t,rs(rr,s))= ord(rr)+1;
STORAGE_LEVEL.stage(t,rs(rr,s))  = ord(rr)+1;
[...]
```

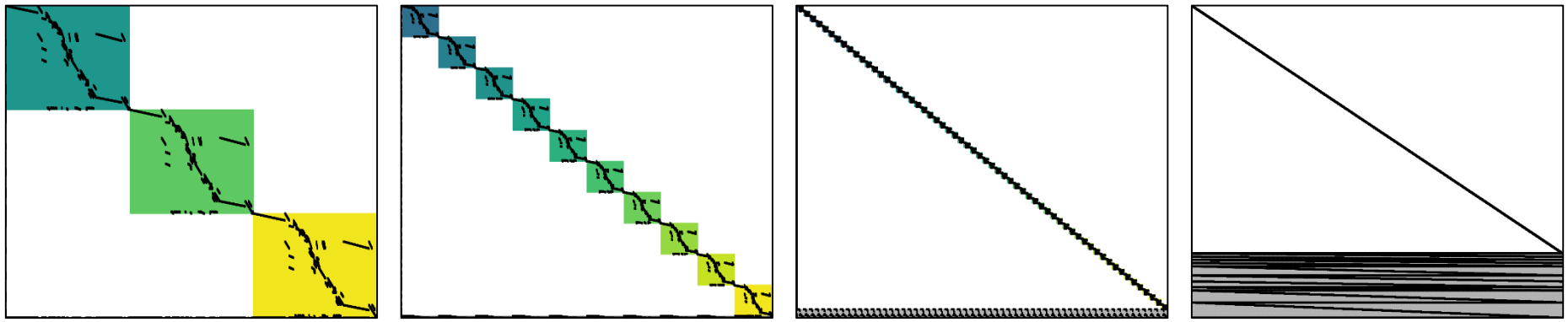
Temporal Annotation (24h Blocks)



Linking elements scale with regions and technologies

Annotation – The Challenge

- How to annotate Model depends on how the model should be “decomposed” (by region, time,…)



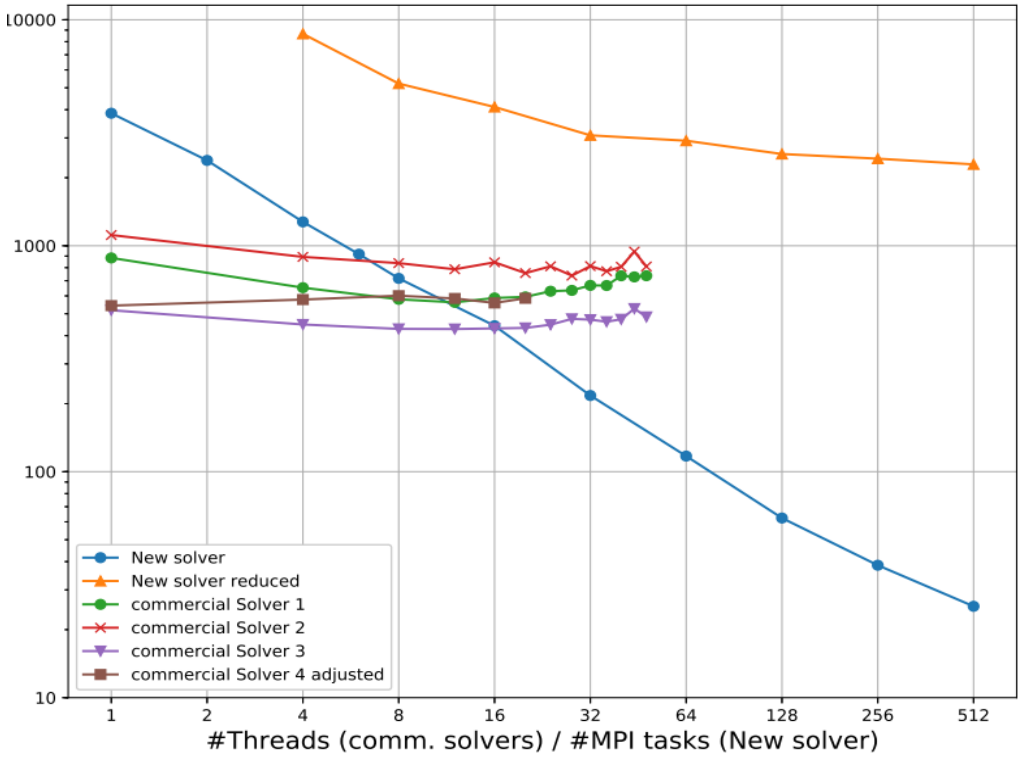
Plots show four different annotations of identical model

- Blocks of equal size are beneficial
- Few linking variables/constraints are beneficial

Computational Results

Computational Results

GAMS/PIPS-IPM Speedup **Potential**:



Scaling results of leading commercial LP solvers and the new solver on a **`SIMPLE`** (`#rows 5.1E6, #columns 5.6E6, #non-zeroes 20.4E6`) model instance. The new solver was run with 2 OpenMP threads per MPI process.

Daniel Rehfeldt, Hannes Hobbie, David Schönheit, Ambros Gleixner, Thorsten Koch, Dominik Möst: A massively parallel interior-point solver for linear energy system models with block structure, ZIB-Report 19-41.

Conputational Results Cont.

Table 1: Computational results for large-scale instances

	Size				Run time (seconds)			
Instance	Variables	Constraints	Non-zeroes	Blocks	New solver	Solver 1	Solver 2	Solver 4
SIMPLE2	95 311,531	86 551 238	344 083 267	1320	244	25 302	31 101	23 339
SIMPLE3	227 060 381	206 036 266	818 449 005	1024	546	38 800	69 377*	NO
ELMOD_CWE14	85 585 234	98 532 392	271 621 021	438	239	6 181*	3 937	21 442
ELMOD_CWE15	85 646 554	98 646 274	271 875 064	438	181	6 321*	6 245	TL
ELMOD_CWE16	85 883 074	98 909 074	272 602 144	438	216	6 984*	5 190	67 941
ELMOD_EU14	223 898 044	253 201 191	709 588 006	876	1 220*	NO	66 105	NO
ELMOD_EU15	224 677 686	254 304 961	712 452 541	876	1 245*	NO	83 715	NO
ELMOD_EU16	226 061 766	256 284 723	717 436 984	876	1 119*	NO	79 094	NO

`*` : could not be solved within the optimality tolerances, but still with a relatively small primal-dual gap (<1%).
`NO`: non-optimal, specifies that the respective solver could not solve the instance within acceptable tolerances
`TL`: (hard) time limit of 24 hours on JUWELS was hit

Hardware:

- a) JUWELS: Dual Intel Xeon Platinum 8168 CPU, 2x24 cores at 2.7 GHz, 96 GB memory
- b) JUWELS: Dual Intel Xeon Platinum 8168 CPU, 2x24 cores at 2.7 GHz, 192 GB memory
- c) ZIB: Intel Xeon CPU E7-8880 v4 2.20GHz processor, 88 cores, and **2 TB** memory

Daniel Rehfeldt, Hannes Hobbie, David Schönheit, Ambros Gleixner, Thorsten Koch, Dominik Möst: A massively parallel interior-point solver for linear energy system models with block structure, ZIB-Report 19-41.

Outlook

Outlook/Challenges

- Parallelization can be extended to Model Generation
  - "Usual Model": model generation time << solver time
  - For LARGE-scale models the model generation may become significant:
    - due to time consumption
    - due to memory consumption
    - due to hard coded limitations of model size (# non-zeroes < ~2.1e9)
  - Generation of separate model blocks as required by solver
    - Fully implemented by user: possible (significant refactorization of code)
    - Annotation provided by user → block sharp generation by GAMS: work in progress
- PIPS-IPM under constant development

Thank You!

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