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Comparison of Enhanced Benders Decomposition Methods for Stochastic Optimization of Energy System Models and Challenges for the Application to High Performance Computing

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GAMS

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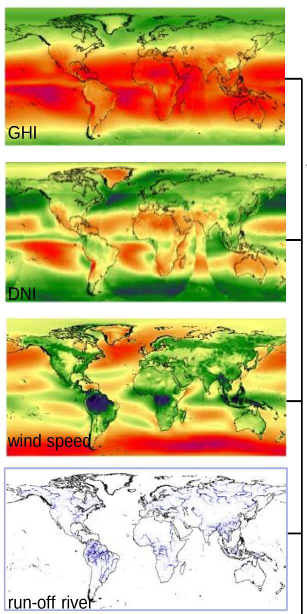
Energy System Model REMix at DLR

Installed capacities and power generation profiles from renewables



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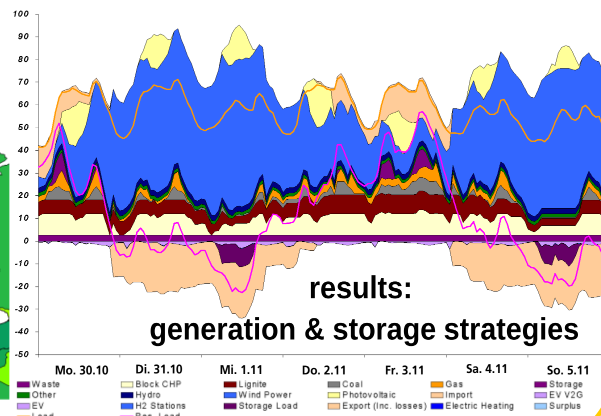
HVDC lines
long-range power exchange and imports

Transmission grid
based on current European AC grid

Scenario analysis with model REMix

cost minimised supply in temporal & spatial resolution

model



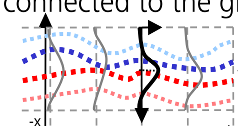
Electricity demand

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

Partner

- **German Aerospace Agency (DLR),** Department for System Analysis and Technology Assessment at the Institute for Technical Thermodynamics (TT)
- **Forschungszentrum Juelich (FZJ),** Juelich Supercomputing Centre (JSC)
- **University of Stuttgart,** High Performance Computing Center Stuttgart (HLRS)
- **Zuse Institute Berlin (ZIB),** Department for Mathematical Optimization and Scientific Information
- **Technical University Berlin,** Institute for Mathematics
- **GAMS Software GmbH**

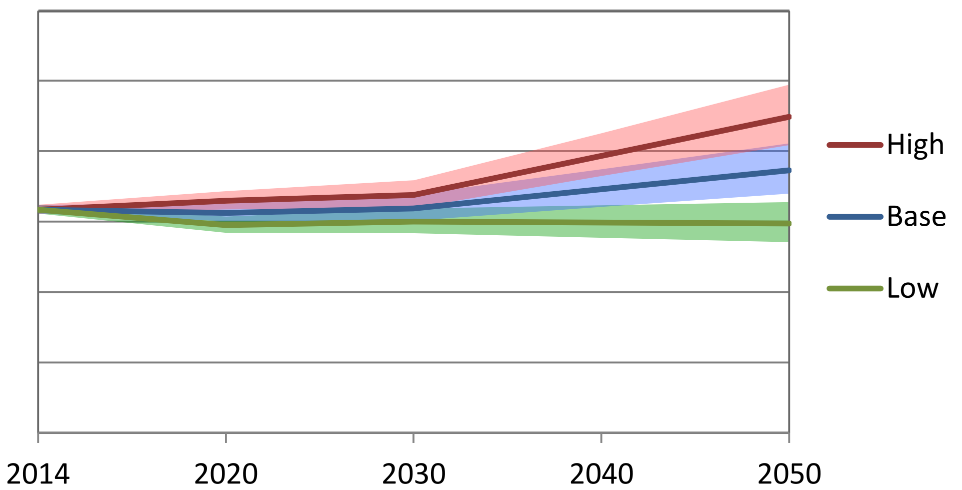
The problem of uncertainty in energy system modelling

Robust scenario High
- ↑ Sensitivity analysis
- ○ Model result High
- ↓ Sensitivity analysis

Robust scenario Base
- ↑ Sensitivity analysis
- ○ Model result Base
- ↓ Sensitivity analysis

Robust scenario Low
- ↑ Sensitivity analysis
- ○ Model result Low
- ↓ Sensitivity analysis

Path development of an uncertain parameter



- Long term capacity expansion planning requires **making decisions now**, which have an impact on the energy system for several decades.
- **Context scenarios** can give a general direction of development, however a large number of **consistent sub-scenarios** are possible. The current approach usually considers only the main scenario and evaluates robustness by sensitivity analysis of sub scenarios.

Benders decomposition for two-stage stochastic optimization

(L-shaped Method)

[Benders 1962 and Van Slyke 1969]

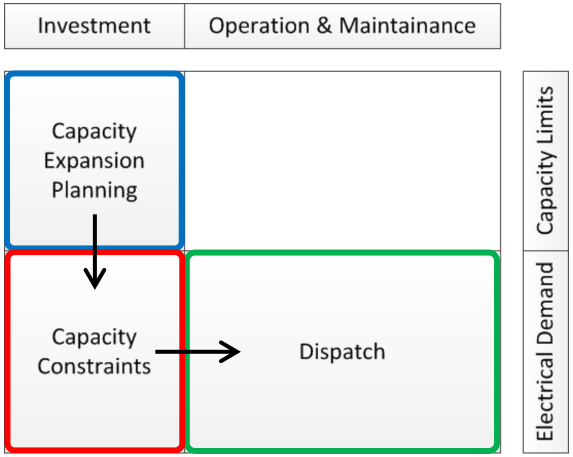
Master problem:

- **Decide now** which capacities should be expanded

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

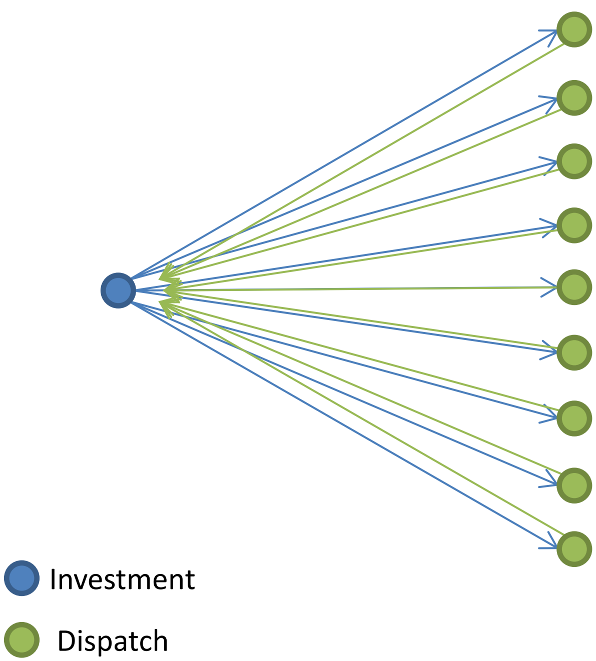
2nd Stage:
Dispatch – Generation variables

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

1. Two-stage decision tree

Stage 1
(Master problem)
Investment decision

Stage 2
(Sub problem)
Stochastic economic dispatch scenarios

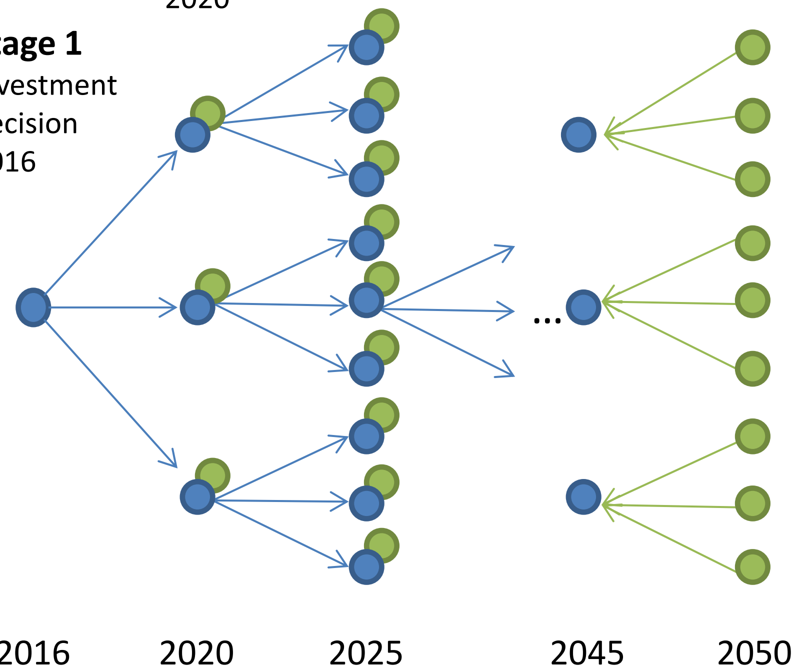


2. Multi-stage decision tree

Stage 1
Investment decision 2016

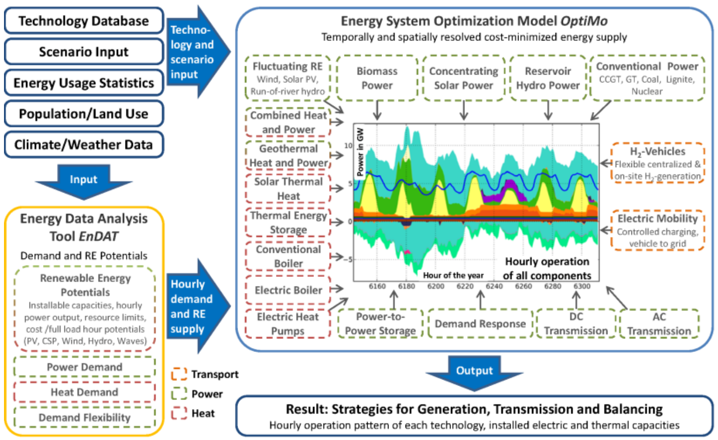
Stage 2
Dispatch & Investment decision 2020

Stage 3
Dispatch & Investment decision 2025



The SIMPLE Model

REMix



- Capacity expansion planning and economic dispatch
- **High** spatial, temporal and technological **resolution**
- **Modular approach** to include heat sector, electromobility, DSM and others

GAMS SIMPLE

- **Simplified version** of REMix, used as a development platform
- **Scalability** of model dimensions by generic data generation
- ➢ Modified for demonstrating implementation approaches for stochastic optimization

Implementation of Enhanced Benders decomposition approaches

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GAMS Simple Model:
- Capacity expansion planning and economic dispatch

Deterministic version of
The GAMS SIMPLE model

1. Implementation of a Benders decomposition approach
Seperating capacity expansion and economic dispatch

Master problem:
Investment decision

Sub problem:
Economic dispatch

Suggested solution

Capacities for installed plant capacities, electric storages and links for each region

Optimality Cut

Information about the marginals of the first stage decision variables

Implementation of Enhanced Benders decomposition approaches

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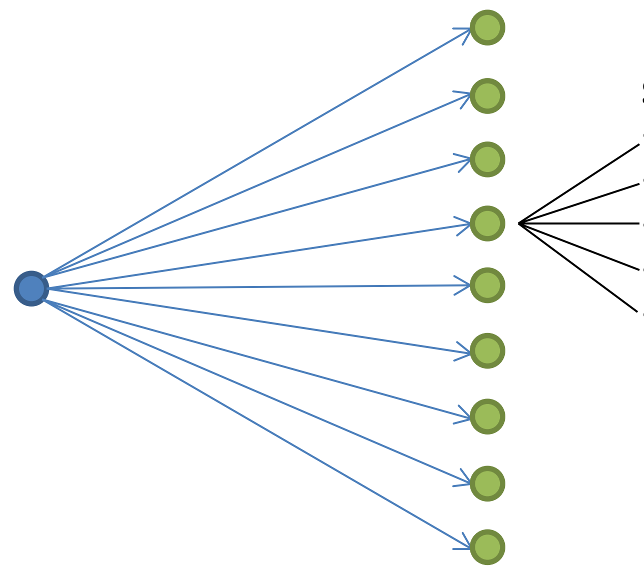
1. Implementation of a Benders decomposition approach
Seperate regions and type

2. Stochastic model with scenarios

- Each scenario has a probability
- Stochastic model is still single threat

Master problem:
Investment decision

Sub problem:
Economic dispatch scenarios



Set of uncertain parameters

- Electrical demand
- Fuel prices
- Wind time series
- Solar time series
- E-mobility usage

- Each subproblem is weighted by a probability and represents a specific set of assumptions for uncertain parameters

Implementation of Enhanced Benders decomposition approaches

2. Stochastic model with scenarios

3. Simple Computing
- Scenarios are processed one after another

4. Grid computing
- Scenarios and parts of the modell can be placed in several threats

5. Deterministic Model
- One modell for master and subproblem

Testing with
Model nodes: 3
Scenarios: 100
<< 3-4 GB RAM

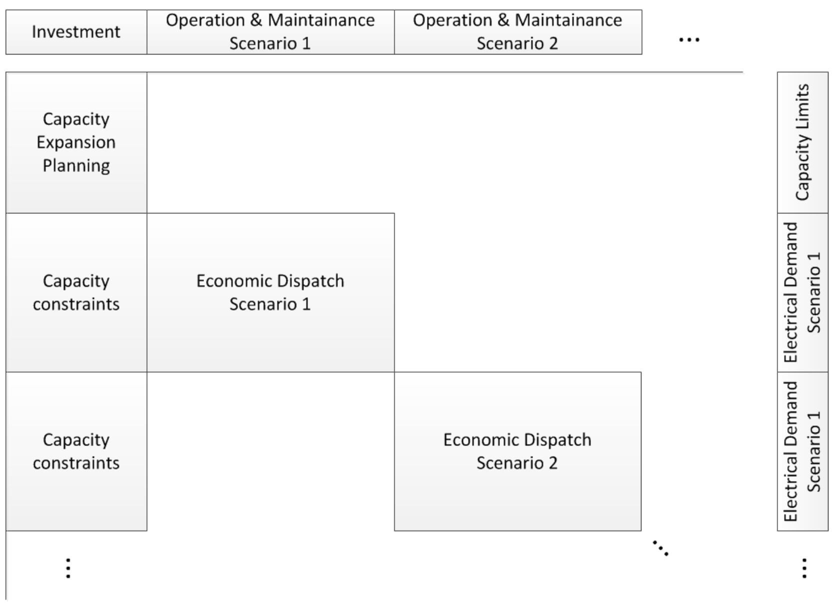
Testing with
Model nodes: 3
Scenarios: 100
= 3-4 GB RAM

Testing with
Model nodes: 3
Scenarios: 100
= 40 GB RAM

- **Small ESM** with 3 power plants, 3 storages, 2 node links and 8760h
- Formulation as Deterministic Equivalent for small problems faster than Benders decomposition, but leads to **memory restrictions** in large models

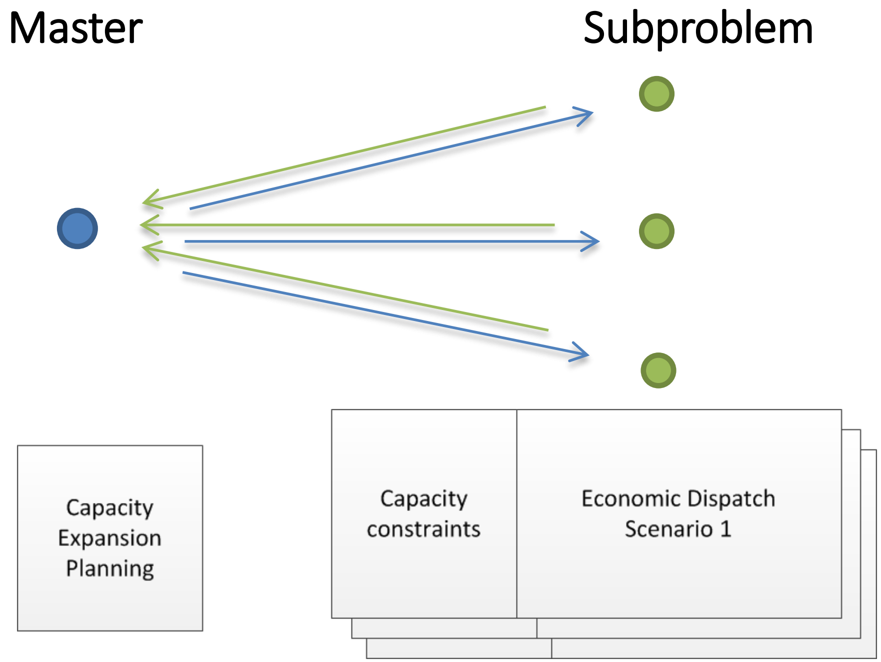
The Deterministic Eqivalent and Benders Decomposition

Deterministic Equivalent



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

Benders Decomposition



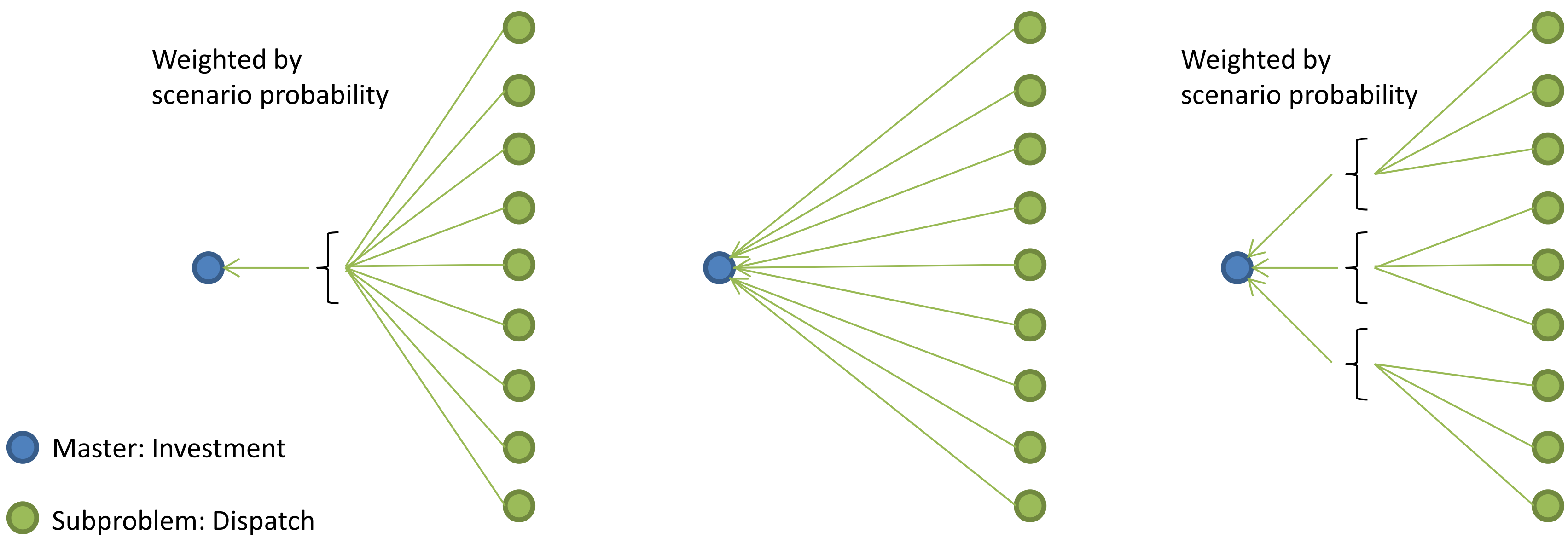
- Subproblems can be **solved in parallel**
- Memory demand **scales** with number of parallel solve processes

Improvement by optimality cut type

Singlecut
- One optimality cut per iteration is submitted to master problem

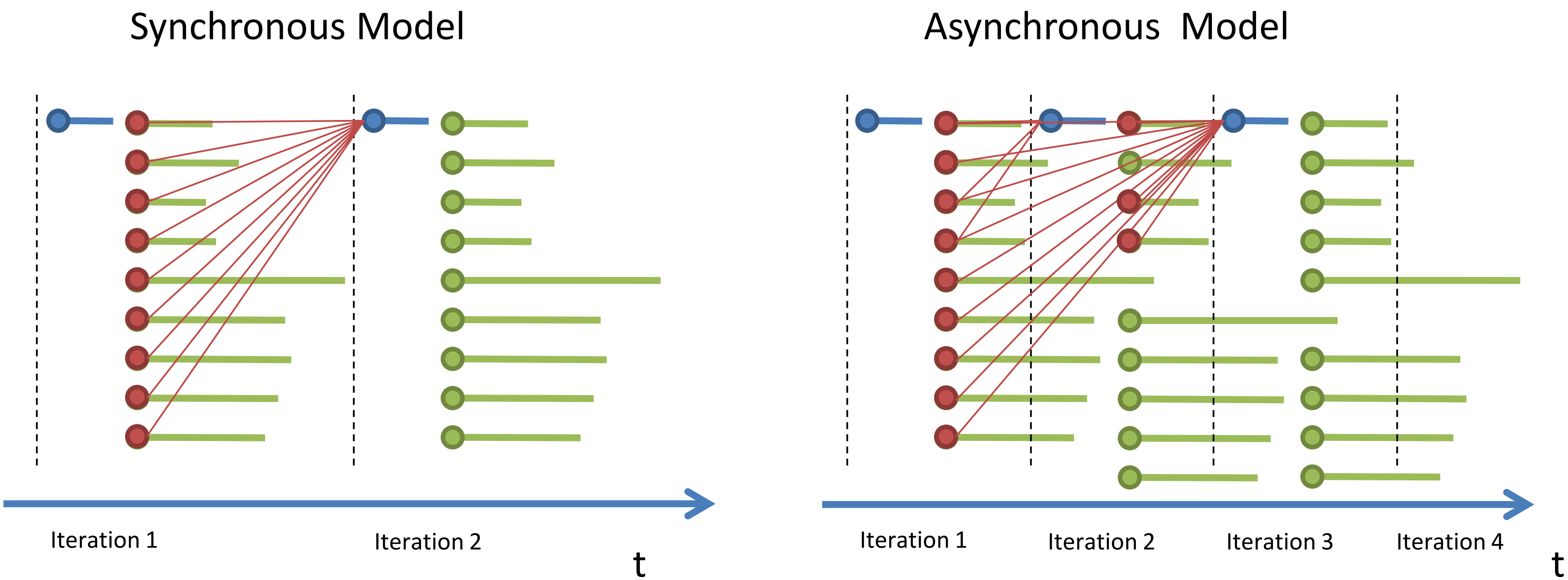
Multicut
- Each subscenario submits an optimality cut each iteration

Clustercut
- Each cluster submits an optimality cut each iteration



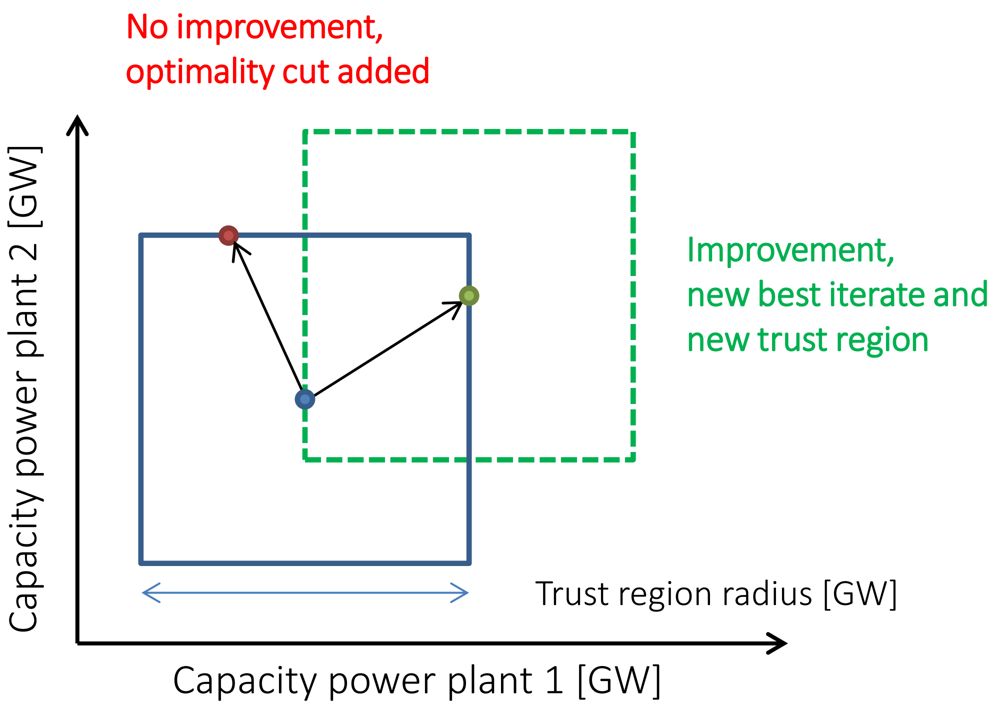
- Multicuts give **detailed information** but increase complexity [Birge 1988]
- Singlecuts **aggregate information** therefore more iterations are necessary
- Dynamic switching between cut-types is possible [Skar 2014]

Improvement to achieve asychronity



- New Master can be started as soon as a **fraction of scenarios are solved**, new iteration has only **partial information** therefore the number of iterations increases [Linderoth 2003]
- Trade-off between more iterations and parallelisation

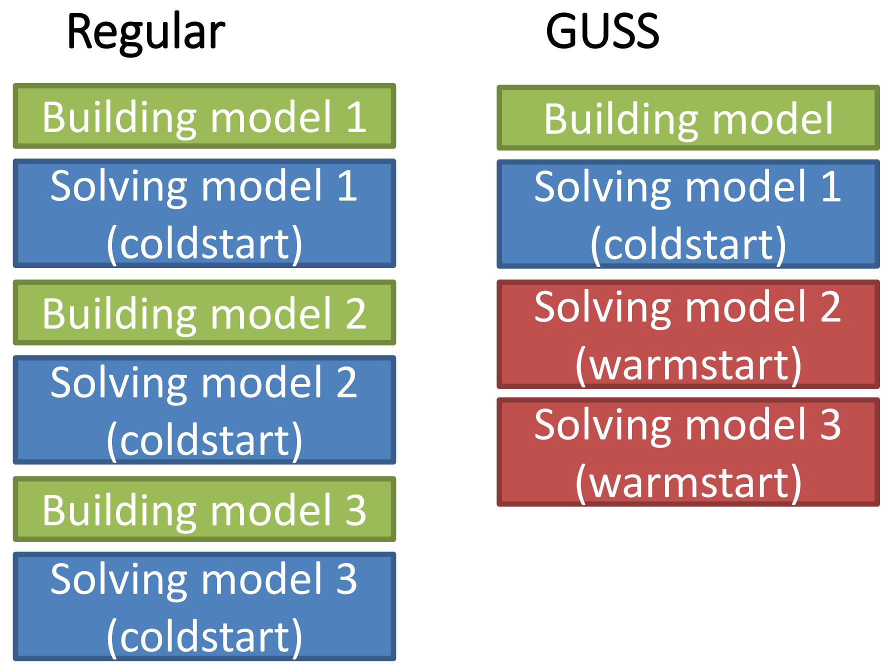
Improvement by Trust Regions



- Typical **oscilation** in Benders Decomposition between best and worst solution **can be kept low**, therefore **starting points are possible**. These can be estimated for stochastic optimization by the mean of scenario values.
- Trust regions can be **dynamically adapted**, based on performance of the new iterations.

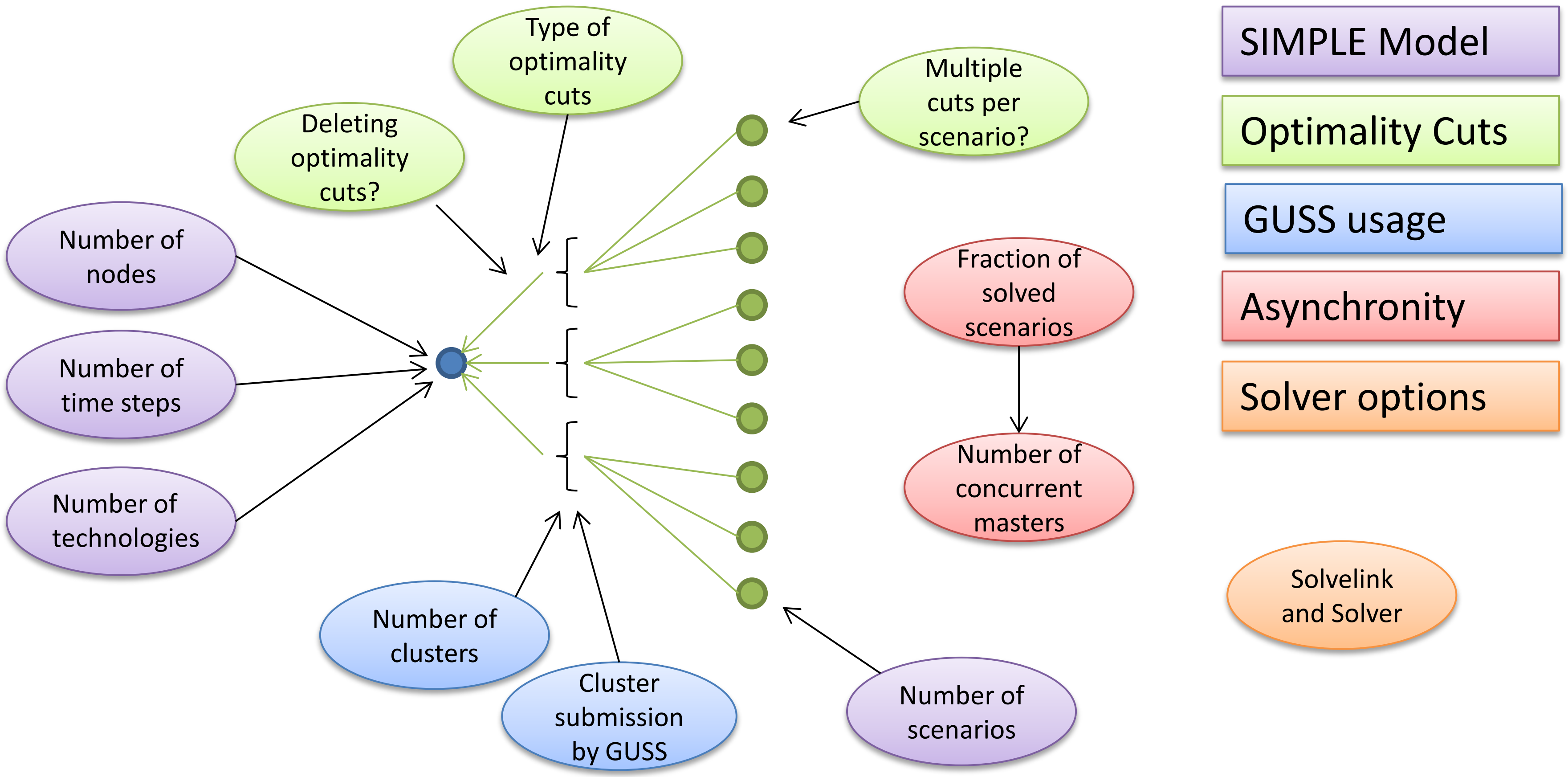
Using GAMS GUSS

- ➢ **Gathers** data from different sources/symbols in collection of models,
- ➢ **Updates** a base model instance with scenario data,
- ➢ **Solves** the updated model instance,
- ➢ **Scatters** the scenario results to output parameters



- Model has to **built only once** and **warmstaring improves solving time** drastically, however a the models in a GUSS instance can **not be solved in parallel**, but GUSS instances can be run in parallel

Algorithm parameters



- Large number of parameters to optimize performance of Enhanced Benders Algorithm making **systematic testing necessary**

Computational results

Nodes	Scenarios	TrustRegion	Cuttype	Syncronity	GUSS usage	Wallclocktime [hh:mm:ss]	Iterations	Avg Time / Iteration [s]
3	5		Multi	Async		00:37:45	129	17.5
3	5		Multi	Sync		00:31:50	135	14.1
3	5		Multi	Sync	GUSS	00:25:40	141	10.9
3	5		Single	Sync		01:07:23	300	13.5
3	5		Single	Sync	GUSS	00:53:07	300	10.6
3	5	TR	Multi	Async		00:17:41	60	17.5
3	5	TR	Multi	Sync		00:12:33	58	12.9
3	5	TR	Multi	Sync	GUSS	00:10:44	59	10.9
3	5	TR	Single	Sync		01:02:35	300	12.5
3	5	TR	Single	Sync	GUSS	00:51:51	300	10.4
3	25		Multi	Async		07:10:55	143	187.8
3	25		Multi	Sync		01:52:12	118	57.0
3	25		Multi	Sync	GUSS	01:04:10	130	29.6
3	25		Single	Sync		05:06:43	300	61.3
3	25		Single	Sync	GUSS	02:33:43	300	30.7
3	25	TR	Multi	Async		01:19:11	55	85.6
3	25	TR	Multi	Sync		00:49:29	53	56.0
3	25	TR	Multi	Sync	GUSS	00:26:14	53	29.6
3	25	TR	Single	Sync		04:30:07	300	54.0
3	25	TR	Single	Sync	GUSS	02:30:21	300	30.1

- All configurations with 8 model nodes instead of 3 were **aborted due to the 300 iterations limit**

Challenges

- **Reducing computational overhead** by using methods which simplify or reduce model building time (Usage of GUSS, externalizing model building)
- **Balancing CPU load** for migration to high performance computing

- **Generating better cuts** - insufficient electrical generation will cause all plant types in a region to be built
- **Deleting unused cuts** in order to keep the masterproblem as small as possible while retaining important information

- **Improving the starting point** for the Trust-Region approach

- Combining stochastic optimization with **decomposition on the scenario level** (decoposition in model nodes or timesteps) in a Nested Benders approach

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