Webinar Jan. 28, 2020

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Agenda

- **Introduction:** short presentation of plan4res (S. Charousset)
- **Case Studies**
  - Introduction and CS1 "Multi-modal European energy concept for achieving COP 21"– D. Most
  - CS2 "Strategic development of the pan-European network"– S. Giannellos
  - CS3 " Assessing cost of RES integration and impact of climate change for the European electricity system" – S. Charousset
- **Modelling** – D. Beulertz
- **Implementation**
  - Transformation tools – M. dell'Amico
  - IT Platform : WorkFlows and Container – U.U. Haus
  - SMS++ - A. Frangioni
- **Solvers**
  - Decomposition – A. Frangioni
  - Solving Large Mixed Integer Linear Problems with SCIP – T. Koch

Introduction

Sandrine Charousset, EDF
Project Coordinator

plan4res Consortium

- ÉLECTRICITÉ DE FRANCE SA (EDF)
- IMPERIAL COLLEGE LONDON (IMPERIAL)
- SIEMENS AG, CORPORATE TECHNOLOGY (SIEMENS)
- CRAY HEWLETT PACKARD ENTERPRISE (CRAY)
- ZUSE INSTITUTE BERLIN (ZIB)
- RWTH AACHEN UNIVERSITY (RWTH)
- CONSORZIO INTERUNIVERSITARIO PER L'OPTTIMIZZAZIONE E LA RICERCA OPERATIVA (ICOOR)

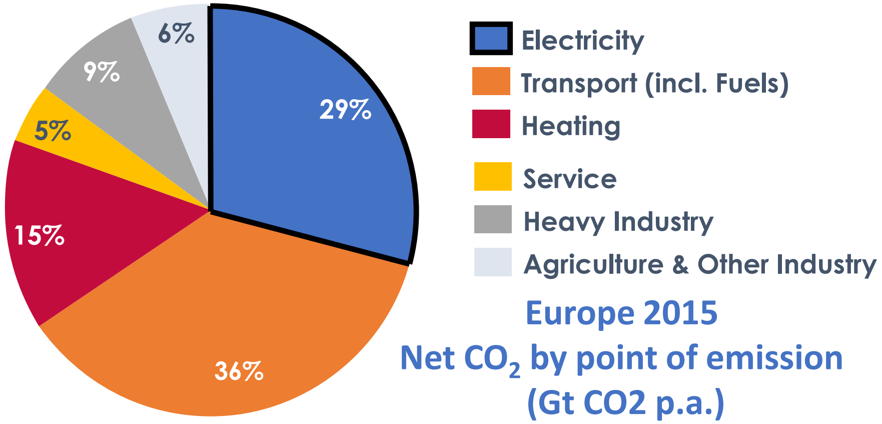
CRAY a Hewlett Packard Enterprise company
eDF
IN SUPREMÆ DIGNITATIS 1343 UNIVERSITÀ DI PISA
RWTH AACHEN UNIVERSITY
SIEMENS Ingenuity for life
UNIVERSITAS STUDIORUM MUTINENSIS ET REGIENSIS 1175 UNIMORE UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
ZIB
Imperial College London
plan4res

plan4res storyline

Facing European targets for reduction of greenhouse gas emissions while maintaining high quality of supply and low cost

⇒ Electricity : Increase Share of renewable

⇒ Other Energies : move uses to low emission energy sources



Europe 2015
Net CO_2 by point of emission
(Gt CO2 p.a.)

- ❖ **Optimise balance between new investments and optimum use of existing assets**
- ❖ **Maximise use of all (both traditionnal and emerging) flexibilities**

plan4res will provide : the **integrated representation of the system** which is necessary in order to simulate the energy system expansion and operation thus helping Europe to achieve its objectives with the lowest cost

Expected Results

An ***end-to-end planning and operation tool,*** composed of a set of optimization models based on an ***integrated modelling*** of the pan-European Energy System;

An ***IT platform*** for providing seamless access to data and high performance computing resources, catering for flexible models (easily replacing submodels and the corresponding ***efficient solution algorithms***) and workflows;

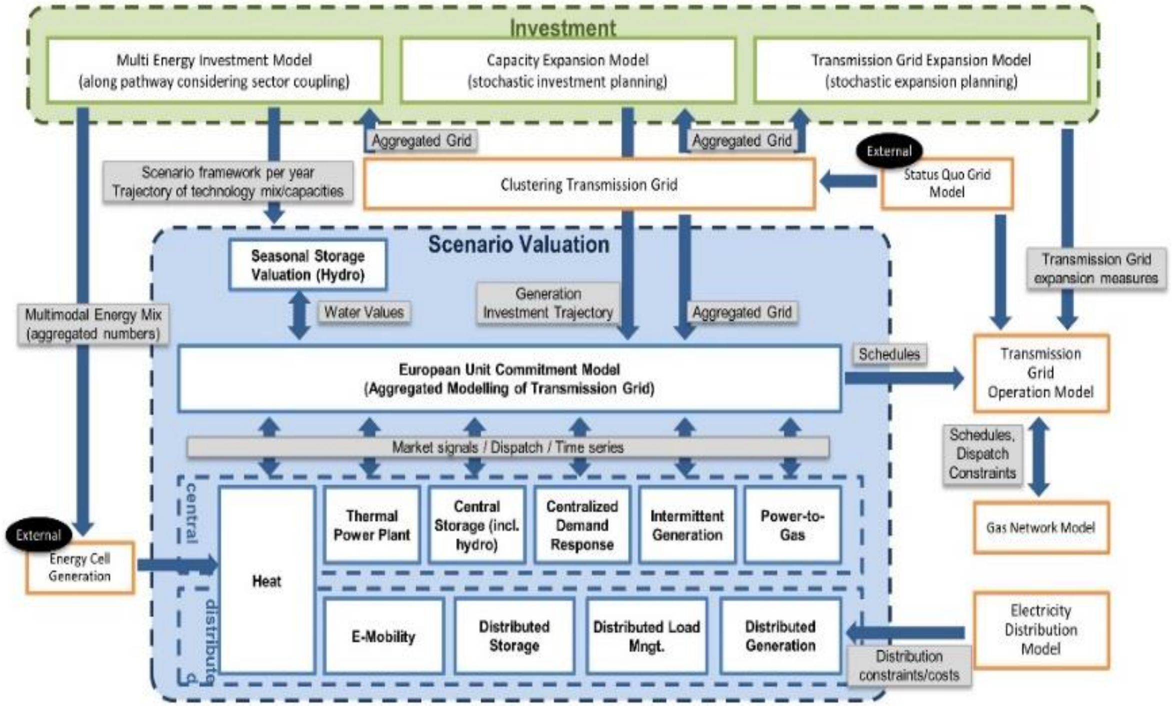
A *database of public data*

3 ***case studies*** highlighting the tool's adequacy and relevance.

An integrated Modelling

An end-to-end planning and operation tool, composed of a set of optimization models based on an integrated modelling of the pan-European Energy System

- **Investment layer**: Determine investment decisions
- **Scenario valuation**: Evalute investment decisions/operational planning
- **Analysis/additional tools**: Impact of scenario on electricity & gas grid



3 Case Studies to highlight the tool's adequacy and relevance

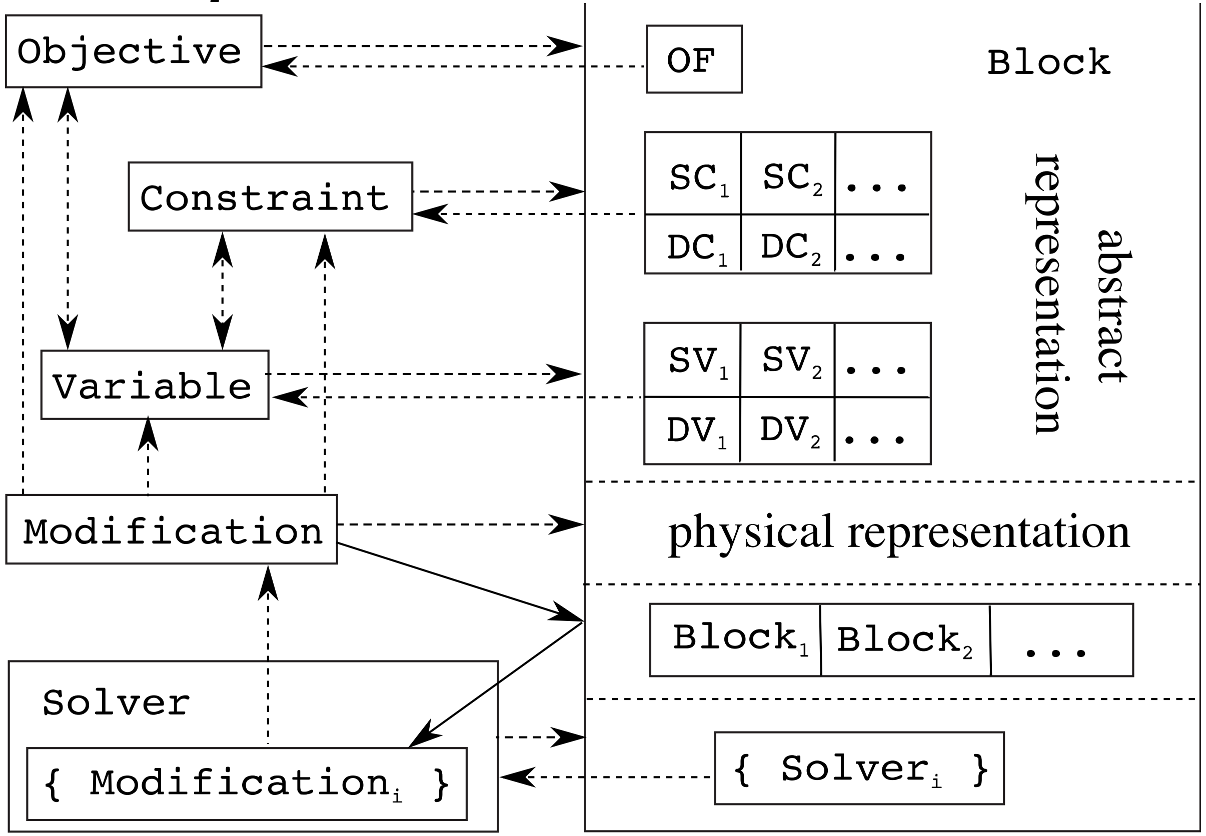
- **Sector coupling: which energy mix for achieving COP 21?**
  - Based on a Multi-modal European energy concept for achieving COP 21
  - with perfect foresight, considering sector coupling of electricity, heat & cold, traffic, fuel/gas; and coupling to gas grids
- **Strategic development of the pan-European transmission network**
  - without perfect foresight and considering long-term uncertainties
- **Assessing cost of RES integration, value of flexibilities and impact of climate change for the European electricity system**
  - Without perfect foresight :

The Modelling System : SMS++

❑ A *modelling system* for *structured problems*

SMS++ is a set of C++ classes implementing a modelling system that:

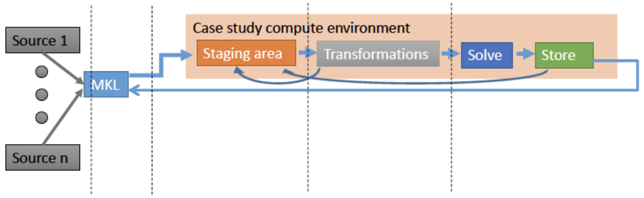
- ❑ allows exploiting specialised solvers
- ❑ manages dynamic changes in the model reformulation/restriction/relaxation
- ❑ does parallel (almost) from the start
- ❑ should be able to deal with almost anything (bilevel, PDE,..)
- ❑ ***Includes specialized blocks for energy system modelling***

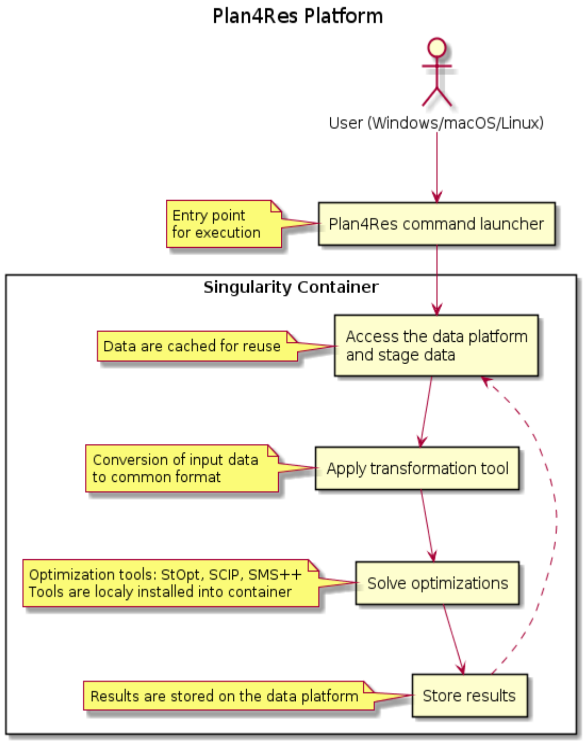


An efficient IT Platform

Containers

Workflows

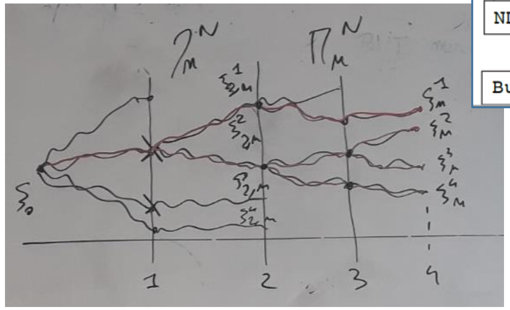


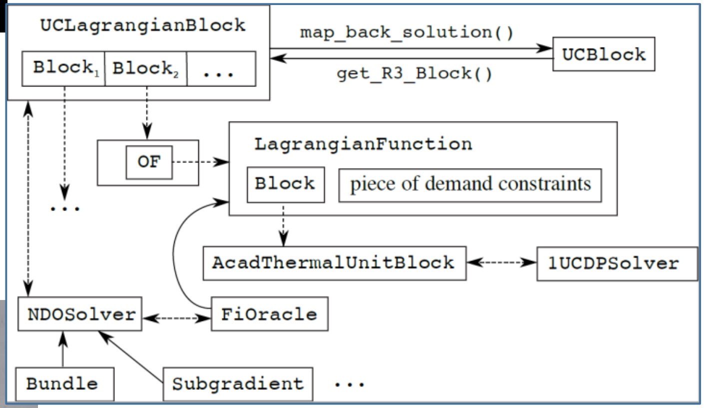


Parallelization

Solving Algorithms

- The latest SCIP release for large-scale MIP problems
- StOpt, an open-source stochastic optimization library for large seasonal storage problems
- NDOSolver/FiOracle, for solving problems induced by decomposition algorithms





Project Schedule

2018 | 2019 | 2020

Case Studies
- Case Studies Definition & requirements
- (test) modules from modelling, data sets and implementation
- Perform Case Studies

Modelling
- Model interconnections & functional/mathematical description

Data Sets
- Identify & Acquire Raw Data
- Transform & construct datasets Data Model
- Cure data

Implementation and solvers
- Implement methods & algorithms
- Implement tools
- Implement models & demonstrators

First Results

- Insights into Case Studies
  - Detailed description of CS D2.1(publ
- Optimization models
  - Simplified modelling :D3.1 (public)
  - Detailed (not public) modelling: D3.2
  - Joint paper (published)
- Data platform (for consortium use only)
- Datasets
  - *Datasets for case studies (not public)*
  - Public dataset (april 2020)
- Data transformation tools (open source / october 2020)
  - Aggregation/disaggregation
  - Data formatting for SMS++
  - Gaslib
- Innovative C++ modelling framework
  - SMS++ will be Open source (oct. 2020)
- (OpenSource) State of the art Solution algorithms:
  - SCIP (very large MILP) (next release 02/20)
  - StOpt (SDDP) (available)
  - NDOSolver/FiOracle (Decomposition) (available 02/20)
- Software architecture and specifications
  - Public deliverable D6.1
- Workflow coordination tool
- Containers

Case Studies

Dieter Most, SIEMENS, WP leader & CS1 leader
Spiros Giannellos, Imperial College, CS2 leader
S. Charousset, EDF, CS3 leader

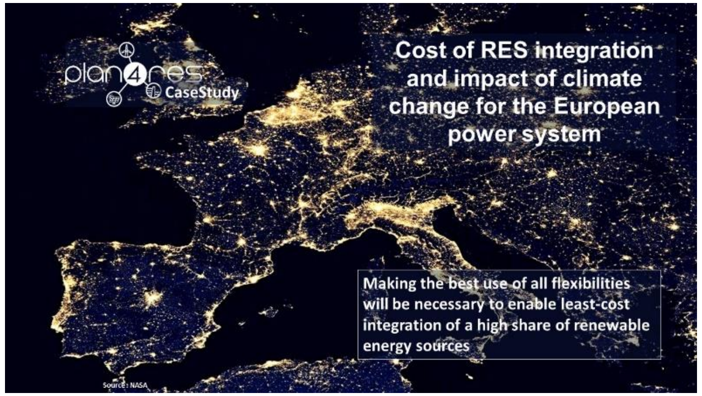
Case Studies

Case Study 1: Multi-modal European energy concept for achieving COP 21

w/ perfect foresight,
considering sector coupling of electricity, heating, cooling, mobility and coupling of electric / gas grids

Case Study 2: Strategic development of the pan-European network

w/o perfect foresight
considering long-term uncertainties



Case Study 3: Assessing cost of RES integration and impact of climate change for the European electricity system

in a future world with high shares of renewable energy sources

Case Studies – Definition & Requirements

- **Main Objective:**
  Performing 3 case studies with different view on the energy system which should demonstrate the adequacy, relevance and feasibility of the plan4res' modelling framework and data base

  Workshop with external stakeholders for Case Study Definition
  April 2018
  - Recommendations and requirements for public data set
  - Recommendations and requirements for case studies
  - Further ideas for sensitivities and case studies

- **D2.1: Definition and Requirements of 3 Case Studies**
  - Specific questions that each case study aims at answering to;
  - Methodology for answering the questions, including a description of the used tools and models used per case study;
  - Description of the various sensitivities planned per case study;
  - Common assumptions, as well as specific data & data sources;
  - List of planned sensitivities per case study
  - Expected results from 3 case studies

D2.1 long version download from www.plan4res.eu

4p-summary of case study definitions

CS① CS ② CS ③

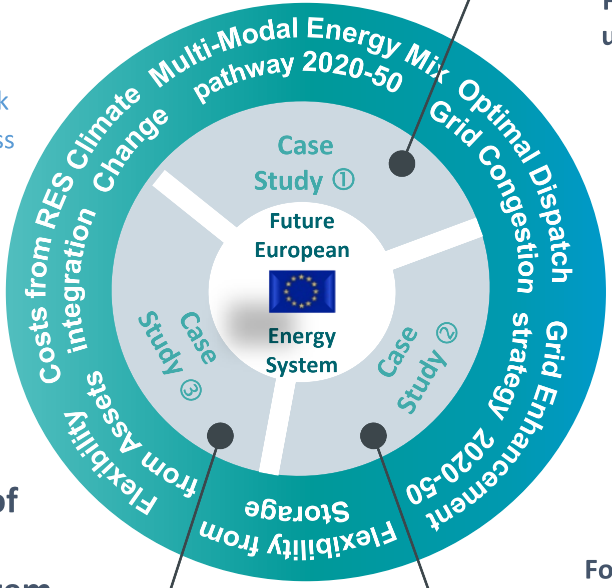
Modular Framework for Analysis of the Pan-European Energy System

Integrated end-to-end planning and operation modelling suite

- Modular Modeling Framework
- IT platform for seamless access to data and high performance computing resources,
- Catering for flexible models (easily replacing sub-models and efficient solution algorithms)
- Public datasets

Assessing cost of RES integration and impact of climate change for the European electricity system

Focus on authorities, utilities



Multi-modal European energy concept for achieving COP 21

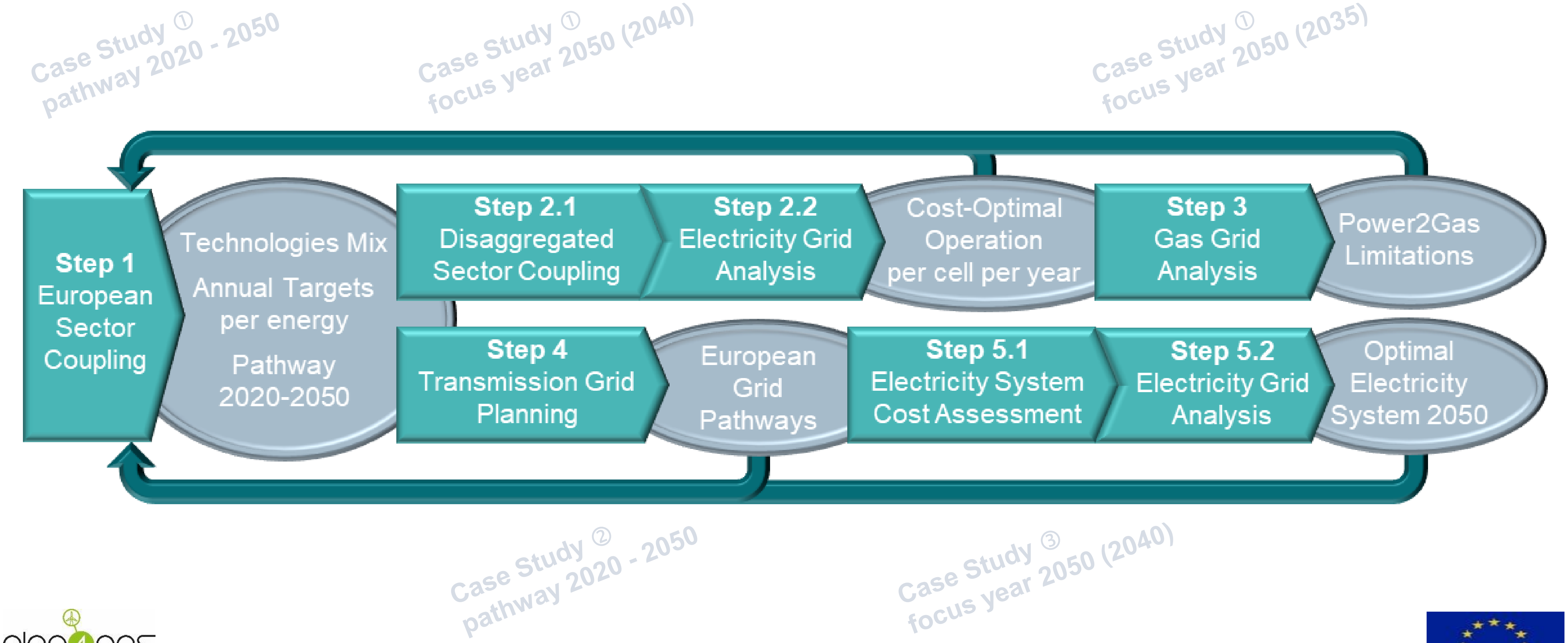
Focus on authorities, operators, utilities, energy system analysts

Strategic development of the pan-European transmission network

Focus on authorities, TSOs/DSOs, investors related to RES / storage

Illustrative Workflow for Joint Modelling

Framework's capability to facilitate joint modeling of different stakeholder viewpoints



Case Study 1

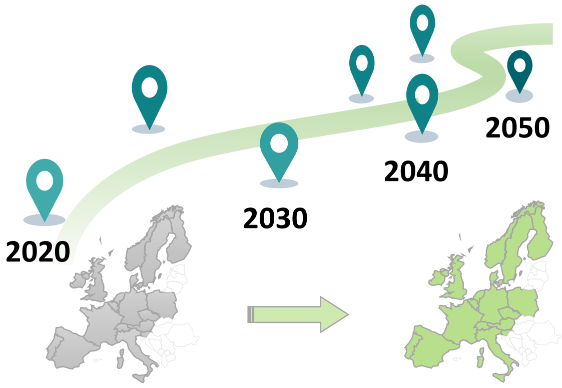
CS1 - Objectives

- **How to meet COP21 targets? What is the optimal pathway?**
  - Determine an optimal future energy mix
  - Propose a cost-effective investment pathway
  - Assess impact of sector coupling on the future generation fleet (eMobility, Power2Heat, Power2Gas)

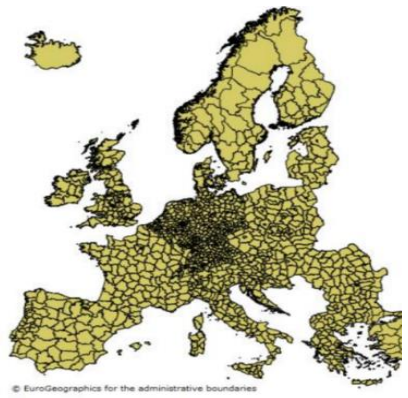
- **Assess the tool's adequacy and relevance to analyze:**
  - Investment trajectory for an integrated energy system
  - Impact of extended pan-European cross-border energy exchange
  - Impact of sector coupling on the future multi-modal energy mix
  - Impact of emerging technologies on the integrated energy system
  - Potentials and constraints from coupling electric grid and gas network via power2gas

CS1 - Multi-modal European energy concept for achieving COP 21 goal

- **Case study 1 will focus on the modeling of the**
  - Cost-effective investment trajectory
  - Future multimodal energy mix for Europe
  - Impact of sector coupling
- **The objective of this case study is to assess the plan4res tool's ability to capture:**
  - The investment trajectory for a cluster of countries
  - The impact of a pan-European energy exchange



Challenges:
- massive linear optimization problem → Several European countries are modeled in parallel in sub-country resolution & along a pathway
- ensure data quality on all spatial resolutions
  - adapt scope and cell sizes level according to available data quality and limiting requirements from modeling & analysis
  - transformation algorithms to aggregate or break down data and results between cell sizes level
- construction of adequate gas grid model (incl. data acquisition)



CS1 - Methodology

Pathway 2020-2050

Focus Year 2050 (2040)

Step 1 / Investment

1 **Multi modal investment**
- Transition pathway
- Scenario-based use-ful energy demand
- Technology neutral optimisation
- Aggregated spatial resolution
- Linear optimization

Step 2 / Operation

2 **European unit commitment**
- Single year optimization
- Disaggregation of Step 1 energy mix scenario
- High spatial reso-lution
- Lagrangian relax-ation

3 **Transmission grid operation**
- Powerflow
- Congestion manage-ment
- Detailed European grid model
- Consideration of sector coupling technologies

4 **Gas grid operation**
- Nomination validation
- Consideration of power-to-gas and gas power plants
- Derive constraints for operation schedules
- Detailed gas grid model

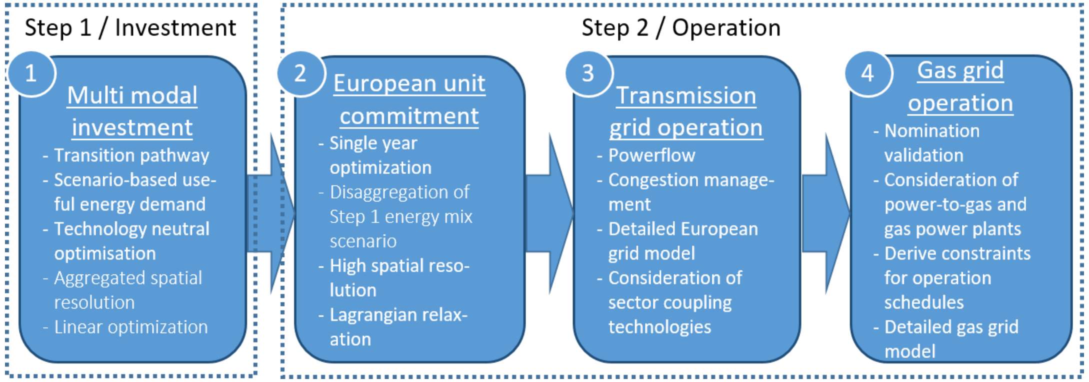
Step 1 provides the optimal energy mix along the transition pathway, investments and retirements

Step 2 performs a detailed bottom up modelling for further analysis of single years of the pathway

Coupling electric and gas grid
→ feasibility of Power2Gas

CS1 – Methodology - Results

- optimizes investment along pathway annual dispatch
- modelling with perfect foresight
- optimisation with constraints from electric grid
- uses two spatial resolution levels (transfer of results / data from Step 1 → Step2)
- explicitly includes sector coupling technologies to capture the impact of interacting multi-modal energy systems
- check feasibility of Power2Gas schedules and location, using a gas grid model



- **Step 1 provides the optimal energy mix along the transition pathway**
  - **early retirements and new installations** for each technology capacities per year
  - **hourly generation and load profiles** for each technology per year
  - **macro-economic cost estimations** and **price levels** for the used energy types
- **Step 2 performs a detailed bottom up modelling for further analysis of single focus years along the pathway**
  - **operation schedules** for power plants, storages and distributed generation units
  - **transmission grid operation** model provides results regarding line utilizations and **congestion management**
  - gas grid models evaluates **feasibility of Power2Gas schedules** decisions

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CS1 – Data Sources

- **technology data related to energy types heating/cooling, mobility, electricity, gas/fuel**
  - efficiency, availability
  - specific CAPEX & O&M costs
  - installed fleet (incl. storage)
  - regional limits for investments
  - public retirements plans
  - plans for forced investment
- **generation profiles Wind/PV/Solar/Hydro**
- **electricity exchange capabilities between regions simplified NTC approach**
- **data about electric and gas grid structure**
- **gas supply / demand forecast for EU28+**
- **projection Demand for 'Direct-Used Energy'**
- **projection of GDP and population**
- **statistical building & sociodemographic data**
- **statistical data about industries ('Kataster')**

CAPEX OPEX	→ EU EC JRC, public data sets
Heating Cooling	→ Heat Roadmap Europe 2050 (HRE4)
Transport	→ EU Ref Scen 2016
Industry	→ EUROSTAT, NAVIGANT Gas For Climate DECHEMA 2017 "Low carbon energy [..] for the European chemical industry"
Installed Base PP	→ entso-e, IRENA, EUROSTAT
Electric Grid	→ entso-e TYNDP, eHighway 2050 (NTCs),
Gas Grid	→ entso-g, public data sets
Weather	→ generation profiles:www.renewables.ninja or EU ECEM (climate change)
GDP, Population	→ Projection of EU Ref Scenario 2016
Building data,	→ EUROSTAT, Digital data service
Socio/demographic	→ Digital data service, EU Ref Scen 2016
Fuel / CO_2 Prices	→ Projections of IEA World Energy Outlook

CS1 - List of Technologies – Sector Coupling

El. Generation Utility & Industry
- Steam PP Coal/Gas/Oil/Lignite
- GT PP Oil / Gas
- CCGT PP Oil / Gas
- Nuclear PP
- CHP Engine (large)

Renewables
- Hydro Run-of-River
- Hydro Lake w/ reservoir
- Solar PV (large farms)
- Wind Onshore,
- Wind Offshore
- Waste
- Biomass / Biogas
- Solar thermal (large)

Generation - decentral
- Rooftop PV (small)
- Micro CHP
- Fuel cells (incl. CHP)
- Solar Heat (roof-top size)

Grids
- Electric (Transmission) Grid
- District Heating
- District Cooling [1)]
- Gas Grid [2)]

Transport (Mobility)
- Classic Mobility (Rail / Road / Ship / Air) [1)]
- Public Bus / Coaches
- Fuel Cell Cars / Trucks / Rail / Bus [1)]
- E-Mobility
  - eCar, eBus, eCoach
  - eTruck heavy & light, eHighway
  - eAircraft [1)]

Transport Demand (short/long distance)
- Passenger in p*km
- Freight in t*km (light/heavy)

Cooling - central / decentral
- Compression Chiller [1)]
- Compression Chiller HVAC [1)]
- Absorption Chiller (large) [1)]

Heating – temperature levels
- LT <100 °C
- MT 100°C – 150°C
- HT 150°C– 500°C
- VHT >500°C

Heating - decentral
- Small Boiler
- Small Electric
- Micro CHP
- Heat Pumps (Air / Water)
- District Heating

Heating - central
- Large Boiler
- Heating rod (electric) LT / MT
- Heating rod (electric) HT /VHT
- Arc Furnace (electric) VHT
- Furnace VHT
- Heat Pump (LT / MT)

Storage
- Pumped Hydro
- Batteries
- Heat Storage HT (small, large)
- Heat Storage MT (small, large)
- Heat Storage LT (small, large)
- Cold Storage H_2O (small, large) [1)]
- Cold Storage Ice (small, large) [1)]
- Gas Storage in Cavern (NG/H_2) [2)]

Power to ...
- Electrolyseur (H_2)
- Power2Gas (CH_4)
- Power2Synfuel (Liquid Fuel)

Industry Demand correlated to P2G [2)]
- Simplified Steam Methane Reforming [1)]
- Simplified Refineries & H_2 Demand [1)]
- Chemical Industry H_2 Demand [1)]
- Ammonia Demand & Simplified Synthesis [1)]
- Methanol Demand & Simplified Synthesis [1)]

1) CS1: Step 1, but not considered in Step 2
2) CS1: Step 3 ‘gas grid modeling’ add-ons

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Case Study 2

Key points

- Capital decisions in power systems are largely **irreversible**.
  This creates the risk of inefficient investment (**stranded assets**).
- There is **learning** regarding future developments (inter-temporal resolution of uncertainty).
- The planner can exert **managerial flexibility** in decision making; ‘Fit-and-forget’ vs. ‘Wait-and-see’.

Planning-under-uncertainty optimisation frameworks are fundamental for identifying openings for strategic action

Storyline

- Pan-European policy dictates reduction of Greenhouse Gas emissions.
- Such a policy motivates increased renewable capacity connections on a pan-European level.
- Increased level of uncertainty around generation, demand and costs.
- High quality of supply at least possible cost must be ensured.
- Energy Storage can play a significant role since it can offer *flexibility to deal with uncertainty*.
- Optimisation balance between new investments and optimum use of existing assets.

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Key Points (1)

- **Consideration of Long-Term Uncertainties.**

  - Key sources of uncertainty:
    - Generation installed capacities (mainly solar, wind)
    - Peak Demand
    - Technology Costs related to energy storage development

  - Exogenous type of uncertainty
    - Use of a scenario tree to represent the process of uncertainty
    - Investment decisions are made in such a way as to hedge against the inherent stranded-asset risks of uncertainty

  - Multi-Dimensional Uncertainty
    - Location-Dependent: uncertainty as to the location of connections
    - Time-Dependent: uncertainty as to the timing of connections
    - Magnitude-Dependent: uncertainty as to the magnitude of connections.

Key Points (2)

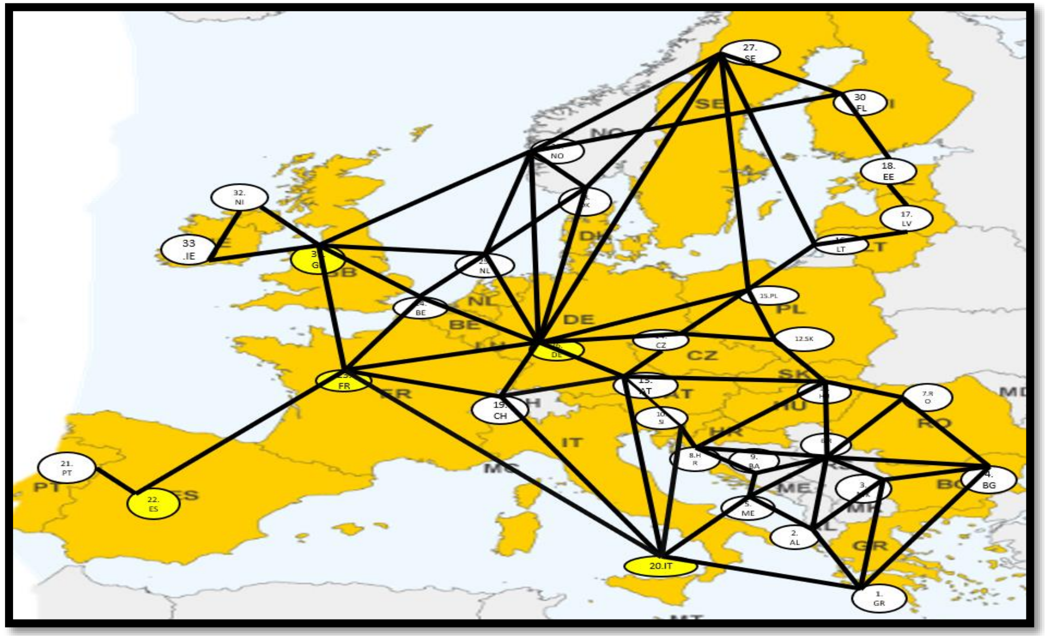
- **Multi-Asset Capability.**
  - Conventional and non-conventional assets as investment alternatives:
    - Conventional Investments: Upgrades of existing transmission interconnectors
    - Non-Conventional or ‘flexible’ investments: Energy Storage
  - Energy Storage technologies
    - Lithium-Ion Batteries
    - Pumped-Hydro Storage
  - Detailed Modelling of Hydro-Units
    - Hydro run-of river
    - Hydro reservoir
  - Detailed Modelling of technical generation-related constraints
    - Ramp-up and ramp-down constraints
    - Consideration of ‘build-time’ delay for investments.

Key Points (3)

- **Optimal Investment Strategies covering 2020 to 2050 in the European Context.**

  - Consideration of thirty three European Countries and their interconnectors.
  - Starting from 2020, the study horizon is broken down in four epochs/stages:
    - 2020-2029
    - 2030-2039
    - 2040-2049
    - 2050-2059

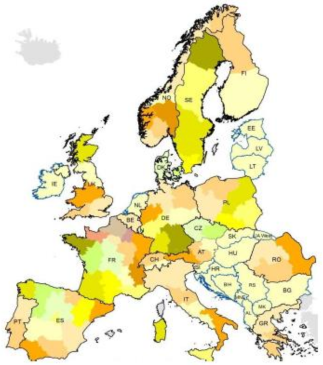
  with investment-decision points at years: 2020, 2030, 2040, 2050.



Case Study 3

CS3 - Objectives

- **Case study 3 will focus on the Pan-European electricity sector in 2050**
- **The objective of this case study is to assess the plan4res tool's ability to capture**
  - **The Impact of different levels of RES integration on the European system costs**
    - Electricity generation cost
    - Cost to ensure the dynamic robustness of the system (Reserves, Inertia)
    - ...
  - **The Value of different flexibility services: system cost reduction coming from using the flexibility potentials of the different system assets.**
    - RES can be represented as non-flexible, i.e. all generation is 'fatal' or we can account for their ability to be curtailed or can contribute to ancillary services
    - Flexibilities from storages and additional storages can be represented
    - Different demand response flexibilities can be modelled
  - **The impacts of climate change**
    - Differences in Temperature scenarios (level, dynamics)
    - Differences in Wind/Sun scenarios with impact on RES generation potentials
    - Including correlations



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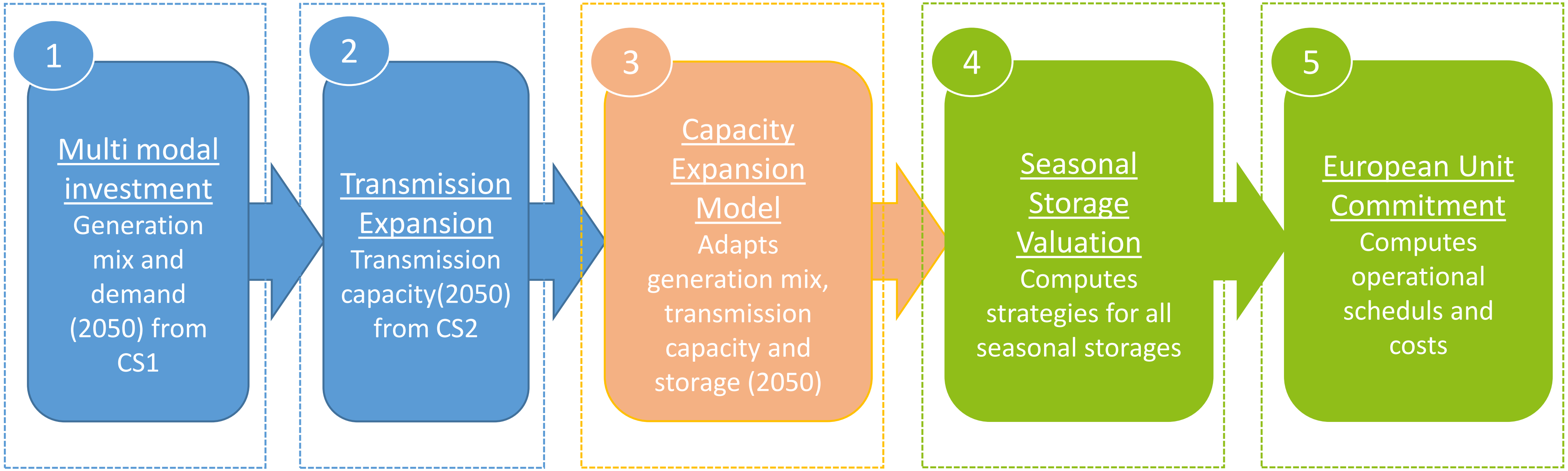
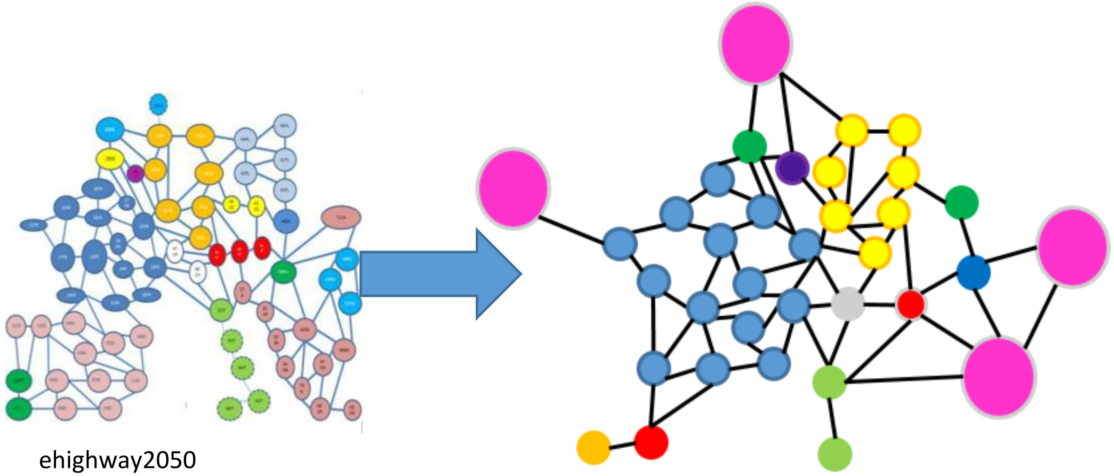
CS3 - Methodology



CS3 - Methodology

- ❑ *The Capacity expansion model computes the optimal mix*
  - electric generation plants,
  - storages,
  - interconnection capacities between clusters
  - distribution grid capacities, *Scenario valuation layer:*
- ❑ The seasonal storage valuation model computes the operation strategy for seasonal storages
  - For Hydro reservoirs
  - And also all other 'seasonal' flexibilities such as Demand response
- ❑ The European unit commitment (EUC) model computes the optimal operation schedule for all the assets dealing with constraints:
  - Supply power demand and ancillary services
  - Minimal inertia in the system
  - Maximum transmission and distribution capacities between clusters
  - Technical constraints of all assets



ehighway2050

CS3 - Methodology

- **Comparing several scenarii / sensitivities:**
  - **For assessing the cost of RES integration:**
    - High share of RES (optimistic scenario)
    - Low share of RES (sensitivity analysis)
  - **For assessing value of flexibility:**
    - No flexibility in the initial scenario
    - Addition of flexibilities individually, and collectively
  - **For assessing the impact of climate change:**
    - Simulation with present climate variables
    - Simulation with future (2040/2050) climate variables

Data Sources:

CAPEX OPEX
Energy targets
Volume of installed mix
=> Case Study 1

Physical constraints of assets
=> eHighway2050

Time series profiles
=> C3S Energy

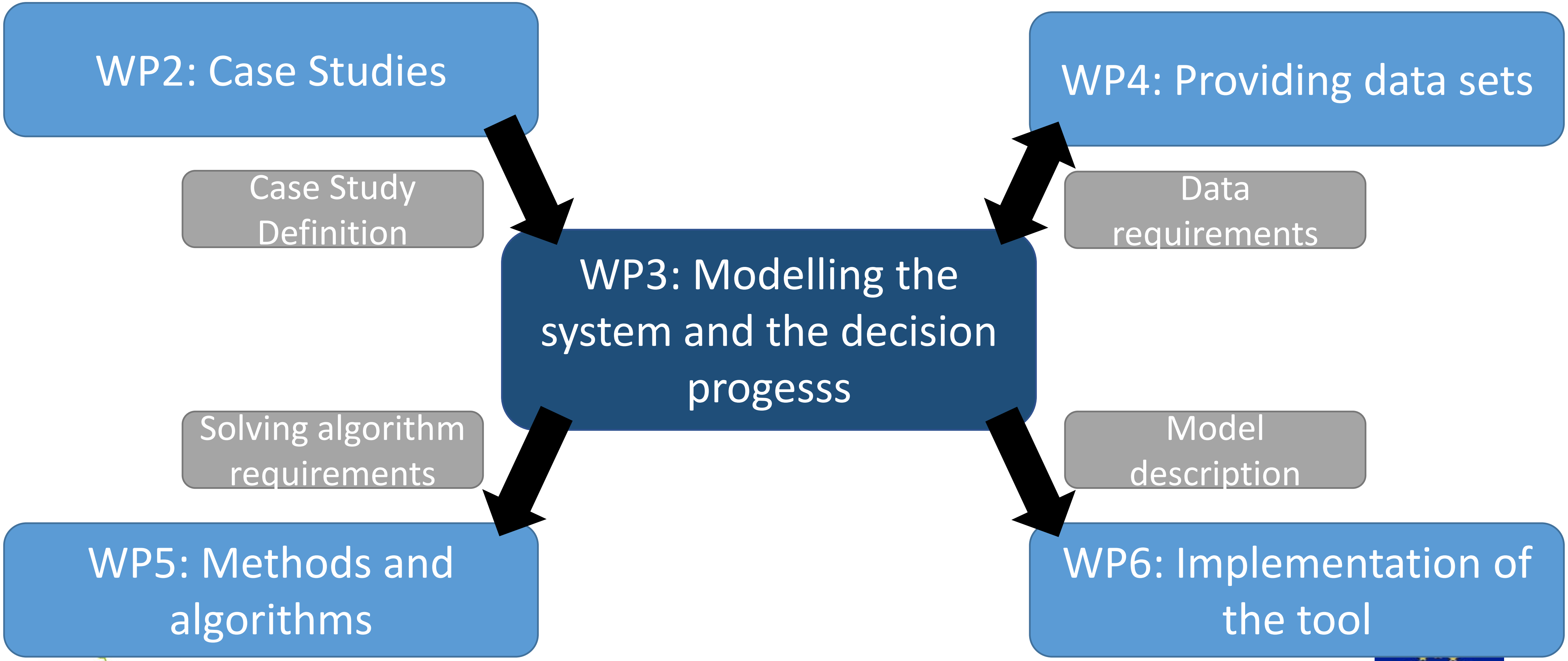
eHighway2050: www.e-highway2050.eu
C3S: https://cds.climate.copernicus.eu

Case Studies – Questions?

Modelling

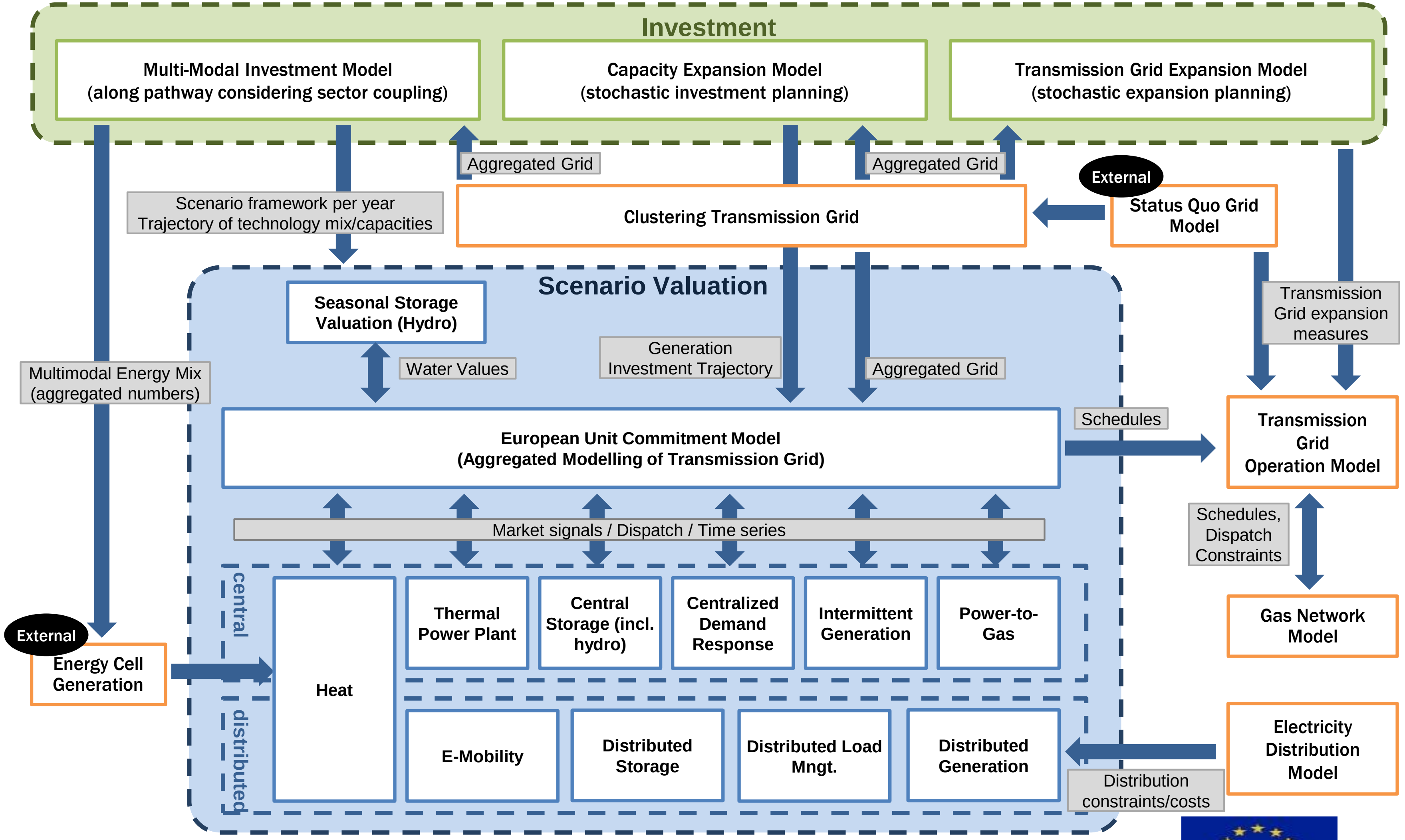
Daniel Beulertz, RWTH Aachen, WP leader

WP3 – Project context



Modeling overview

- Investment layer: Determine investment decisions
- Scenario valuation: Evalute investment decisions/operation al planning
- Analysis/additional tools: Impact of scenario on electricity & gas grid



Multi-Modal Investement Model

CS 1

- Minimize total system costs for investment pathway considering electricity, heat and transport

$$\min\left(C^{inv} + C^{opr}\right)$$

- Constraints for power balance and CO_2 emissions

$$\sum_{cs} p^{In}_{cs,t,x,y} + p^{In,slack}_{co,t,x,y} + g_{co,t,x,y} = \sum_{cs} p^{Out}_{cs,t,x,y} + p^{Out,slack}_{co,t,x,y}$$

$$o^{tot,Y}_{y} = \sum_{cs} e^{out}_{cs,y} * F^{CO_2}_{cs,y} \leq O^{CO_2}_{y}$$

$$\sum_{y} F^{mult}_{y} * o^{tot,Y}_{y} \leq \sum_{y} O^{CO_2}_{y}$$

$\boldsymbol{co}$: Commodity
$\boldsymbol{cs}$: Transformation process
$\boldsymbol{t}$: Timestep
$\boldsymbol{x}$: Region
$\boldsymbol{y}$: $Year$
$\boldsymbol{p^{In}_{cs,t,x,y}}$, $\boldsymbol{p^{Out}_{cs,t,x,y}}$: Input/Output to process cs
$\boldsymbol{p^{In,slack}_{co,t,x,y}}$, $\boldsymbol{p^{Out,slack}_{co,t,x,y}}$: Slack Input/Output to commodity co
$\boldsymbol{g_{co,t,x,y}}$: Net-Import to commodity co
$\boldsymbol{e^{out}_{cs,y}}$: Total energy output of process cs per year
$\boldsymbol{F^{CO_2}_{cs,y}}$: Specific CO_2 emissions of process cs in year y
$\boldsymbol{O^{CO_2}_{y}}$: Maximum allowable CO_2 emissions in year y
$\boldsymbol{F^{mult}_{y}}$: Number of occurences of year y

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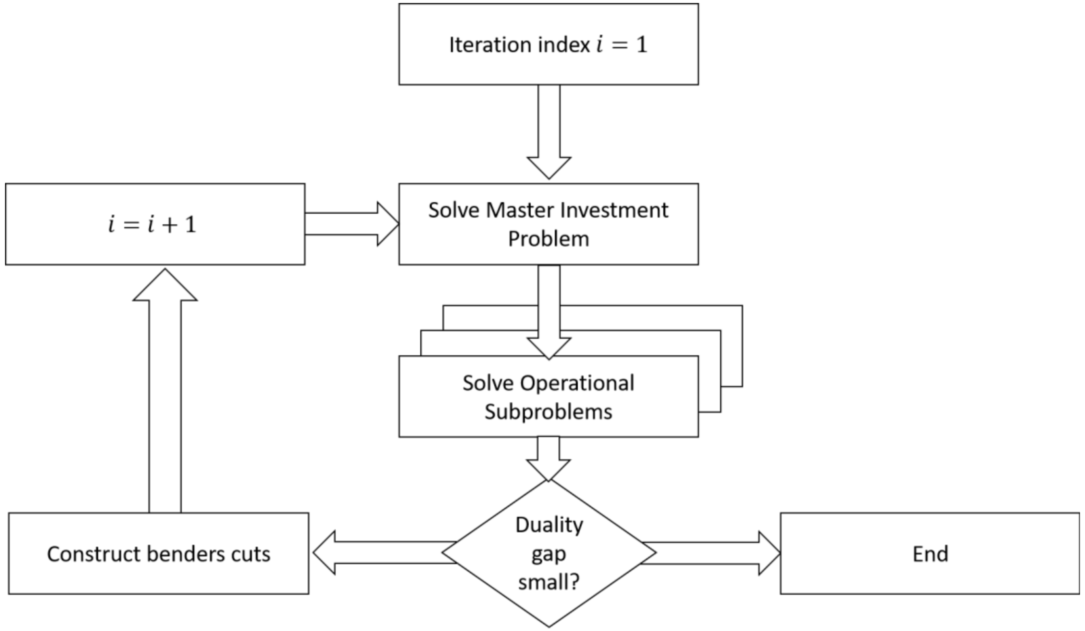
Transmission Grid Expansion Model

CS 2

- **Optimal investment decisions for energy storage deployment and power transmission corridor upgrad/construction**
- **Use of benders decomposition to seperate investment and operation decisions**
- **Minimize total investment costs in the master problem**

$$min \sum_{m} \pi_m r_{\epsilon_m} C_m^{inv,tot} + \alpha_m$$



π_m: Probability of the scenario tree's node m occuring
r_{ϵ_m}: Discount factor for investment costs with respect
$C_m^{inv,tot}$: Total investment cost for node m
and the stage ϵ_m that the m node belongs to
α_m^i: Approximation of operational costs for node m

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Capacity Expansion Model

CS 3

- **Long term horizon**
- **Optimal generation mix with the optimal transmission and distribution grid capacities**

$$\min_{\kappa}\left\{C^{inv}(\kappa)+\max_{\eta\epsilon\Upsilon} C^{op}(\kappa,\eta)\right\}$$

- **Considering meta-scenarios (Υ), e.g. choice of climate change trajectory**
- **Operational costs determined for a discrete meta-scenario and fixed investment capacities in mid/short term problem**

$\boldsymbol{\kappa}$: Investment capacities of generation/lines
$\boldsymbol{\Upsilon}$: Set of meta–scenarios
$\boldsymbol{C^{inv}(\kappa)}$: Annualized investment costs induced by installing capacitiy κ
$\boldsymbol{C^{op}(\kappa)}$: Annualized operational costs with given capacity κ under assumption of meta-scenario η

Seasonal storage valuation

CS 3

- **Mid term horizon, minimizing the sum of operation costs on each sub-period (e.g. each week)**

$$C^{op}(\kappa) = \min_{x \in \mathcal{M}} \mathbb{E}\left[\sum_{s \in S} C_s(x_s)\right]$$

- **Operational costs C_s depend on installed capacity and uncertainties (load, inflows, renewable generation, outages) revealed at beginning of sub-period s**
- **Expextation $\mathbb{E}$ related to the probability distribution of uncertainties**
- **Evaluation of operational costs for sub-period provided by short term problem (EUC)**

$\boldsymbol{C^{op}(\kappa)}$: Operational costs depending on investment decisions κ
$\boldsymbol{C_s}$: Operational costs on sub-period s
$\boldsymbol{\mathcal{M}}$: Feasible set associated with operation decisions
$\boldsymbol{S}$: Set of sub-periods (e.g. weeks)
$\boldsymbol{x}$: Operation decisions on sub-period s
$\boldsymbol{\kappa}$: Investment decisions taken by capacity expansion model

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European Unit Commitment Model

CS 1

CS 3

- **Minimize operational costs of available units**

$$\min \sum_i C_i^{op}(p_{:,i}, p_{:,i}^{pr}, p_{:,i}^{sc}, p_{:,i}^{he}) + \alpha(v^{hy})$$

$$(p_{:,i}, p_{:,i}^{pr}, p_{:,i}^{sc}, p_{:,i}^{he}) \epsilon \mathcal{M}$$

- **Power balance constraint**

$$\sum_{i \epsilon I_n} p_{t,i} = D_{n,t}$$

- **Use of Lagrangian decomposition to decouple units**

$$\Theta(\lambda) = \min \sum_i C_i^{op}(p_{:,i}, p_{:,i}^{pr}, p_{:,i}^{sc}, p_{:,i}^{he}) + \lambda * \left(\sum_n D_{n,:} - \sum_i p_{:,i}\right) + \alpha(v^{hy})$$

$\boldsymbol{C_i^{op}}$: Operational costs of unit i subject to it's operational variables
$\boldsymbol{p_{t,i}, p_{t,i}^{pr}, p_{t,i}^{sc}, p_{t,i}^{he}}$: Provision of power, primary/secondary reserve, heat by unit i in timestep t
$\boldsymbol{\alpha}$: Approximation of the value of seasonal storages
$\boldsymbol{v^{hy}}$: Storage level
$\boldsymbol{D_{n,t}}$: Electrical demand at node n in tempstep t
$\boldsymbol{\lambda}$: Lagrangian multiplier

European Unit Commitment Model (2)

CS 3

- Consideration multiple regions and electricity exchange in EUC
- Updated power balance constraint

$$\sum_{i \epsilon I_n} p_{t,i} - D_{n,t} = \sum_{l=(n,.)\epsilon L} \sum_{n' \epsilon N} (B_t)_{(l,n')} \left(\sum_{i \epsilon I_{n'}} p_{t,i} - D_{n',t} \right)$$

$$- \sum_{l=(.,n)\epsilon L} \sum_{n' \epsilon N} (B_t)_{(l,n')} \left(\sum_{i \epsilon I_{n'}} p_{t,i} - D_{n',t} \right)$$

- Flow limit constraint

$$P_{l,t}^{mn} \leq \sum_{n' \epsilon N} (B_t)_{(l,n')} \left(\sum_{i \epsilon I_{n'}} p_{t,i} - D_{n',t} \right) \leq P_{l,t}^{mx}$$

$\boldsymbol{p_{t,i}}$ **:** Provision of power by unit i in timestep t
$\boldsymbol{D_{n,t}}$: Electrical demand at node n in tempstep t
$\boldsymbol{P_{l,t}^{mn}/P_{l,t}^{mx}}$: Minimum/Maximum allowable flow on line l in timestep t
$\boldsymbol{B}$: PTDF-Matrix

European Unit Commitment Model (3)

CS 1

- Country-specific load constraint
- Coupling of countries by market coupling algorithm
- Positive quantities for production-bids and negative quantities for demand-bids
- Price for supply bids defined by the Lagrangian multiplier of current EUC‘s iteration

$$\min_a \sum_z \sum_b M_{z,b}^{bid} \, C_{z,b}^{bid} \, a_{z,b}$$

$$\sum_{b \epsilon B^z} M_{z,b}^{bid} \, a_{z,b} + \sum_l f_l^{el} \, I_{z,l} = 0$$

$$f_l^{el} \le F_l^{el}$$

$\boldsymbol{f_l^{el}}$: Flow on line l
$\boldsymbol{F_l^{el}}$: Maximum line capacity for line l
$\boldsymbol{I_{z,l}}$: Indicator if line l is connected to zone z
$\boldsymbol{M_{z,b}^{bid}}$: Quantity of bid b in zone z
$\boldsymbol{C_{z,b}^{bid}}$: Price of bid b in zone z
$\boldsymbol{a_{z,b}}$: Ratio of acceptance for bid b in zone z

Submodels (1)

CS 1

CS 3

Power plants

- Operational decision of power plants based on their specific fuel costs
- Technical constraints (ramping, min up-/downtimes,...)

Storages

- Hydro storages including complex cascaded systems
- Battery storages

Heat

- Aggregation of decentral thermal & electric units (boilers, heatpumps, CHP, thermal storages)
- Supply of thermal demands by aggregated units and power plants via district heating

Submodels (2)

CS 1

CS 3

- **E-mobility**
  - Storage capability of electric vehicles (vehicle-to-grid, power-to-vehicle)
  - Limitation of storage availability by driving profiles
- **Centralized demand response/Distributed load management**
  - Load shifting of a given energy consumption during a sub-period
  - Load curtailment based on a given potential (e.g. during one year)
- **Intermittent/Distributed generation**
  - Generation of wind, solar, run of river based on meteorological profiles
- **Power-to-gas**
  - Operation of power-to-gas units based on a given gas price

Submodels – Power plants

CS 1

CS 3

- **Minimize operational costs with respect to Lagrangian multiplier**

$$\min_{p,u,z}(C - \lambda\ \ )p - \lambda^{pr} p^{pr} - \lambda^{sc} p^{sc} + C^{fx} u + C^{st} z^{st}$$

- **Operational constraints**

$$p_t \ + p_t^{pr} + p_t^{sc} \leq P_t^{mx} u_t$$

$$p_t \ - p_t^{pr} - p_t^{sc} \geq P_t^{mn} u_t$$

$$p_t^{pr} \leq \rho_t^{pr} p_t$$

$$p_t^{sc} \leq \rho_t^{sc} p_t$$

$$p_t \ \leq p_{t-1} + u_{t-1} G_t^{up} + (1 - u_{t-1}) P_t^{mn}$$

$$p_{t-1} \leq p_t \ + u_t G_t^{dn} + (1 - u_t) P_t^{mn}$$

$$u_t \geq u_{t'} - u_{t'-1}, for\ t' = t - \tau^{up}$$

$$u_t \leq 1 - u_{t'-1} + u_{t'}, for\ t' = t - \tau^{dn}$$

$$u_t - u_{t-1} \leq z_t^{st}$$

$\boldsymbol{p_t}$: Power generated by a unit in timestep t
$\boldsymbol{p_t^{pr}}, \boldsymbol{p_t^{sc}}$: Primary/secondary reserve generated by a unit in timestep t
$\boldsymbol{u_t}$: Status (on/off) of unit in timestep t
$\boldsymbol{z^{st}}$: Auxiliary variable indicating start of a unit in timestep t
$\boldsymbol{C}, \boldsymbol{C^{fx}}, \boldsymbol{C^{st}}$: Variable production, fixed production and startup costs
$\boldsymbol{\rho_t^{pr}}, \boldsymbol{\rho_t^{sc}}$: Partition of power generation that can be used for primary/secondary reserve in timestep t
$\boldsymbol{P_t^{mn}}, \boldsymbol{P_t^{mx}}$: Minimum/Maximum production level in timestep t
$\boldsymbol{G_t^{up}}, \boldsymbol{G_t^{dn}}$: Allowable ramping rate in timestep t
$\boldsymbol{\tau^{up}}, \boldsymbol{\tau^{dn}}$: Minimum up-/downtime of a unit

Supplementary models – Gas Network Optimization Models

CS 1

Nomination Validation (NoVa)

- Is the given nomination that specifies amounts of gas flow at entries and exits technically feasible?
- Stationary gas network model
- Network decisions are discrete, gas physics are continuous and non-linear: A mixed integer non-linear program (MINLP)
- Two model extensions to NoVa:
  - Allowable limits for electricity induced nomination
  - Re-dispatch electricity induced nomination (optional)

Given:

- ❑ **A detailed description of gas network**
- ❑ **A nomination**

Constraints:

- ❑ **Flow conservation at nodes**
- ❑ **Pipelines: Weymouth Equation**
- ❑ **Active devices: Valves (open or closed); Control valves (active, bypassed or closed), Compressor stations**

Output:

- ❑ **Settings for the active devices**
- ❑ **Values for the physical parameters of the network that comply with gas physics technical limitations**

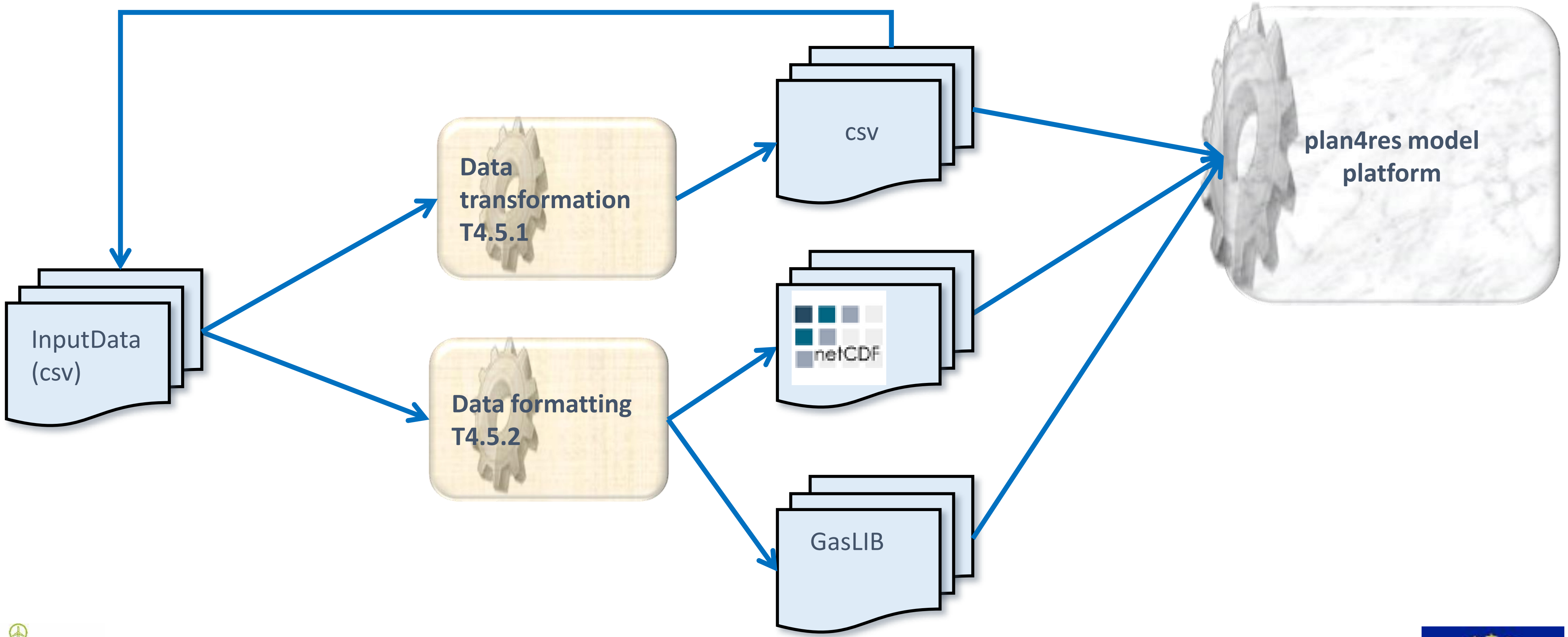
Modelling – Questions?

Implementation

Utz-Uwe Haus, CRAY HPE, WP leader
Antonio Frangioni, University of Pisa
Mauro Dell'Amico, University of Modena

Data Transformation Tools

Transformation tools input-output

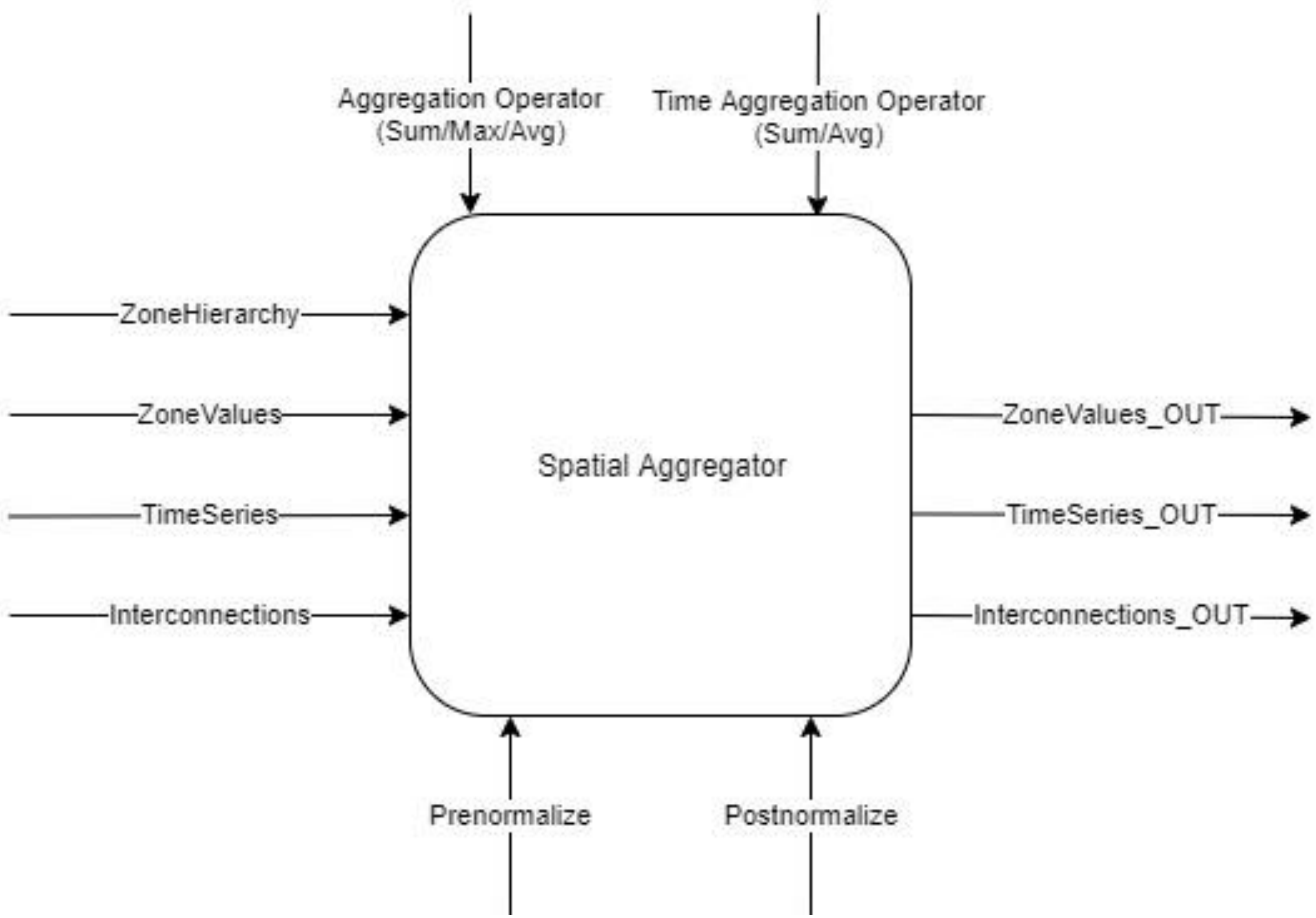


Transformations…

- Data Transformation
  - Spatial aggregation/disaggregation
  - Time aggregation
  - Gas timeseries transformation
- Data Formatting
  - Scenarios to NetCDF format
  - Gas raw data transformation into GasLib format
- Transformation utility
  - Massive data format transformation

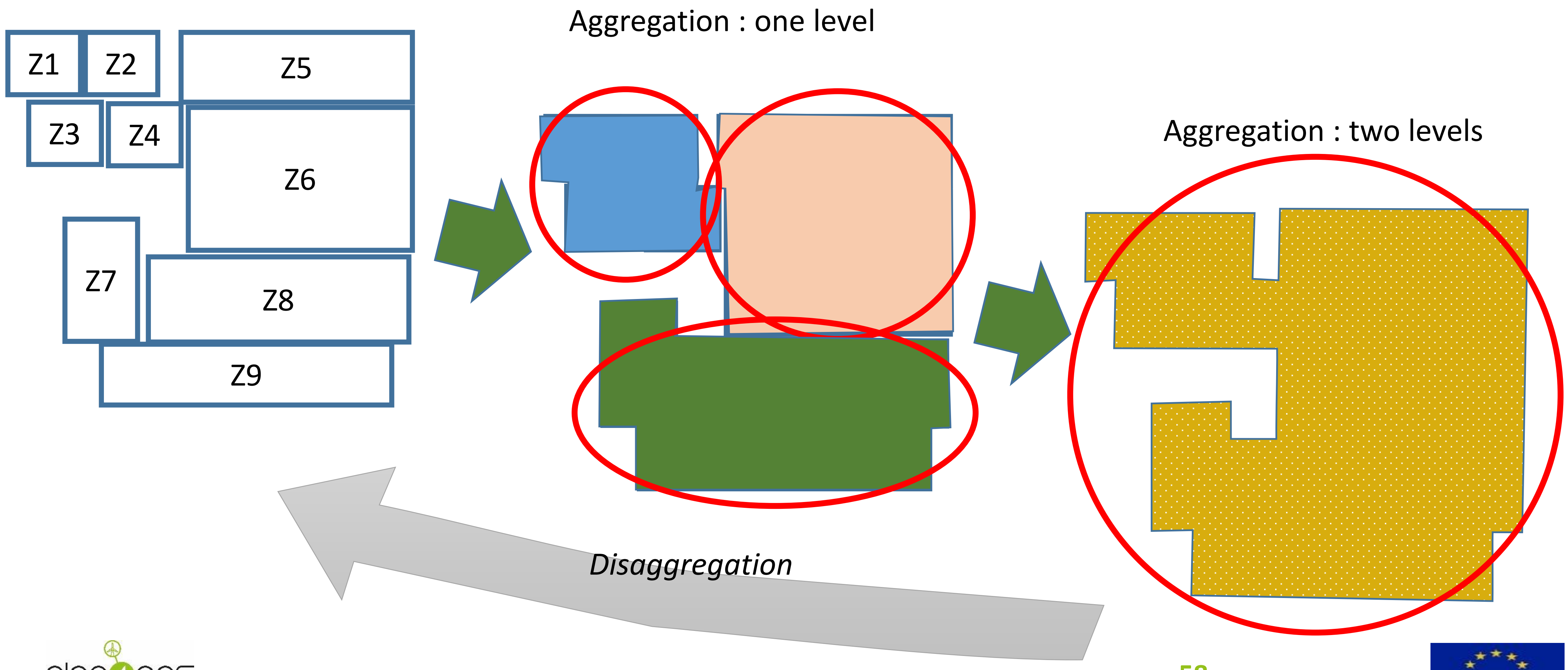
Transformation: Spatial Aggregation

- Provides data aggregation over Zone Hierarchy for multiple data types (Energy, timeseries, interconnections)



Aggregation/disaggregation example

Input data (timeseries) at zone level

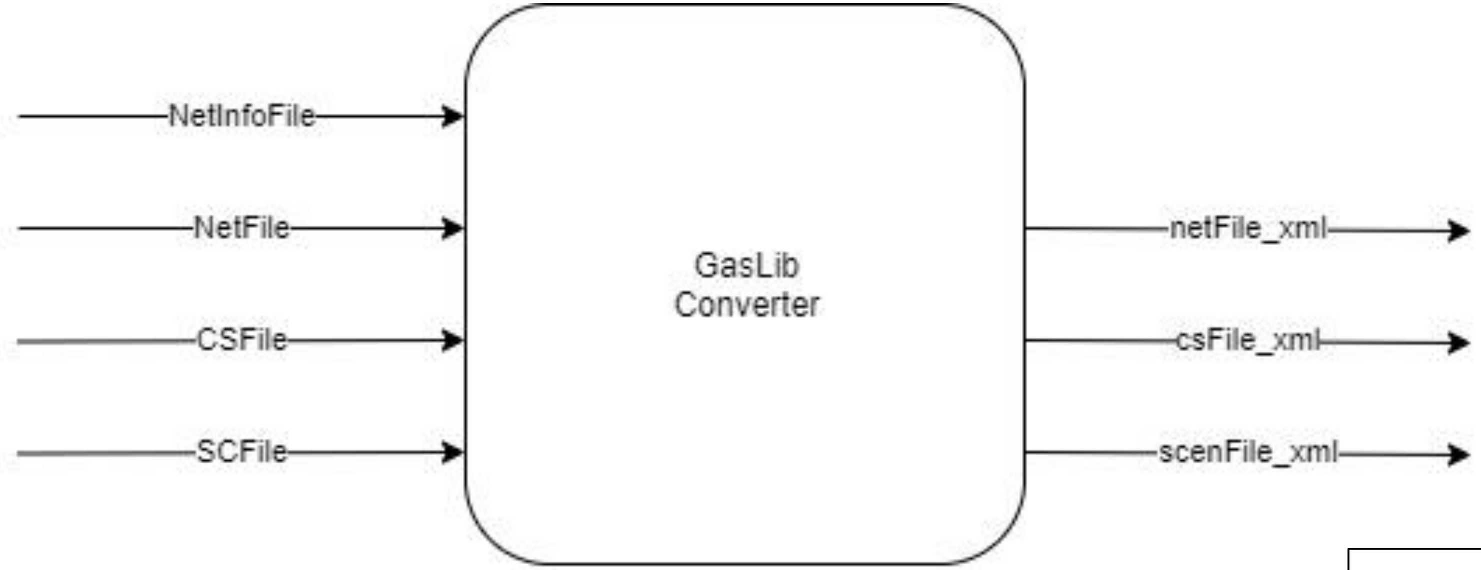


Formatting: NetCDF Transformation

- Transforms excel file and timeseries files into a NetCDF file that describes the UC Problem

Formatting: GasLib Transformation

- Transforms raw data files into GasLib XML format

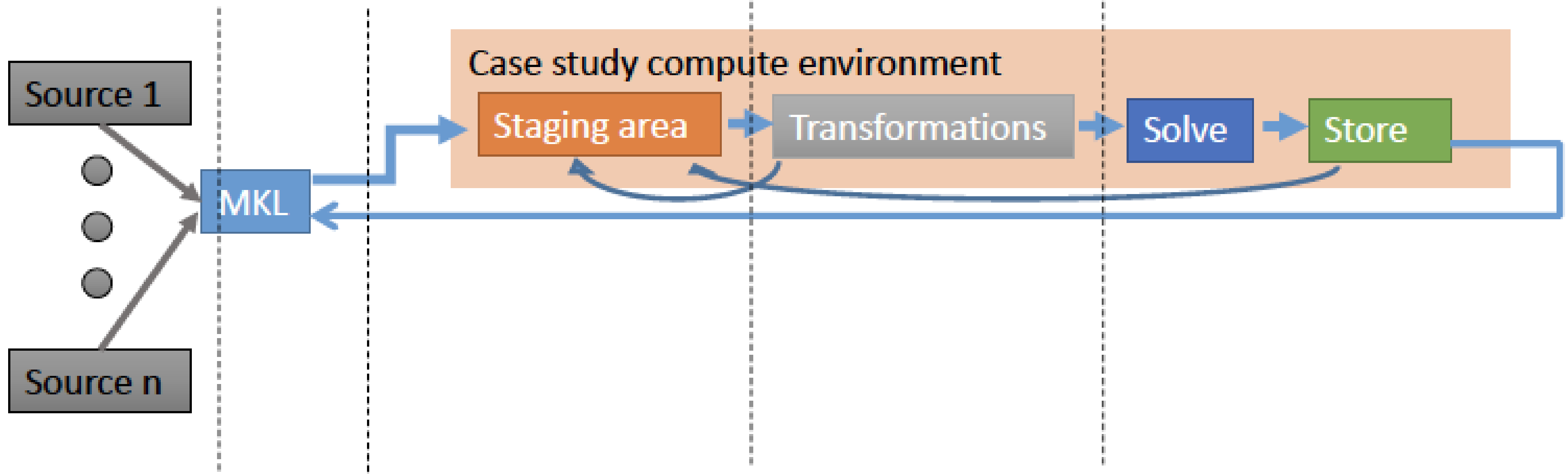


gaslib.zib.de

IT Platform : WorkFlows and Container

Workflow

- Data from several sources are collected on MarketLab (MKL)
- Move data to Staging→Transformations→Solve→Store phases

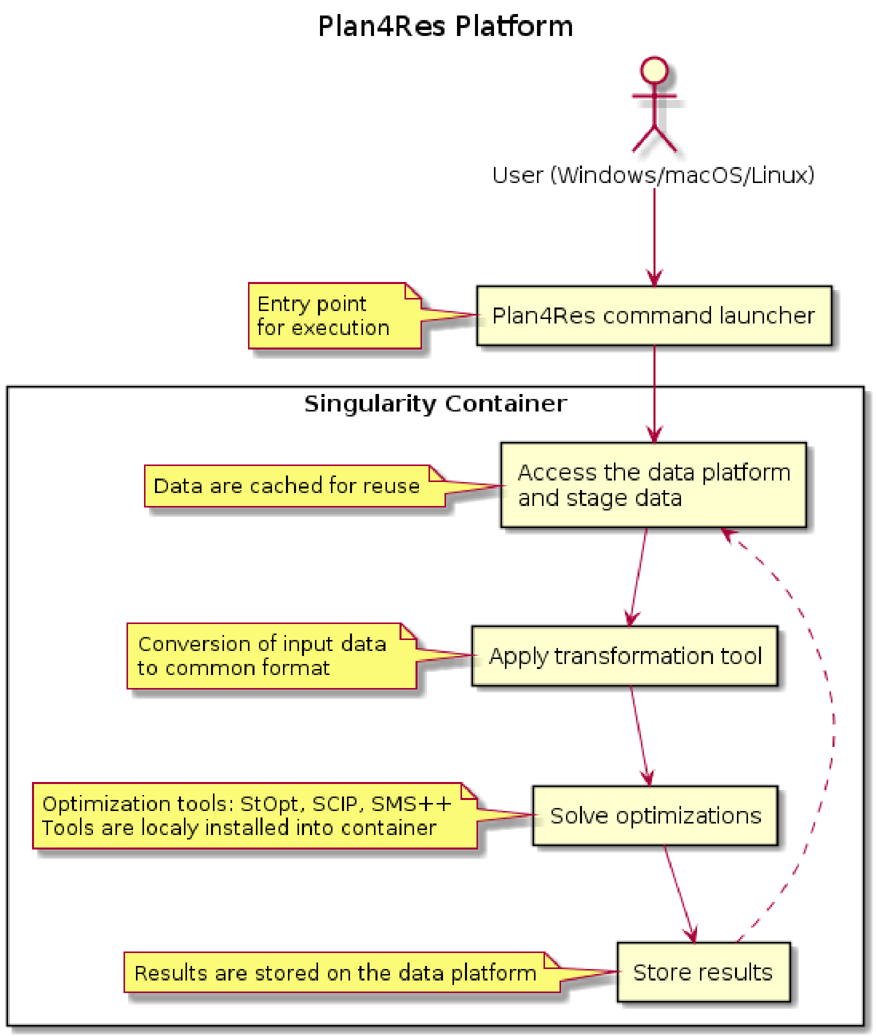


Core components

- Software deployment environment
  - Container (+VM where needed)
- Core tool
  - Data Movement library UDJ
- Modeling and Solver framework
  - SMS++

Containerized Compute Environment

- Same executables run everywhere
- No dependency issues
- Add-on software (license restricted) can be locally added in a standardized way
- Directory structure layout predefined so software can rely on it cross-site
- Using [singularity]
- Windows needs virtual machine, macOS and Linux run containers natively

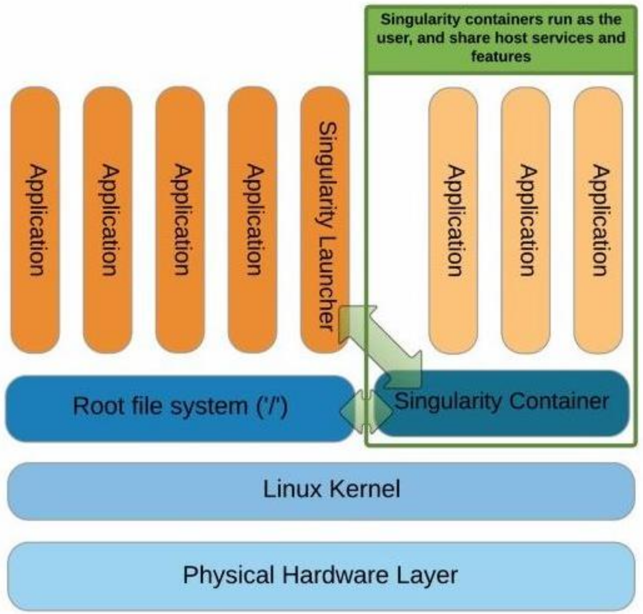


Containers: Why?

- **Containers solve the problem of making your software to run reliably when moved from one computing environment to another**
  - Using containers allows to deploy applications across operating systems without having to build and configure separately
  - In contrast to virtual machines, which virtualize the hardware and need a complete operating system, containers interface directly with the host’s Linux kernel, so they are faster to deploy and run

Singularity Privileges Design

- Singularity launches the container with calling user privileges in the appropriate process context

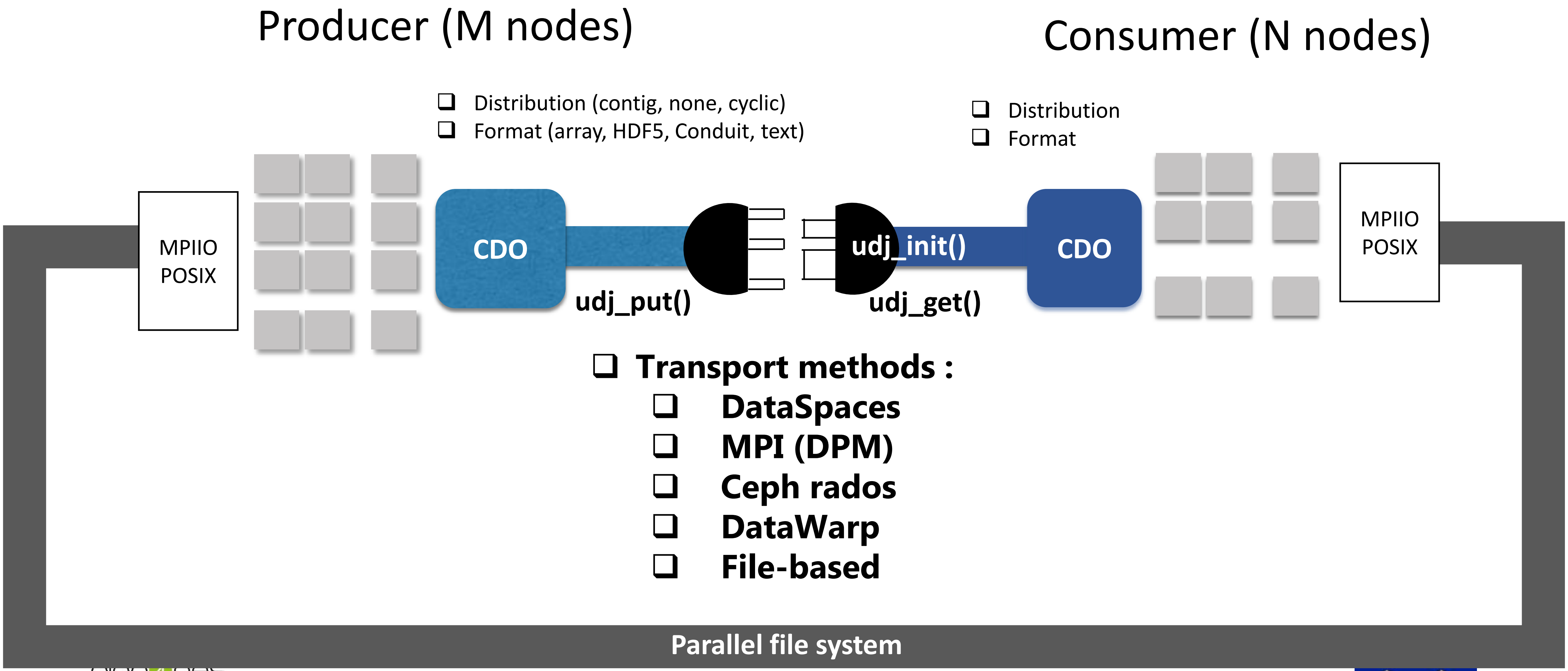


- There is no root daemon process and no escalation of privileges within the container
  - Limits user's privileges (inside user == outside user)

Recurring Problem in Computational Workflows:

- Data movement is primary bottleneck
- Massive interest in flexibility and insulation/abstraction
  - Cpu / accelerator
  - Memory
  - Interconnect
  - Abstraction layers should not tie into an architecture
- Memory is 20x slower than 1980
  - The complex memory hierarchy isn't even here yet!
- I/O to disk is used to couple applications because of a lack of general-purpose tools
  - Workflow coupling can often be abstracted as input/output
  - Not every communication needs a full-fledged protocol

Universal Data Junction (UDJ)



UDJ features

- Library-based, no runtime
- Transport method selected at runtime (file, cephfs, rados, MPI[-DPM])
- Based on data description + 0-copy semantics
- BSD 3-clause licensing
- Features:
  - Automatic redistribution for cyclic an block-cyclic tensors (ASPEN algorithm) integrated
  - Aggregation and chunking at transport layer
  - Transparent MPI-DPM without user-visible client-server semantics
  - MPI transport using fully nonblocking operations
  - Fortran interface

Using UDJ

Use and initialization:

- `#include "udj.h"`
- link with `-ludj`
- call `udj_init()`

- Define CDO views for data to be transported using UDJ
  - No data copying needed
  - Distribution description and size
    - *General case*
    - *... and convenience methods*
  - CDO ID ("Tag")
- Send/Receive as needed
- Synchronous or asynchronous

- call `udj_finalize()`

Runtime configuration

- Set specific transport method
  - Env UDJ_TRANSPORT_ORDER=MPI,RADOS,FS
    - *Default is to automatically choose best available*

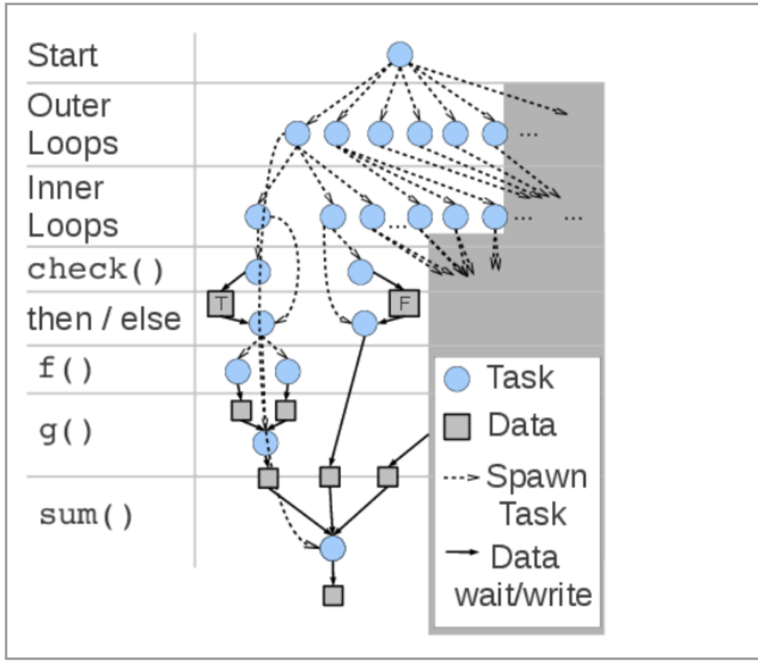
Advanced usage

- Use multiple transports explicitly
- Use scripting language interface
  - SWIG wrappers for python for udj.h (WIP)

Defining workflows: Data-driven

- **Using [swift/t] scripting language**
- **Data-dependency driven tasking environment**
  - Tasks can be swift/t scripts, shell scripts, executables
  - Built-in support for common mathematical operations
  - Transparent access to MarketLab service implemented as library functions

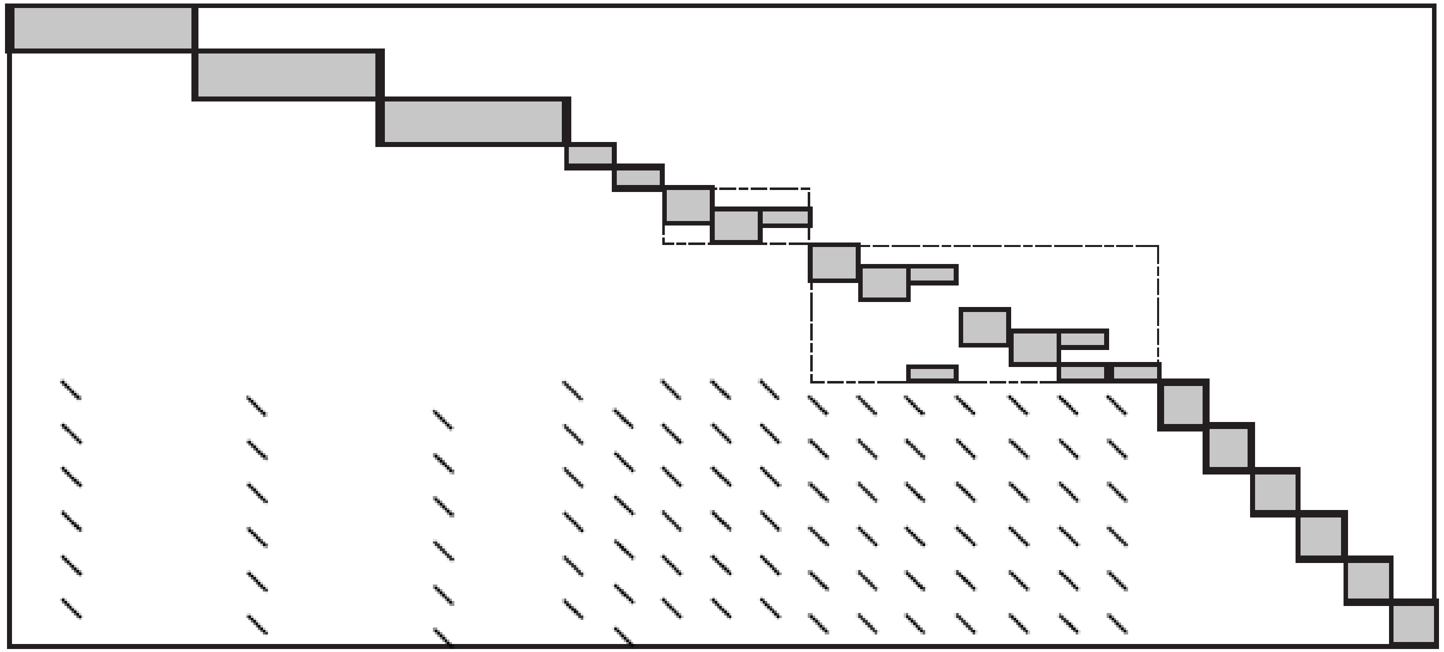
```
int X = 100, Y = 100;
int A[][];
int B[];
foreach x in [0:X-1] {
  foreach y in [0:Y-1] {
    if (check(x, y)) {
      A[x][y] = g(f(x), f(y));
    } else {
      A[x][y] = 0;
    }
  }
  B[x] = sum(A[x]);
}
```



SMS++

The European Unit Commitment in SMS++

- Schedule a set of generating units to satisfy the demand at each node of the transmission network at each time instant of the horizon (24h)



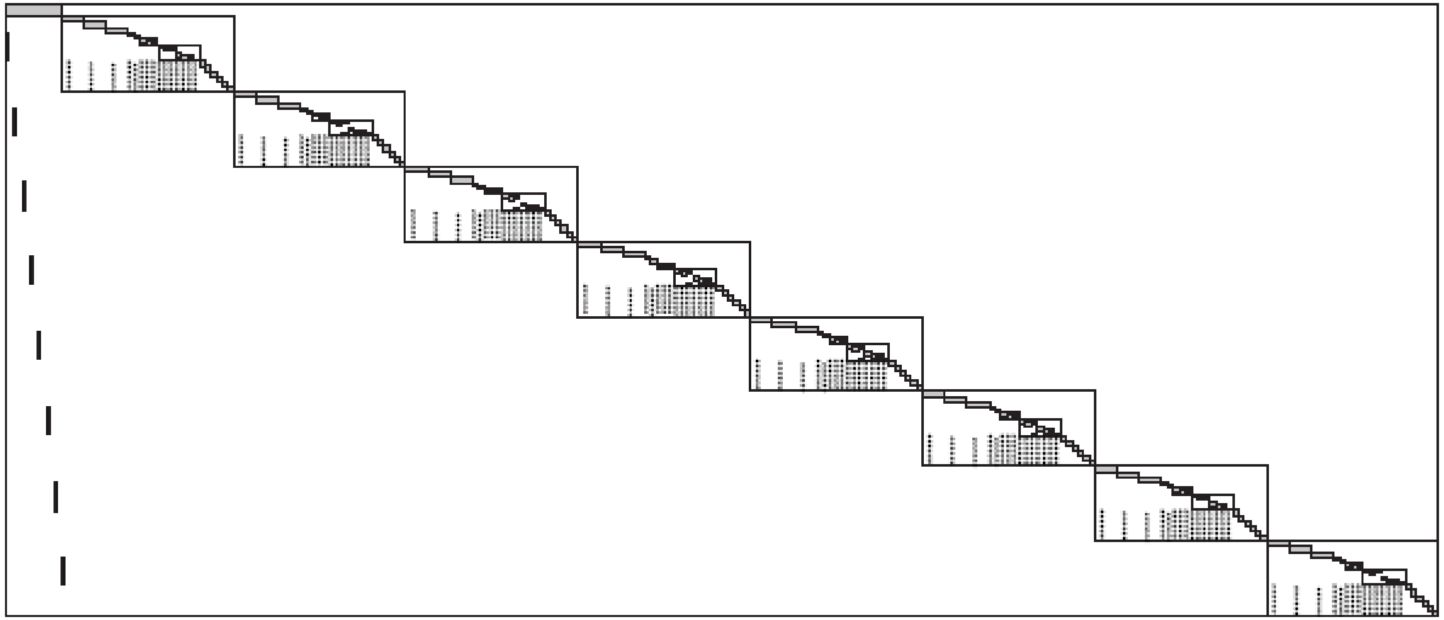
- Several types of almost independent blocks + linking constraints
- Perfect structure for Lagrangian relaxation[1,2]

[1] Borghetti, F., Lacalandra, Nucci "Lagrangian Heuristics Based on Disaggregated Bundle Methods [. . .]", *IEEE TPWRS*, 2003

[2] Scuzziato, Finardi, F. "Comparing Spatial and Scenario Decomposition for Stochastic [. . .]" *IEEE Trans. Sust. En.*, 2018

The Seasonal Storage Valuation in SMS++

- Manage water levels in reservoirs considering uncertainties (inflows, temperatures, demands, . . .) to minimize costs over the time horizon (1y)



- Very large size, nested structure
- Perfect structure for Stochastic Dual Dynamic Programming[3,4] with multiple EUC inside

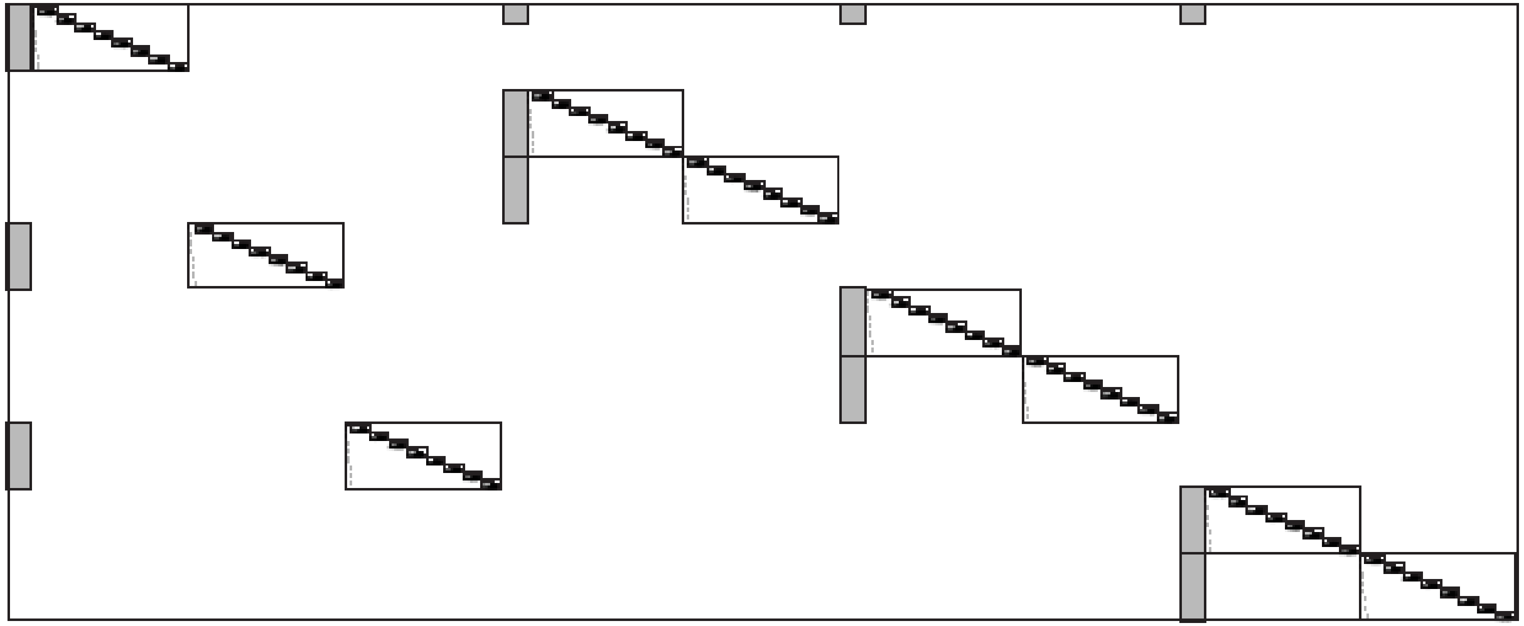
[3] Pereira, Pinto "Multi-stage stochastic optimization applied to energy planning" *Math. Prog.*, 1991

[4] van-Ackooij, Warin "On conditional cuts for Stochastic Dual Dynamic Programming" arXiv:1704.06205, 2017

plan4res

The Investment Layer in SMS++

- Plan production/transmission investments considering uncertainties (technology, economy, politics, ...) to optimally achieve goals (cost, pollution, CO_2 emissions, ...) over the time horizon (30y)



- Many scenarios, huge size, multiple nested structure
- Perfect structure for either Benders' or Lagrangian decomposition[5] with multiple SSV inside, each with multiple EUC inside

5 van Ackooij, Danti Lopez, F., Lacalandra, Tahanan "Large-scale Unit Commitment Under Uncertainty [...]" *AOR*, 2018

How do you actually solve such a thing?

- Modeling system: easily construct a huge, flat = unstructured matrix to be passed to a general-purpose, flat solver (= no way)
- Some solvers offer one-level decomposition (Benders, CG = DW)
- Automatically recovering structure from a matrix[6], but only one level
- Only one tool (that I know of) for multiple nested structure[7,8], but only solves continuous problems by Interior Point methods
- Nothing for multilevel, heterogeneous approaches (such as, but not only, decomposition), e.g., allowing specialized solvers for each block
- So far

---

[6] Furini, Lübbecke, Traversi et. al. "Automatic Dantzig–Wolfe reformulation of mixed integer programs" *Math. Prog.* 2015

[7] Gondzio, Grothey "Exploiting Structure in Parallel Implementation of Interior Point Methods [...]" *Comput. Man. Sci.*, 2009

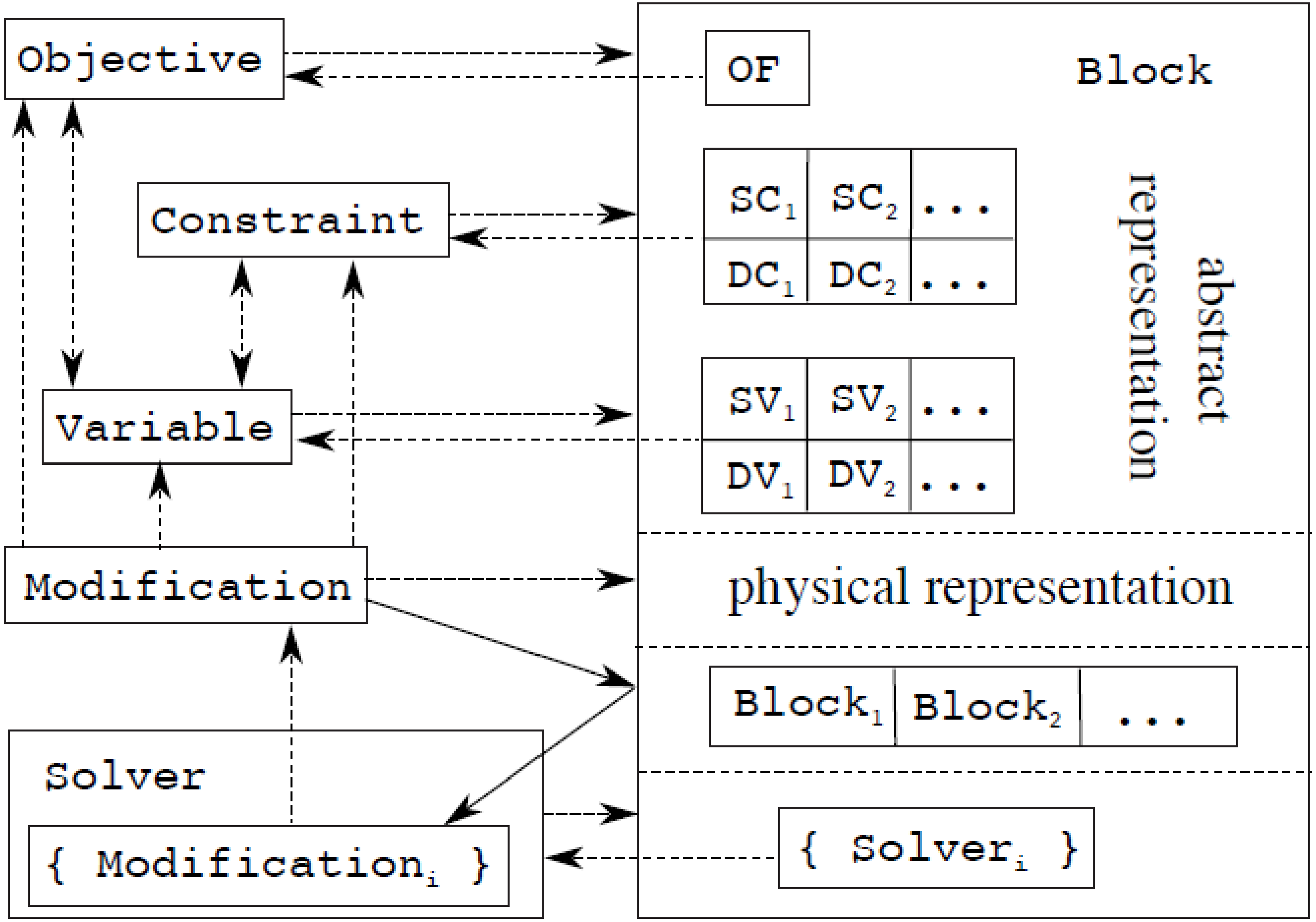
[8] Colombo et al. "A Structure-Conveying Modelling Language for Mathematical [...] Programming" *Mathe. Prog. Comp.*, 2009

Design goals

- A modelling system which:
  - explicitly supports the notion of block $\equiv$ nested structure
  - separately provides "semantic" information from "syntactic" details (list of constraints/variables $\equiv$ one specific formulation among many)
  - allows exploiting specialised solvers on blocks with specific structure
  - caters all needs of complex solution methods: dynamic generation of constraints/variables, modifications in the data, reoptimization, . . .
- Open source (LGPL3) `C++17` library

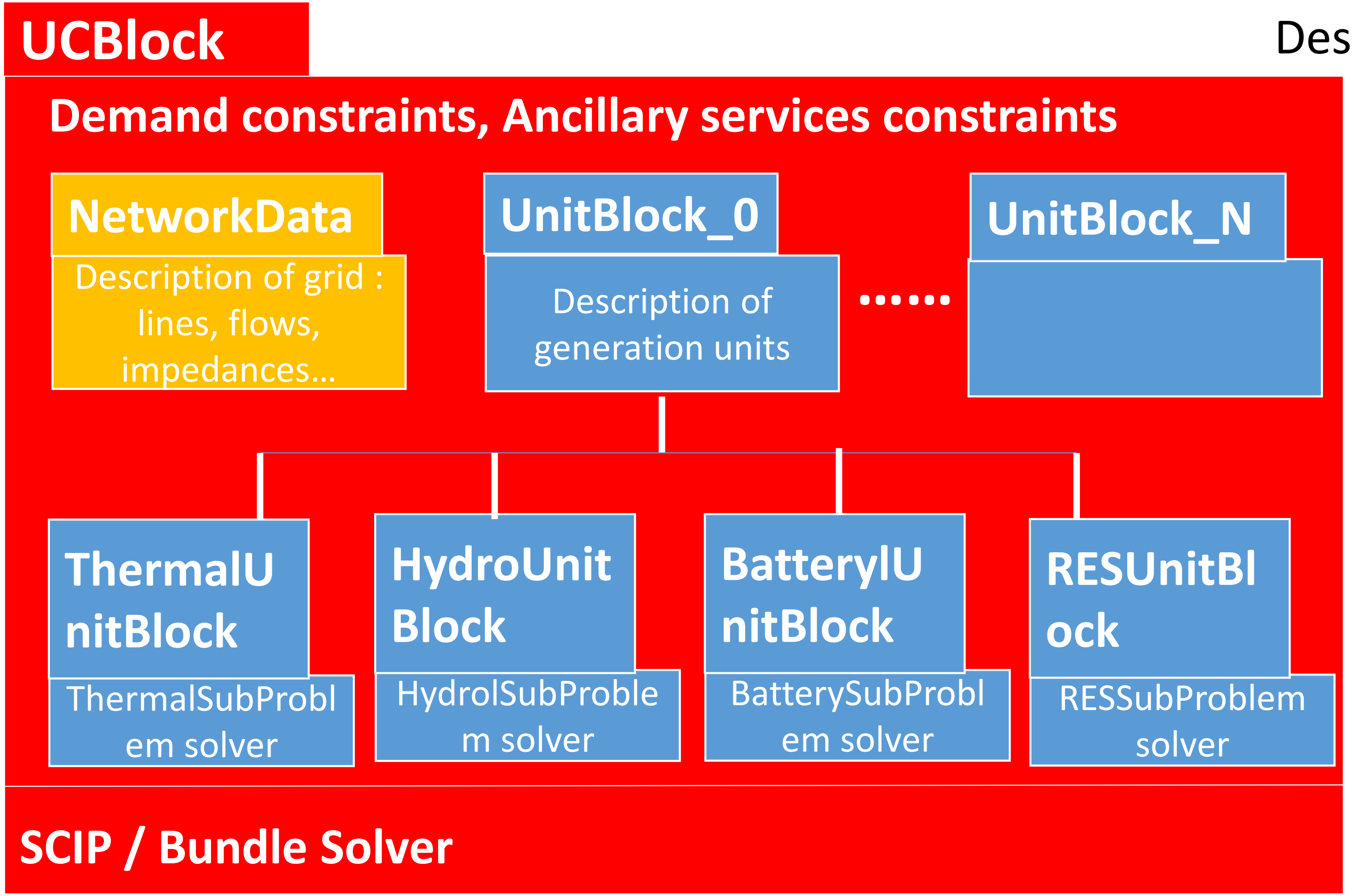
  `https://gitlab.com/smspp/smspp-project`
- Easily extendable "core" classes + [interface with] efficient general solvers
- Built-in asynchronous and parallel capabilities (thanks Cray!)
- Set of (more or less) specialized blocks/solvers for plan4res

The core SMS++



Objective
Constraint
Variable
Modification
Solver
{ Modification$_i$ }
OF
Block
SC$_1$ SC$_2$ ...
DC$_1$ DC$_2$ ...
SV$_1$ SV$_2$ ...
DV$_1$ DV$_2$ ...
abstract representation
physical representation
Block$_1$ Block$_2$ ...
{ Solver$_i$ }

The Unit Commitment in SMS++

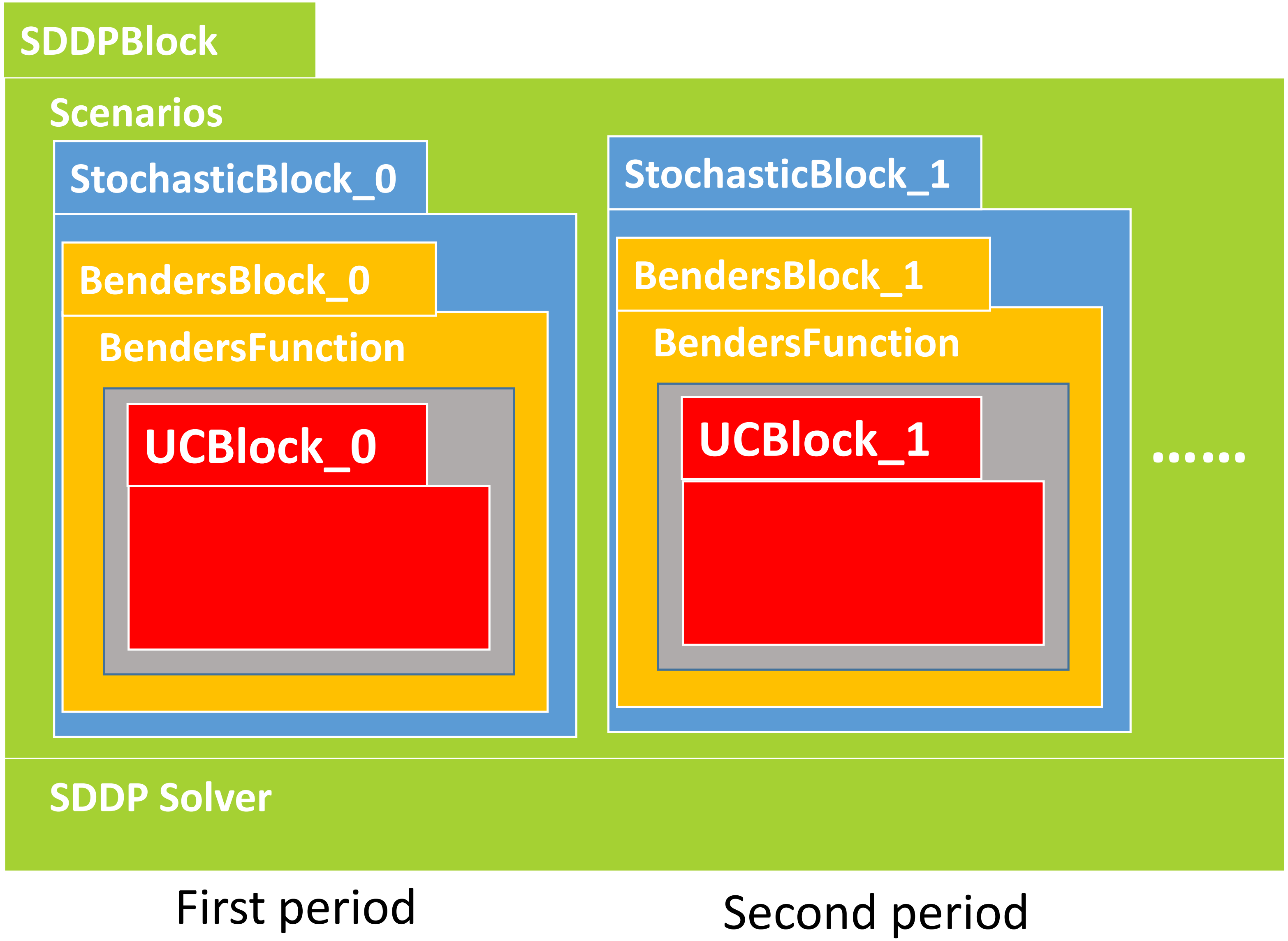


Description of UC problem

Coupling constraints

Sub problems

The Seasonal Storage in SMS++



Description of SSV problem

Contains all scenarized data

UC problems for each period

Solvers in SMS++

Existing Solvers

- MILPSolver (wrapper for CPLEX/SCIP)
- BundleSolver
- SDDPSolver (wrapper for StOpt)
- Specialised Solvers for SubProblems related to units (ThermalDPSolver, MCFSolver, ...)

Existing Block & support components

- MCFBlock, MILPSolver, AbstractBlock, PolyhedralFunctionBlock, AbstractPath
- Function (inexact computation), C05Function (1st-order information), LinearFunction, DQuadFunction ...
- LagBFunction/BendersBFunction for Lagrangian/Benders' decomposition, PolyhedralFunction
- StochasticBlock (handles data change with "methods factory")
- UCBlock, UnitBlock, NetworkBlock, many derived ones (ThermalUnitBlock, HydroUnitBlock ...)
- SDDPBlock to interface with StOpt

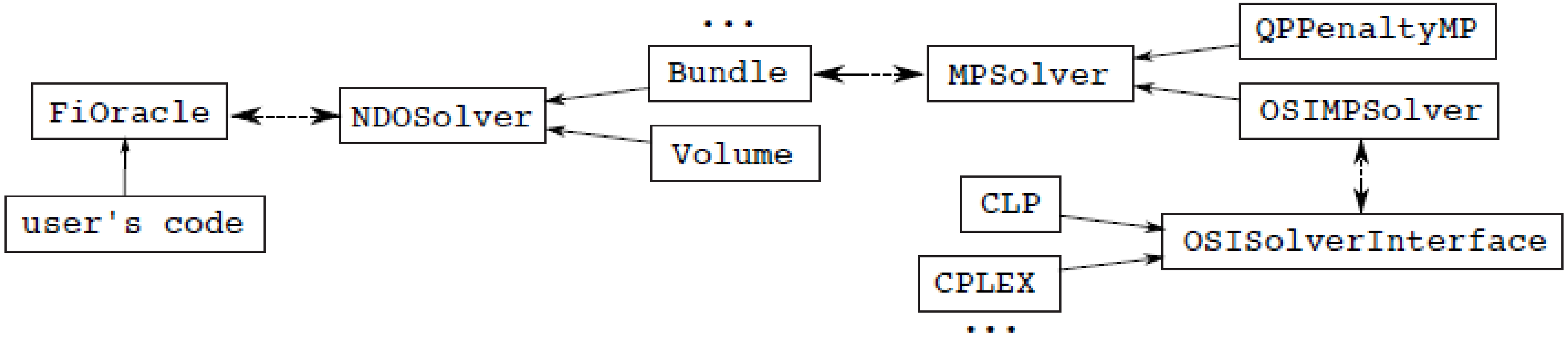
Solvers

Thorsten Koch, ZIB, WP leader
Antonio Frangioni, University of Pisa

Decomposition

Original version: NDOSolver/FiOracle

- General framework for convex non-differentiable optimization



- Clean interface separation between solver and user's code ("oracle")
- Different :NDOSolver with various cost/convergence trade-offs
- Best one most often generalized[9] Bundle method ≡ different forms of the "master problem"
- Again, clean interface separation: MPSolver in charge of master problem

[9] F. "Generalized Bundle Methods" *SIOPT*, 2002

MPSolvers

- Specialized QP solver for proximal aggregated version[10]
- However, disaggregated version often much better[11]
- Use general-purpose LP/QP solver via `OsiSolverInterface`
- Benefit: can solve arbitrarily-structured master problems
- Crucial if some components are "easy"[12] $\equiv$
  Lagrangian function of small, explicitly know LPs/QPs
- Happens a lot in (E)UC, can have a huge impact on performances[2,12]

---

[10] F. "Solving semidefinite quadratic problems within nonsmooth optimization algorithms" *Computers & O.R.*, 1996
[11] Borghetti, F., Lacalandra, Nucci "Lagrangian [...] for Hydrothermal Unit Commitment", *IEEE Trans. Power Sys.*, 2003
[12] F., Gorgone "Bundle methods for sum-functions with "easy" components [...]" *Math. Prog.*, 2014

The NDOSolver/FiOracle project

- Open source (LGPL3) C++11 library

  https://gitlab.com/frangio68/ndosolver_fioracle_project

- Supports complex interaction between solver and oracle:
  - multiple components, one linear component, "easy" components
  - inexact function computation[13]
  - multiple subgradients and dynamic linear constraints
  - changes in the function

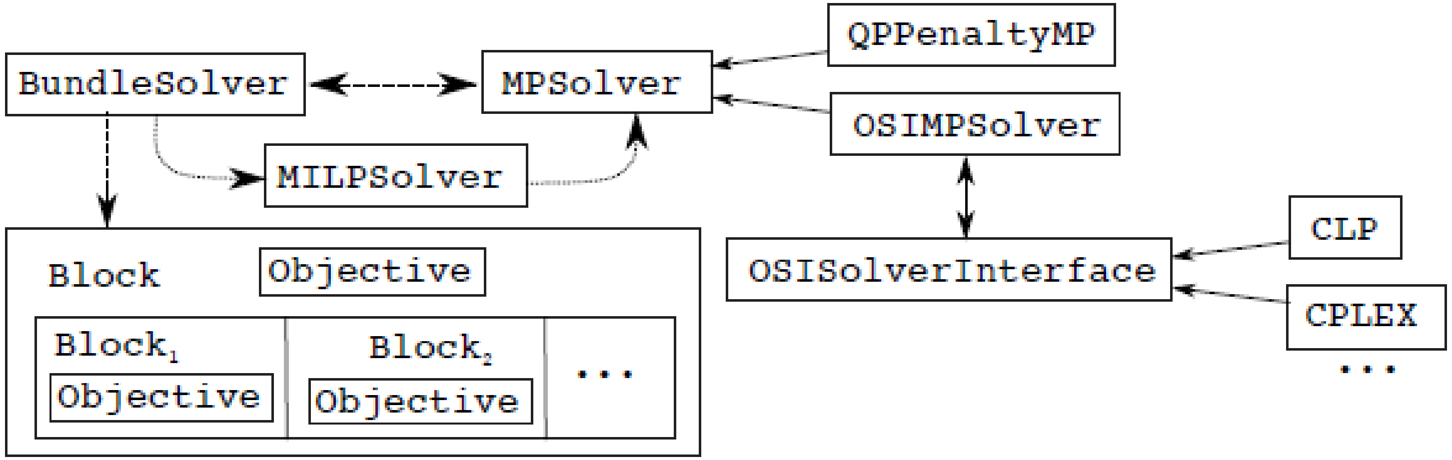
- Particularly suited for Lagrangian-based approached to integer programs:
  - computation of "convexified" primal solution for branching/heuristics
  - support of dynamic separation of linking inequalities[14]
  - support for reoptimization after branching

---

[13] van Ackooij, F. "Incremental bundle methods using upper models" *SIOPT*, 2018

[14] F., Lodi, Rinaldi "New approaches for optimizing over the semimetric polytope" *Math. Prog.*, 2005

New version: BundleSolver



- Native re-implementation incorporating all recent developments[13,15]
- Solves any `:Block` with `C05Function`/`LinearFunction` objective, comprised in sub-`Block` $\equiv$ natively supports disaggregated version
- (temporarily) re-uses existing `MPSolver` but exploiting `MILPSolver` for "easy" components[2,12] $\equiv$ `LagBFunction` (with linear stuff)
- Full support for all `Modification` $\Longrightarrow$ almost ready for dynamic "easy" components $\equiv$ Stabilized Structured Dantzig-Wolfe[16]

[15] F. "Standard Bundle Methods: Untrusted Models and Duality" in *Numerical nonsmooth optimization*, 2020

[16] F., Gendron "A Stabilized Structured Dantzig-Wolfe Decomposition Method" *Math. Prog.*, 2013

BundleSolver distinguishing features

- Ready for all `C05Function`: `LagBFunction`, `BendersBFunction`, `PolyhedralFunction`, ...
- Any `:Block` + `:Solver` + `LagBFunction`/`BendersBFunction` = Lagrangian/Benders' decomposition almost without user's code
- `LagrangianDualBlock`/`BendersDecompositionBlock` possible to automate production of `LagBFunction`/`BendersBFunction`
- Support all `Modification` ≡ Stabilized Structured Dantzig-Wolfe[16] ⟹ Stabilized[17] Structured Benders' decomposition (?!)
- Still a lot to learn about practicality of incremental Bundle methods[13]
- Native parallel support in `Solver` ≡ fully asyncronous Bundle methods[18] both in function computation and master problem solution

[17] van Ackooij, F., de Oliveira "Inexact Stabilized Benders' Decomposition Approaches, with Application to [...]" *CO&A*, 2016

[18] van Ackooij, F., de Oliveira, Malick "Asynchronous Bundle methods" *working paper*, 2020

Solving Large Mixed Integer Linear Problems with SCIP

What is SCIP?

SCIP (Solving Constraint Integer Programs)

- provides a full-scale MIP and MINLP solver,
- is constraint based,
- Incorporates:
  - MIP features (cutting planes, LP relaxation), and
  - MINLP features (spatial branch-and-bound, OBBT)
  - CP features (domain propagation),
  - SAT-solving features (conflict analysis, restarts),
- is a branch-cut-and-price framework,
- has a modular structure via plugins,
- is free for academic purposes,
- and is available in source-code under http://scip.zib.de !

SCIP Optimization Suite

Toolbox for generating and solving constraint integer programs, in particular Mixed Integer (Non-)Linear Programs:

ZIMPL

- model and generate LPs, MIPs, and MINLPs

SCIP

- MIP, MINLP and CIP solver, branch-cut-and-price framework

SoPlex

- revised primal and dual simplex algorithm

GCG

- generic branch-cut-and-price solver

UG

- framework for parallelization of MIP and MINLP solvers

SCIP in plan4res

SCIP has been enhanced with the purpose of efficiently solving atomic LP and MIP models appearing in several parts of the plan4res project.

Besides improving out-of-the-box LP and MIP solution performance of SCIP, these enhancements have also been focused on:

- Problem-specific primal heuristics for time-indexed MIP formulations which appear frequently in the plan4res context
- Exploitation of shared-memory parallelization complementary to the task-based parallelization infrastructure developed in plan4res

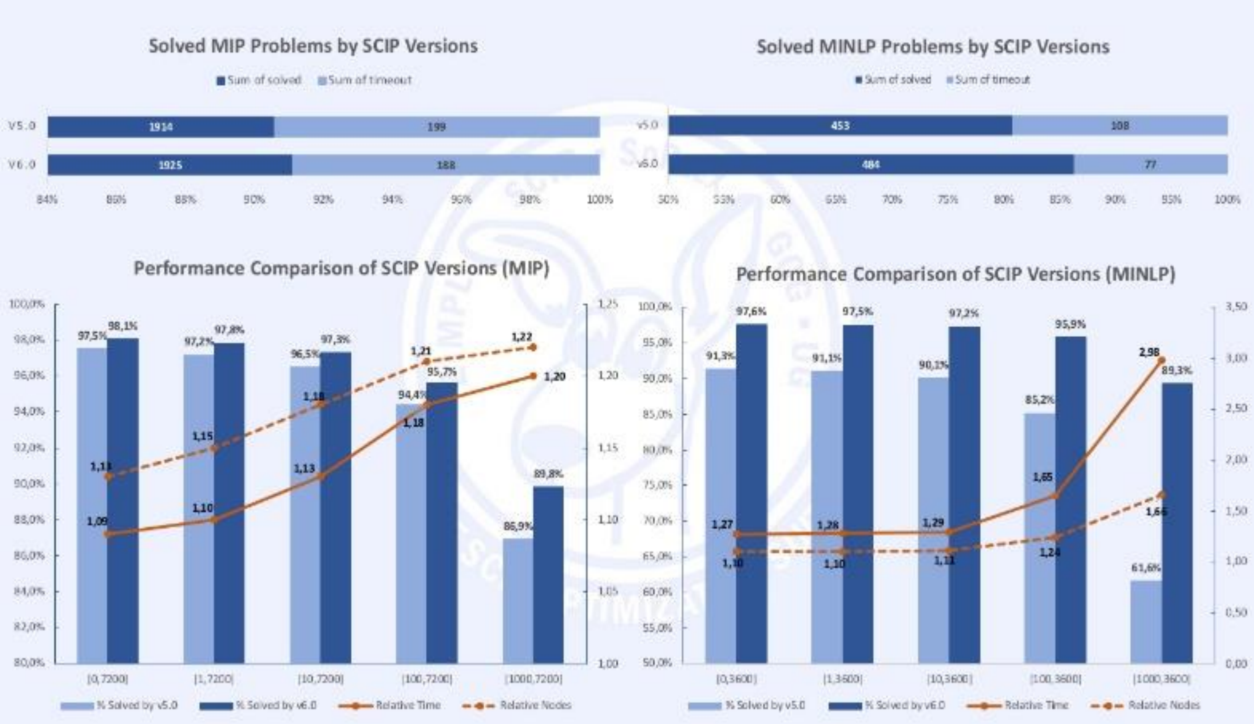
SCIP Releases - 1

SCIP Optimization Suite 6.0 (July 2018) & 6.0.1(Jan 2019) released

- ❑18% speedup on hard MIPs
- ❑66% speedup on hard MINLPs

Enhancements

- ❑New primal heuristics to improve solution of MIPs with time-indexed structure
- ❑Improved selection of cutting planes to improve MIP performance
- ❑Enhanced LP performance by updating SCIP's underlying LP solver SoPlex
- ❑Focus on decomposition methods
  - new generic Benders decomposition framework
  - new version of the generic column generation solver GCG



SCIP Releases - 2

SCIP Optimization Suite 7.0 is planned in February 2020:

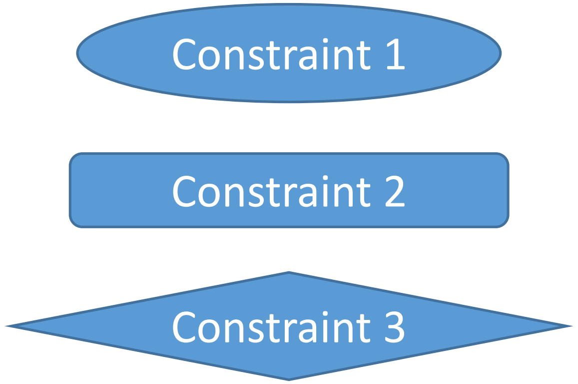
- 22% speed up on ZIB MIP benchmark problems (Preliminary test results)
- 35% speed-up on hard MIP instances (Preliminary test results)

Enhancements:

- Parallel Presolving Library is released with SCIP Optimization Suite 7.0
  - for (mixed integer) linear problems
  - integration in SCIP yields a 4% speed-up (sequential)
- The primal-heuristic GINS (Graph-Induced Neighborhood Search) has been extended to exploit user provided decomposition information
- Degeneracy-aware branching rule has been implemented to improve branching on problems with high-degeneracy
- Symmetry handling has been revised

Parallel Presolving Library -1

Constraint-Based View



Model-Based View

$$Ax \leqslant b$$

- SCIP has a general constraint-based view of possibly not even linear constraints
- Presolve libray has a global view on linear constraint matrix which is important for a fast implementation of some MILP-specific presolving steps

Parallel Presolving Library -2

Parallelization

- Parallel implementations of expensive presolving steps
  - probing, dominated columns, sparsification, parallel rows/columns
- Presolving steps can run in parallel: Presolving library detects and discards conflicting reductions
- Same results regardless of thread number by exploiting data parallelism

Plan4res Public Results

❑ Documents

Modelling documents: D3.1 & Joint paper

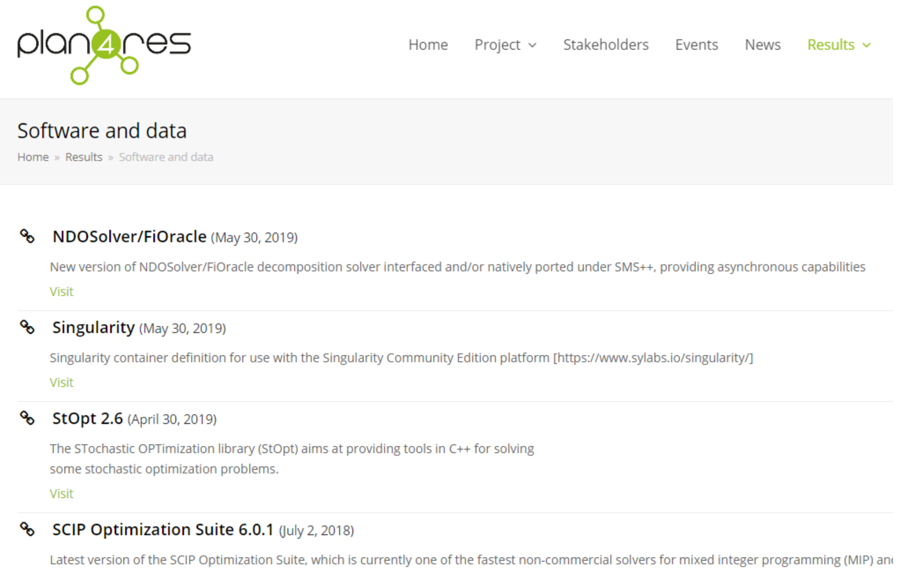
Case Study: D2.1 (detailed description) & D2.2/3/4 (Results)

Software Architecture D6.1

Scientific papers

❑ Data

Public Dataset (and document describing how it was built)



❑ Software

UDJ (BSD-3 license)

Demonstrator code base

SMS++

BundleSolver

MILPSolver

SDDPSolver

StOPT

SCIP

Data Transformation tools

The plan4res team

❑ EDF

Sandrine Charousset
Dominique Daniel
Wim van Ackooij
Nadia Oudjane
Slimane Noceir
Thomas Ouillon

❑ SIEMENS

Dieter Most

❑ CRAY HPE

Utz-Uwe Haus
Alfio Lazzaro
Nina Mujkanovic

❑ RWTH AACHEN

Daniel Beulertz
Carlo Schmitt
Marco Franken
Henrik Schwaeppe

❑ IMPERIAL COLLEGE

Danny Pudjianto
Spyros Giannellos
Goran Strbac
Paola Falugi
Alex Moreira

❑ UNIVERSITY MODENA

Mauro Dell'Amico
Jaffar Jamal

❑ UNIVERSITY PISA

Antonio Frangioni
Rafael Lobato
Niccolò Iardella
Ali Ghezelsoflu
Enrico Gorgone

❑ ZIB

Janina Zittel
Thorsten Koch
Ambros Gleixner
Inci Yueksel-Erguen
Leona Gottwald

Thank you

www.plan4res.eu

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Questions?

@plan4res

sandrine.charousset@edf.fr