SMS++: a Structured Modelling System for Optimization

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Outline

- The plan4res project
- SMS++
- Stochastic SMS++
- Current and future work

The plan4res H2020 project

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

- An accurate depiction of long-term effects of strategic choices on the pan-European Energy System $\equiv$

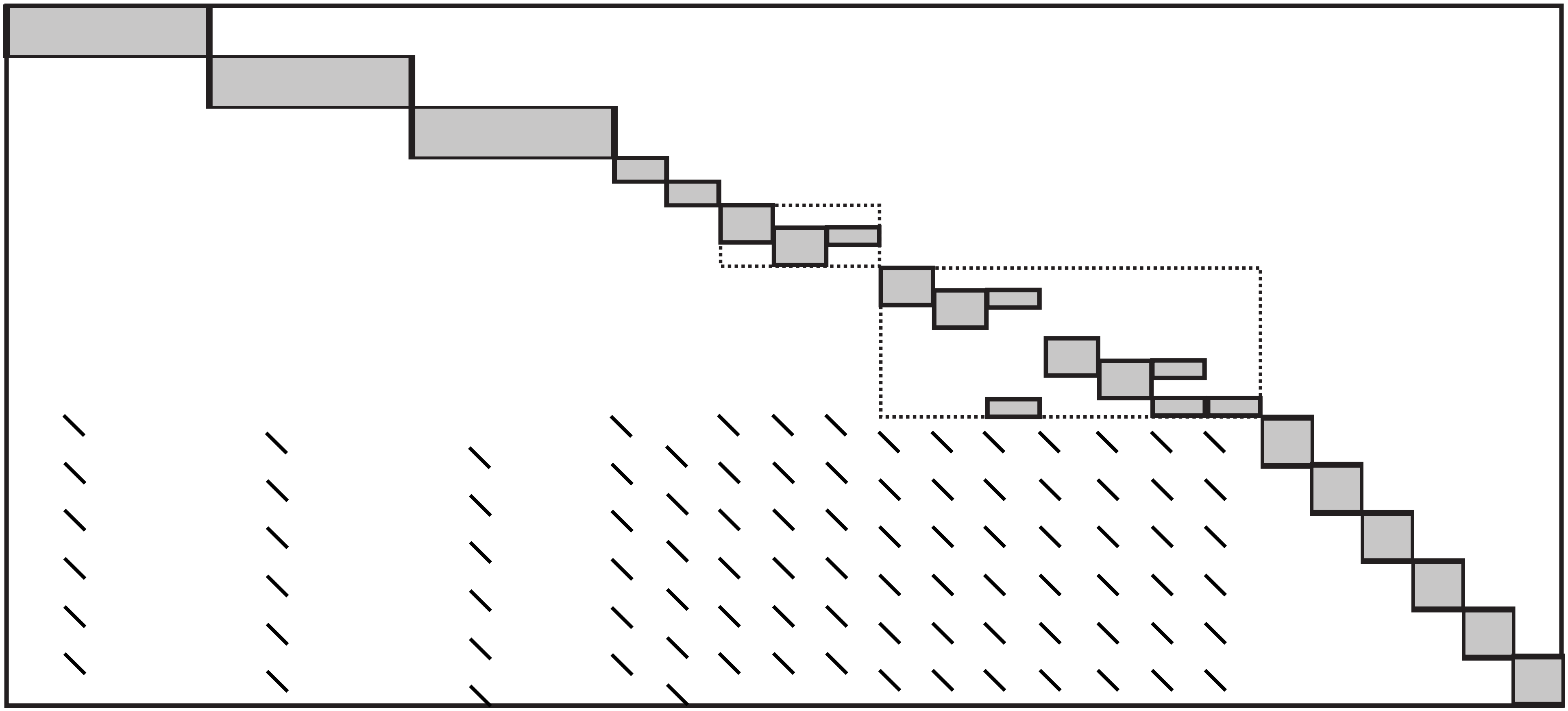
  modelling the next 30 years with 1h timescale
  and huge amounts of uncertainty over everything

- An unfeasibly large optimization problem with lots of structure

Short-term problem: Unit Commitment (UC)

- Find a (near-)optimal schedule of a large number of units satisfying the demand at each node of the network, while respecting a set of technical constraints, at each time instant of the horizon (e.g., 1 hour)
- Three natural sources of structure: unit, time, and network
- Relaxing demand constraints decomposes by unit and network: one problem per unit across all horizon and a network problem per time instant

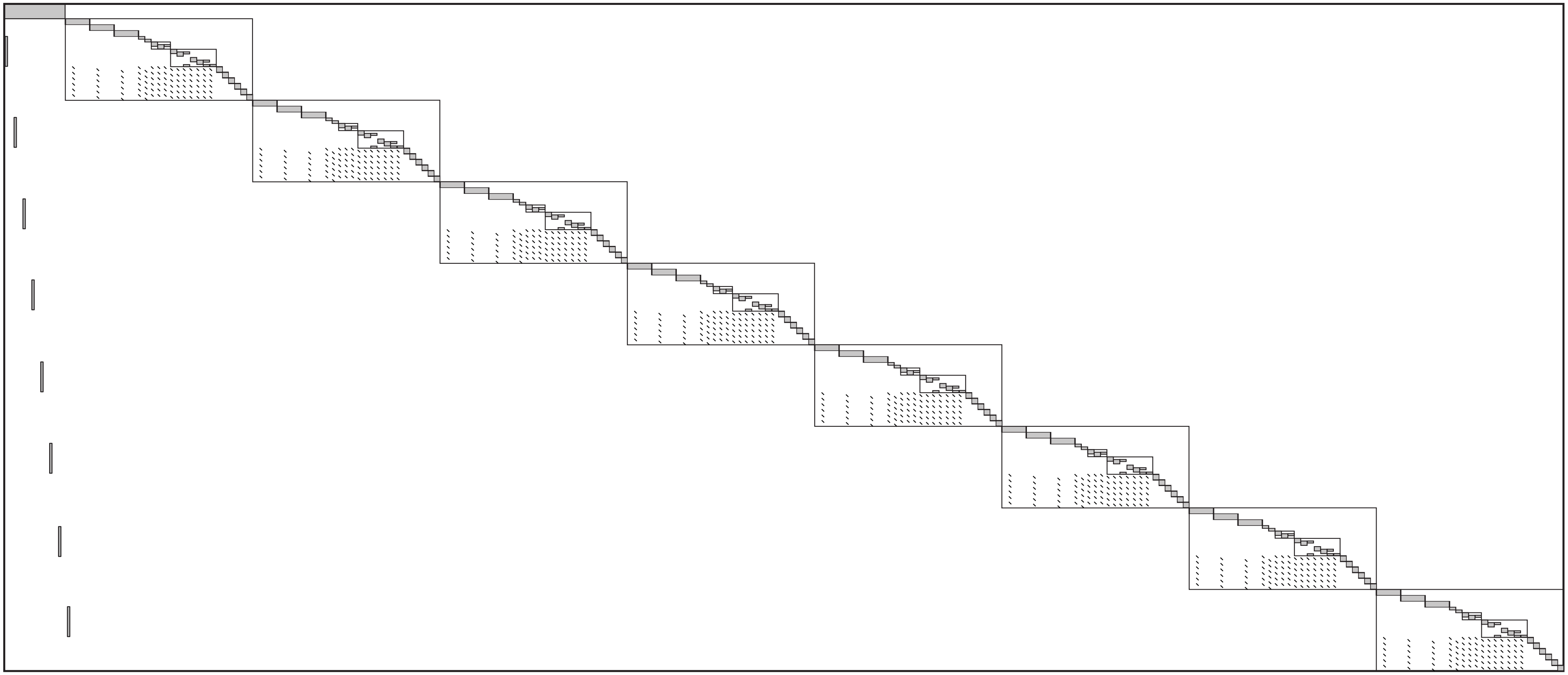
Short-term problem: Unit Commitment (UC)



Mid-term problem: Seasonal storage valuation

- UC is a (deterministic) short-term problem and lacks long-term strategies
- The mid-term (e.g., 1 year) problem provides the UC with approximations of the cost-2-go function
- UC then arises at each stage (e.g., 1 week) of the mid-term problem
- Uncertainties: inflows, demand, outages, intermittent generation
- A multi-stage stochastic optimization problem

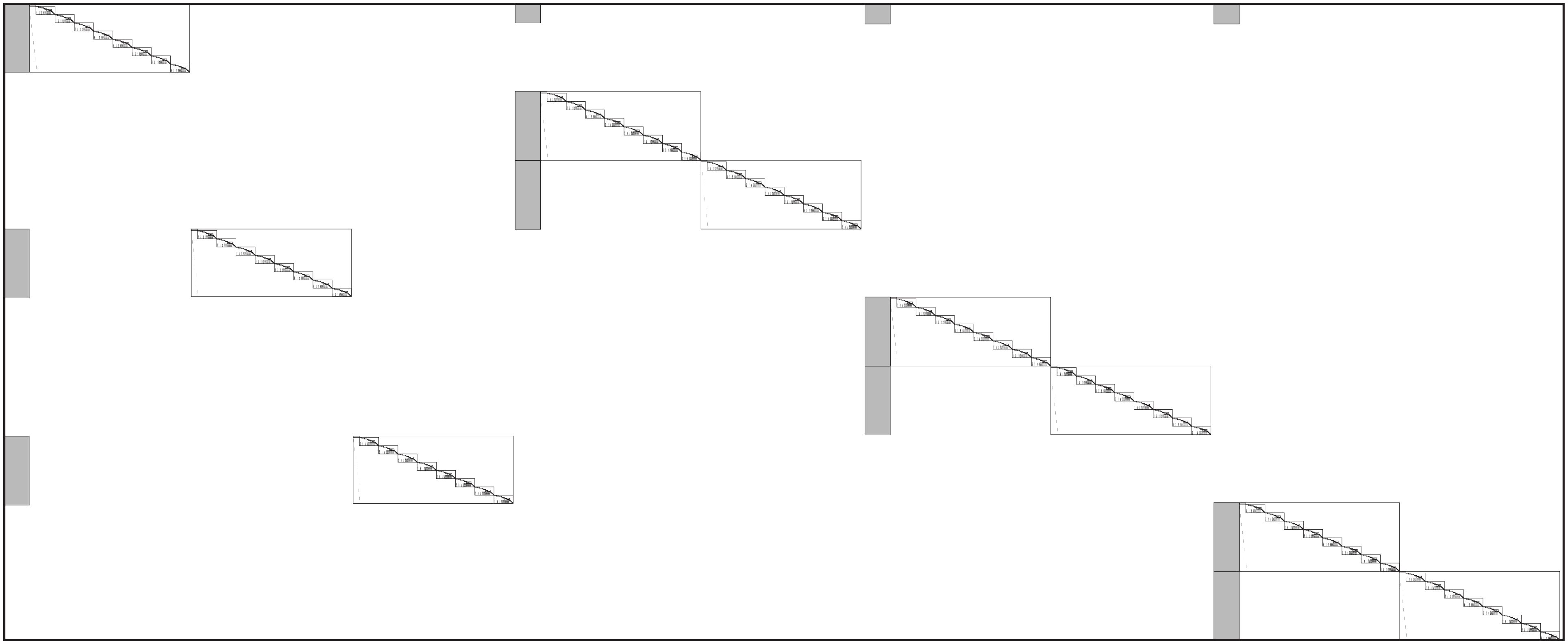
Mid-term problem: Seasonal storage valuation

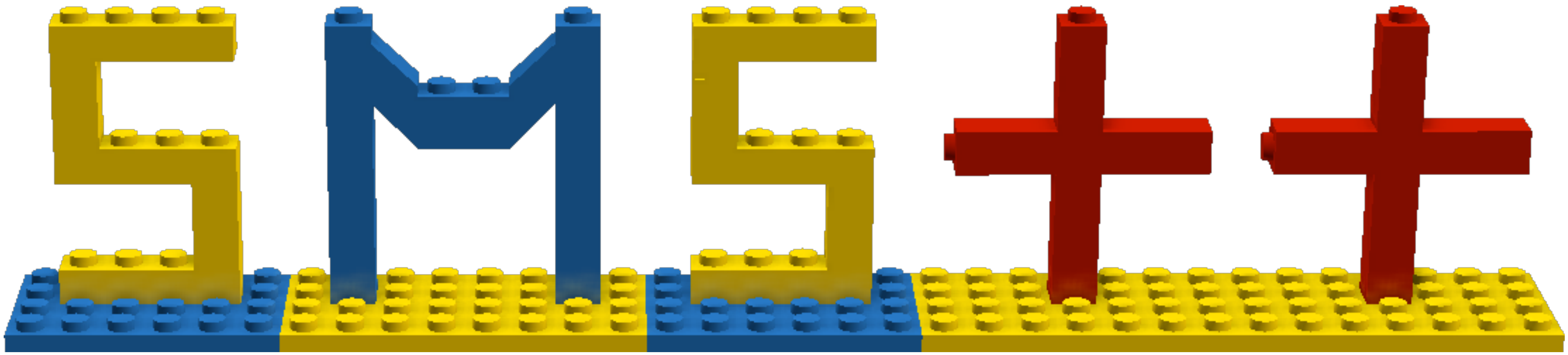


Long-term problem: Investment layer

- Long-term planning needed: the energy system changes frequently, but modifications are slow and costly
- Uncertainties in demand and production:
  - shifts in consumption patterns (EV, cryptocurrencies, . . .)
  - regulatory factors (EU energy market, . . .),
  - political factors (CO_2 emission treaties, nuclear power, . . .)
  - . . .
- Design the optimal generation mix with the optimal transmission and distribution grid capacities
- 30-year horizon with 5-year steps (multi-level recourse), many scenarios

Long-term problem



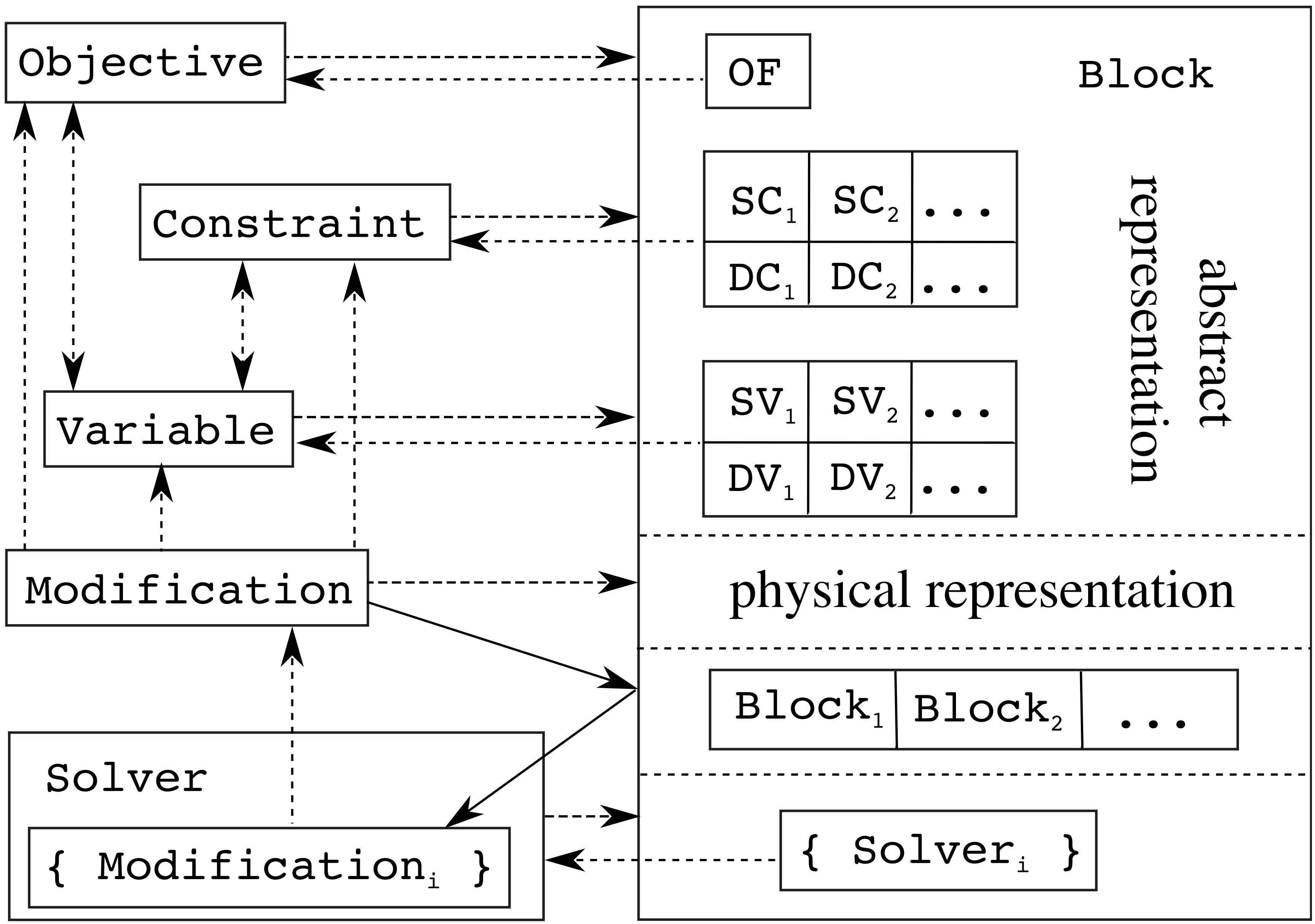

SMS++

SMS++

A set of C++ classes implementing a modelling system that:

- explicitly supports the notion of block ≡ nested structure
- separately provides "semantic" information from "syntactic" details (objective and list of constraints/variables ≡ one specific formulation among many)
- allows exploiting specialised solvers on blocks with specific structure
- manages dynamic changes in the model beyond "just" generation of constraints/variables
- manages reformulation/restriction/relaxation

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$_i$ }

SMS++
`Block`

- `Block` is an abstract class representing the general concept of "a part of a mathematical model with a well-understood identity".
- Each `:Block` is a model with specific structure (e.g., `MCFBlock:Block` = a Min-Cost Flow problem).
- Physical representation of a `Block`: whatever data structure is required to describe the instance (e.g., for a `MCFBlock`, a graph, source and sink nodes, cost and capacity of each arc, . . .)
- Abstract representation of a `Block`: an `Objective` and an "unstructured" list of `Constraints` and `Variables`.

SMS++
Block and Solver

- :Solver for a specific :Block can use the physical representation
  $\Longrightarrow$ no need for explicit Constraint or Objective
  $\Longrightarrow$ abstract representation of Block only constructed on demand

- A general-purpose Solver uses the abstract representation

- Dynamic Variable/Constraint can be generated on demand (user cuts/lazy constraints/column generation)

- Objective of sub-Blocks summed to that of father Block if it has same sense, otherwise $\min / \max$

SMS++
Solver

- Solver = interface between a Block and algorithms solving it
- Each Solver attached to a single Block, from which it picks all the data, but any # of Solver can be attached to the same Block
- Individual Solver can be attached to sub-Block of a Block
- Tries to cater for all the important needs:
  - optimal and sub-optimal solutions, provably unbounded/infeasible
  - time/resource limits for solutions, but restarts (reoptimization)
  - any # of multiple solutions produced on demand
  - lazily reacts to changes in the data of the Block via Modification

- Most Block components can change, but not all:
  - set of sub-Block
  - # and shape of groups of Variable/Constraint
- Any change is communicated to each interested Solver (attached to the Block or any of its ancestor) via a Modification object
- However, two different kinds of Modification (what changes):
  - physical Modification, only specialized Solver concerned
  - abstract Modification, only Solver using it concerned

Example: Capacitated Facility Location

Given a set L of locations and a set D of customers, the problem consists in selecting a subset of the locations in which facilities will be placed in order to serve the given set of customers.

Example: Capacitated Facility Location

$$
\begin{aligned}
\min \quad & \sum_{i \in L} f_i y_i + \sum_{i \in L} \sum_{j \in D} c_{ij} x_{ij} \\
\text{s.t.} \quad & \sum_{i \in L} x_{ij} = 1, \forall j \in D \\
& \sum_{j \in D} d_j x_{ij} \leq u_i y_i, \forall i \in L \\
& x \geq 0 \\
& y \in \{0, 1\}^{|L|}
\end{aligned}
$$

Example: Capacitated Facility Location
Abstract representation

$$
\begin{aligned}
\min \quad & f(x, y) \\
\text{s.t.} \quad & h_i(x) = 0, \forall i \in I \\
& g_j(x) \leq 0, \forall j \in J \\
& x \in X \\
& y \in Y
\end{aligned}
$$

Example: Capacitated Facility Location
Physical representation

- L and D
- $f_i,\ \forall i \in L$
- $c_{ij},\ \forall\ i \in L,\ \forall j \in D$
- $d_j,\ \forall j \in D$

Example: Capacitated Facility Location

$$
\begin{aligned}
\min \quad & \sum_{i \in L} f_i y_i \\
\text{s.t.} \quad & \sum_{j \in D} d_j x_{ij} \leq u_i y_i, \forall i \in L \\
& y \in \{0,1\}^{|L|}
\end{aligned}
$$

j-th sub-Block:

$$
\begin{aligned}
\min \quad & \sum_{i \in L} c_{ij} x_{ij} \\
\text{s.t.} \quad & \sum_{i \in L} x_{ij} = 1 \\
& x_j \geq 0
\end{aligned}
$$

Stochastic SMS++

SMS++ is (almost) ready for deterministic optimization.

Stochastic SMS++

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What about stochastic optimization?

Stochastic SMS++

We must represent uncertainty in SMS++.

Stochastic SMS++

We must represent uncertainty in SMS++.

`UCBlock`	`ThermalUnitBlock`
`UnitBlock`	`EMobilityUnitBlock`
`HeatBlock`	`PowerToGasUnitBlock`
`NetworkBlock`	`BatteryUnitBlock`
`HydroUnitBlock`	`IntermittentUnitBlock`
`DCNetworkBlock`	`CentralizedDemandResponseUnitBlock`
`BusNetworkBlock`	...

Ideally, without changing the implementation of the `Blocks`.

Stochastic SMS++

$$\min_{\text{s.t. } x_1 \in X_1} f_1(x_1) + \mathbb{E}\Bigg[\min_{\text{s.t. } x_2 \in X_2(x_1,\xi_2)} f_2(x_2;\xi_2) + \mathbb{E}_{|\xi_{[2]}}\Bigg[\cdots + \mathbb{E}_{|\xi_{[T-1]}}\Bigg[\min_{\text{s.t. } x_T \in X_T(x_{T-1},\xi_T)} f_T(x_T;\xi_T) \Bigg]\Bigg]\Bigg]$$

$\{\xi_t\}_{t \in \{2,\dots,T\}}$ is a stochastic process

Stochastic SMS++

$$\begin{array}{ll}\min & f_1(x_1)\\ \text{s.t.} & x_1 \in X_1\end{array} + \mathbb{E}\left[\begin{array}{ll}\min & f_2(x_2;\xi_2)\\ \text{s.t.} & x_2 \in X_2(x_1,\xi_2)\end{array} + \mathbb{E}_{|\xi_{[2]}}\left[\cdots + \mathbb{E}_{|\xi_{[T-1]}}\left[\begin{array}{ll}\min & f_T(x_T;\xi_T)\\ \text{s.t.} & x_T \in X_T(x_{T-1},\xi_T)\end{array}\right]\right]\right]$$

$\{\xi_t\}_{t\in\{2,\ldots,T\}}$ is a stochastic process

Stochastic dual dynamic programming (SDDP)

Stochastic SMS++

$$
\begin{aligned}
V_t(x_{t-1}, \xi_t) = \min_{x_t} \quad & f_t(x_t; \xi_t) + \mathcal{V}_{t+1}(x_t, \xi_t) \\
\text{s.t.} \quad & x_t \in X_t(x_{t-1}, \xi_t)
\end{aligned}
$$

$$
\mathcal{V}_{t+1}(x_t, \xi_t) = \mathbb{E}\left[V_{t+1}(x_t, \xi_{t+1}) \mid \xi_{[t]}\right]
$$

Stochastic SMS++

$$
\begin{aligned}
V_t(x_{t-1}, \xi_t) = \min_{x_t} \quad & f_t(x_t; \xi_t) + \mathcal{V}_{t+1}(x_t, \xi_t) \\
\text{s.t.} \quad & x_t \in X_t(x_{t-1}, \xi_t)
\end{aligned}
$$

$$
\mathcal{V}_{t+1}(x_t, \xi_t) = \mathbb{E}\left[V_{t+1}(x_t, \xi_{t+1}) \mid \xi_{[t]} \right]
$$

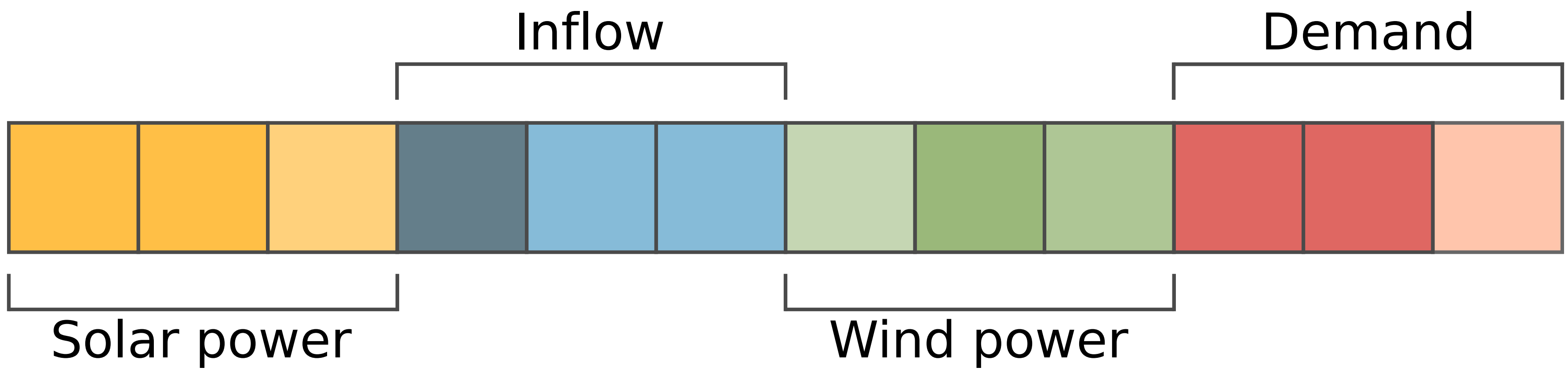
$$
\begin{aligned}
\min_{x_t} \quad & f_t(x_t; \tilde{\xi}_t) + \mathcal{P}_{t+1}(x_t) \\
\text{s.t.} \quad & x_t \in X_t(\tilde{x}_{t-1}, \tilde{\xi}_t)
\end{aligned}
$$

Stochastic SMS++

We must be able to:

- Simulate the random variables.
- Update the data of the `Blocks` for a given realization of the random variables.

Stochastic SMS++



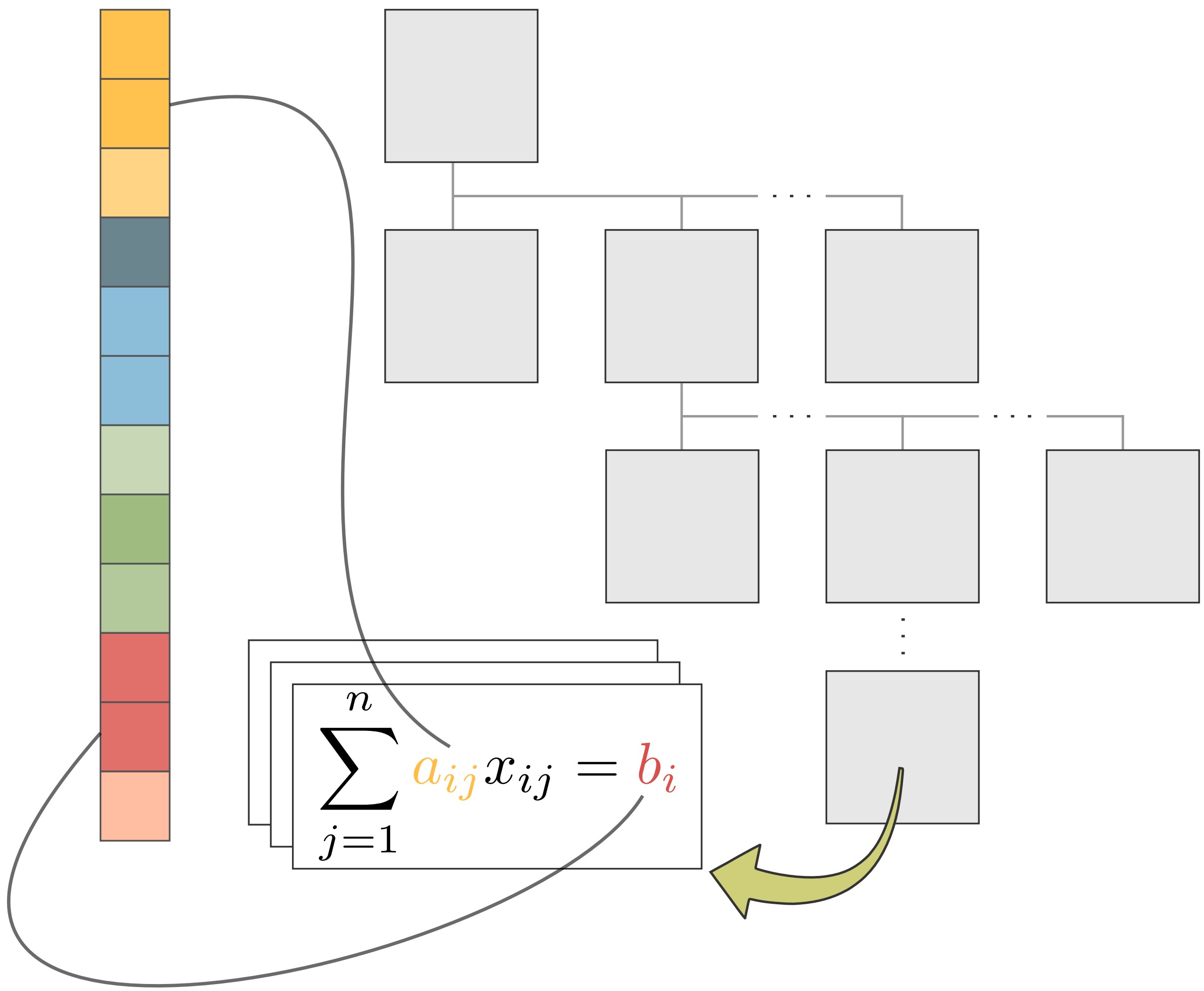
Setting the data

We can set the data by using either the abstract or the physical representation of the `Block`.

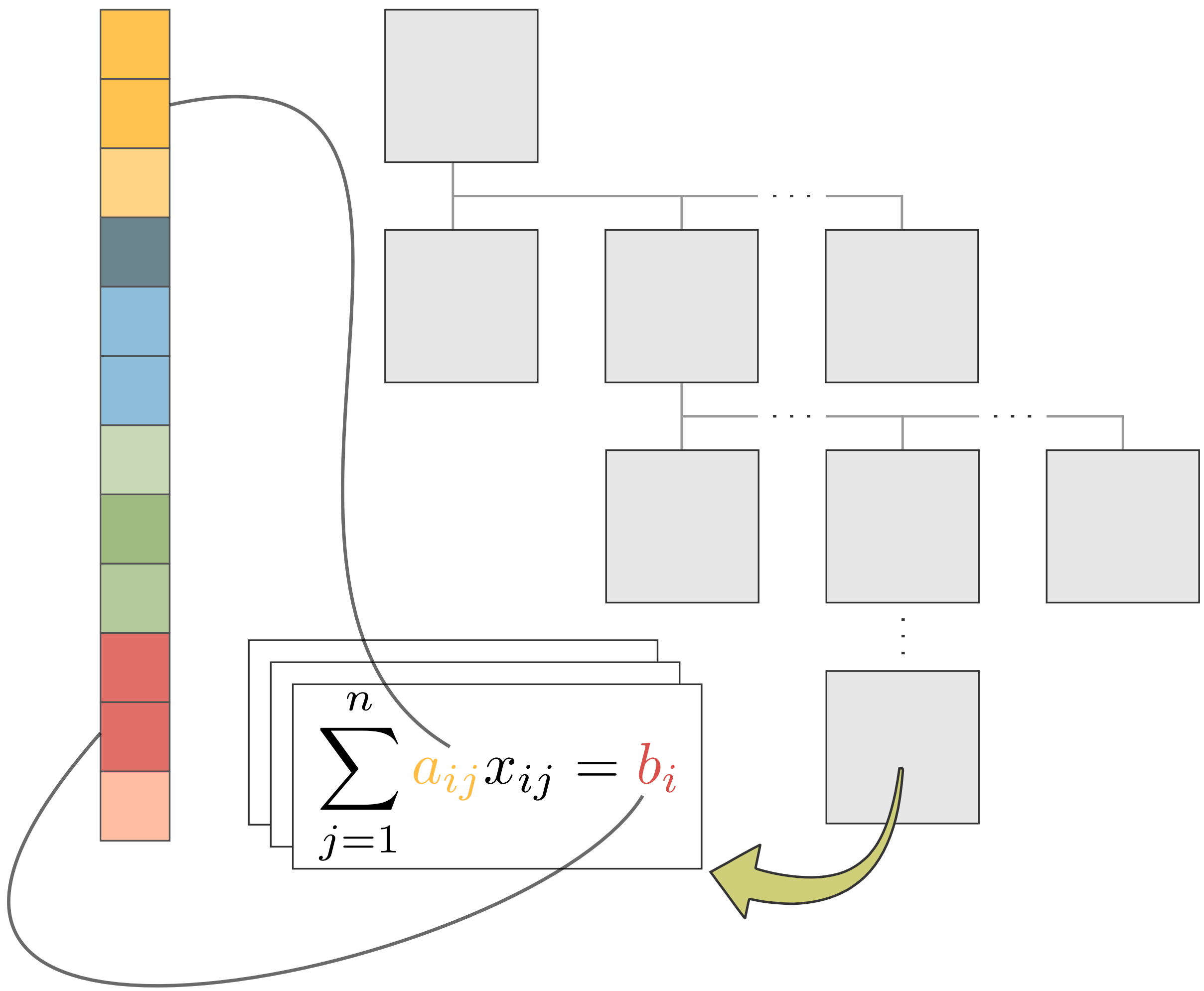
Setting the data
Abstract representation

- A random variable may appear in the `Objective` and/or in the `Constraints`.
- Let's assume that a random variable appears in the right-(or left-)hand side of a `RowConstraint` or as the coefficient of some `Variable`.

Setting the data
Abstract representation



Setting the data
Abstract representation



It is doable, but can be complicated for the user.

Setting the data
Physical representation

- We set the data by using the available methods in the `Blocks`.

```
void HydroUnitBlock::set_inflow(std::vector<double> inflow);
```

- The methods are first registered in the methods factory.
- Pointer to a method can be retrieved by its name.

Setting the data
Physical representation

- What if the available methods are not enough?
- One can write their own method and register it in the methods factory.

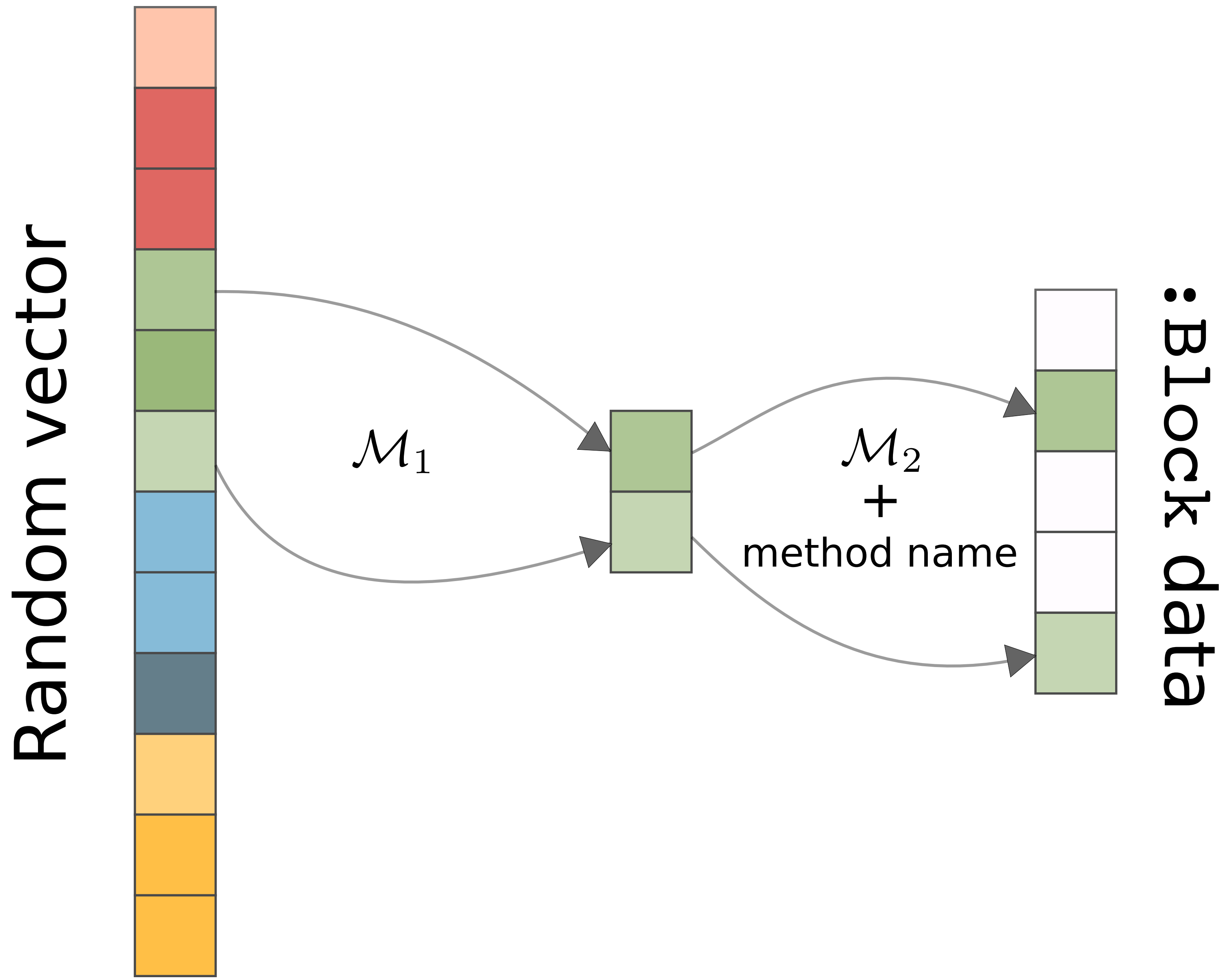
```
void customized_set_inflow(Block * block, ...) {
    ...
}

Block::register_method
  ("HydroUnitBlock::customized_set_inflow",
   new Block::FunctionType<...>(customized_set_inflow));
```

Data Mapping

- Data mapping identifies the random variables in the `Blocks`.
- At the same time, it provides means to set the values of those variables.
- It associates methods in the methods factory with instances of `:Block`.

Data Mapping



StochasticBlock

- It has a (single) nested `Block` (which is becoming stochastic).

- It has a data mapping.

- It has a probability distribution or a "partial stochastic process".

Current and future work

- `BendersBlock` turns a Block into its Benders' reformulation

- `LagrangianDualBlock` turns any `Block` into its Lagrangian Dual w.r.t. constraints linking its sub-`Block`

- Asynchronous execution of the computationally heavy parts.

Acknowledgements

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