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# Outline

GREDOR as an optimisation problem

Finding  $m^*$ , the optimal interaction model

Finding  $i^*$ , the optimal investment strategy

Finding  $o^*$ , the optimal operation strategy

Finding  $r^*$ , the optimal real-time control strategy

Conclusion

# From fit and forget to active network management

Distribution networks traditionally operated according to the **fit and forget doctrine**.

## Fit and forget.

Network planning is made with respect to a set of critical scenarios to ensure that sufficient operational margins are always guaranteed (i.e., no over/under voltage problems, overloads) without any control over the loads or the generation sources.

## Shortcomings.

With rapid growth of distributed generation resources, maintaining such conservative margins comes at continuously increasing network reinforcement costs.

The buzzwords for avoiding prohibitively reinforcement costs:  
**active network management.**

### Active network management.

Smart modulation of generation sources, loads and storages so as to safely operate the electrical network without having to rely on significant investments in infrastructure.

### GREDOR project.

Redesigning in an integrated way the **whole decision chain** used for managing distribution networks in order to perform active network management optimally (i.e., maximisation of social welfare).



# Decision chain

The **four stages of the decision chain** for managing distribution networks:

1. Interaction models
2. Investments
3. Operational planning
4. Real-time control

## 1. Interaction models

An interaction model defines the **flows of information, services and money** between the different actors. Defined (at least partially) in the regulation.

**Example:** The Distribution System Operator (DSO) may curtail a wind farm at a regulated activation cost.

## 2. Investments

Planning of the investments needed to upgrade the network.

**Examples:** Decisions to build new cables, investing in telemeasurements, etc.

### 3. Operational planning

Decisions taken a few minutes to a few days before real-time.  
Decisions that may interfere with energy markets.

**Example:** Decision to buy the day-ahead load flexibility to solve overload problems.

### 4. Real-time control

Virtually real-time decisions. In the normal mode (no emergency situation caused by an “unfortunate event”), these decisions should not modify production/consumption over a market period.

**Examples:** modifying the reactive power injected by wind farms into the network, changing the tap setting of transformers.

# GREDOR as an optimization problem

- $\mathcal{M}$  : Set of possible **m**odels of interaction
- $\mathcal{I}$  : Set of possible **i**nvestment strategies
- $\mathcal{O}$  : Set of possible **o**perational planning strategies
- $\mathcal{R}$  : Set of possible **r**eal-time control strategies

Solve:

$$\arg \max_{(m,i,o,r) \in \mathcal{M} \times \mathcal{I} \times \mathcal{O} \times \mathcal{R}} \text{social\_welfare}(m, i, o, r)$$

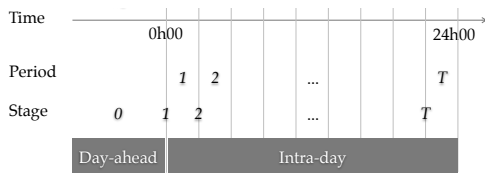


# A simple example

$\mathcal{M}$ : Reduced to one single element.

Interaction model mainly defined by these two components:

1. The DSO can buy the day-ahead load flexibility service.
2. Between the beginning of every market period, it can decide to curtail generation for the next market period or activate the load flexibility service. Curtailment decisions have a cost.



$\mathcal{I}$ : Made of two elements. Either to invest in an asset  $A$  or not to invest in it.

$\mathcal{O}$ : The set of operational strategies is the set of all algorithms that:

- (i) In the day-ahead process information available to the DSO to decide which flexible loads to buy
- (ii) Process before every market period this information to decide
  - ▶ how to modulate the flexible loads
  - ▶ how to curtail generation.

$\mathcal{R}$ : Empty set. No real-time control implemented.

$social\_welfare(m, i, o, r)$ : The (expected) costs for the DSO.

# The optimal operational strategy

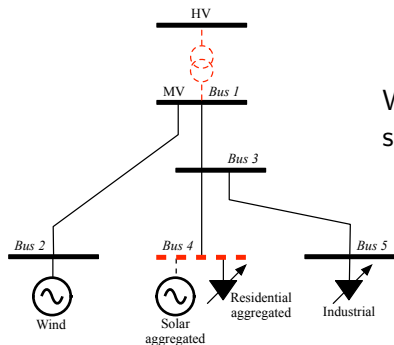
Let  $o^*$  be an optimal operational strategy. Such a strategy has the following characteristics:

1. For every market period, it leads to a safe operating point of the network (no overloads, no voltage problems).
2. There are no strategies in  $\mathcal{O}$  leading to a safe operating point and having a lower (expected) **total cost** than  $o^*$ . This cost is defined as the cost of buying flexibility plus the costs for curtailing generation.

It can be shown that the optimal operation strategy can be written as a **stochastic sequential optimization problem**.

Solving this problem is challenging. Getting even a good suboptimal solution may be particularly difficult for large distribution networks and/or when there is strong uncertainty on the power injected/withdrawn day-ahead.

## Illustrative problem



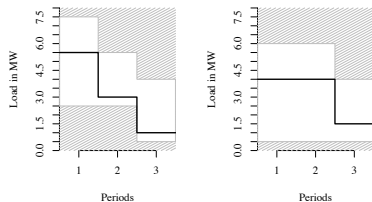
When Distributed Generation (DG) sources produce a lot of power:

- ▶ overvoltage problem at *Bus 4*,
- ▶ congestion problem on the *MV/HV* transformer.

Two flexible loads; only three market periods; possibility to curtail the two DG sources before every market period (at a cost).

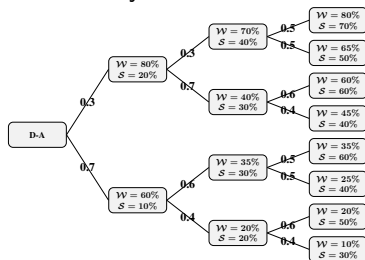
# Information available to the DSO on the day-ahead

The flexible loads offer:



Residential aggregated (left) and industrial (right).

Scenario tree for representing uncertainty:



$W$  = Wind;  $S$  = Sun.

Additional information: a load-flow model of the network; the price (per MWh) for curtailing generation.

# Decisions output by $o^*$

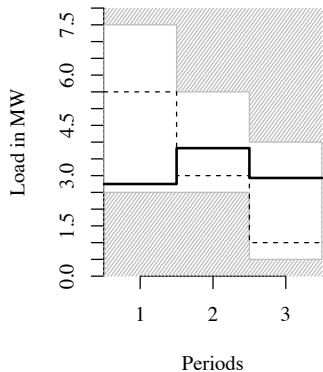
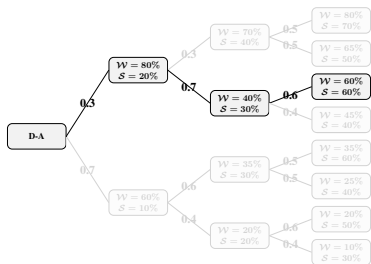
**The day-ahead:** To buy flexibility offer from the *residential aggregated load*.

**Before every market period:** We report results when generation follows this scenario.

*Results:*

Generation never curtailed.

Load modulated as follows:



## On the importance of managing uncertainty well

	$E\{cost\}$	$max\_cost$	$min\_cost$	$std\_dev.$
$\rho^*$	46\$	379\$	30\$	72\$
MSA	73\$	770\$	0\$	174\$

where MSA stands for Mean Scenario Strategy.

### Observations:

Managing uncertainty well leads to lower expected costs than working along a mean scenario.

### More results in:

Q. Gemine, E. Karangelos, D. Ernst and B. Cornélusse. “Active network management: planning under uncertainty for exploiting load modulation”.

# The optimal investment strategy

Remember that we had to choose between making investment  $A$  or not. Let  $AP$  be the recovery period and  $cost\_A$  the cost of investment  $A$ . The optimal investment strategy can be defined as follows:

1. Simulate using operational strategy  $o^*$  the distribution network with element  $A$  several times over a period of  $AP$  years. Extract from the simulations the expected cost of using  $o^*$  during  $AP$  years. Let  $cost\_o^*\_with\_A$  be this cost.
2. Simulate using operational strategy  $o^*$  the distribution network without element  $A$  several times over a period of  $AP$  years. Extract from the simulations the expected cost of using  $o^*$  during  $AP$  years. Let  $cost\_o^*\_without\_A$  be this cost.
3. If  $cost\_A + cost\_o^*\_with\_A \leq cost\_o^*\_without\_A$ , do investment  $A$ . Otherwise, not.



# Solving the GREDOR optimization problem

Solving the complete optimization problem

$$\arg \max_{(m,i,o,r) \in \mathcal{M} \times \mathcal{I} \times \mathcal{O} \times \mathcal{R}} \text{social\_welfare}(m, i, o, r)$$

in a single step is too challenging. Therefore, the problem has been decomposed in 4 subproblems:

1. Finding  $m^*$ , the optimal interaction model,
2. Finding  $i^*$ , the optimal investment strategy,
3. Finding  $o^*$ , the optimal operation strategy,
4. Finding  $r^*$ , the optimal real-time control strategy.

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## Finding $m^*$

The set  $\mathcal{M}$  of interaction models is only limited by our imagination. In the GREDOR project, we have selected **four interaction models** to study in more detail.

These interaction models are defined by:

1. The type of access contract between the users of the grid and the DSO,
2. The financial compensation of flexibility services.

For simplicity, we focus only on the **access contract** feature of the interaction models in this presentation.

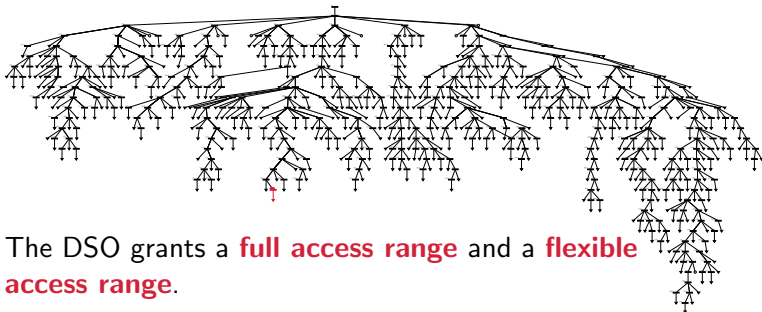
### More information

S. Mathieu, Q. Louveaux, D. Ernst, and B. Cornélusse, “*DSIMA: A testbed for the quantitative analysis of interaction models within distribution networks*”.

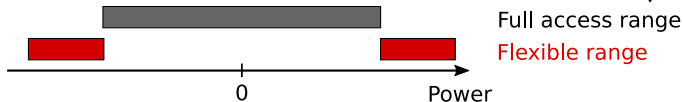
# Access agreement

The interaction models are based on **access contracts**.

- ▶ The grid user **requests** access to a given bus.



- ▶ The DSO grants a **full access range** and a **flexible access range**.

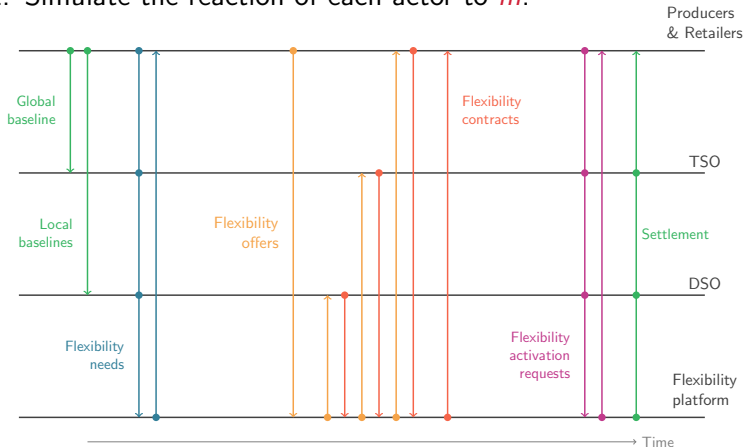


- ▶ The **width** of these ranges depends on the **interaction model**.

# Flow of interactions

One method to obtain  $social\_welfare(m, i, o, r)$  is to simulate the distribution system with all its actors and compute the surpluses and costs of each of them. This simulation requires us to:

1. Define all decision stages as function of  $m$ ,
2. Simulate the reaction of each actor to  $m$ .



# One day in the life of a producer selling flexibility services

A **producer** performs the following actions:

1. Sends its **baseline** to the **TSO** at the **high-voltage** level.  
*I will produce 15MWh in distribution network 42 between 8am and 9am.*
2. Sends its **baseline** to the **DSO** at the **medium-voltage** level.  
*I will produce 5MWh in bus 20 between 8am and 9am.*
3. Obtains **flexibility needs** of the flexibility services users.  
*The DSO needs 3MWh downward in bus 20 between 8am and 9am.*
4. Proposes **flexibility offers**.  
*I can curtail my production by 2MWh in bus 20 between 8am and 9am.*
5. Receives **activation requests** for the contracted services.  
*Curtail production by 1MWh in bus 20 between 8am and 9am.*
6. Decides the final **realizations**.  
*Produce 4MWh, or 5MWh if more profitable, in bus 20 between 8am and 9am.*

# Parameters of the interaction models

The implementation of the models are based on 3 **access contracts**:

- ▶ **“Unrestricted” access**: Allow the grid users access to the network **without restriction**.



- ▶ **“Restricted” access**: **Restrict** the grid users so that no problems can occur.



- ▶ **“Flexible” access**: Allow the users to produce/consume as they wish but if they are **in the flexible range**, they are obliged to propose **flexibility services** to the DSO.



In this presentation, we assume that these flexibility services are paid by the **DSO** at a cost which **compensates** the **imbalance** created by the activation of the service.

# Effects of the access range on the baseline of an actor

The access restriction of the DSO is shown by the red dotted line.

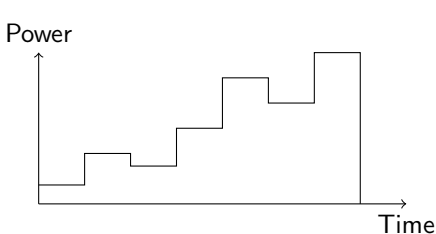


Figure : Unrestricted access

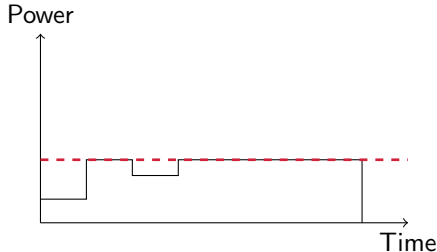


Figure : Restricted access

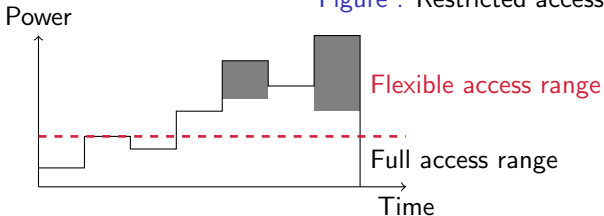


Figure : Flexible access - The filled areas represents the energy curtailed by the DSO by the activation of mandatory flexibility services.



## Back to our optimization problem

These models are studied for a given investment, operation planning and real-time control strategy, i.e. **one strategy**  $(i, o, r)$ .

$$\arg \max_{(m,i,o,r) \in \mathcal{M} \times I \times \mathcal{O} \times \mathcal{R}} \text{social\_welfare}(m, i, o, r)$$

Consider the simplified subset of interaction models

$\mathcal{M} = \{ \text{"unrestricted"} , \text{"restricted"} , \text{"flexible"} \}$ .

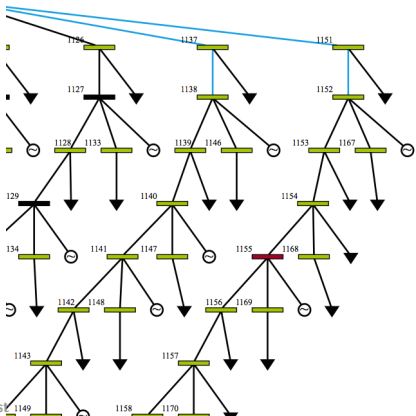
$\text{social\_welfare}(m, i, o, r)$ : the sum of the surpluses minus the costs of all actors and a cost given by the protection scheme of the real-time control strategy.

# Open-source testbed

The testbed evaluating interaction models is available as an open source code at the address

<http://www.montefiore.ulg.ac.be/~dsima/>.

It is based on an agent-based model where every agent solves an optimization problem for each decision stage.

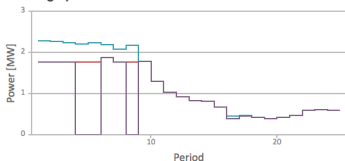


## Bus 56

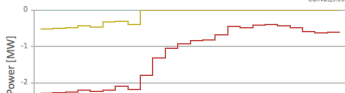
### Data

<b>Shed</b>	in period(s) 4, 5, 8
<b>Flexibility used</b>	in period(s) 1, 2, 3, 4, 5, 6, 7, 8
<b>Downward access request bound</b>	0.00
<b>Upward access request bound</b>	2.71
<b>Safe downward access bound</b>	0.00
<b>Safe upward access bound</b>	1.77

### Time graphs



— Announced baseline — Corrected baseline — Realization CanvasJS.com



## Comparison of the interaction models

Simulation of a **75 bus** system in an **expected 2025 year** with **3 producers and 3 retailers** owning assets connected to the DN.

Interaction model	Unrestricted	Restricted	Flexible	
<b>Welfare</b>	<b>29077</b>	<b>27411</b>	<b>39868</b>	€
Protections cost	12071	0	914	€
TSO surplus	2878	2879	2873	€
DSO costs	0	0	444	€
Producers surplus	37743	24005	37825	€
Retailers surplus	527	527	528	€

**Table :** Mean daily welfare and its distribution between the actors.

### Key messages

**Unrestricted:** Too much renewable production leading to high protections cost. Who would pay this cost?

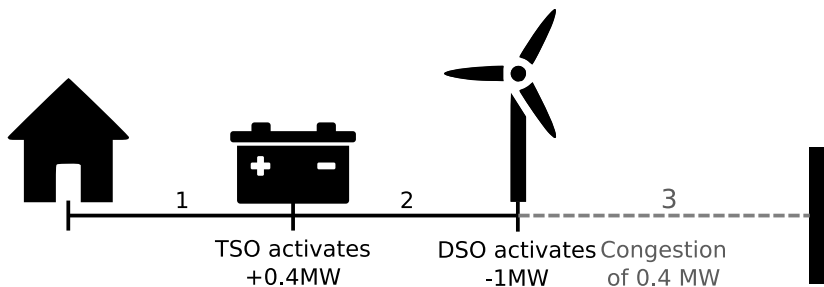
**Restricted:** Little allowed renewable generation but a secure network.

**Flexible:** Large amount of renewable generation but still requiring a few sheddings due to coordination problems.

## Coordination problem

The model “flexible” suffers from the **lack of coordination** between the **DSO** and the **TSO**.

Assume that the flow exceeds the capacity of line 3 by 1MW. To solve this issue, the **DSO curtails** a windmill by 1MW. In the same time, assume that the **TSO asks** a storage unit to **inject** 0.4MW. These activations leads to a remaining congestion of 0.4MW.



# Outline

GREDDOR as an optimisation problem

Finding  $m^*$ , the optimal interaction model

**Finding  $i^*$ , the optimal investment strategy**

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Conclusion

# Finding $i^*$

The investment strategy  $i^*$  is divided in two parts:

1. Announcing the capacity of renewables that may be connected to the network: **Global Capacity ANnouncement.**
2. Determining the target optimal network: **Investment planning tool.**

# GCAN: Global Capacity ANnouncement

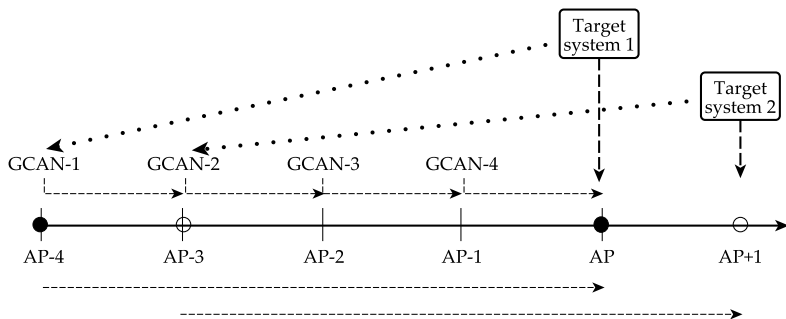
GCAN is a tool that determines the maximum hosting capacity of a medium voltage distribution network.

Features of GCAN:

- ▶ Determines the capacity of each bus.
- ▶ Accounts for the future of the system.
- ▶ Relies on the tools that are routinely used by DSOs (repeated power flows).
- ▶ Results may be published in appropriate form (tabular, map, through the regulator, etc.).

GCAN is not meant to be a replacement for more detailed computations for generation connection projects.

# GCAN procedure



The procedure is implemented in a **rolling horizon** manner. The results are refreshed at each step of the planning horizon.

## More information:

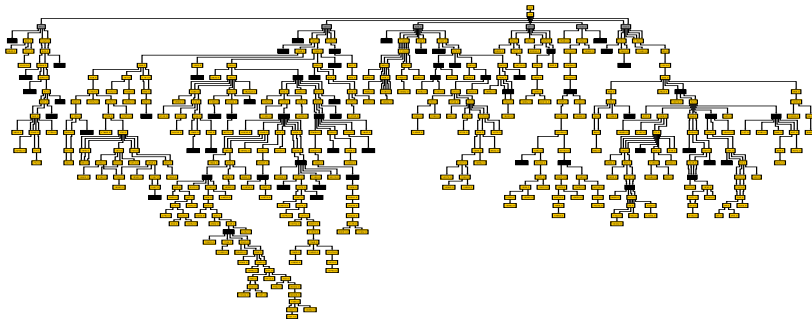
B. Cornélusse, D. Vangulick, M. Glavic, D. Ernst: *“Global capacity announcement of electrical distribution systems: A pragmatic approach”*.



# GCAN results

Subst. name	Feeder name	Voltage (kV)	Gener. (MW)	Gener. type
99	FN1	10.0	<b>0.75</b>	PV
2064	FN1	10.0	<b>0.30</b>	PV
...	...	...	...	...

Black squares in one-line diagram indicate generation substations.



# Investment planning tool

## Main software tools

**Smart Sizing** – determines the main features of the ideal network.

*Rating of cables, number of substations, etc.*

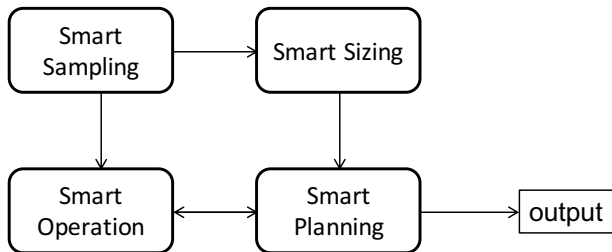
**Smart Planning** – development of grid expansion plans.

*Change cable between bus 16 and 17 in 2020.*

## Supporting software tools

**Smart Operation** – mimics the grid operation. Proxy of  $o^*$ .

**Smart Sampling** – provides exogenous data such as load profiles.



# Smart sampling

Smart Sampling creates calibrated **time series models** able to generate **synthetic load and generation profiles** mimicking the statistical properties of real measurements.

## Advantages

- ▶ **Compactness:** as they are represented by mathematical formula with a few parameters.
- ▶ **Information reduction:** computational burden can be reduced by working on a reduced statistically relevant data set.

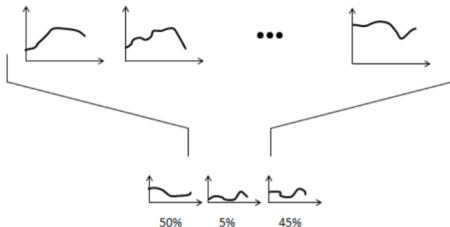
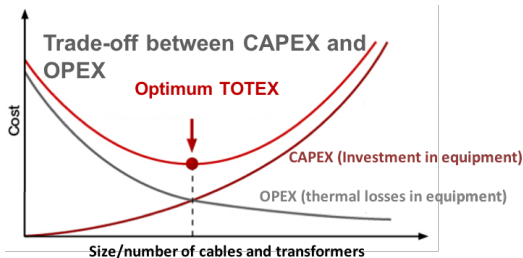


Figure : A large set of profiles is reduced to 3 profiles.

# Smart Sizing

A tool for long-term planning to find **“least cost features of the distribution network”**, taking into account CAPEX/OPEX while meeting voltage constraint given **targets of load and DG penetration**.



Smart sizing evaluates the **“traditional aspects”** just like any traditional planning tool (number of transformer, infrastructure cost, cost due to losses, etc.), the **benefits of flexibility** and the impact of **distributed generation** on grid costs.

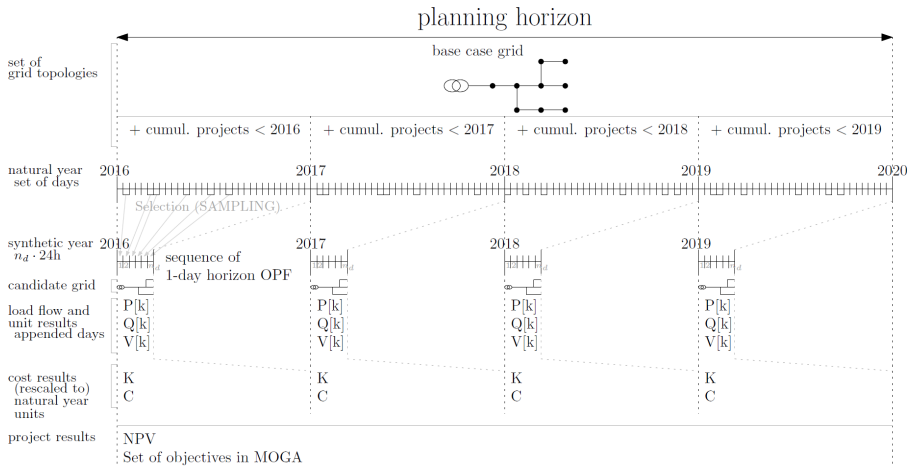
# Smart Planning

The multistage investment planning problem is hard to tackle as planning decisions are subject to **uncertainty**.

The smart planning tool **schedules optimal investment plans** from today to target architecture (with smart planning) integrating the optimal future system operation (with smart operation). It decides:

- ▶ The type of grid investment and optimal year of investment,  
*Install a cable between node A and B in 2016.*
- ▶ The optimal use of available flexibility,  
*Load shifting, PV curtailment.*
- ▶ Reactive power support.  
*From PV/storage.*

# Smart Planning - Overview



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## Finding $o^*$ - Goal

Given an electrical distribution system, described by:

- ▶  $\mathcal{N}$  and  $\mathcal{L}$ , the network infrastructure;
- ▶  $\mathcal{D}$ , the electrical devices connected to the network;
- ▶  $\mathcal{C}$ , a set of operational limits;
- ▶  $\mathcal{T}$ , the set of time periods in the planning horizon.

We want the best strategy  $o^*$  which defines the set of **power injections** of the devices

$$\{(P_d, Q_d) \mid d \in \mathcal{D}\}$$

to be such that the **operational constraints**

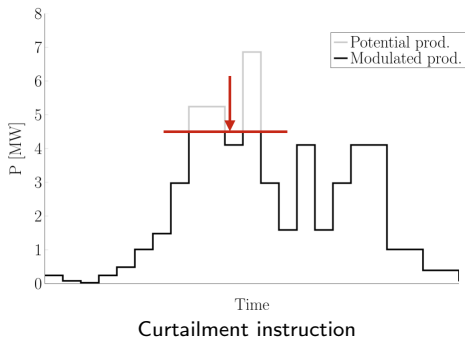
$$\{g_c(\cdot) \geq 0 \mid c \in \mathcal{C}\}$$

are respected for all  $t \in \mathcal{T}$ .



## Control actions - curtailment

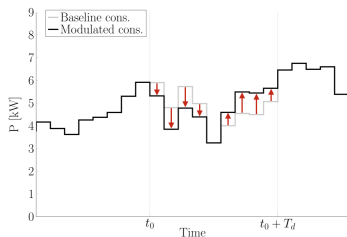
A **curtailment instruction**, i.e. an upper limit on the production level of a generator, can be imposed for some distributed generators.



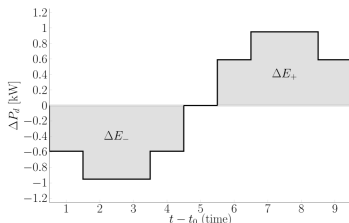
The DSO has to **compensate for the energy that could not be produced** because of its curtailment instructions, at a price that is proportional to the amount of curtailed energy.

# Control actions - load modulation

The **consumption** of the flexible loads can be **modulated**, as described by a modulation signal over a certain time period.



Load modulation instruction



Load modulation signal

The **activation** of a flexible load is acquired **in exchange for a fee** that is defined by the flexibility provider.

# Decisional Framework

We rely on a **Markov Decision Process** framework for modeling and decision-making purposes. At each time-step  $t$ , the system is described by its state  $\mathbf{s}_t$  and the control decisions of the DSO are gathered in  $\mathbf{a}_t$ .

The evolution of the system is governed by:

$$\mathbf{s}_{t+1} \sim p(\cdot | \mathbf{s}_t, \mathbf{a}_t),$$

which models that the next state of the system follows a probability distribution that is conditional on the current state and on the actions taken at the corresponding time step.

# Decisional Framework

A **cost function** evaluates the efficiency of control actions for a given transition of the system:

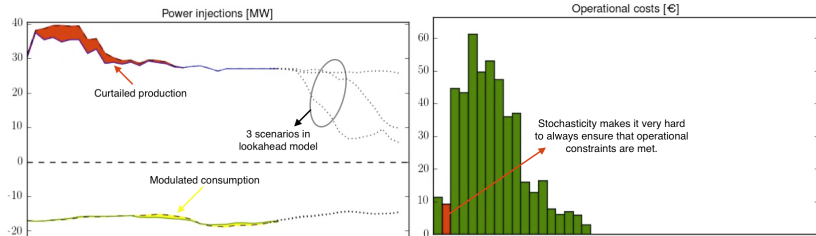
$$\begin{aligned} \text{cost}(\mathbf{s}_t, \mathbf{a}_t, \mathbf{s}_{t+1}) = & \text{curtailment costs} + \\ & \text{flex. activation costs} + \\ & \text{penalties for violated op. constraints.} \end{aligned}$$

Finally, we associate the operational planning problem with the minimization of the **expected sum** of the **costs** that are accumulated over a  $T$ -long trajectory of the system:

$$\min_{\mathbf{a}_1, \dots, \mathbf{a}_T} \mathbb{E}_{\mathbf{s}_1, \dots, \mathbf{s}_T} \left( \sum_{t=1}^{T-1} \text{cost}(\mathbf{s}_t, \mathbf{a}_t, \mathbf{s}_{t+1}) \right)$$

# Computational Challenge

Finding an **optimal sequence** of control actions is **challenging** because of many computational obstacles. The figures illustrate a simple lookahead policy on an ANM simulator.



This **simulator** and a 77-buses test system are available at

<http://www.montefiore.ulg.ac.be/~anm/>.

## More information

Q. Gemine, D. Ernst, B. Cornélusse. "Active network management for electrical distribution systems: problem formulation, benchmark, and approximate solution".

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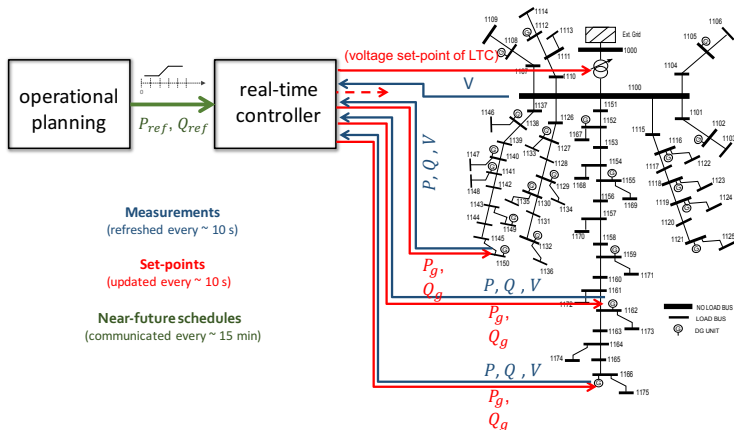
Conclusion

# Centralized real-time controller

The **role** of the real-time controller is to **handle limit violations** observed or predicted close to real-time.

*Over/under-voltage, thermal overload.*

To bring the system to a **safe state**, the controller controls the **DG units outputs** and adjusts the **transformers' tap positions**.



# Multistep optimization problem

Consider a set of **control horizon** periods  $\mathcal{T}$ . For each time step  $k$  we solve the following problem:

$$\min_{P_g, Q_g} \sum_{i \in \mathcal{T}} \pi^P \|P_g(k+i) - P_{ref}(k+i)\|^2 + \sum_{i \in \mathcal{T}} \pi^C \|Q_g(k+i) - Q_{ref}(k+i)\|^2$$

where  $\pi^P$  and  $\pi^C$  are coefficients prioritizing active over reactive control.

## Linearized system evolution

For all  $i \in \mathcal{T}$ ,

$$V(k+i | k) = V(k+i-1 | k) + S_V [u(k+i-1) - u(k+i-2)]$$

$$I(k+i | k) = I(k+i-1 | k) + S_I [u(k+i-1) - u(k+i-2)]$$

where  $S_V$  and  $S_I$  are sensitivities matrices of voltages and currents with respect to control changes.

## Operational constraints

For all  $i \in \mathcal{T}$ ,

$$V^{low}(k+i) \leq V(k+i | k) \leq V^{up}(k+i)$$

$$I(k+i | k) \leq I^{up}(k+i)$$

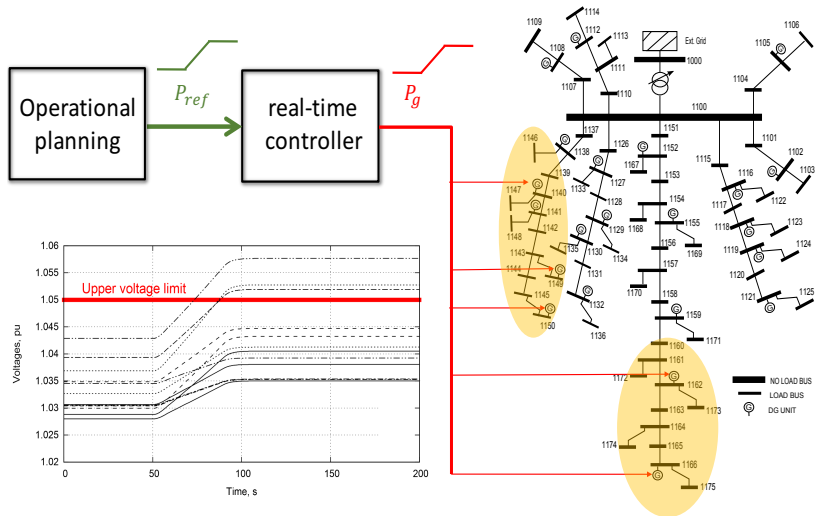
For all  $i \in \mathcal{T}$ ,

$$u^{min} \leq u(k+i | k) \leq u^{max}$$

$$\Delta u^{min} \leq u(k+i | k) - u(k+i-1 | k) \leq \Delta u^{max}$$



# Network behavior without real-time corrective control



# Network behaviour with real-time corrective control

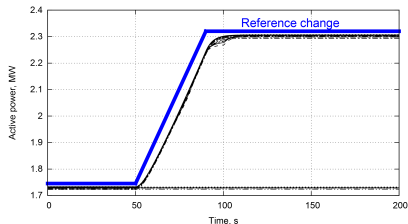


Figure : Active power

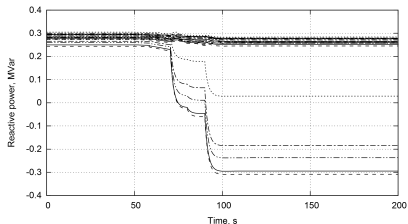


Figure : Reactive power

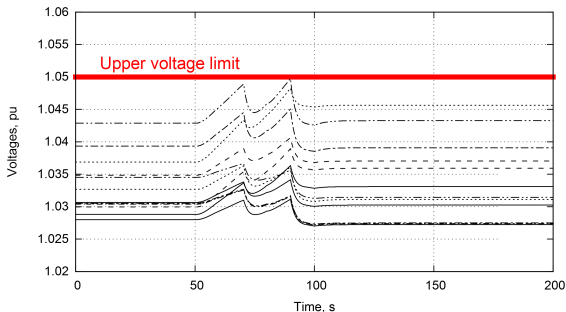


Figure : Voltages

# Outline

GREDDOR as an optimisation problem

Finding  $m^*$ , the optimal interaction model

Finding  $i^*$ , the optimal investment strategy

Finding  $o^*$ , the optimal operation strategy

Finding  $r^*$ , the optimal real-time control strategy

Conclusion

# Four main challenges of the GREDOR project

## Data:

Difficulties for DSOs to gather the right data for building the decision models (especially for real-time control).

## Computational challenges:

Many of the optimization problems in GREDOR are out of reach of state-of-the-art techniques.

## Definition of *social\_welfare*( $\cdot, \cdot, \cdot, \cdot$ ) function:

Difficulties to reach a consensus on what is social welfare, especially given that actors in the electrical sector have conflicting interests.

## Human factor:

Engineers from distribution companies have to break away from their traditional practices. They need incentives to change their working habits.

# Acknowledgements

1. To all the partners of the GREDOR project:



2. To the Public Service of Wallonia - Department of Energy and Sustainable Building for funding this research.



# GREDOR project website

More information, as well as the list of all our **published scientific papers** are available at the address:

<https://www.gredor.be>

The screenshot displays the GREDOR project website interface. At the top, a navigation menu includes links for Home, Work packages, Partners, Publications, and Links. Below the menu is a large QR code. The text "GREDOR is a research project in the framework of the 'Gestion des Ressources Economiques et Sociales' (GRES) program" is visible. Below the QR code, there is a banner image featuring wind turbines and solar panels. The text "Communication day" is prominently displayed, along with the social media handle "www.lu.be/GredorProject". At the bottom, a small text block states: "The event was held in the Media de Boveron Wednesday April 29, 2015 with 10 attendees. For those interested, presentations can be found [here](#)."

# Bibliography

- ▶ S. Mathieu, Q. Louveaux, D. Ernst, and B. Cornélusse, "DSIMA: a testbed for the quantitative analysis of interaction models within distribution networks," *Sustainable Energy, Grids and Networks*, vol. 5, pp. 78–93, 2016
- ▶ B. Cornélusse, D. Vangulick, M. Glavic, and D. Ernst, "Global capacity announcement of electrical distribution systems: a pragmatic approach," *Sustainable Energy, Grids and Networks*, vol. 4, pp. 43–53, 2015
- ▶ Q. Gemine, D. Ernst, and B. Cornélusse, "Active network management for electrical distribution systems: problem formulation and benchmark," *arXiv preprint arXiv:1405.2806*, 2014
- ▶ H. Soleimani Bidgoli, M. Glavic, and T. Van Cutsem, "Model predictive control of congestion and voltage problems in active distribution networks," in *CIREC Workshop 2014 "Challenges of implementing Active Distribution System Management"*, 2014
- ▶ V. François-Lavet, Q. Gemine, D. Ernst, and R. Fonteneau, "Towards the minimization of the levelized energy costs of microgrids using both long-term and short-term storage devices," in *Smart Grid: Networking, Data Management, and Business Models*. CRC Press, 2016, pp. 295–319