09.06.2021

Enlarging the Flow-based Domain in The European Day-ahead Market Clearing through the Full Integration of Grid Flexibilities and Costly Remedial Actions

Emily Little*‡, Adrien Atayi†, Jean-Yves Bourmaud*, Sandrine Bortolotti*, Marjorie Cosson*, Efthymios Karangelos•, Yannick Perez‡

*RTE, †EPEX Spot, ‡Centralesupelec, •University of Liège

Plan

1. Context and Objective
   - Remedial Actions and Grid Flexibility
   - Day Ahead Market and Capacity Calculation

2. Multi-domain Approach
   - Flow-based Operational Description
   - Integration of Multi-domain Approach

3. Case Study

1 Context and Objective

Remedial Actions

Costly	Non-Costly		
Redispatch	FACTS/PSTs	HVDC	Topology Change

Remedial Actions

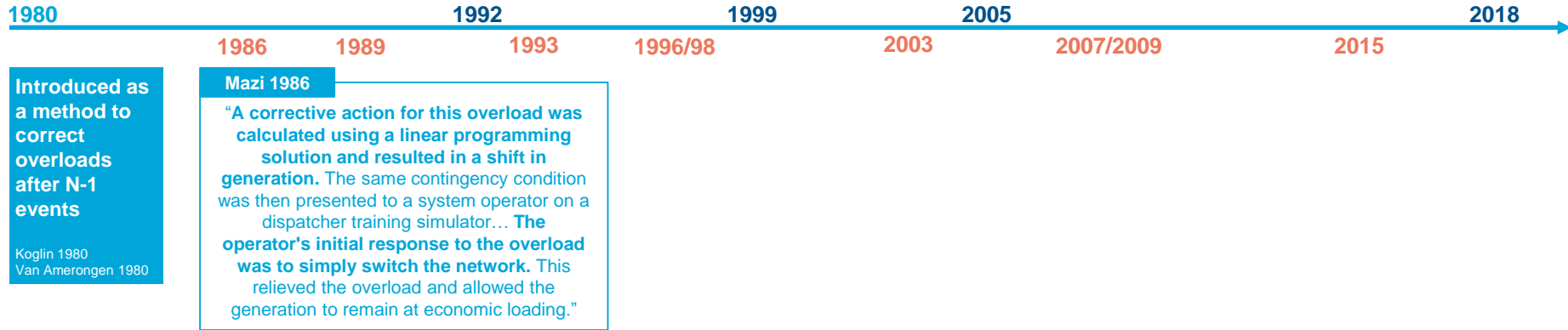| Costly	Non-Costly		
Redispatch	FACTS/PSTs	HVDC	Topology Change

Transmission Switching

- Different types of switching operations:
  - Transmission lines/transformers
  - Bus couplers
  - Shunt elements

- Much more difficult to model →
  - Requires binary variables
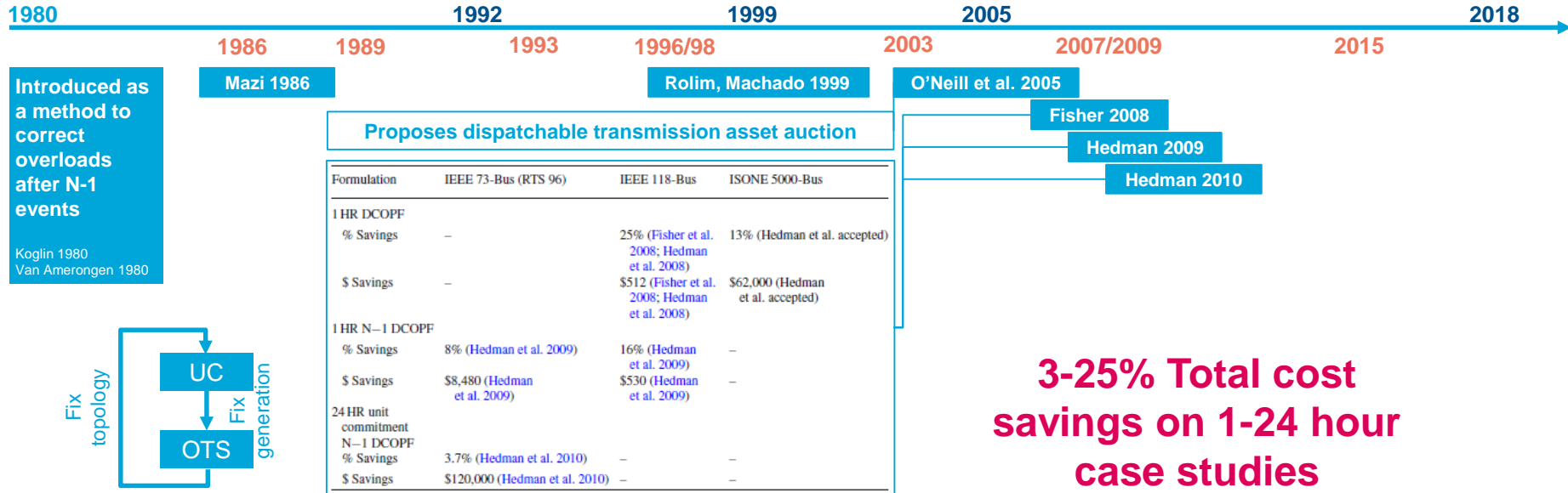 - Huge combinatorial problem
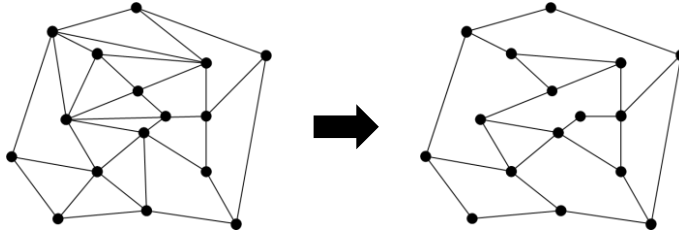
Optimal Transmission Switching (OTS) or Optimal Topology Control (OTC)

OTC Problem

1980   1992   1999   2005   2018

1986   1989   1993   1996/98   2003   2007/2009   2015

Introduced as a method to correct overloads after N-1 events
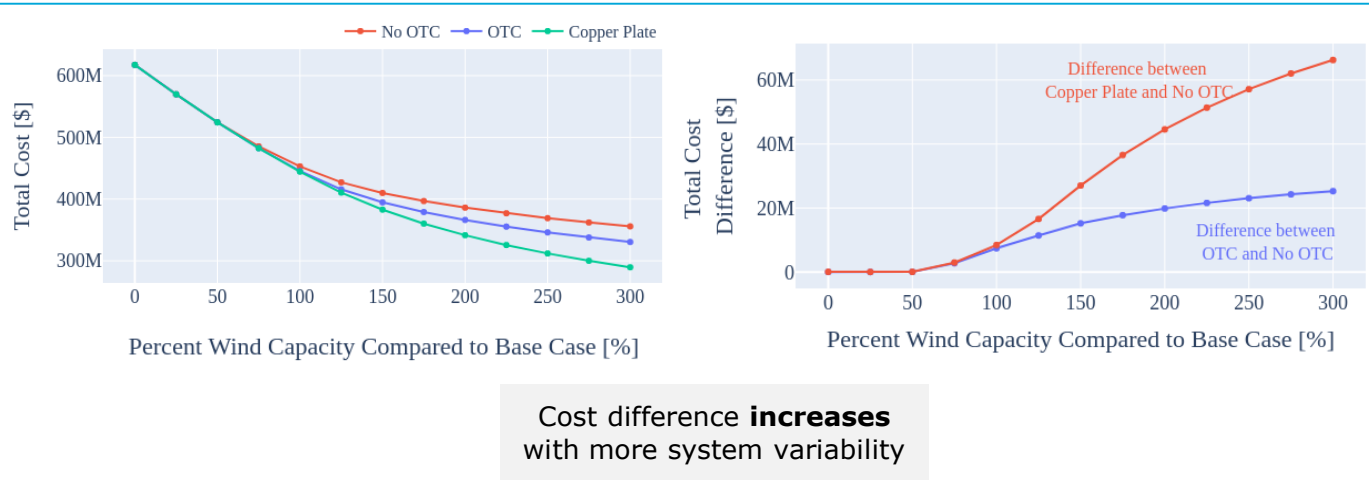
Koglin 1980
Van Amerongen 1980

Mazi 1986

"**A corrective action for this overload was calculated using a linear programming solution and resulted in a shift in generation.** The same contingency condition was then presented to a system operator on a dispatcher training simulator… **The operator's initial response to the overload was to simply switch the network.** This relieved the overload and allowed the generation to remain at economic loading."

OTC Problem

1986   **1989**   **1992**   **1993**   **1996/98**   **1999**   **2003**   **2005**   **2007/2009**   **2015**   **2018**

Mazi 1986

Rolim, Machado 1999

O'Neill et al. 2005

Fisher 2008

Hedman 2009

Hedman 2010

Introduced as a method to correct overloads after N-1 events

Koglin 1980
Van Amerongen 1980

Proposes dispatchable transmission asset auction

Formulation	IEEE 73-Bus (RTS 96)	IEEE 118-Bus	ISONE 5000-Bus
1 HR DCOPF			
% Savings	–	25% (Fisher et al. 2008; Hedman et al. 2008)	13% (Hedman et al. accepted)
$ Savings	–	$512 (Fisher et al. 2008; Hedman et al. 2008)	$62,000 (Hedman et al. accepted)
1 HR N−1 DCOPF			
% Savings	8% (Hedman et al. 2009)	16% (Hedman et al. 2009)	–
$ Savings	$8,480 (Hedman et al. 2009)	$530 (Hedman et al. 2009)	–
24 HR unit commitment N−1 DCOPF			
% Savings	3.7% (Hedman et al. 2010)	–	–
$ Savings	$120,000 (Hedman et al. 2010)	–	–

Fix topology

UC

Fix generation

OTS

3-25% Total cost savings on 1-24 hour case studies

OTC Problem

1980   **1992**   **1999**   **2005**   **2018**

1986   **1989**   **1993**   **1996/98**   **2003**   **2007/2009**   **2015**

Mazi 1986   **Rolim, Machado 1999**   **O'Neill et al. 2005**   **Hedman 2010**   **Little et al. 2021**

Introduced as a method to correct overloads after N-1 events

Koglin 1980
Van Amerongen 1980

Cost difference **increases** with more system variability

Flow-based Day Ahead Market
EUPHEMIA Algorithm

Day-Ahead Market Coupling

Objective: Associate Purchase and Sale offers while maximizing social welfare – the sum of profits earned by all agents

1. **Everything sold is purchased**
   Ensured across all zones connected by a common market border

2. **Border constraints**
   ATC – Ensured for each market border
   Flow-based – Ensured for each critical branch

3. **Total amount of power accepted is within range offered**
   Ensured for each order

Flow-based Day Ahead Market
EUPHEMIA Algorithm

Day-Ahead Market Coupling

Objective: Associate Purchase and Sale offers while maximizing social welfare – the sum of profits earned by all agents

1. **Everything sold is purchased**
   Ensured across all zones connected by a common market border

2. **Border constraints**
   ATC – Ensured for each market border
   Flow-based – Ensured for each critical branch

3. **Total amount of power accepted is within range offered**
   Ensured for each order
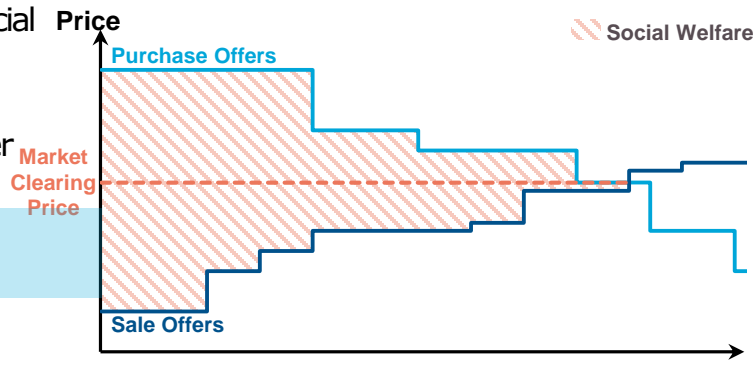
General Context

Cross-border Exchanges

CONSTRAINTS LIMITING CROSS-BORDER EXCHANGES

- Available Transfer Capacity (ATC)
  - TSO determines a Net Transfer Capacity (NTC) for **each direction on each border**
  - Each interconnection is **independent** from others
  - Hides the underlying physics from market actors

- Flow-based (FB)
  - Approaches the physical reality of the network
  - Defines a **security domain** from linear constraints
  - 2 elements:
    1) Critical Network Elements (CNEs):
       What are the network elements influenced the most by the cross-border exchanges?
    2) Power Transfer Distribution Factors (PTDFs):
       How does an exchange affect the flow along each CNE?

■ **Current Flow-based region (CWE+)**
▨ **FB coming soon (CORE)**

General Context

Cross-border Exchanges
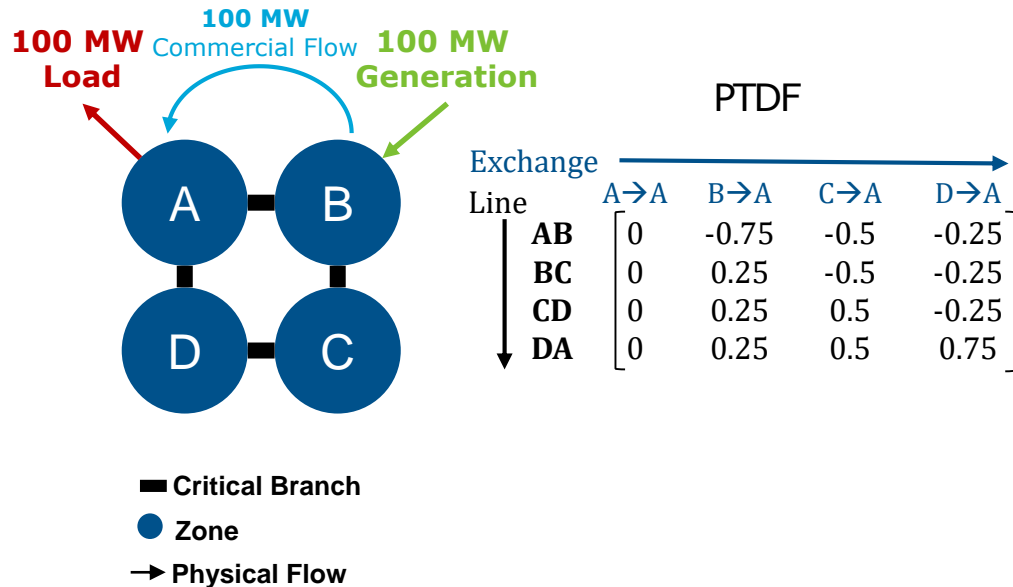
FLOW-BASED CONSTRAINTS

100 MW **Load**

100 MW **Commercial Flow**

100 MW **Generation**

PTDF

Exchange Line	A→A	B→A	C→A	D→A
AB	0	-0.75	-0.5	-0.25
BC	0	0.25	-0.5	-0.25
CD	0	0.25	0.5	-0.25
DA	0	0.25	0.5	0.75

■ **Critical Branch**

● **Zone**

→ **Physical Flow**

ATC Border

FB Border

General Context

Cross-border Exchanges

FLOW-BASED CONSTRAINTS

PTDF

Exchange Line	A→A	B→A	C→A	D→A
AB	0	-0.75	-0.5	-0.25
BC	0	0.25	-0.5	-0.25
CD	0	0.25	0.5	-0.25
DA	0	0.25	0.5	0.75

■ Critical Branch

● Zone

→ Physical Flow

ATC Border

FB Border

General Context
Cross-border Exchanges

FLOW-BASED CONSTRAINTS

100 MW Load

100 MW Commercial Flow

100 MW Generation

75 MW

25 MW

25 MW

25 MW

A B
D C

■ Critical Branch
● Zone
→ Physical Flow

PTDF

$$
\begin{array}{c}
\text{Exchange} \\
\text{Line} \\
\end{array}
\begin{array}{ccccc}
 & A\rightarrow A & B\rightarrow A & C\rightarrow A & D\rightarrow A \\
AB & 0 & -0.75 & -0.5 & -0.25 \\
BC & 0 & 0.25 & -0.5 & -0.25 \\
CD & 0 & 0.25 & 0.5 & -0.25 \\
DA & 0 & 0.25 & 0.5 & 0.75 \\
\end{array}
$$
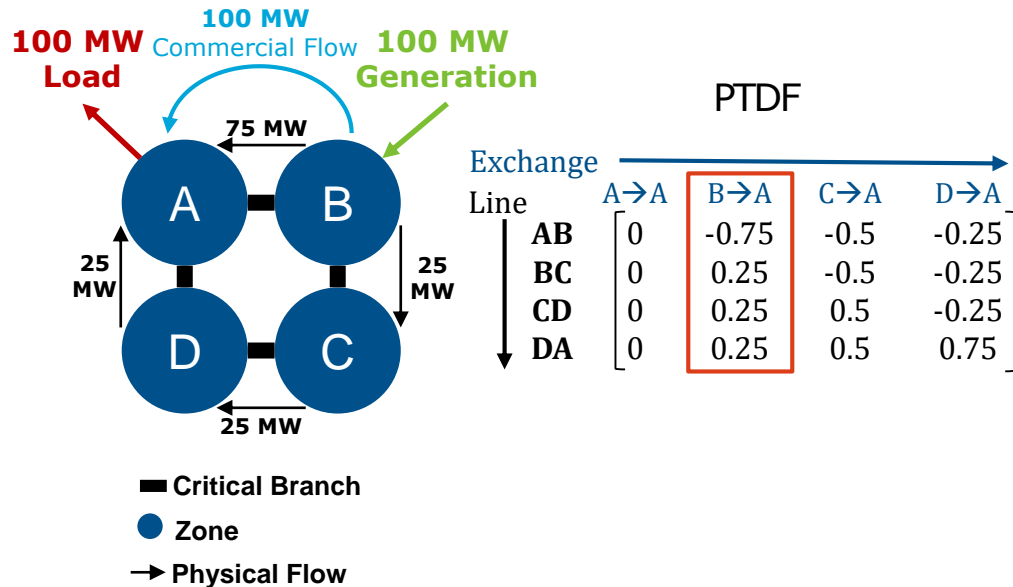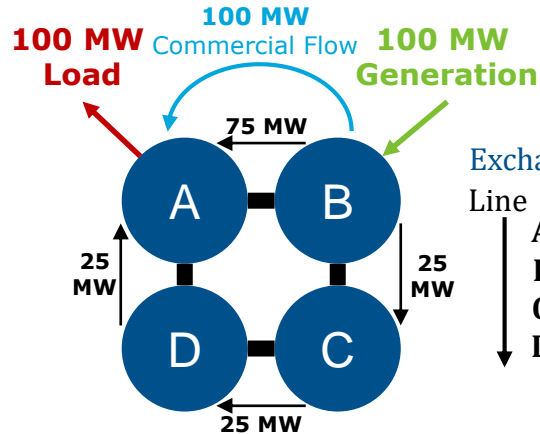
The admissible domaine of exchanges is extended for flow-based compared to ATC for the same level of risk

ATC Border
FB Border

A→B

A→C

□ ATC Domain
□ Flow-based Domain
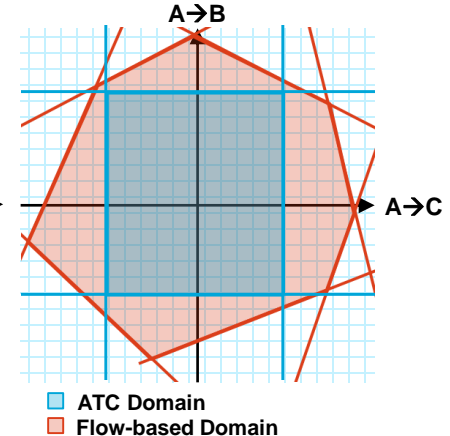
Capacity Calculation

Variety of Perspectives

LEGISLATORS / REGULATORS / COMMISSION

Bigger domains, updated more **frequently**, in order to increase **European social welfare**…

Capacity Calculation

TSOs

… while **limiting deviations** between **market outputs** and (physics) reality, to ensure the **system security**, in a context of **increasing uncertainties**…

MARKET ACTORS

… and with **full transparency**, so market participants can anticipate.

Objective of the Study

DEVELOP A METHODOLOGY TO INTEGRATE GRID FLEXIBILITY AND OTHER REMEDIAL ACTIONS IN THE EXISTING EUROPEAN FLOW-BASED MARKET THAT ARE CONSISTENT WITH THE DAY-AHEAD MARKET OUTCOME

2 Multi-domain Approach

Flow-based Calculation

Operational Timeline

Remaining Available Margin: The amount on each branch available to be allocated during the day-ahead market

FB PARAMETER CALCULATION

Inputs

Merging | Initial Calculation | Adjustments | Final Calculation

FB Params
RAM
PTDFs

D-1 MC

D-2 19h | D-2 20h | D-1 3h | D-1 9h30

FB Domain

$A \to B$

$A \to C$

Haut

BIEN-ÊTRE SOCIAL

Bas

Power Transfer Distribution Factors: How each branch is affected by a change in the net import/export of each zone

Flow-based Domain

Each TSO gives a forecast of the **generation**, **demand** and **network state** that it expects in real time, based on a forecast **market direction**

Renewable forecast

Conventional generation

Exchanges

Grid topology

Load forecast

A market direction refers to a set of imports/exports for all bidding zones

Flow-based Domain

Merging

Each TSO gives a forecast of the **generation**, **demand** and **network state** that it expects in real time, based on a forecast **market direction**

Renewable forecast

Conventional generation

Exchanges

Load forecast

Grid topology
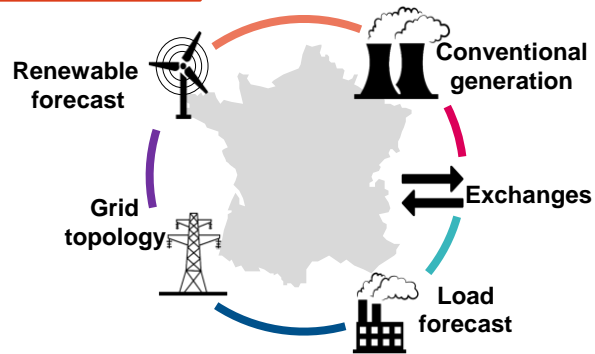
A market direction refers to a set of imports/exports for all bidding zones
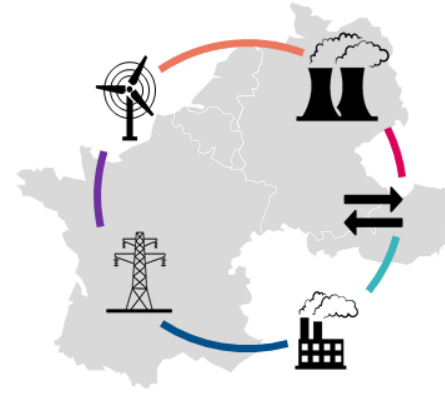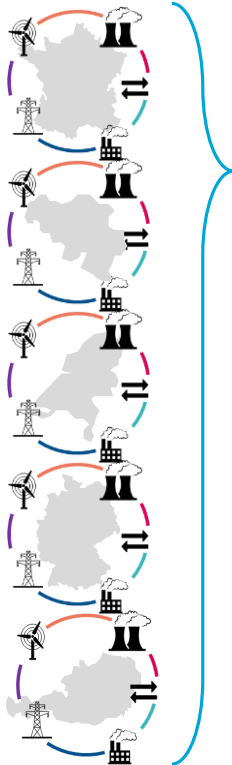
These are then merged into a single forecasted state, from which we can calculate an initial domain

Net Position: The import/export of the bidding zone

NP_A

NP_B

09/06/2021
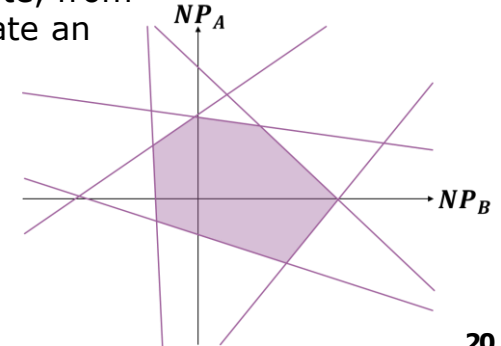
Flow-based Domain

Adjustments

TSOs coordinate to expand the flow-based domain in a "likely" market direction
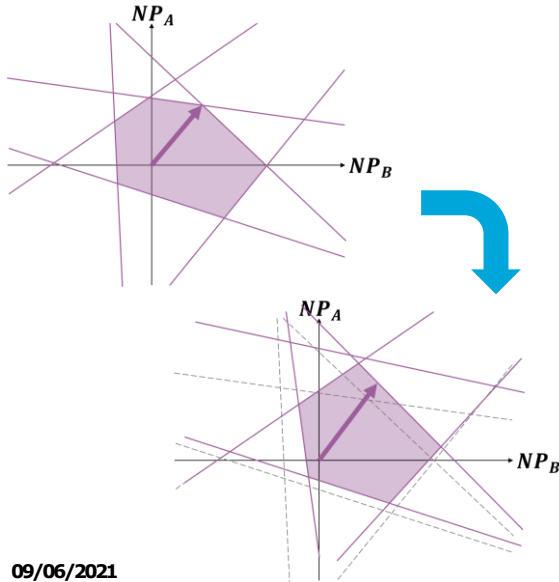
PST Tap Change

Topological RA

Forecast Market Direction

Flow-based Domain

TSOs coordinate to expand the flow-based domain in a "likely" market direction

PST Tap Change
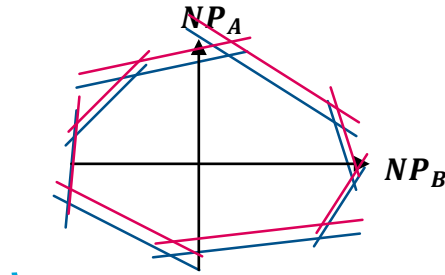
Topological RA
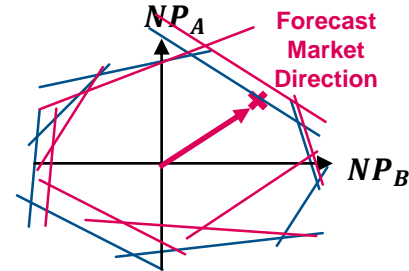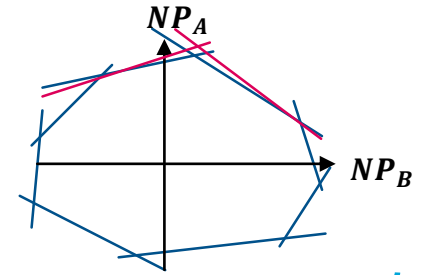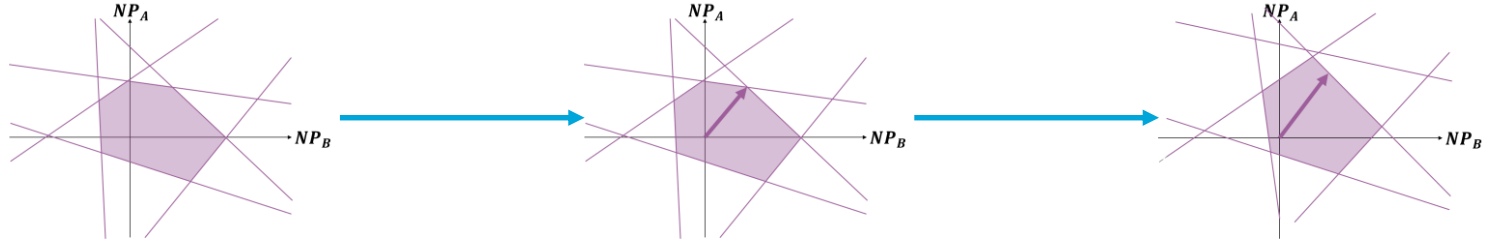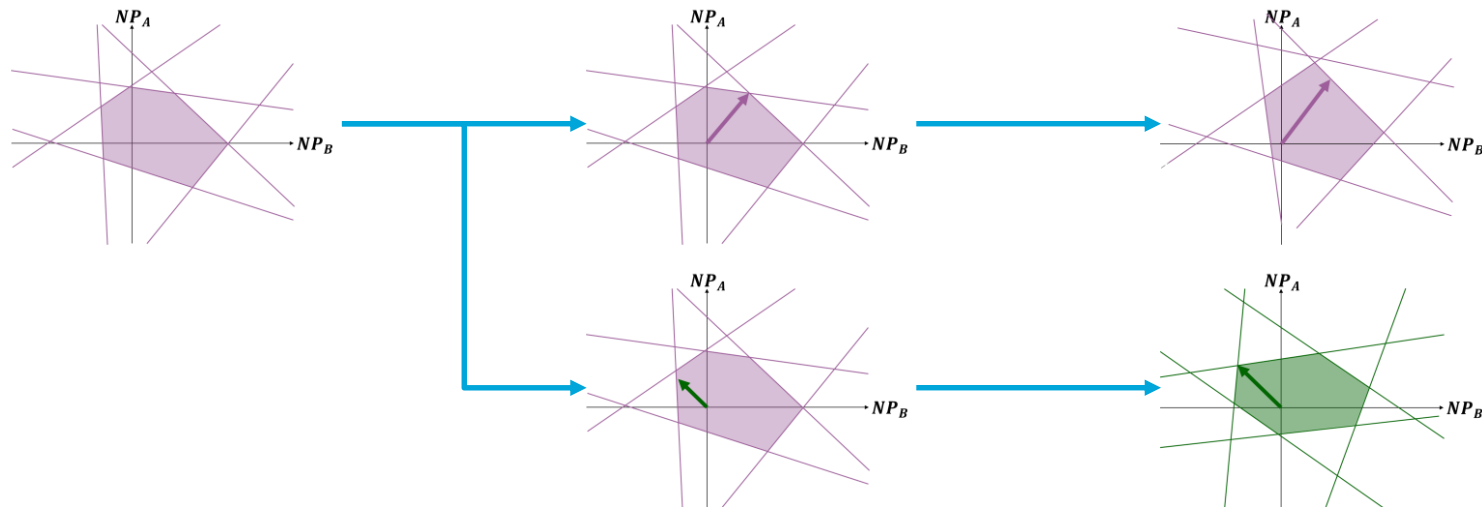
Forecast Market Direction

Flow-based Domain

Flow-based Domain

Flow-based Domain
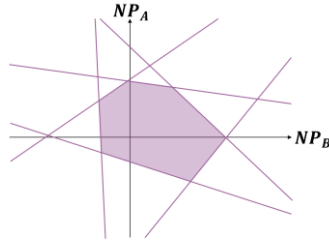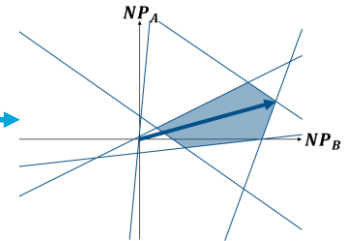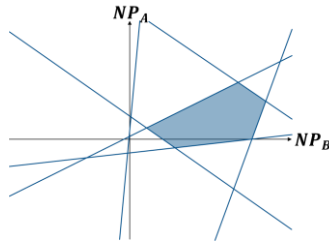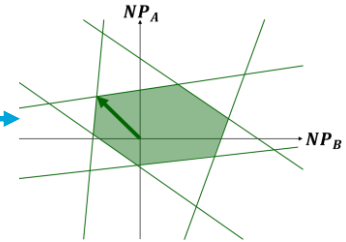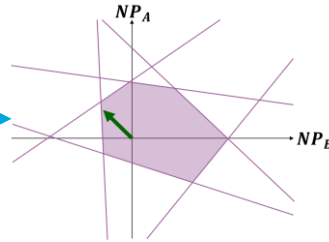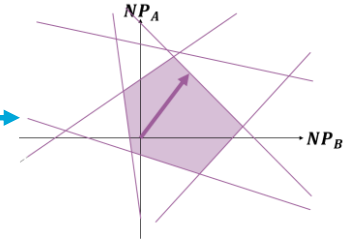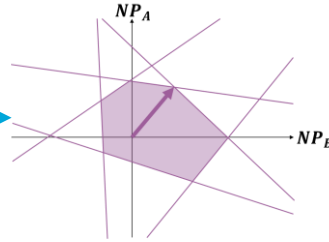
Flow-based
Integration of RAs
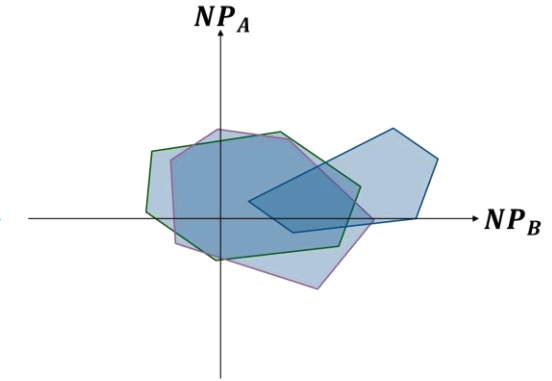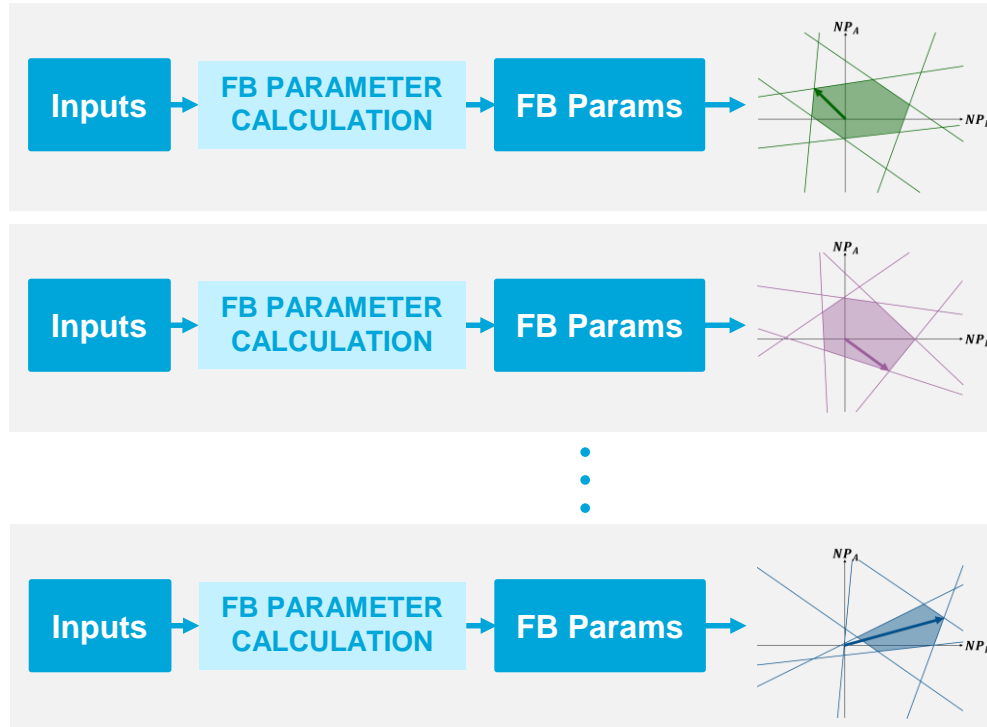
- Increased **cross-border capacity** available to the market
- Increased **transparency** to market participants regarding grid flexibility actions
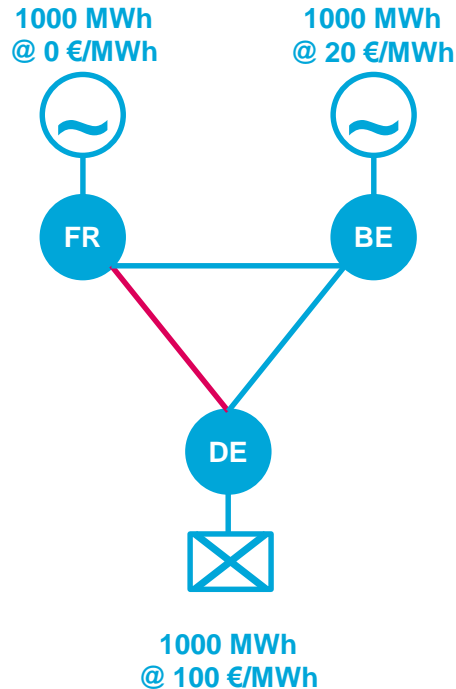- Increased **system security**

3 Case Study

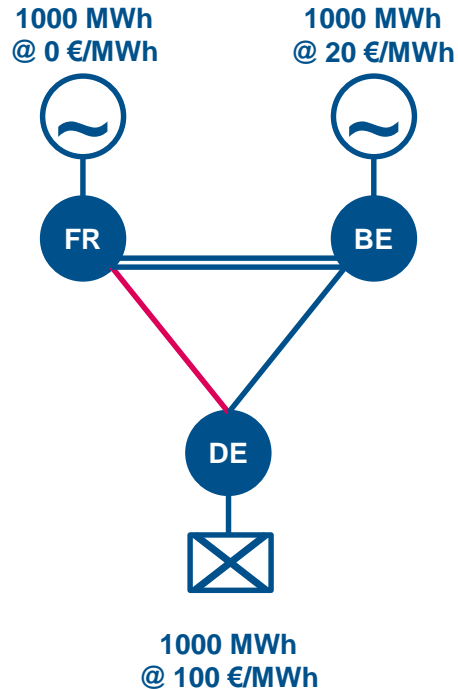# Remedial Action Integration

Example

Remedial Action Integration

Example

1000 MWh
@ 0 €/MWh

1000 MWh
@ 20 €/MWh

FR

BE

DE

1000 MWh
@ 100 €/MWh

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \rightarrow DE}$
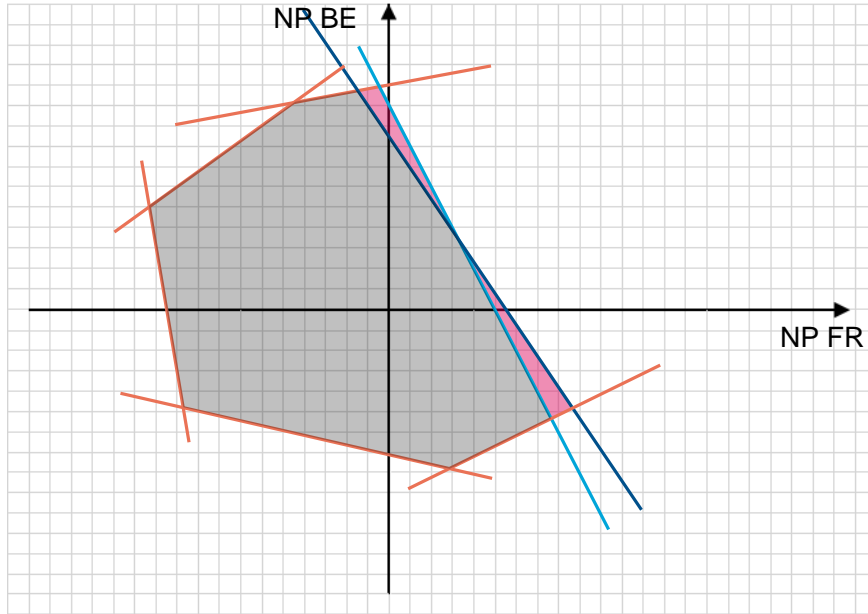
Remedial Action Integration

Example

1000 MWh @ 0 €/MWh

1000 MWh @ 20 €/MWh

1000 MWh @ 100 €/MWh
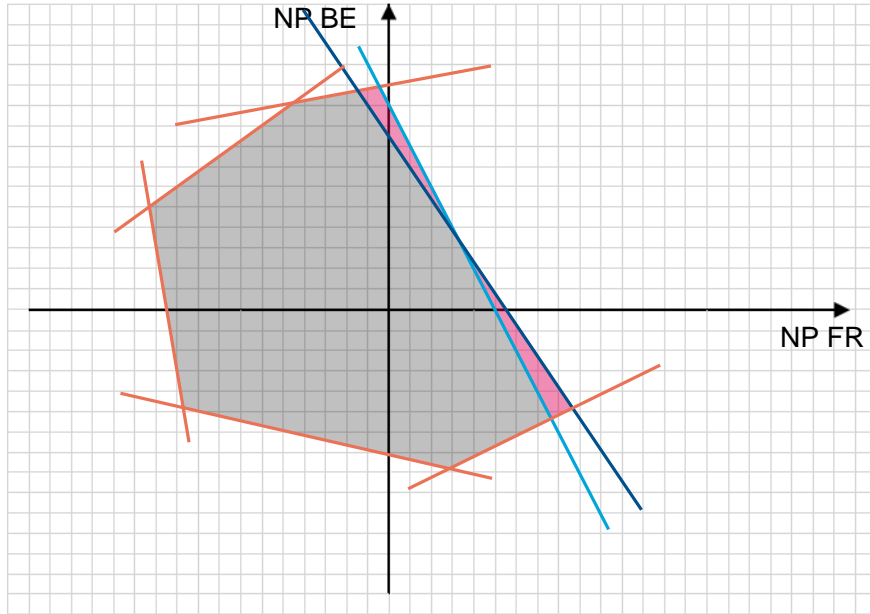
Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR\to DE}$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR\to DE}$

Remedial Action Integration

Example

Option 1: $\frac{2}{3} NP^{FR} + \frac{1}{3} NP^{BE} \leq RAM_{FR \to DE}$

Option 2: $\frac{3}{5} NP^{FR} + \frac{2}{5} NP^{BE} \leq RAM_{FR \to DE}$

Remedial Action Integration

Example

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE}$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE}$

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE} + \xi M$

$\xi \in \{0, 1\}$
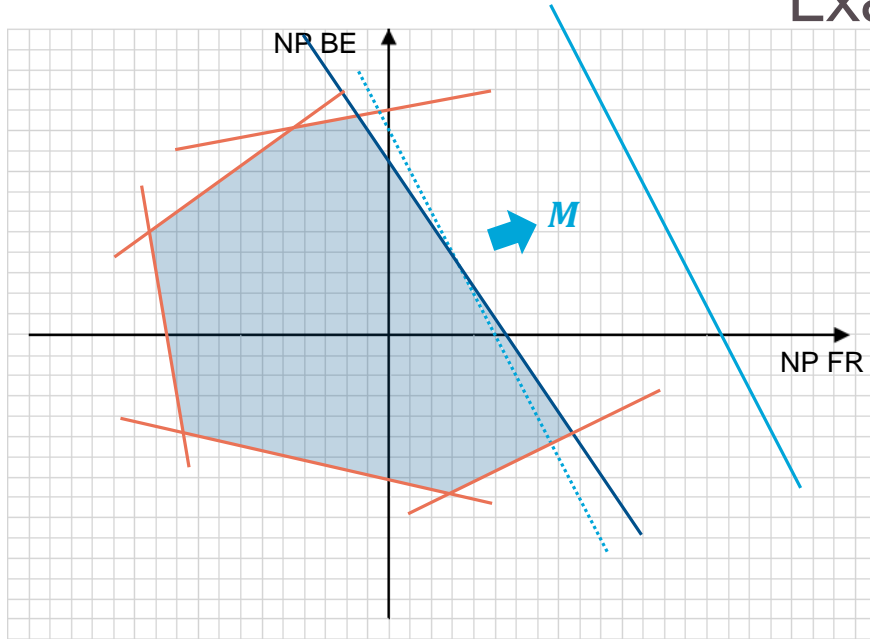
$M \gg RAM$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE} + (1 - \xi)M$

Remedial Action Integration

Example

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE}$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE}$

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE} + \xi M$

$\xi \in \{0, 1\}$

$M \gg RAM$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE} + (1 - \xi)M$

Remedial Action Integration

Example

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE}$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE}$

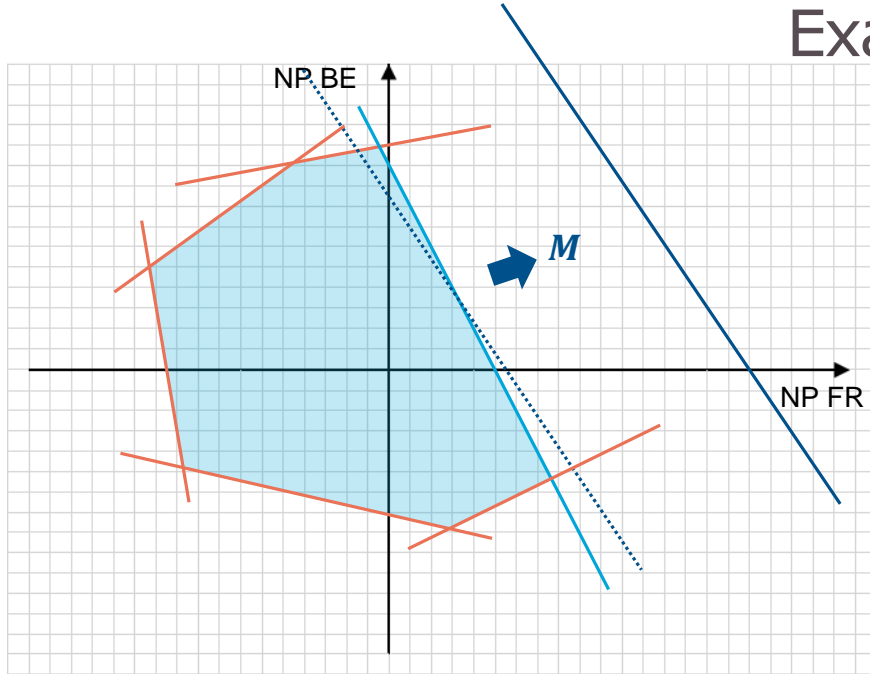Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \to DE} + \xi M$

$\xi \in \{0, 1\}$

Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \to DE} + (1 - \xi)M$

$M \gg RAM$

Remedial Action Integration

Example

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR \rightarrow DE} + \xi M$

$M \gg RAM$

$\xi \in \{0, 1\}$
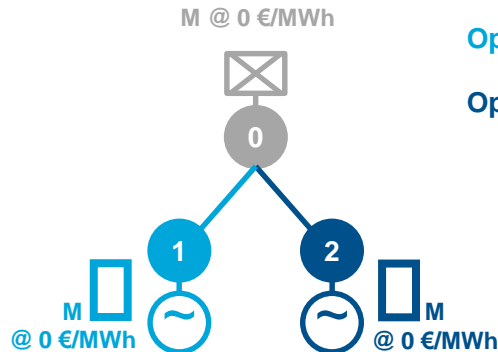
Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR \rightarrow DE} + (1 - \xi)M$

- In the existing EUPHEMIA algorithm, binary variables are associated with block offers
- So to represent $\mathbf{M}$ and $\mathbf{\xi}$ we will introduce some virtual bidding zones:

M @ 0 €/MWh

Must be either:
- **Accepted at M**
- **Refused**

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} - NP^{VZ_1} \leq RAM_{FR \rightarrow DE}$

Option 2: $\frac{2}{5}NP^{FR} + \frac{1}{5}NP^{BE} - NP^{VZ_2} \leq RAM_{FR \rightarrow DE}$

M @ 0 €/MWh

M @ 0 €/MWh

Remedial Action Integration

Example

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR\to DE} + \xi M$

$\xi \in \{0, 1\}$ $\qquad M \gg RAM$

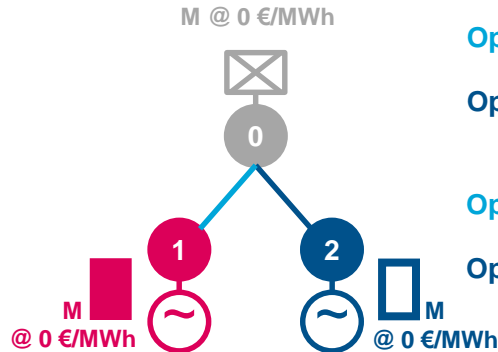Option 2: $\frac{3}{5}NP^{FR} + \frac{2}{5}NP^{BE} \leq RAM_{FR\to DE} + (1 - \xi)M$

- In the existing EUPHEMIA algorithm, binary variables are associated with block offers
- So to represent **M** and **ξ** we will introduce some virtual bidding zones:

M @ 0 €/MWh

Must be either:
- **Accepted at M**
- **Refused**

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} - NP^{VZ_2} \leq RAM_{FR\to DE}$
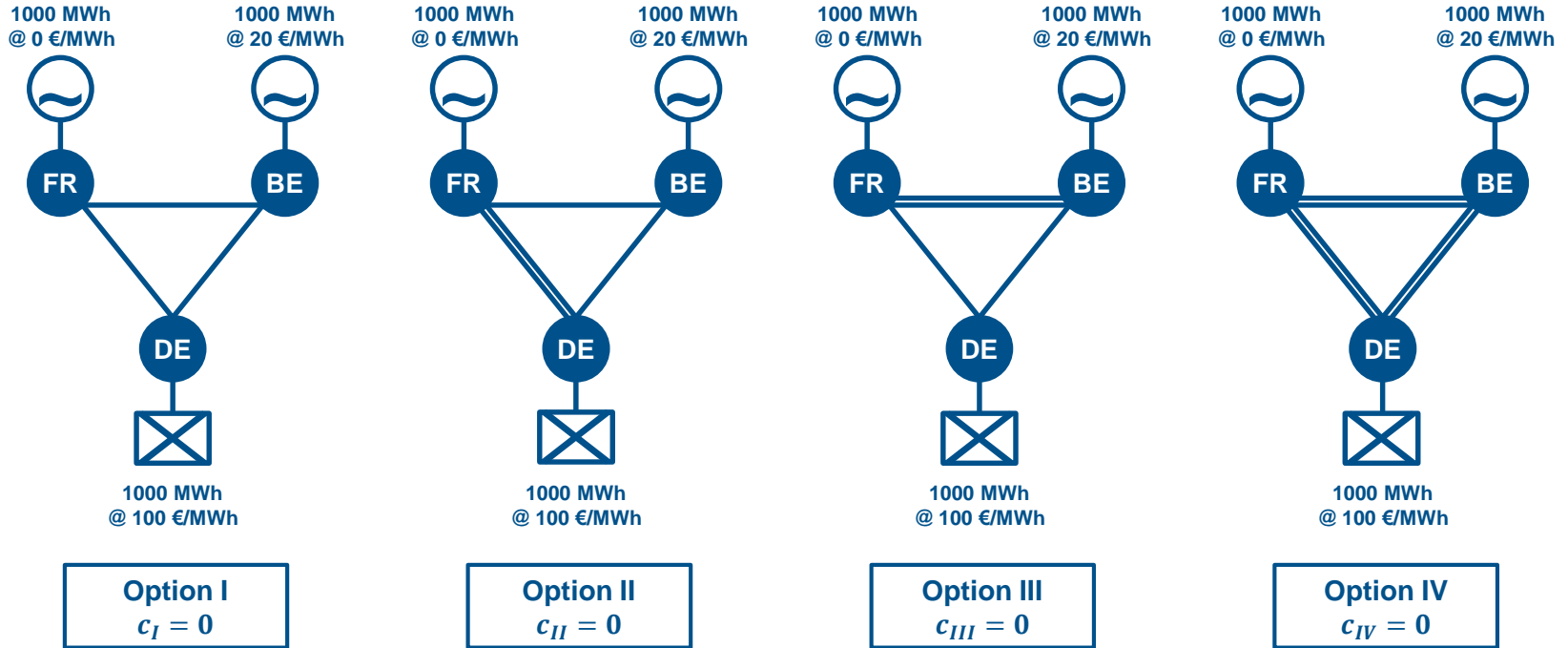
Option 2: $\frac{2}{5}NP^{FR} + \frac{1}{5}NP^{BE} - NP^{VZ_1} \leq RAM_{FR\to DE}$

Option 1: $\frac{2}{3}NP^{FR} + \frac{1}{3}NP^{BE} \leq RAM_{FR\to DE}$

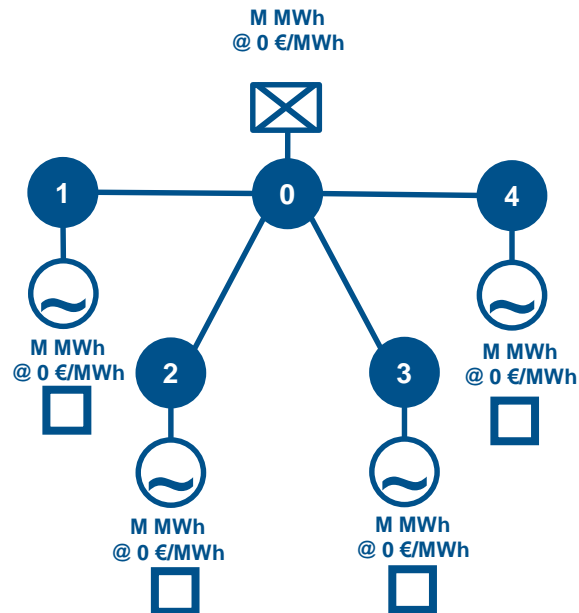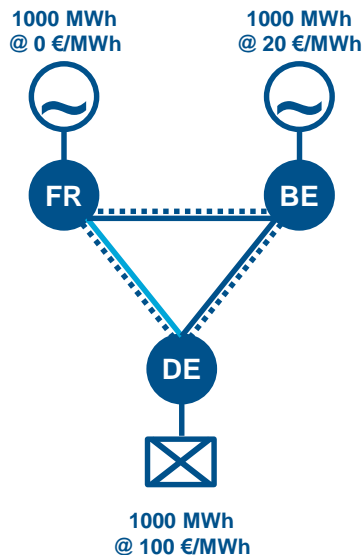Option 2: $\frac{2}{5}NP^{FR} + \frac{1}{5}NP^{BE} \leq RAM_{FR\to DE} + M$

0

1 2

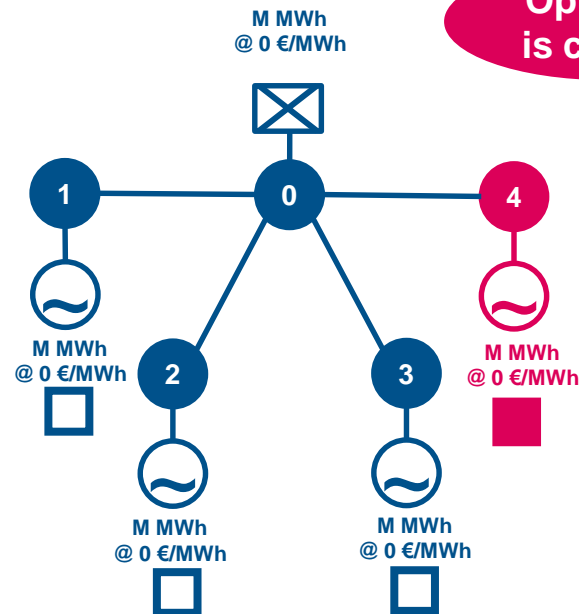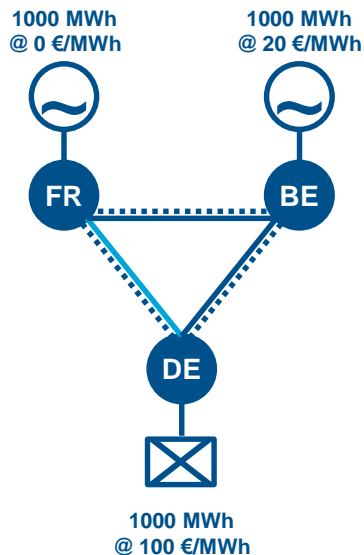M @ 0 €/MWh

M @ 0 €/MWh

Integration of RAs - EUPHEMIA

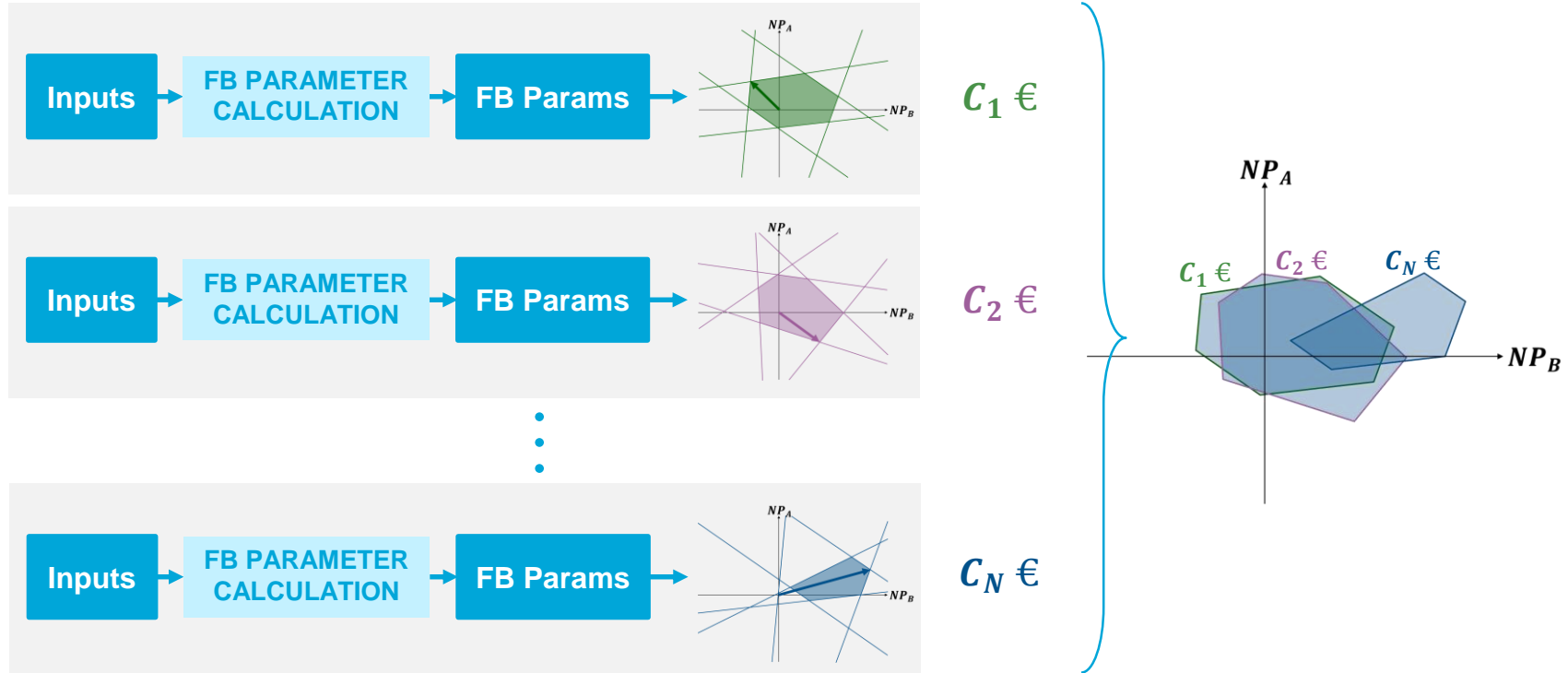## Case Study Run in EUPHEMIA

Non-Costly Remedial Actions

Integration of RAs - EUPHEMIA

Non-Costly

Flow-based

Integration of RAs

Integration of RAs - EUPHEMIA

Full PTDF Matrix

Original Market Coupling Constraint

$$\forall\, l \in CB$$

$$\sum_{z \in BZ} PTDF_z^l \, \boldsymbol{NP_Z} \leq RAM^l$$

$$[PTDF_I]_{CB \times BZ} [\boldsymbol{NP_{BZ}}]_{BZ \times 1} \leq [RAM_I]_{CB \times 1}$$

$$\begin{bmatrix} \begin{bmatrix} PTDF_I \\ PTDF_{II} \\ \vdots \\ PTDF_N \end{bmatrix} & \begin{bmatrix} 0 & -1 & \cdots & -1 \\ -1 & 0 & \cdots & -1 \\ \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & \cdots & 0 \end{bmatrix} \end{bmatrix} \begin{bmatrix} [\boldsymbol{NP_{BZ}}] \\ [\boldsymbol{NP_{VZ}}] \end{bmatrix} \leq \begin{bmatrix} \begin{bmatrix} RAM_I \\ RAM_{II} \\ \vdots \\ RAM_N \end{bmatrix} \end{bmatrix}$$

Original Bidding Zones

Virtual Zones

Price of Virtual production zones:
$$p_i = \frac{c_i}{M}$$

Integration of RAs - EUPHEMIA

Computational Tradeoff

Original Market Coupling Constraint

$$[PTDF_I]_{CB \times BZ}[\boldsymbol{NP_{BZ}}]_{BZ \times 1} \leq [RAM_I]_{CB \times 1}$$

Each time we add a new topology option, we may need to add a full PTDF of length to the matrix

$$\left[\begin{bmatrix} PTDF_I \\ PTDF_{II} \\ \vdots \\ PTDF_N \end{bmatrix} \begin{bmatrix} 0 & -1 & \cdots & -1 \\ -1 & 0 & \cdots & -1 \\ \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & \cdots & 0 \end{bmatrix}\right] \begin{bmatrix} [\boldsymbol{NP_{BZ}}] \\ [\boldsymbol{NP_{VZ}}] \end{bmatrix} \leq \left[\begin{bmatrix} RAM_I \\ RAM_{II} \\ \vdots \\ RAM_N \end{bmatrix}\right]$$

Original Bidding Zones

Virtual Zones

Conclusion

- Advantages:

  - Increased **cross-border capacity** available to the market

  - Increased **transparency** to market participants regarding grid flexibility actions

  - Increased **system security**

- Disadvantages:

  - Increased **computational complexity**