Analyzing the market power in day-ahead electricity market and provision of flexibility services under different TSO-DSOs coordination schemes

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In this work we are concerned with evaluating different coordination schemes for TSO and DSO's

for the provision of **flexibility services** to the transmission and distribution networks

from the **resources connected to distribution networks** (e.g., programmable generators, flexible loads, …)

In particular, we want to compare the different coordination schemes that have been proposed

with regard to the **possibility for market participants to exercise market power**,

i.e. apply strategies to **maximize the market participant's profit**,

which, on the other end, may result in **significant cost increase for the system**

Example:

- by an appropriate bidding behaviour, a producer can create **artificial congestions** to make **its own generators indispensable** to satisfy the load

- further opportunities of exercising market power are provided by the existence of **multiple markets in cascade** (DAM followed by real time markets)

We have developed a procedure to **detect possible exercise of market power**

for the following TSO-DSOs' coordination schemes:

A. Two-stage architecture

1. DAM
2. real-time: common market for $\mathcal{T} + \mathcal{D}$

B. Three-stage architecture 1

1. DAM
2. real-time market in each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. real-time market in transmission $\mathcal{T}$, with resources in $\mathcal{T}$

C. Three-stage architecture 2

1. DAM
2. real-time market in each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. real-time market in transmission $\mathcal{T}$, with resources in $\mathcal{T}$ + residual resources in $\mathcal{D}$

Bids on the DAM and real-time markets are submitted by the **Aggregators**,

each of which manages a **set of programmable generation units and/or flexible loads**.

The Aggregators are assumed

- to offer all available quantity, and
- to compete on prices,

therefore we develop an optimization model for the single Aggregator, that determines the **bid prices on DAM and real time markets** that maximize the Aggregator's total profit.

Using an iterative procedure that cycles through the set of the Aggregators,

we search for a **Nash equilibrium solution**,

i.e. a solution from which none of the Aggregators is willing to deviate unilaterally.

Finally, the Nash equilibrium solution is analysed to see if any of the Aggregators have had strategic profit maximisation behaviour.

The presentation is organized as follows:

- The Aggregator's optimization models under

  - **A. Two-stage architecture**
  - **B. Three-stage architecture 1**
  - **C. Three-stage architecture 2**

- Preliminary numerical results on a small CIGRE test network

Model of Aggregator i in case A

A. Two-stage architecture

1. DAM
2. real-time market common for $\mathcal{T} + \mathcal{D}$

Decisions of Aggregator i			
$u \in \mathcal{U}_i$	$b_u^{\mathcal{U}}$	price of sell bid	on DAM
$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\uparrow}$	price of upward regulation bid	on real-time market
$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\downarrow}$	price of downward regulation bid	on real-time market
$n \in \mathcal{N}_i$	$b_n^{\mathcal{N},\downarrow}$	price of load curtailment bid	on real-time market

Objective: maximize the sum of profits on DAM and on real-time market

$$\max \underbrace{\sum_{u \in \mathcal{U}_i} \left(\lambda - C_u^{\mathcal{U}}\right) g_u}_{\text{profit on } \textbf{DAM}} + \sum_{u \in \mathcal{U}_i} \left(b_u^{\mathcal{U},\uparrow} - C_u^{\mathcal{U},\uparrow}\right) g_u^{\uparrow} + \sum_{n \in \mathcal{N}_i} b_n^{\mathcal{N},\downarrow} d_n^{\downarrow} - \sum_{u \in \mathcal{U}_i} \left(b_u^{\mathcal{U},\downarrow} - C_u^{\mathcal{U},\downarrow}\right) g_u^{\downarrow}$$

$u \in \mathcal{U}_i$	$C_u^{\mathcal{U}}$	generation cost	
	λ	clearing price	**decided** by DAM Operator
$u \in \mathcal{U}_i$	g_u	accepted quantity	**decided** by DAM Operator

The Day-Ahead Market Operator problem

The **DAM Operator**, given

D_n	load at nodes $n \in \mathcal{N}$
W_n	non-programmable generation at nodes $n \in \mathcal{N}$
$(G_u, b_u^{\mathcal{U}})$	sell bids of generators $u \in \mathcal{U}$ (maximum quantity, minimum price)

determines the quantities g_u to be accepted as follows

$u \in \mathcal{U} \quad 0 \le g_u \le G_u$	accepted quantity not greater than offered quantity
$\sum_{u \in \mathcal{U}} g_u = \sum_{n \in \mathcal{N}} D_n - \sum_{n \in \mathcal{N}} W_n$	satisfy residual load (dual variable λ: clearing price)
$\min \sum_{u \in \mathcal{U}} b_u^{\mathcal{U}} g_u$	quantities g_u are accepted in non-decreasing order of bid price

This model refers to a **bus-bar** Day-Ahead Market (as it is in France, Germany, Spain,…)

In Italy, Norway and Sweden, the DAM markets are divided into zones due to their geographical shape.

In the **model of Aggregator** i,

the accepted quantities g_u, $u \in \mathcal{U}_i$, and the clearing price λ are determined

by the **optimality conditions of DAM problem**

	$\sum_{u \in \mathcal{U}} g_u = \sum_{n \in \mathcal{N}} D_n - \sum_{n \in \mathcal{N}} W_n$
$u \in \mathcal{U}$	$0 \leq (G_u - g_u) \perp v_u \geq 0$
$u \in \mathcal{U}_i$	$0 \leq g_u \perp \left(b_u^{\mathcal{U}} - \lambda + v_u\right) \geq 0$
$u \in \mathcal{U} \backslash \mathcal{U}_i$	$0 \leq g_u \perp \left(b_u^{\mathcal{U}} - \lambda + v_u\right) \geq 0$

The prices $b_u^{\mathcal{U}}$ of the competitors' bids, $u \in \mathcal{U} \backslash \mathcal{U}_i$, **are guessed by Aggregator** i

(based on some hypothesis)

Objective of Aggregator i: maximize the sum of profits on DAM and on real-time markets

$$\max \sum_{u \in \mathcal{U}_i} \left(\lambda - C_u^{\mathcal{U}}\right) g_u + \underbrace{\sum_{u \in \mathcal{U}_i} \left(b_u^{\mathcal{U},\uparrow} - C_u^{\mathcal{U},\uparrow}\right) g_u^{\uparrow} + \sum_{n \in \mathcal{N}_i} b_n^{\mathcal{N},\downarrow} d_n^{\downarrow} - \sum_{u \in \mathcal{U}_i} \left(b_u^{\mathcal{U},\downarrow} - C_u^{\mathcal{U},\downarrow}\right) g_u^{\downarrow}}_{\text{profit on the \textbf{real-time market}}}$$

$u \in \mathcal{U}_i$	$C_u^{\mathcal{U},\uparrow}, C_u^{\mathcal{U},\downarrow}$	cost of upward and downward regulation	
$u \in \mathcal{U}_i$	$g_u^{\uparrow}, g_u^{\downarrow}$	accepted quantities of regulation bids	**decided** by the operator of the real-time market
$n \in \mathcal{N}_i$	$d_n^{\downarrow}$	load curtailment: ($\delta_n > 0$ maximum fraction that can be curtailed)	

The real-time Market Operator problem (case A: common $\mathcal{T}+\mathcal{D}$ market)

The **operator of the real-time market**, given

$\widetilde{D}_n$ real-time load at nodes $n \in \mathcal{N}$

$\widetilde{W}_n$ real-time non-programmable generation at nodes $n \in \mathcal{N}$

the bids

	bid price	offered quantity	
$u \in \mathcal{U}$	$b_u^{\mathcal{U},\uparrow}$	$G_u - g_u$	upward regulation
	$b_u^{\mathcal{U},\downarrow}$	g_u	downward regulation
$n \in \mathcal{N}$	$b_n^{\mathcal{N},\downarrow}$	$\delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$)

from all generation units and flexible loads in the system ($\mathcal{T}+\mathcal{D}_k$, $1 \le k \le K$)

determines

$g_u^{\uparrow}$, $g_u^{\downarrow}$	accepted quantities of up- and downward regulation bids
$d_n^{\downarrow}$	load curtailment
$w_n^{\downarrow}$	curtailment of non-programmable generation

subject to

1. accepted quantities not greater than offered quantities

$u \in \mathcal{U}$	$0 \le g_u^{\uparrow} \le G_u - g_u$	upward regulation in $\mathcal{T}$ and $\mathcal{D}$
	$0 \le g_u^{\downarrow} \le g_u$	downward regulation in $\mathcal{T}$ and $\mathcal{D}$

$n \in \mathcal{N}$	$0 \le d_n^{\downarrow} \le \delta_n \widetilde{D}_n$	load curtailment ($\delta_n > 0$) in $\mathcal{T}$ and $\mathcal{D}$

2. curtailment of non-programmable generation in $\mathcal{T}$ and $\mathcal{D}$

$n \in \mathcal{N}$	$0 \le w_n^{\downarrow} \le \widetilde{W}_n$

3. resolve **imbalance** $\Delta = \sum_{n \in \mathcal{N}} \left(\widetilde{D}_n - D_n\right) - \sum_{n \in \mathcal{N}} \left(\widetilde{W}_n - W_n\right)$ using resources in $\mathcal{T}$ and $\mathcal{D}$

$$\sum_{u \in \mathcal{U}} g_u^{\uparrow} + \sum_{n \in \mathcal{N}} d_n^{\downarrow} - \sum_{u \in \mathcal{U}} g_u^{\downarrow} - \sum_{n \in \mathcal{N}} w_n^{\downarrow} = \Delta$$

4. **manage congestions** for all lines in the system $\left(\mathcal{L} = \mathcal{L}^{\mathcal{T}} \cup \mathcal{L}^{\mathcal{D}_1} \cup \ldots \cup \mathcal{L}^{\mathcal{D}_K}\right)$

$$l \in \mathcal{L} \qquad \sum_{n \in \mathcal{N}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\uparrow} - g_u^{\downarrow} \right) + \left(\widetilde{W}_n - w_n^{\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\downarrow} \right) \right] \leq \overline{F}_l$$

where $H_{l,n}$ PTDF of line l and node n

$\overline{F}_l$ maximum flow through line l

5. objective function:

$$\min \sum_{u \in \mathcal{U}} b_u^{\mathcal{U},\uparrow} g_u^{\uparrow} + \sum_{n \in \mathcal{N}} b_u^{\mathcal{N},\downarrow} d_n^{\downarrow} - \sum_{u \in \mathcal{U}} b_u^{\mathcal{U},\downarrow} g_u^{\downarrow}$$

Order of bid acceptance:

- $g_u^{\uparrow}$, $d_n^{\downarrow}$ **non-decreasing bid price**
- $g_u^{\downarrow}$ **non-increasing bid price**

In the **model of Aggregator** i

- the accepted quantities $g_u^{\uparrow}$ and $g_u^{\downarrow}$, $u \in \mathcal{U}_i$, of the upward and downward regulation bids presented by Aggregator i

- the curtailment of flexible loads managed by Aggregator i

are determined by the **optimality conditions of real-time market problem**

1. Primal constraints, dual variables and associated complementarity constraints

	$\sum_{u\in\mathcal{U}} g_u^{\uparrow} + \sum_{n\in\mathcal{N}} d_n^{\downarrow} - \sum_{u\in\mathcal{U}} g_u^{\downarrow} - \sum_{n\in\mathcal{N}} w_n^{\downarrow} = \Delta$	α
$l \in \mathcal{L}$	$0 \leq \left\{\overline{F}_l - \sum_{n\in\mathcal{N}} H_{l,n}\left[\sum_{u\in\mathcal{U}_n}\left(g_u + g_u^{\uparrow} - g_u^{\downarrow}\right) + \left(\widetilde{W}_n - w_n^{\downarrow}\right) - \left(\widetilde{D}_n - d_n^{\downarrow}\right)\right]\right\} \perp \mu_l \geq 0$	
$u \in \mathcal{U}$	$0 \leq \left(G_u - g_u - g_u^{\uparrow}\right) \perp \beta_u \geq 0$	
$u \in \mathcal{U}$	$0 \leq \left(g_u - g_u^{\downarrow}\right) \perp \varphi_u \geq 0$	
$n \in \mathcal{N}$	$0 \leq \left(\delta_n \widetilde{D}_n - d_n^{\downarrow}\right) \perp \gamma_n \geq 0$	
$n \in \mathcal{N}$	$0 \leq \left(\widetilde{W}_n - w_n^{\downarrow}\right) \perp \chi_n \geq 0$	

2. Primal variables, dual constraints and associated complementarity constraints,

where **competitors' bid prices** $b_u^{\mathcal{U},\uparrow}$, $b_u^{\mathcal{U},\downarrow}$ and $b_n^{\mathcal{N},\downarrow}$, for $u \in \mathcal{U}\backslash\mathcal{U}_i$, **are guessed by Aggregator** i

$u \in \mathcal{U}_i$	$0 \le g_u^{\uparrow} \perp \left(b_u^{\mathcal{U},\uparrow} - \alpha + \sum_{l\in\mathcal{L}} H_{l,n(u)}\, \mu_l + \beta_u\right) \ge 0$
$u \in \mathcal{U}\backslash\mathcal{U}_i$	$0 \le g_u^{\uparrow} \perp \left(b_u^{\mathcal{U},\uparrow} - \alpha + \sum_{l\in\mathcal{L}} H_{l,n(u)}\, \mu_l + \beta_u\right) \ge 0$

$u \in \mathcal{U}_i$	$0 \le g_u^{\downarrow} \perp \left(-b_u^{\mathcal{U},\downarrow} + \alpha - \sum_{l\in\mathcal{L}} H_{l,n(u)}\, \mu_l + \varphi_u\right) \ge 0$
$u \in \mathcal{U}\backslash\mathcal{U}_i$	$0 \le g_u^{\downarrow} \perp \left(-b_u^{\mathcal{U},\downarrow} + \alpha - \sum_{l\in\mathcal{L}} H_{l,n(u)}\, \mu_l + \varphi_u\right) \ge 0$

$n \in \mathcal{N}_i$	$0 \le d_n^{\downarrow} \perp \left(b_n^{\mathcal{N},\downarrow} - \alpha + \sum_{l\in\mathcal{L}} H_{l,n}\, \mu_l + \gamma_n\right) \ge 0$
$n \in \mathcal{N}\backslash\mathcal{N}_i$	$0 \le d_n^{\downarrow} \perp \left(b_n^{\mathcal{N},\downarrow} - \alpha + \sum_{l\in\mathcal{L}} H_{l,n}\, \mu_l + \gamma_n\right) \ge 0$

$n \in \mathcal{N}$	$0 \le w_n^{\downarrow} \perp \left(\alpha - \sum_{l\in\mathcal{L}} H_{l,n}\, \mu_l + \chi_n\right) \ge 0$

MILP formulation of the Aggregator model: **bid prices** chosen from a **finite number of alternative prices**

For the **sell bid** of generator $u \in \mathcal{U}_i$

- alternative bid prices: $B^{\mathcal{U}}_{u,a}$, $1 \le a \le A^{\mathcal{U}}_u$
- selection constraints:

$u \in \mathcal{U}_i$	$b^{\mathcal{U}}_u = \sum_{a=1}^{A^{\mathcal{U}}_u} B^{\mathcal{U}}_{u,a}\, x^{\mathcal{U}}_{u,a}$	$\sum_{a=1}^{A^{\mathcal{U}}_u} x^{\mathcal{U}}_{u,a} = 1$	$x^{\mathcal{U}}_{u,a} \in \{0,1\}$ $1 \le a \le A^{\mathcal{U}}_u$

Eliminate bilinear terms $\lambda\, g_u$, $u \in \mathcal{U}_i$, related to the DAM:

1. combine complementarity conditions of DAM problem to get

$$\left.\begin{array}{l}(G_u - g_u)\, v_u = 0 \\ g_u\left(b^{\mathcal{U}}_u - \lambda + v_u\right) = 0\end{array}\right\} \Rightarrow \lambda\, g_u = b^{\mathcal{U}}_u\, g_u + G_u\, v_u$$

2. substitute $b^{\mathcal{U}}_u = \sum_{a=1}^{A^{\mathcal{U}}_u} B^{\mathcal{U}}_{u,a}\, x^{\mathcal{U}}_{u,a}$ to obtain (binary × real) products $x^{\mathcal{U}}_{u,a} \cdot g_u$

3. McCormick linear reformulation of product $p = x \cdot g$, $x \in \{0,1\}$ and $0 \le g \le G$

$0 \le p \le G\, x$	$g + G\,(x-1) \le p \le g$

MILP formulation: bid prices chosen from a **finite number of alternative prices**

Similarly, for **bids submitted to the real time market**:

- set of alternative bid prices

upward regulation	downward regulation	load curtailment
$B_{u,a}^{\mathcal{U},\uparrow} \quad 1 \leq a \leq A_u^{\mathcal{U},\uparrow}$	$B_{u,a}^{\mathcal{U},\downarrow} \quad 1 \leq a \leq A_u^{\mathcal{U},\downarrow}$	$B_{n,a}^{\mathcal{N},\downarrow} \quad 1 \leq a \leq A_n^{\mathcal{N},\downarrow}$

- selection constraints using variables $x_{u,a}^{\mathcal{U},\uparrow}$, $x_{u,a}^{\mathcal{U},\downarrow}$, $x_{n,a}^{\mathcal{N},\downarrow}$

- eliminate products $b_u^{\mathcal{U},\uparrow}\, g_u^{\uparrow}$, $\quad b_u^{\mathcal{U},\downarrow}\, g_u^{\downarrow}$, $\quad b_n^{\mathcal{N},\downarrow}\, d_n^{\downarrow}$ in the objective function

To eliminate bilinear terms reformulate **complementarity constraints** $s \cdot y = 0, \quad s, y \geq 0$

using *Special Ordered Set of type* 1 (sets in which no more than 1 element may be non-zero)

Summarizing, the MILP model of Aggregator i under the two-stage architecture is as follows

$\max\limits_{x^{\mathcal{U}}_{u,a},\, x^{\mathcal{U},\uparrow}_{u,a},\, x^{\mathcal{U},\downarrow}_{u,a}, x^{\mathcal{N},\downarrow}_{n,a}}$	$\sum\limits_{u\in\mathcal{U}_i}\left[\sum\limits_{a=1}^{A_u^{\mathcal{U}}}\left(B^{\mathcal{U}}_{u,a}\, x^{\mathcal{U}}_{u,a}\, g_u\right) + G_u\, v_u - C^{\mathcal{U}}_u\, g_u\right] + \sum\limits_{u\in\mathcal{U}_i}\left[\sum\limits_{a=1}^{A_u^{\mathcal{U},\uparrow}}\left(B^{\mathcal{U},\uparrow}_{u,a}\, x^{\mathcal{U},\uparrow}_{u,a}\, g^{\uparrow}_u\right) - C^{\mathcal{U},\uparrow}_u g^{\uparrow}_u\right] +$
	$+\sum\limits_{n\in\mathcal{N}_i}\sum\limits_{a=1}^{A_n^{\mathcal{N},\downarrow}}\left(B^{\mathcal{N},\downarrow}_{n,a}\, x^{\mathcal{N},\downarrow}_{n,a}\, d^{\downarrow}_n\right) - \sum\limits_{u\in\mathcal{U}_i}\left[\sum\limits_{a=1}^{A_u^{\mathcal{U},\uparrow}}\left(B^{\mathcal{U},\downarrow}_{u,a}\, x^{\mathcal{U},\downarrow}_{u,a}\, g^{\downarrow}_u\right) - C^{\mathcal{U},\downarrow}_u g^{\downarrow}_u\right]$
	• constraints on binary variables $x^{\mathcal{U}}_{u,a}$, $x^{\mathcal{U},\uparrow}_{u,a}$, $x^{\mathcal{U},\downarrow}_{u,a}$ and $x^{\mathcal{N},\downarrow}_{n,a}$ for selection of bid prices
	• optimality conditions of DAM problem to determine g_u and v_u, $u \in \mathcal{U}$
specific for Case A	• optimality conditions of RTM problem to determine $g^{\uparrow}_u$, $g^{\downarrow}_u$, $u \in \mathcal{U}$, and $d^{\downarrow}_n$, $n \in \mathcal{N}$
	• constraints for McCormick reformulation of (binary × real) bilinear terms
	• constraints for reformulation of complementarity constraints by $SOS1$ variables

Model of Aggregator i in case B

B. <u>Three-stage</u> architecture 1

1. DAM
2. a real-time market for each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. a real-time market for transmission $\mathcal{T}$, with resources in $\mathcal{T}$

Case B: a real-time market for each distribution network $\mathcal{D}_k$, $1 \le k \le K$

The **operator of the real-time market of distribution network** $\mathcal{D}_k$, given

$\widetilde{D}_n$	real-time load at nodes $n \in \mathcal{N}^{\mathcal{D}_k}$
$\widetilde{W}_n$	real-time non-programmable generation at nodes $n \in \mathcal{N}^{\mathcal{D}_k}$

the **bids submitted by the resources connected to** $\mathcal{D}_k$

	bid price	offered quantity	
$u \in \mathcal{U}^{\mathcal{D}_k}$	$b_u^{\mathcal{U},\uparrow}$	$G_u - g_u$	upward regulation
	$b_u^{\mathcal{U},\downarrow}$	g_u	downward regulation
$n \in \mathcal{N}^{\mathcal{D}_k}$	$b_n^{\mathcal{N},\downarrow}$	$\delta_n \widetilde{D}_n$	load curtailment ($\delta_n > 0$)

determines

$g_u^{\uparrow}$, $g_u^{\downarrow}$	accepted quantities of upward and downward regulation bids
$d_n^{\downarrow}$	load curtailment
$w_n^{\downarrow}$	curtailment of non-programmable generation

subject to

1. accepted quantities not greater than offered quantities

$u \in \mathcal{U}^{\mathcal{D}_k}$	$0 \leq g_u^{\uparrow} \leq G_u - g_u$	upward regulation in $\mathcal{D}_k$
	$0 \leq g_u^{\downarrow} \leq g_u$	downward regulation in $\mathcal{D}_k$

$n \in \mathcal{N}^{\mathcal{D}_k}$	$0 \leq d_n^{\downarrow} \leq \delta_n \widetilde{D}_n$	load curtailment ($\delta_n > 0$) in $\mathcal{D}_k$

2. curtailment of non-programmable generation in $\mathcal{D}_k$

$n \in \mathcal{N}^{\mathcal{D}_k}$	$0 \leq w_n^{\downarrow} \leq \widetilde{W}_n$

3. manage congestions in $\mathcal{D}_k$

$l \in \mathcal{L}^{\mathcal{D}_k}$	$\sum_{n \in \mathcal{N}^{\mathcal{D}_k}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\uparrow} - g_u^{\downarrow}\right) + \left(\widetilde{W}_n - w_n^{\downarrow}\right) - \left(\widetilde{D}_n - d_n^{\downarrow}\right) \right] \leq \overline{F}_l$

4. the **exchange between** $\mathcal{D}_k$ **and** $\mathcal{T}$ after real-time market is equal to the exchange resulting from the DAM clearing: this condition corresponds to "inner balancing" constraint

$$\sum_{u\in\mathcal{U}^{\mathcal{D}_k}}\left(g_u^{\uparrow}-g_u^{\downarrow}\right)+\sum_{n\in\mathcal{N}^{\mathcal{D}_k}} d_n^{\downarrow}-\sum_{n\in\mathcal{N}^{\mathcal{D}_k}} w_n^{\downarrow}=\sum_{n\in\mathcal{N}^{\mathcal{D}_k}}\left(\widetilde{D}_n-D_n\right)-\sum_{n\in\mathcal{N}^{\mathcal{D}_k}}\left(\widetilde{W}_n-W_n\right)$$

Objective function

$$\min \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\uparrow}\, g_u^{\uparrow}+\sum_{n\in\mathcal{N}^{\mathcal{D}_k}} b_u^{\mathcal{N},\downarrow}\, d_n^{\downarrow}-\sum_{u\in\mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\downarrow}\, g_u^{\downarrow}$$

The real-time market in transmission network $\mathcal{T}$ in Case B

The **operator of the real-time market of transmission network** $\mathcal{T}$, given

$\widetilde{D}_n$	real-time load at nodes $n \in \mathcal{N}^{\mathcal{T}}$
$\widetilde{W}_n$	real-time non-programmable generation at nodes $n \in \mathcal{N}^{\mathcal{T}}$

the **bids submitted by the resources connected to** $\mathcal{T}$

	bid price	offered quantity	
$u \in \mathcal{U}^{\mathcal{T}}$	$b_u^{\mathcal{U},\uparrow}$	$G_u - g_u$	upward regulation
	$b_u^{\mathcal{U},\downarrow}$	g_u	downward regulation
$n \in \mathcal{N}^{\mathcal{T}}$	$b_n^{\mathcal{N},\downarrow}$	$\delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$)

determines

$g_u^{\uparrow}$, $g_u^{\downarrow}$	accepted quantities of upward and downward regulation bids
$d_n^{\downarrow}$	load curtailment
$w_n^{\downarrow}$	curtailment of non-programmable generation

subject to

1. accepted quantities not greater than offered quantities

$u \in \mathcal{U}^{\mathcal{T}}$	$0 \le g_u^{\uparrow} \le G_u - g_u$	upward regulation in $\mathcal{T}$
	$0 \le g_u^{\downarrow} \le g_u$	downward regulation in $\mathcal{T}$

$n \in \mathcal{N}^{\mathcal{T}}$	$0 \le d_n^{\downarrow} \le \delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$) in $\mathcal{T}$

2. curtailment of non-programmable generation in $\mathcal{T}$

$n \in \mathcal{N}^{\mathcal{T}}$	$0 \le w_n^{\downarrow} \le \widetilde{W}_n$

3. resolve **imbalance** $\Delta^{\mathcal{T}} = \sum_{n \in \mathcal{N}^{\mathcal{T}}} \left(\widetilde{D}_n - D_n\right) - \sum_{n \in \mathcal{N}^{\mathcal{T}}} \left(\widetilde{W}_n - W_n\right)$ using resources in $\mathcal{T}$

$$\sum_{u \in \mathcal{U}^{\mathcal{T}}} g_u^{\uparrow} + \sum_{n \in \mathcal{N}^{\mathcal{T}}} d_n^{\downarrow} - \sum_{u \in \mathcal{U}^{\mathcal{T}}} g_u^{\downarrow} - \sum_{n \in \mathcal{N}^{\mathcal{T}}} w_n^{\downarrow} = \Delta^{\mathcal{T}}$$

4. manage congestions in transmission (flow on line $l \in \mathcal{L}^{\mathcal{T}}$ depending on all nodes $n \in \mathcal{N}$)

$l \in \mathcal{L}^{\mathcal{T}}$

$$\underbrace{\sum_{n \in \mathcal{N}^{\mathcal{T}}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\uparrow} - g_u^{\downarrow} \right) + \left(\widetilde{W}_n - w_n^{\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\downarrow} \right) \right]}_{\text{contribution to flow on } l \in \mathcal{L}^{\mathcal{T}} \text{ from nodes in transmission}} + F^{\mathcal{D}} \leq \overline{F}_l$$

where

$$F^{\mathcal{D}} = \underbrace{\sum_{k \in K} \sum_{n \in \mathcal{N}^{\mathcal{D}}k} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\uparrow} - g_u^{\downarrow} \right) + \left(\widetilde{W}_n - w_n^{\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\downarrow} \right) \right]}_{\text{contribution to flow on } l \in \mathcal{L}^{\mathcal{T}} \text{ from nodes in distribution}}$$

Objective function

$$\min \sum_{u \in \mathcal{U}^{\mathcal{T}}} b_u^{\mathcal{U},\uparrow} g_u^{\uparrow} + \sum_{n \in \mathcal{N}^{\mathcal{T}}} b_u^{\mathcal{N},\downarrow} d_n^{\downarrow} - \sum_{u \in \mathcal{U}^{\mathcal{T}}} b_u^{\mathcal{U},\downarrow} g_u^{\downarrow}$$

The MILP model of Aggregator i under the three-stage architecture 1

$\max\limits_{x_{u,a}^{\mathcal{U}},\, x_{u,a}^{\mathcal{U},\uparrow},\, x_{u,a}^{\mathcal{U},\downarrow},\, x_{n,a}^{\mathcal{N},\downarrow}}$	profit of Aggregator i
	• constraints on binary variables $x_{u,a}^{\mathcal{U}}$, $x_{u,a}^{\mathcal{U},\uparrow}$, $x_{u,a}^{\mathcal{U},\downarrow}$ and $x_{n,a}^{\mathcal{N},\downarrow}$ for selection of bid prices
	• optimality conditions of DAM problem to determine g_u and v_u, $u \in \mathcal{U}$
specific for Case B	• optimality conditions of **RTM problem for each distribution** network $\mathcal{D}_k$, $1 \le k \le K$, to determine $g_u^{\uparrow}$, $g_u^{\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}}$, and $d_n^{\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}}$
specific for Case B	• optimality conditions of **RTM problem in transmission** $\mathcal{T}$ to determine $g_u^{\uparrow}$, $g_u^{\downarrow}$, $u \in \mathcal{U}^{\mathcal{T}}$, and $d_n^{\downarrow}$, $n \in \mathcal{N}^{\mathcal{T}}$
	• constraints for McCormick reformulation of (binary × real) bilinear terms
	• constraints for linear reformulation of complementarity constraints

Model of Aggregator i in case C

C. Three-stage architecture 2

1. DAM
2. real-time market in each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. real-time market in transmission $\mathcal{T}$, with resources in $\mathcal{T}$ + residual resources in $\mathcal{D}$

Case C: a real-time market for each distribution network $\mathcal{D}_k$, $1 \le k \le K$

The **operator of the real-time market of distribution network** $\mathcal{D}_k$, given

$\widetilde{D}_n$	real-time load at nodes $n \in \mathcal{N}^{\mathcal{D}_k}$
$\widetilde{W}_n$	real-time non-programmable generation at nodes $n \in \mathcal{N}^{\mathcal{D}_k}$

the **bids submitted by the resources connected to** $\mathcal{D}_k$

	bid price	offered quantity	
$u \in \mathcal{U}^{\mathcal{D}_k}$	$b_u^{\mathcal{U},\mathcal{D},\uparrow}$	$G_u - g_u$	upward regulation
	$b_u^{\mathcal{U},\mathcal{D},\downarrow}$	g_u	downward regulation
$n \in \mathcal{N}^{\mathcal{D}_k}$	$b_n^{\mathcal{N},\mathcal{D},\downarrow}$	$\delta_n \widetilde{D}_n$	load curtailment ($\delta_n > 0$)

determines

$g_u^{\mathcal{D},\uparrow}$, $g_u^{\mathcal{D},\downarrow}$	accepted quantities of upward and downward regulation bids
$d_n^{\mathcal{D},\downarrow}$	load curtailment
$w_n^{\mathcal{D},\downarrow}$	curtailment of non-programmable generation

subject to

1. accepted quantities not greater than offered quantities

$u \in \mathcal{U}^{\mathcal{D}_k}$	$0 \leq g_u^{\mathcal{D},\uparrow} \leq G_u - g_u$	upward regulation in $\mathcal{D}_k$
	$0 \leq g_u^{\mathcal{D},\downarrow} \leq g_u$	downward regulation in $\mathcal{D}_k$

$n \in \mathcal{N}^{\mathcal{D}_k}$	$0 \leq d_n^{\mathcal{D},\downarrow} \leq \delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$) in $\mathcal{D}_k$

2. curtailment of non-programmable generation in $\mathcal{D}_k$

$n \in \mathcal{N}^{\mathcal{D}_k}$	$0 \leq w_n^{\mathcal{D},\downarrow} \leq \widetilde{W}_n$

3. **manage congestions** in $\mathcal{D}_k$

$l \in \mathcal{L}^{\mathcal{D}_k}$	$\sum_{n \in \mathcal{N}^{\mathcal{D}_k}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow} \right) + \left(\widetilde{W}_n - w_n^{\mathcal{D},\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\mathcal{D},\downarrow} \right) \right] \leq \overline{F}_l$

4. the **exchange between** $\mathcal{D}_k$ **and** $\mathcal{T}$ after real-time market is equal to the exchange resulting from the DAM clearing:

$$\sum_{u \in \mathcal{U}^{\mathcal{D}_k}} \left(g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow} \right) + \sum_{n \in \mathcal{N}^{\mathcal{D}_k}} d_n^{\mathcal{D},\downarrow} - \sum_{n \in \mathcal{N}^{\mathcal{D}_k}} w_n^{\mathcal{D},\downarrow} = \sum_{n \in \mathcal{N}^{\mathcal{D}_k}} \left(\widetilde{D}_n - D_n \right) - \sum_{n \in \mathcal{N}^{\mathcal{D}_k}} \left(\widetilde{W}_n - W_n \right)$$

Objective function

$$\min \sum_{u \in \mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\uparrow} \, g_u^{\mathcal{D},\uparrow} + \sum_{n \in \mathcal{N}^{\mathcal{D}_k}} b_u^{\mathcal{N},\downarrow} \, d_n^{\mathcal{D},\downarrow} - \sum_{u \in \mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\downarrow} \, g_u^{\mathcal{D},\downarrow}$$

The real-time market in transmission network $\mathcal{T}$ in Case C

The **operator of the real-time market of transmission network** $\mathcal{T}$, given

$\widetilde{D}_n$ real-time load at nodes $n \in \mathcal{N}^{\mathcal{T}}$

$\widetilde{W}_n$ real-time non-programmable generation at nodes $n \in \mathcal{N}^{\mathcal{T}}$

the **bids submitted by the resources connected to** $\mathcal{T}$

	bid price	offered quantity	
$u \in \mathcal{U}^{\mathcal{T}}$	$b_u^{\mathcal{U},\mathcal{T},\uparrow}$	$G_u - g_u$	upward regulation
	$b_u^{\mathcal{U},\mathcal{T},\downarrow}$	g_u	downward regulation
$n \in \mathcal{N}^{\mathcal{T}}$	$b_n^{\mathcal{N},\mathcal{T},\downarrow}$	$\delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$)

the **bids submitted by resources connected to distribution networks** $\mathcal{D} = \bigcup_{k=1}^{K} \mathcal{D}_k$

	bid price	the residual quantity is offered	
$u \in \mathcal{U}^{\mathcal{D}}$	$b_u^{\mathcal{U},\mathcal{T},\uparrow}$	$G_u - \left(g_u + g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow}\right)$	upward regulation
	$b_u^{\mathcal{U},\mathcal{T},\downarrow}$	$g_u + g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow}$	downward regulation
$n \in \mathcal{N}^{\mathcal{D}}$	$b_n^{\mathcal{N},\mathcal{T},\downarrow}$	$\delta_n \, \widetilde{D}_n - d_n^{\mathcal{D},\downarrow}$	load curtailment ($\delta_n > 0$)

detemines

The **operator of the real-time market of transmission network** $\mathcal{T}$ determines

$g_u^{\mathcal{T},\uparrow}$, $g_u^{\mathcal{T},\downarrow}$	$u \in \mathcal{U}^{\mathcal{T}}$	$u \in \mathcal{U}^{\mathcal{D}}$	accepted quantities of upward and downward regulation bids
$d_n^{\mathcal{T},\downarrow}$	$n \in \mathcal{N}^{\mathcal{T}}$	$n \in \mathcal{N}^{\mathcal{D}}$	load curtailment
$w_n^{\mathcal{T},\downarrow}$	$n \in \mathcal{N}^{\mathcal{T}}$	$n \in \mathcal{N}^{\mathcal{D}}$	curtailment of non-programmable generation

subject to

1. accepted quantities not greater than offered quantities

$u \in \mathcal{U}^{\mathcal{T}}$	$0 \le g_u^{\mathcal{T},\uparrow} \le G_u - g_u$	upward regulation
$u \in \mathcal{U}^{\mathcal{D}}$	$0 \le g_u^{\mathcal{T},\uparrow} \le G_u - \left(g_u + g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow}\right)$	

$u \in \mathcal{U}^{\mathcal{T}}$	$0 \le g_u^{\mathcal{T},\downarrow} \le g_u$	downward regulation
$u \in \mathcal{U}^{\mathcal{D}}$	$0 \le g_u^{\mathcal{T},\downarrow} \le g_u + g_u^{\mathcal{D},\uparrow} - g_u^{\mathcal{D},\downarrow}$	

$n \in \mathcal{N}^{\mathcal{T}}$	$0 \le d_n^{\mathcal{T},\downarrow} \le \delta_n \, \widetilde{D}_n$	load curtailment ($\delta_n > 0$)
$n \in \mathcal{N}^{\mathcal{D}}$	$0 \le d_n^{\mathcal{T},\downarrow} \le \delta_n \, \widetilde{D}_n - d_n^{\mathcal{D},\downarrow}$	

2. curtailment of non-programmable generation

$n \in \mathcal{N}^{\mathcal{T}}$	$0 \leq w_n^{\mathcal{T},\downarrow} \leq \widetilde{W}_n$
$n \in \mathcal{N}^{\mathcal{D}}$	$0 \leq w_n^{\mathcal{T},\downarrow} \leq \widetilde{W}_n - w_n^{\mathcal{D},\downarrow}$

3. resolve **imbalance**

$$\sum_{u \in \mathcal{U}} g_u^{\mathcal{T},\uparrow} + \sum_{n \in \mathcal{N}} d_n^{\mathcal{T},\downarrow} - \sum_{u \in \mathcal{U}} g_u^{\mathcal{T},\downarrow} - \sum_{n \in \mathcal{N}} w_n^{\mathcal{T},\downarrow} = \Delta^{\mathcal{T}}$$

4. **manage congestions in transmission** (flow on line $l \in \mathcal{L}^{\mathcal{T}}$ depending on all nodes $n \in \mathcal{N}$)

$l \in \mathcal{L}^{\mathcal{T}}$	$\sum_{n \in \mathcal{N}^{\mathcal{T}}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\mathcal{T},\uparrow} - g_u^{\mathcal{T},\downarrow} \right) + \left(\widetilde{W}_n - w_n^{\mathcal{T},\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\mathcal{T},\downarrow} \right) \right] +$ $+ \sum_{n \in \mathcal{N}^{\mathcal{D}}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_u^{\mathcal{D},\uparrow} + g_u^{\mathcal{T},\uparrow} - g_u^{\mathcal{D},\downarrow} - g_u^{\mathcal{T},\downarrow} \right) + \right.$ $\left. + \left(\widetilde{W}_n - w_n^{\mathcal{D},\downarrow} - w_n^{\mathcal{T},\downarrow} \right) - \left(\widetilde{D}_n - d_n^{\mathcal{D},\downarrow} - d_n^{\mathcal{T},\downarrow} \right) \right] \leq \overline{F}_l$

Objective function

$$\min \sum_{u \in \mathcal{U}} b_u^{\mathcal{U},\mathcal{T},\uparrow} g_u^{\mathcal{T},\uparrow} + \sum_{n \in \mathcal{N}} b_u^{\mathcal{N},\mathcal{T},\downarrow} d_n^{\mathcal{T},\downarrow} - \sum_{u \in \mathcal{U}} b_u^{\mathcal{U},\mathcal{T},\downarrow} g_u^{\mathcal{T},\downarrow}$$

The MILP model of Aggregator i under the three-stage architecture 2

$x_{u,a}^{\mathcal{U},\mathcal{D},\uparrow}$, $x_{u,a}^{\mathcal{U},\mathcal{D},\downarrow}$, $x_{u,a}^{\mathcal{U},\mathcal{T},\uparrow}$, $x_{u,a}^{\mathcal{U},\mathcal{T},\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}}$	$x_{u,a}^{\mathcal{U},\mathcal{T},\uparrow}$, $x_{u,a}^{\mathcal{U},\mathcal{T},\downarrow}$, $u \in \mathcal{U}^{\mathcal{T}}$
$x_{n,a}^{\mathcal{N},\mathcal{D},\downarrow}$, $x_{n,a}^{\mathcal{N},\mathcal{T},\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}}$	$x_{n,a}^{\mathcal{N},\mathcal{T},\downarrow}$, $n \in \mathcal{N}^{\mathcal{T}}$

max	profit of Aggregator i
	• constraints on binary variables $x_{u,a}^{\mathcal{U}}$, $x_{u,a}^{\mathcal{U},\uparrow}$, $x_{u,a}^{\mathcal{U},\downarrow}$ and $x_{n,a}^{\mathcal{N},\downarrow}$ for selection of bid prices
	• optimality conditions of DAM problem determine g_u and v_u, $u \in \mathcal{U}$
specific for Case C	• optimality conditions of RTM problem for each distribution network $\mathcal{D}_k$, $\leq k \leq K$, to determine $g_u^{\mathcal{D},\uparrow}$, $g_u^{\mathcal{D},\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}}$, and $d_n^{\mathcal{D},\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}}$
specific for Case C	• optimality conditions of RTM problem of transmission network $\mathcal{T}$, to determine $g_u^{\mathcal{T},\uparrow}$, $g_u^{\mathcal{T},\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}}$, and $d_n^{\mathcal{T},\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}}$ $g_u^{\mathcal{T},\uparrow}$, $g_u^{\mathcal{T},\downarrow}$, $u \in \mathcal{U}^{\mathcal{T}}$, and $d_n^{\mathcal{T},\downarrow}$, $n \in \mathcal{N}^{\mathcal{T}}$
	• constraints for McCormick reformulation of (binary × real) bilinear terms
	• constraints for linear reformulation of complementarity constraints

Iterative procedure to determine a Nash equilibrium solution

Assign initial values to bid prices of all resources: $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_{k=0}$, $u \in \mathcal{U}$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_{k=0}$ $n \in \mathcal{N}$.

For $k = 1, \dots, Kmax$

For $i = 1, \dots, I$

Given the current values of the competitors' bid prices, i.e.

$\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_k$, $u \in \mathcal{U}_1 \cup \dots \cup \mathcal{U}_{i-1}$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_k$, $n \in \mathcal{N}_1 \cup \dots \cup \mathcal{N}_{i-1}$

$\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_{k-1}$, $u \in \mathcal{U}_{i+1} \cup \dots \cup \mathcal{U}_I$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_{k-1}$, $n \in \mathcal{N}_{i+1} \cup \dots \cup \mathcal{N}_I$

compute optimal bid prices for Aggregator i:

$\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_k$, $u \in \mathcal{U}_i$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_k$, $n \in \mathcal{N}_i$ (*)

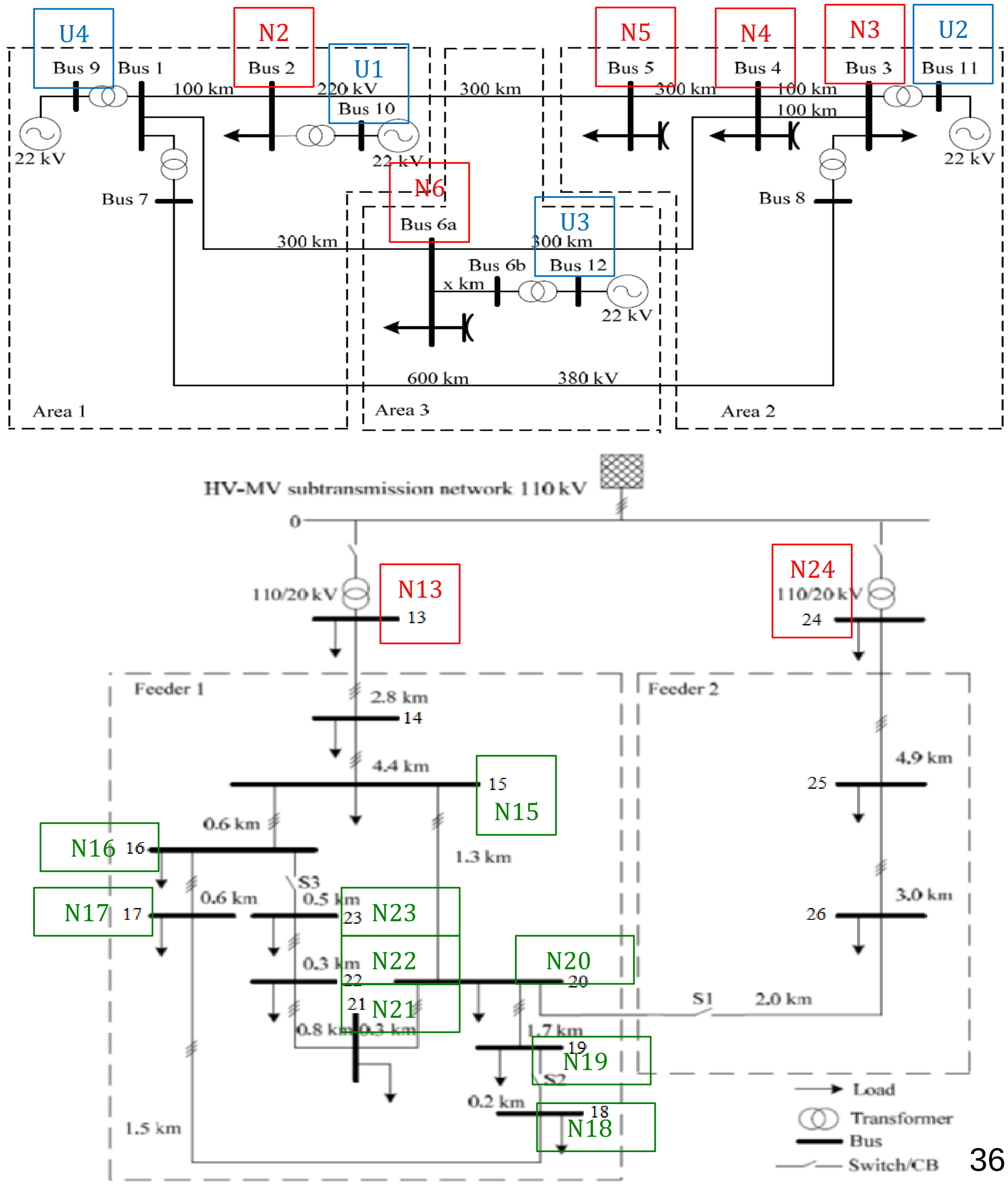
If optimal bid prices (*) differ from those computed at iteration $k-1$, set flag $\varphi_i = 1$, otherwise set $\varphi_i = 0$.

If $\varphi_i = 0$, for all $i \in I$, STOP, since none of the Aggregators has unilaterally deviated from the solution computed at the previous iteration.

Numerical experiments

CIGRE network with

- **Programmable** generation
  - U4 connected at N9
  - U1 connected at N10
  - U2 connected at N11
  - U3 connected at N12
- **Curtailable** loads at nodes
  - N2-N6
- **Curtailable** loads at nodes
  - N13, N24
- Non curtailable loads at nodes
  - N15-N23, N25, N26
- Non-Programmable generation
  - at nodes N15-N23



TEST: consider positive imbalance ($\tilde{D}_n = D_n \cdot 1.1$ for all n)

$$\Delta = \sum_{n \in \mathcal{N}} \left(\tilde{D}_n - D_n\right) - \sum_{n \in \mathcal{N}} \left(\tilde{W}_n - W_n\right) > 0$$

$\Rightarrow$ upward regulation, load curtailment

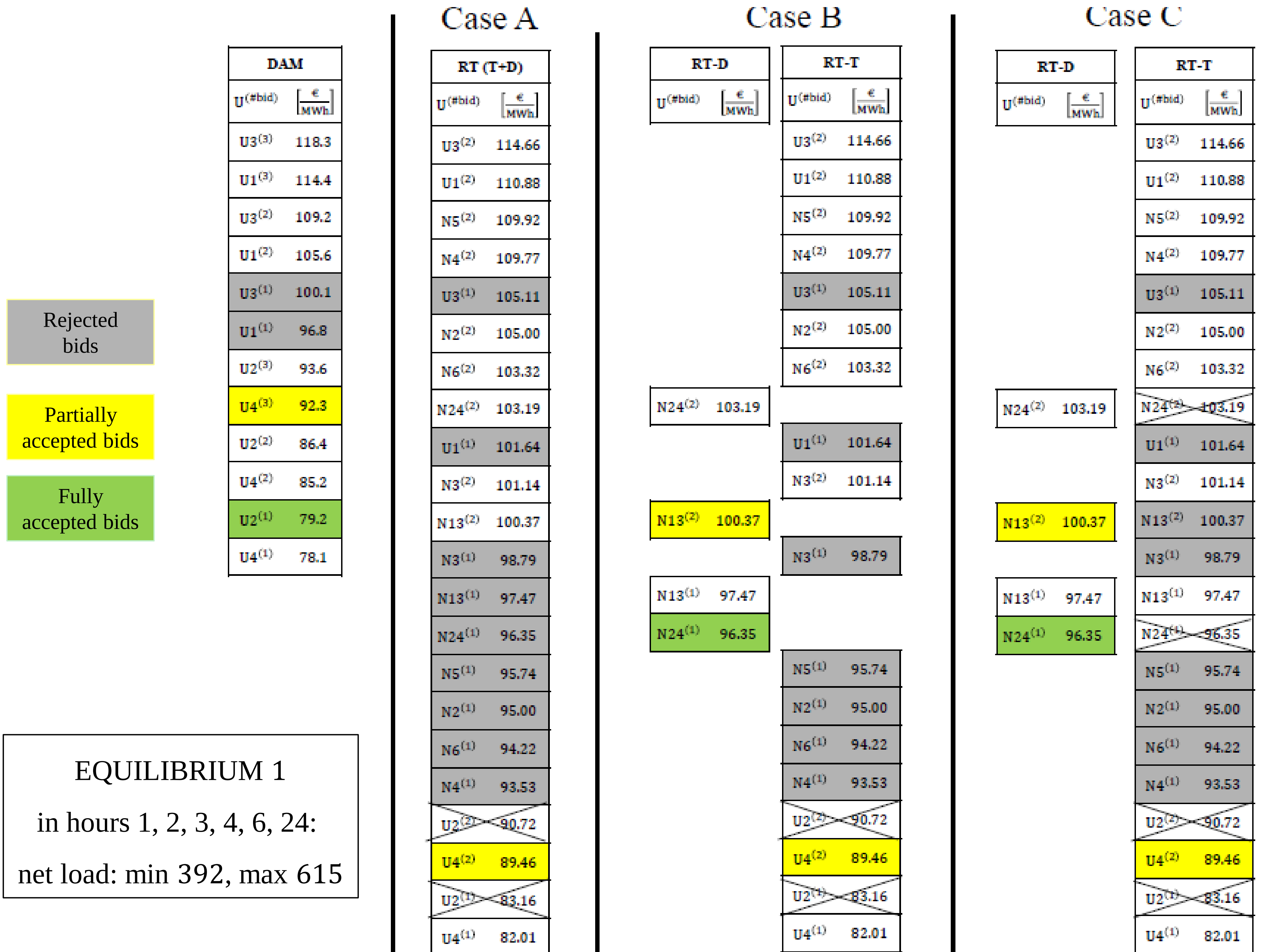
DAM mark-up: 10%, 20%, 30%

RT mark-up: 10%, 20%

We consider 24 hours and analyze the equilibria reached in each hour in schemes A, B and C.

Results:

- Equilibria reached over the 24 hours can be grouped in five patterns, where aggregators adopt different bidding strategies.
- The equilibrium of the system depends on the total system net load.


Case A
Case B
Case C
Rejected bids
Partially accepted bids
Fully accepted bids
DAM
U(#bid) [€/MWh]
U3(3) 118.3
U1(3) 114.4
U3(2) 109.2
U1(2) 105.6
U3(1) 100.1
U1(1) 96.8
U2(3) 93.6
U4(3) 92.3
U2(2) 86.4
U4(2) 85.2
U2(1) 79.2
U4(1) 78.1
RT (T+D)
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(2) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
U(#bid) [€/MWh]
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(2) 105.00
N6(2) 103.32
U1(1) 101.64
N3(2) 101.14
N3(1) 98.79
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
U(#bid) [€/MWh]
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(2) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
EQUILIBRIUM 1
in hours 1, 2, 3, 4, 6, 24:
net load: min 392, max 615

Rejected bids
Partially accepted bids
Fully accepted bids

EQUILIBRIUM 2

in hours 5, 23:

net load: min 673, max 695

DAM	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
$U3^{(3)}$	118.3
$U1^{(3)}$	114.4
$U3^{(2)}$	109.2
$U1^{(2)}$	105.6
$U3^{(1)}$	100.1
$U1^{(1)}$	96.8
$U2^{(3)}$	93.6
$U4^{(3)}$	92.3
$U2^{(2)}$	86.4
$U4^{(2)}$	85.2
$U2^{(1)}$	79.2
$U4^{(1)}$	78.1

Case A

RT (T+D)	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
$U3^{(2)}$	114.66
$U1^{(2)}$	110.88
$N5^{(2)}$	109.92
$N4^{(2)}$	109.77
$U3^{(1)}$	105.11
$N2^{(1)}$	105.00
$N6^{(2)}$	103.32
$N24^{(2)}$	103.19
$U1^{(1)}$	101.64
$N3^{(2)}$	101.14
$N13^{(2)}$	100.37
$N3^{(1)}$	98.79
$N13^{(1)}$	97.47
$N24^{(1)}$	96.35
$N5^{(1)}$	95.74
$N2^{(1)}$	95.00
$N6^{(1)}$	94.22
$N4^{(1)}$	93.53
$U2^{(2)}$	90.72
~~$U4^{(2)}$~~	~~89.46~~
$U2^{(1)}$	83.16
~~$U4^{(1)}$~~	~~82.01~~

Case B

RT-D		RT-T	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$	$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
		$U3^{(2)}$	114.66
		$U1^{(2)}$	110.88
		$N5^{(2)}$	109.92
		$N4^{(2)}$	109.77
		$U3^{(1)}$	105.11
		$N2^{(1)}$	105.00
		$N6^{(2)}$	103.32
$N24^{(2)}$	103.19		
		$U1^{(1)}$	101.64
		$N3^{(2)}$	101.14
$N13^{(2)}$	100.37		
		$N3^{(1)}$	98.79
$N13^{(1)}$	97.47		
$N24^{(1)}$	96.35		
		$N5^{(1)}$	95.74
		$N2^{(1)}$	95.00
		$N6^{(1)}$	94.22
		$N4^{(1)}$	93.53
		$U2^{(2)}$	90.72
		~~$U4^{(2)}$~~	~~89.46~~
		$U2^{(1)}$	83.16
		~~$U4^{(1)}$~~	~~82.01~~

Case C

RT-D		RT-T	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$	$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
		$U3^{(2)}$	114.66
		$U1^{(2)}$	110.88
		$N5^{(2)}$	109.92
		$N4^{(2)}$	109.77
		$U3^{(1)}$	105.11
		$N2^{(1)}$	105.00
		$N6^{(2)}$	103.32
$N24^{(2)}$	103.19	~~$N24^{(2)}$~~	~~103.19~~
		$U1^{(1)}$	101.64
		$N3^{(2)}$	101.14
$N13^{(2)}$	100.37	$N13^{(2)}$	100.37
		$N3^{(1)}$	98.79
$N13^{(1)}$	97.47	$N13^{(1)}$	97.47
$N24^{(1)}$	96.35	~~$N24^{(1)}$~~	~~96.35~~
		$N5^{(1)}$	95.74
		$N2^{(1)}$	95.00
		$N6^{(1)}$	94.22
		$N4^{(1)}$	93.53
		$U2^{(2)}$	90.72
		~~$U4^{(2)}$~~	~~89.46~~
		$U2^{(1)}$	83.16
		~~$U4^{(1)}$~~	~~82.01~~

Rejected bids

Partially accepted bids

Fully accepted bids

EQUILIBRIUM 3

in hours 7, 8, 9, 11, 12, 13:

net load: min 744, max 914

DAM	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
$U3^{(3)}$	118.3
$U1^{(3)}$	114.4
$U3^{(2)}$	109.2
$U1^{(2)}$	105.6
$U3^{(1)}$	100.1
$U1^{(1)}$	96.8
$U2^{(3)}$	93.6
$U4^{(3)}$	92.3
$U2^{(2)}$	86.4
$U4^{(2)}$	85.2
$U2^{(1)}$	79.2
$U4^{(1)}$	78.1

Case A

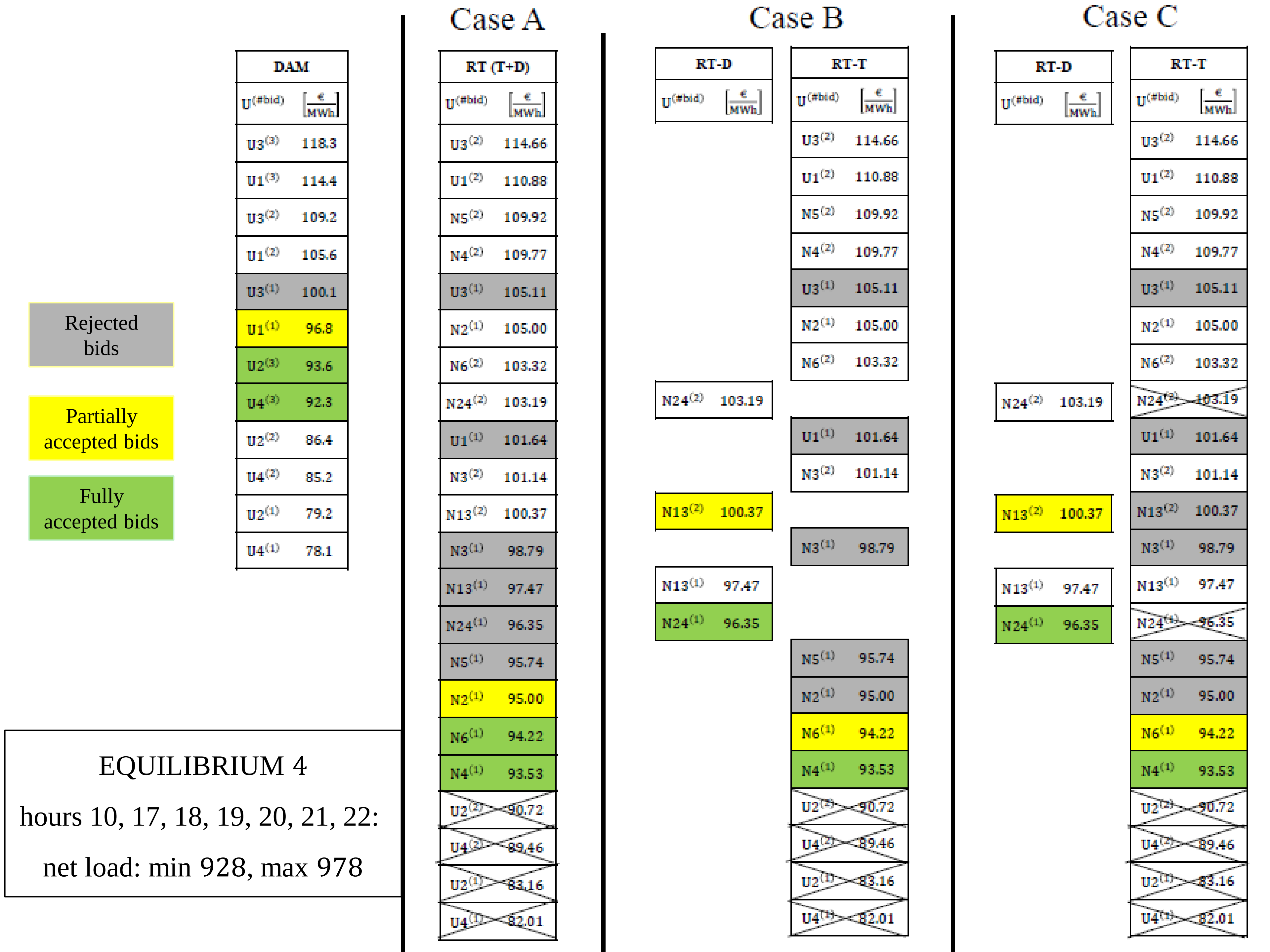
RT (T+D)	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
$U3^{(2)}$	114.66
$U1^{(2)}$	110.88
$N5^{(2)}$	109.92
$N4^{(2)}$	109.77
$U3^{(1)}$	105.11
$N2^{(1)}$	105.00
$N6^{(2)}$	103.32
$N24^{(2)}$	103.19
$U1^{(1)}$	101.64
$N3^{(2)}$	101.14
$N13^{(2)}$	100.37
$N3^{(1)}$	98.79
$N13^{(1)}$	97.47
$N24^{(1)}$	96.35
$N5^{(1)}$	95.74
$N2^{(1)}$	95.00
$N6^{(1)}$	94.22
$N4^{(1)}$	93.53
~~$U2^{(2)}$~~	~~90.72~~
~~$U4^{(2)}$~~	~~89.46~~
~~$U2^{(1)}$~~	~~83.16~~
~~$U4^{(1)}$~~	~~82.01~~

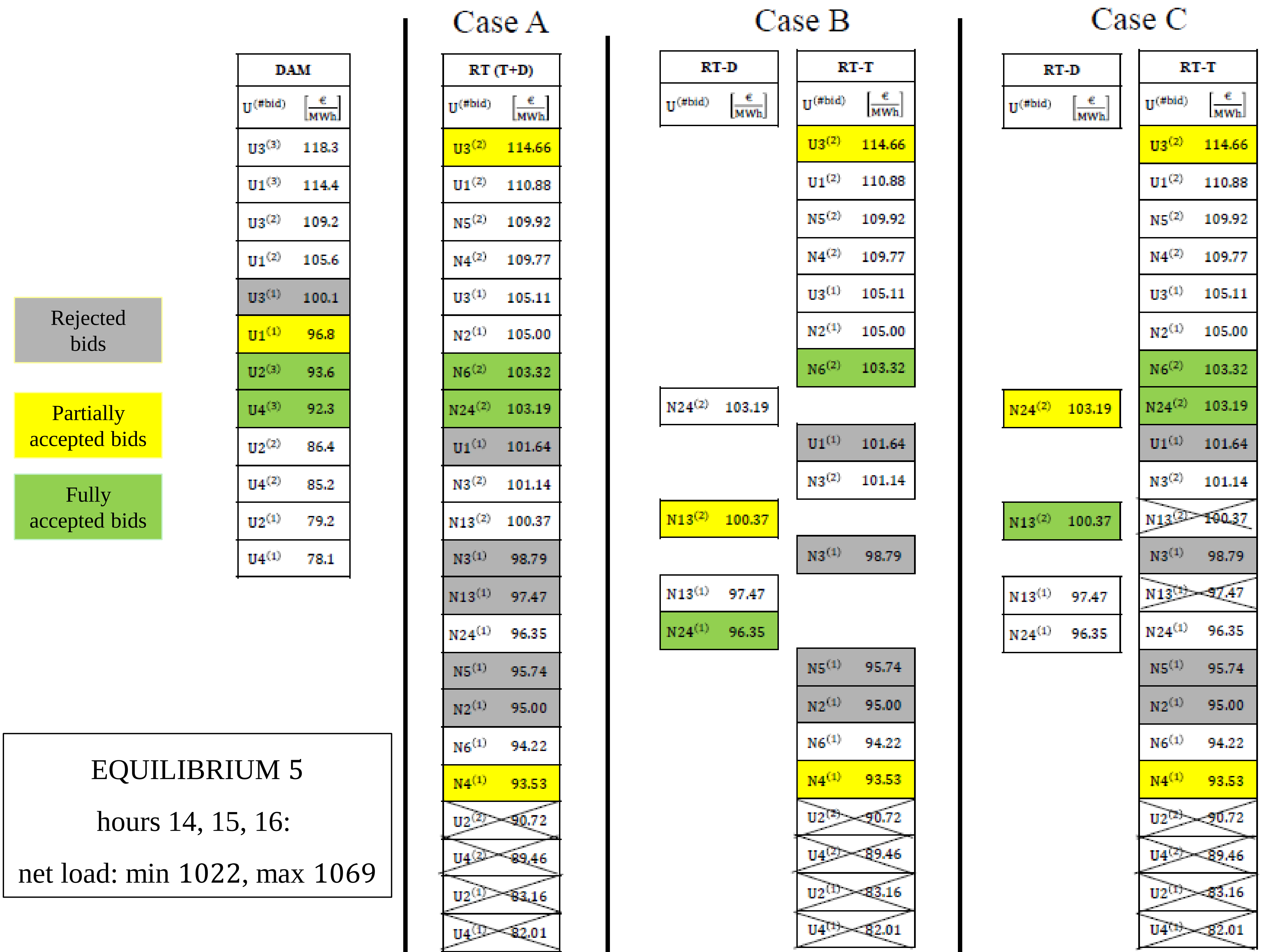
Case B

RT-D		RT-T	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$	$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
		$U3^{(2)}$	114.66
		$U1^{(2)}$	110.88
		$N5^{(2)}$	109.92
		$N4^{(2)}$	109.77
		$U3^{(1)}$	105.11
		$N2^{(1)}$	105.00
		$N6^{(2)}$	103.32
$N24^{(2)}$	103.19		
		$U1^{(1)}$	101.64
		$N3^{(2)}$	101.14
$N13^{(2)}$	100.37		
		$N3^{(1)}$	98.79
$N13^{(1)}$	97.47		
$N24^{(1)}$	96.35		
		$N5^{(1)}$	95.74
		$N2^{(1)}$	95.00
		$N6^{(1)}$	94.22
		$N4^{(1)}$	93.53
		~~$U2^{(2)}$~~	~~90.72~~
		~~$U4^{(2)}$~~	~~89.46~~
		~~$U2^{(1)}$~~	~~83.16~~
		~~$U4^{(1)}$~~	~~82.01~~

Case C

RT-D		RT-T	
$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$	$U^{(\#bid)}$	$\left[\frac{€}{MWh}\right]$
		$U3^{(2)}$	114.66
		$U1^{(2)}$	110.88
		$N5^{(2)}$	109.92
		$N4^{(2)}$	109.77
		$U3^{(1)}$	105.11
		$N2^{(1)}$	105.00
		$N6^{(2)}$	103.32
$N24^{(2)}$	103.19	~~$N24^{(2)}$~~	~~103.19~~
		$U1^{(1)}$	101.64
		$N3^{(2)}$	101.14
$N13^{(2)}$	100.37	$N13^{(2)}$	100.37
		$N3^{(1)}$	98.79
$N13^{(1)}$	97.47	$N13^{(1)}$	97.47
$N24^{(1)}$	96.35	~~$N24^{(1)}$~~	~~96.35~~
		$N5^{(1)}$	95.74
		$N2^{(1)}$	95.00
		$N6^{(1)}$	94.22
		$N4^{(1)}$	93.53
		~~$U2^{(2)}$~~	~~90.72~~
		~~$U4^{(2)}$~~	~~89.46~~
		~~$U2^{(1)}$~~	~~83.16~~
		~~$U4^{(1)}$~~	~~82.01~~


Case A
Case B
Case C
DAM
U(#bid) [€/MWh]
U3(3) 118.3
U1(3) 114.4
U3(2) 109.2
U1(2) 105.6
U3(1) 100.1
U1(1) 96.8
U2(3) 93.6
U4(3) 92.3
U2(2) 86.4
U4(2) 85.2
U2(1) 79.2
U4(1) 78.1
RT (T+D)
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
U1(1) 101.64
N3(2) 101.14
N3(1) 98.79
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
Rejected bids
Partially accepted bids
Fully accepted bids
EQUILIBRIUM 4
hours 10, 17, 18, 19, 20, 21, 22:
net load: min 928, max 978


Case A
Case B
Case C
DAM
U(#bid) [€/MWh]
U3(3) 118.3
U1(3) 114.4
U3(2) 109.2
U1(2) 105.6
U3(1) 100.1
U1(1) 96.8
U2(3) 93.6
U4(3) 92.3
U2(2) 86.4
U4(2) 85.2
U2(1) 79.2
U4(1) 78.1
Rejected bids
Partially accepted bids
Fully accepted bids
EQUILIBRIUM 5
hours 14, 15, 16:
net load: min 1022, max 1069
RT (T+D)
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
U(#bid) [€/MWh]
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
U1(1) 101.64
N3(2) 101.14
N3(1) 98.79
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01
RT-D
U(#bid) [€/MWh]
N24(2) 103.19
N13(2) 100.37
N13(1) 97.47
N24(1) 96.35
RT-T
U(#bid) [€/MWh]
U3(2) 114.66
U1(2) 110.88
N5(2) 109.92
N4(2) 109.77
U3(1) 105.11
N2(1) 105.00
N6(2) 103.32
N24(2) 103.19
U1(1) 101.64
N3(2) 101.14
N13(2) 100.37
N3(1) 98.79
N13(1) 97.47
N24(1) 96.35
N5(1) 95.74
N2(1) 95.00
N6(1) 94.22
N4(1) 93.53
U2(2) 90.72
U4(2) 89.46
U2(1) 83.16
U4(1) 82.01

Equilibrium solutions 1-4:

in schemes B and C, where only resources in distributions can provide flexibility to the distribution network, the bidding price of resources in distribution is higher than in scheme A, which results in more costly flexibility services in distribution.

Equilibrium solution 5:

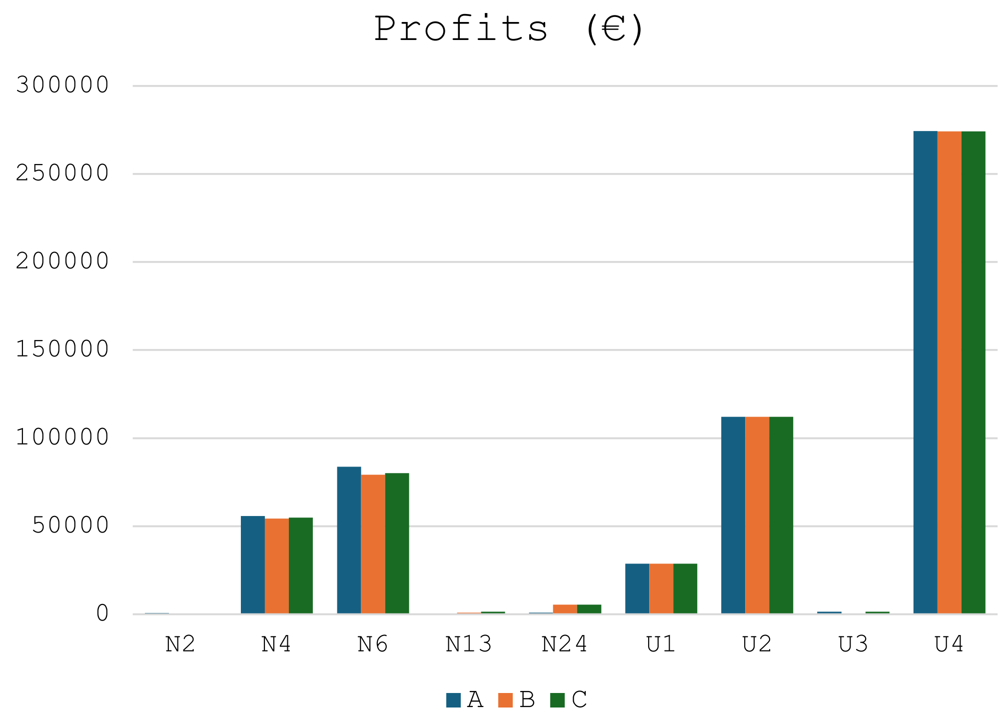
- At peak load, because of the congestion of transmission line 1-6, **two bids are partially accepted** in all 3 schemes: the bid of flexible load N4 and the bid of generator U3, which has the **highest bidding price**

- Flexible load N24, connected to the distribution network
    - In scheme A, it submits to RT(T+D) the higher price bid, which is fully accepted.
    - In scheme B, it submits to RT-D the lower price bid, so that it is fully accepted and wins competition with N13, which is only partially accepted.
    - In scheme C, it submits to RT-D the higher price bid, so that it is partially accepted; the residual capacity is offered on RT-T at the higher price and is fully accepted.

Profits earned by aggregators

In cases B and C (with local markets in distribution) it has been observed

- an increase of profits earned by flexible loads in distribution (N13 and N24), with load N24 favored over load N13, since N24[1] is the cheapest curtailment bid in distribution



- a reduction of profit earned by N6, the main transmission load, since in schemes B and C it is curtailed less than in scheme A.

Conclusions

The analysis of the total system costs suggests that

- scheme A is the most efficient in most hours.
- scheme B (local RT markets separated from the transmission RT market) may be more efficient at peak load hours, as high prices in the transmission RT market do not affect the local RT markets.

Further testing is underway on larger networks.