Integrating Demand-Side-Management in decentralized electricity systems: a few examples from EDF research projects

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Smart Energy and Stochastic Optimization 2017

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Outline

Decentralizing in electricity systems: a few main ingredients

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- local data / information (privacy concerns...)
  ⇒ Design of (strategic) information exchange scheme **[Crawford 1982, Larrousse 2014]**

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End of the year suscribe again? → Fair (compared to my neighbour)? How much effort?

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Day by day 30 Texan Electric VehicleS (+ furnaceS) flexibility $\rightarrow$ numerical setting

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$$C_t(\ell_t) = \widetilde{C}(\ell_{0,t} + \sum_i \ell_{i,t})$$

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  - max (resp. min) power $\overline{\ell}_i$ (resp. $\underline{\ell}_i = 0$)

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$$b_i\left(\ell_i, \ell_{-i}\right) = \frac{E_i}{\sum_j E_j} \sum_t C_t\left(\ell_t\right)$$

with $\ell_t = \sum_i \ell_{i,t}$ and $\ell_{-i} = (\ell_1, \cdots, \ell_{i-1}, \ell_{i+1}, \cdots, \ell_I)$

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Hourly-Load-Proportional (HLP) **[Jacquot 2017]**

$$b_i\left(\ell_i, \ell_{-i}\right) = \sum_t \frac{\ell_{i,t}}{\ell_t} \times C_t\left(\ell_t\right)$$

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Game $\mathcal{G}$ under **"normal form"**

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Game $\mathcal{G}$ under **"normal form"**

- **Players** flexible consumers $\mathcal{I}$
- **Actions/strategies** flexible consumption profile

$$\mathcal{L}_i = \left\{ \ell_i = (\ell_{i,t})_{t=1,\cdots,T} \text{ s.t. } \underline{\ell}_{i,t} \leq \ell_{i,t} \leq \overline{\ell}_{i,t}, \sum_t \ell_{i,t} = E_i \right\}$$

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- **Cost function**

$$C_i(\ell_i, \ell_{-i}) = b_i(\ell_i, \ell_{-i}) + f_i(\ell_i)$$

with $b_i = b_i^{\mathrm{DLP}}$ or $b_i = b_i^{\mathrm{HLP}}$

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Remark "add" $\forall t, \sum_i \ell_{i,t} \leq \overline{\ell}_t \ \rightarrow$ "generalized game"

Game? Play in practice?

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$\rightarrow$ possible implementation = **Best-Response-Dynamics**

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Input $\left(\ell_i^{(k=0)}\right)_i$, η, K for stopping criterion

Initial iteration $k = 0$

while $\sum_i \|\ell_i^{(k)} - \ell_i^{(k-1)}\|_2^2 \geq \eta$ **and** $k \leq K$ **do**

Next iteration $k = k + 1$

for $i \in \{1, \cdots, I\}$ **do**

(I) Solve a pb for i: $\min_{\ell_i} C_i(\ell_i, \ell_{-i}^{(k)})$ with

$$\ell_{-i}^{(k)} = (\ell_1^{(k+1)}, \cdots, \ell_{i-1}^{(k+1)}, \ell_{i+1}^{(k)}, \cdots, \ell_I^{(k)})$$

(II) Choose $\ell_i^{(k+1)}$ minimizing $C_i(\cdot, \ell_{-i}^{(k)})$

end for

end while

Coordination dynamics: convergence?

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Convergence of BRD?

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Convergence of BRD? Yes!

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Definition

G **potential game** *if it exists a function* Φ *(potential) s.t.*

$$\forall i, \forall \ell_i, \ell'_i \in \mathcal{L}_i, \forall \ell_{-i} \in \mathcal{L}_{-i},$$
$$C_i\left(\ell'_i, \ell_{-i}\right) - C_i\left(\ell_i, \ell_{-i}\right) \geq 0 \Leftrightarrow \Phi\left(\ell'_i, \ell_{-i}\right) - \Phi\left(\ell_i, \ell_{-i}\right) \geq 0$$

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Proposition (Mohsenian-Rad et al. 2010)

$\mathcal{G}^{\mathrm{DLP}}$ **potential game** *with*

$$\Phi(\ell) = \sum_t C_t(\ell_t) + \sum_i \frac{E}{E_i} f_i(\ell_i)$$

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Proposition (Jacquot et al. 2017)

If $C_t(\ell_t) = a_{1,t}\ell_t + a_{2,t}\left(\ell_t\right)^2$, $\mathcal{G}^{\mathrm{HLP}}$ **potential game** *with*

$$\Phi(\ell) = \sum_t \frac{a_{2,t}}{2}\left[\left(\ell_t\right)^2 + \sum_i \left(\ell_{i,t}\right)^2\right] + a_{1,t}\ell_t + \sum_i f_i(\ell_i)$$

Coordination dynamics: convergence? (2)

Convergence of BRD? Yes!

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*In a finite (resp. "infinite") **potential game** Best-Response-Dynamics converges to a (resp. ϵ) Nash Equilibrium.*

N.B. finite game = finite number of players with finite strategy sets

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Definition (Nash, 1951)

$\ell^* = (\ell_i^*, \ell_{-i}^*)$ *Nash Equilibrium if*

$$\forall i \in \mathcal{I}, \forall \ell_i \in \mathcal{L}_i, C_i(\ell_i^*, \ell_{-i}^*) \leq C_i(\ell_i, \ell_{-i}^*)$$

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Warning individual stability (collective profitable deviation may exist...)

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Convergence of BRD? Yes! Existence/uniqueness of point of convergence?

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There exists a unique point of convergence of BRD in $\mathcal{G}^{\mathrm{DLP}}$, unique Nash Equilibrium of this game (= unique point of minimum of Φ^{DLP}).

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Remark existence + uniqueness also obtained with more general system cost functions C_t using "concave games" of **[Rosen, 1965]** (but NOT convergence of BRD...)

Coordination dynamics: convergence? (4)

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Convergence of BRD? Yes!

In practice!

Coordination dynamics: convergence? (5)

Convergence of BRD? Yes!

Coordination dynamics: convergence? (5)

Convergence of BRD? Yes! Speed?

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Convergence of BRD? Yes! Speed? Numerically (with $f_i = 0$)...

Coordination dynamics: convergence? (5)

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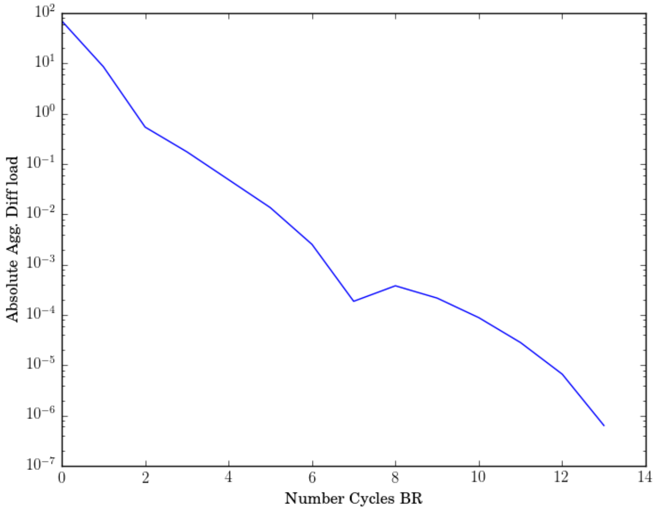

Coordination dynamics: convergence? (6)

Numerically

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Numerically Total load profiles with on/off peak scheduling

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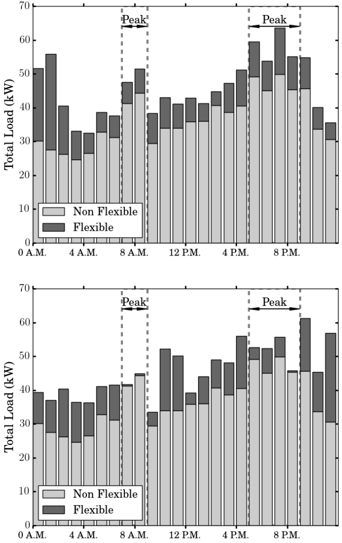

Figure: Real data = all nonflexible (top), on/off peak (bottom)

Coordination dynamics: convergence? (7)

Convergence of BRD? Yes!

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Convergence of BRD? Yes! Total load at Nash Eq. ($f_i = 0$)

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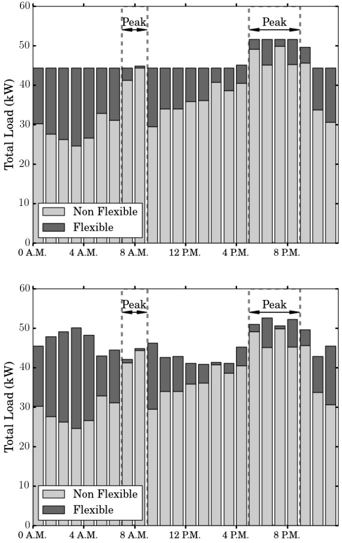

Figure: For DLP (top) and HLP (bottom)

Obtained equilibrium: efficient?

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Efficiency in game-theory

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Efficiency in game-theory

Definition (Koutsoupias, 1999)

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$$\text{PoA} = \frac{\text{biggest total cost of an equilibrium}}{\text{smallest total cost}}$$

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- "system" $\sum_t C_t(\sum_i \ell_{i,t})$

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- "system" $\sum_t C_t(\sum_i \ell_{i,t})$

Fundamental relation $1 \leq \mathrm{PoA} \leq +\infty$

Obtained equilibrium: efficient? (2)

Supergame for game-theory researchers = **find smallest possible bound on Price of Anarchy**

$$1 \leq \mathrm{PoA} \leq 1 + \mathrm{bound}(\mathrm{design})$$

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$$1 \leq \mathrm{PoA} \leq 1 + \mathrm{bound}(\mathrm{design})$$

Proposition (Mohsenian-Rad et al. 2010)

In $\mathcal{G}^{\mathrm{DLP}}$, $\mathrm{bound}^{\mathrm{DLP}} = 0$

Obtained equilibrium: efficient? (2)

Supergame for game-theory researchers = **find smallest possible bound on Price of Anarchy**

$$1 \leq \mathrm{PoA} \leq 1 + \mathrm{bound}(\mathrm{design})$$

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If $C_t(\ell_t) = a_{1,t}\ell_t + a_{2,t}(\ell_t)^2$, *in* $\mathcal{G}^{\mathrm{HLP}}$

$$\mathrm{bound}^{\mathrm{HLP}} = \frac{3}{4}\sup_t \frac{1}{1 + \frac{a_{1,t}}{a_{2,t}\overline{\ell}_t}}$$

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Numerically $\text{bound}^{\text{HLP}} \leq 0.0015$

Introduce fairness in flexibility mechanisms

Original idea of [Baharlouei, 2014]

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Original idea of [Baharlouei, 2014] → fairness?

Introduce fairness in flexibility mechanisms

Original idea of [Baharlouei, 2014] $\rightarrow$ fairness?

Definition (Baharlouei, 2014)

Using marginal contribution of i to system cost

$V_i = \textit{minimal syst. cost with } \mathcal{I} - \textit{minimal syst. cost with } \mathcal{I} \backslash \{i\}$,

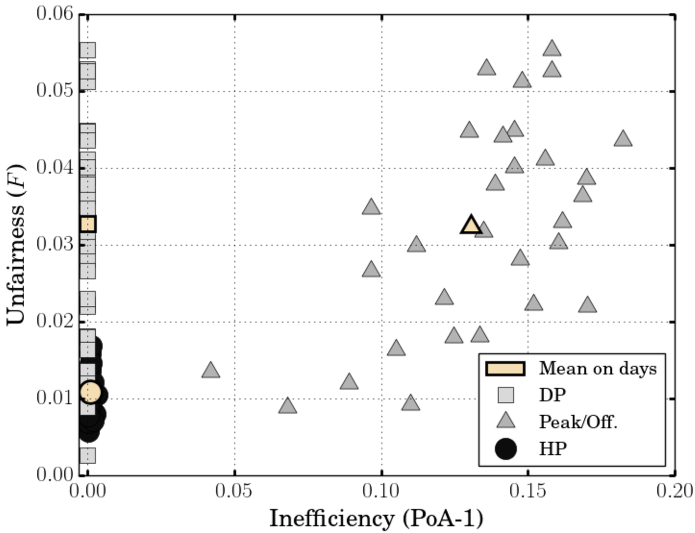
fairness index *F is*

$$F = \sup_{\ell^* \in \mathcal{L}^{\mathrm{NE}}} \sum_i \left| \frac{V_i}{\sum_j V_j} - \frac{b_i(\ell^*)}{\sum_j b_j(\ell^*)} \right|$$

N.B. $\mathcal{L}^{\mathrm{NE}}$ = set of Nash Equilibria

Introduce fairness in flexibility mechanisms (2)

Efficiency-fairness tradeoff with texan Electric Vehicles ($f_i = 0$)



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$\rightarrow$ on-going work

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   - Demand-Side-Management: in future real life?
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Rules designer at upper level

Demand-Side-Management operator = leader at upper level

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$$\underset{(C_t)_t}{\text{minimize}} \;\; \sum_t \widehat{C}_t \left(\sum_i \ell_{i,t}\right)$$

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Flexible consumers at lower level

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Flexible consumers at lower level → study of previous section

[Busic 2016]: coordinating by playing dice

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Step by step, in maths

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Step by step, in maths

- **flexible electrical applianceS** (discretized) states **as Markov chains**

$$x_{i,t+1} = x_{i,t} P_\zeta$$

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$\rightarrow$ [Busic 2016] **strict positive-real condition** (automatics!)

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Step by step, in practice

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Step by step, in practice

- DSM operator updates ζ using a **Proportional-Integral controller** (PI)

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- $\zeta(t)$ sent to all electrical appliances
- law of large numbers does the rest: each electrical appliance (independently) **rolls a dice**, and switch to a new consumption level according to P_ζ and the value of the dice

Figure: *Source* https://fr.fotolia.com/tag/"jeu de dés"

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  "there is a considerable history of user passivity to consider and address" **[Darby 2010]**

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  - **share of all-day efforts** ex Koom

    "Vos actions ont de l'impact, vous en doutez ?"

Concluding remarks: nothing with nobody!

Figure: French people protesting before Paris COP...

Concluding remarks: nothing with nobody!

Figure: French people protesting before Paris COP...

"All things are difficult before they are easy"

DSM: integrating consumers by playing?

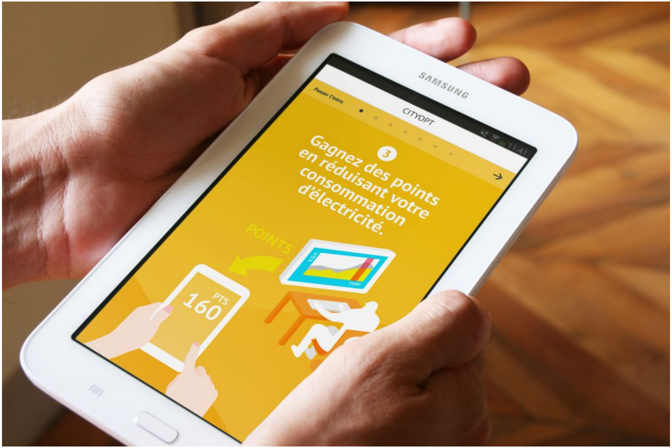

Figure: *Cityopt* - save energy (and money!) together

<u>*Source*</u> http://blog.experientia.com/united-energy-economy-experientia-helps-wrap-cityopt-nice-pilot-project/

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Flexible load scheduling = routing in parallel-arcs networks

Reinterprete flexible elec. consumption game $\mathcal{G}^{\mathrm{HLP}}$ with **[Orda et al. 1993]**

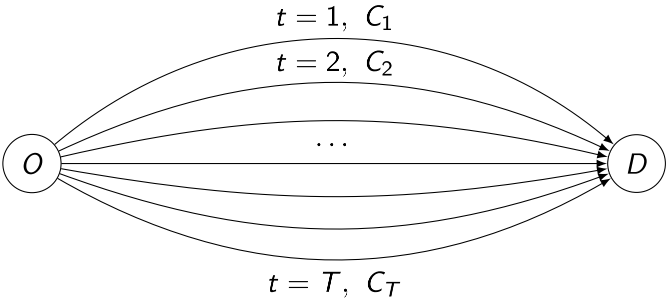

Figure: Network of the equivalent routing game.

$\rightarrow \ell_{i,t}$ = flow routed by i on arc t