Accommodating fairness in a shared-energy allocation problem with uncertainties
ICSP 2023 - UC Davis

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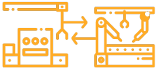
WHAT IS A PROSUMER?

Prosumer (consumer and producer)

Factory



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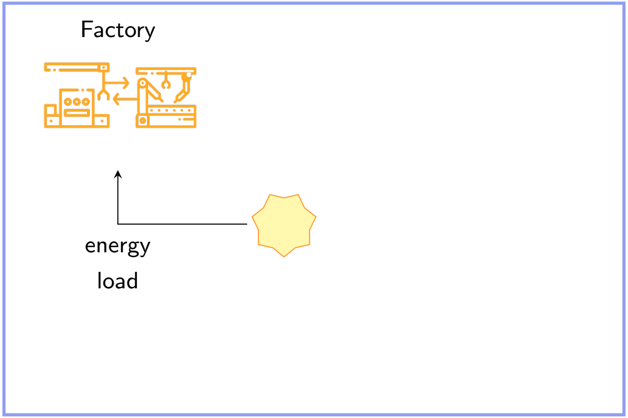

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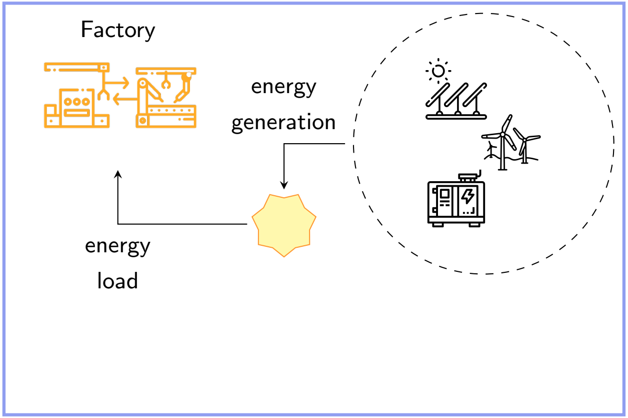

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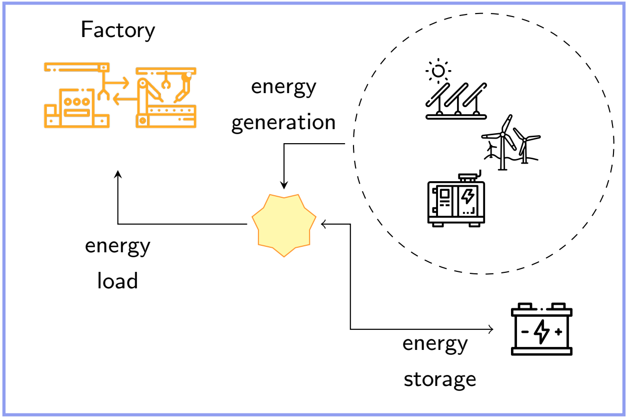

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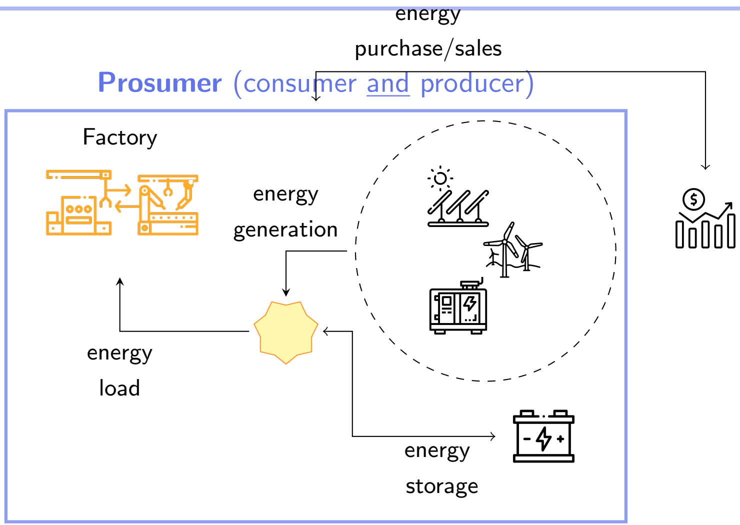
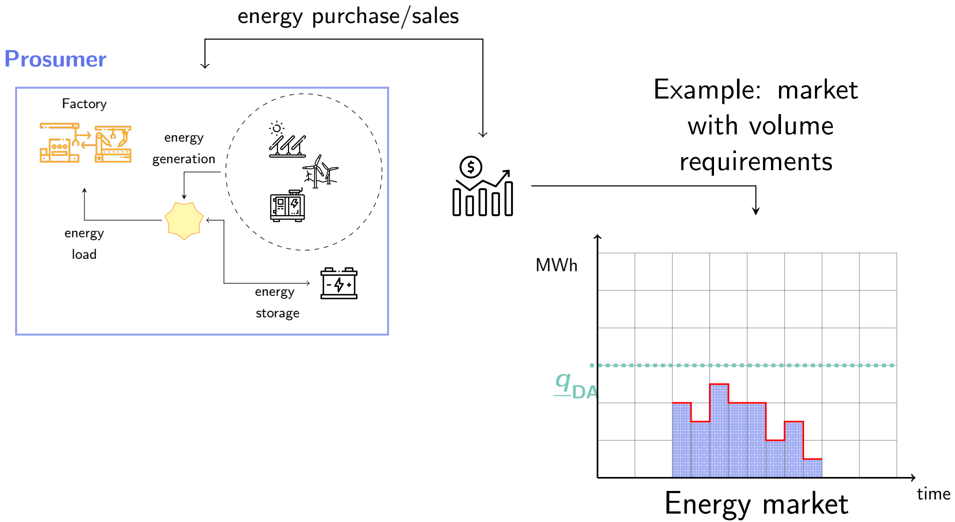


AN EXAMPLE OF ENERGY MARKET



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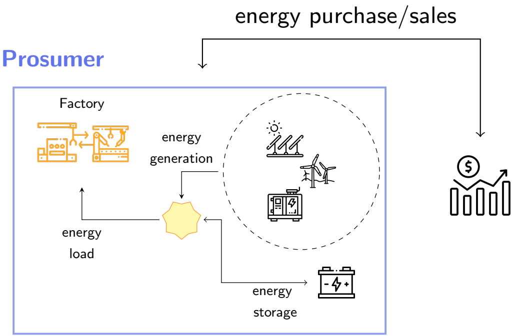
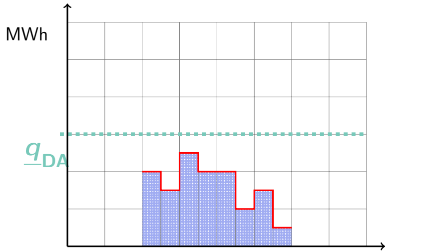


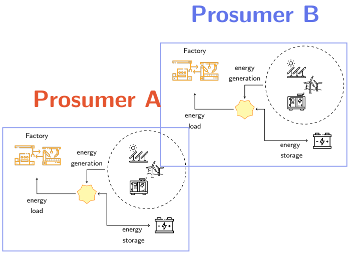
Example: market with volume requirements



Energy market

➥ A prosumer is too small to access some markets

A NEED FOR AGGREGATION



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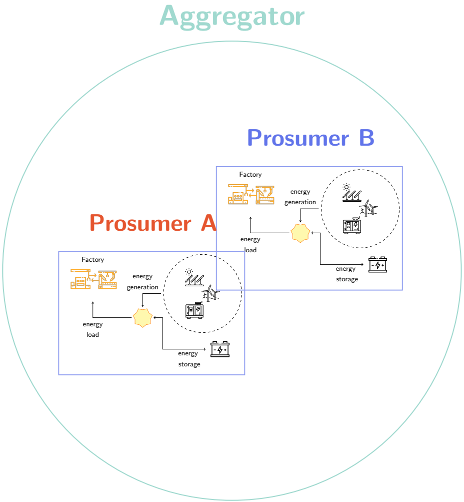

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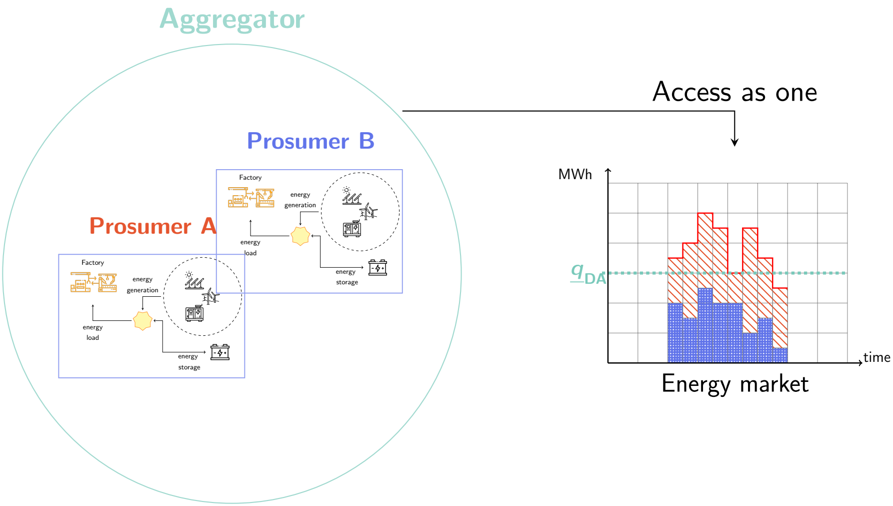

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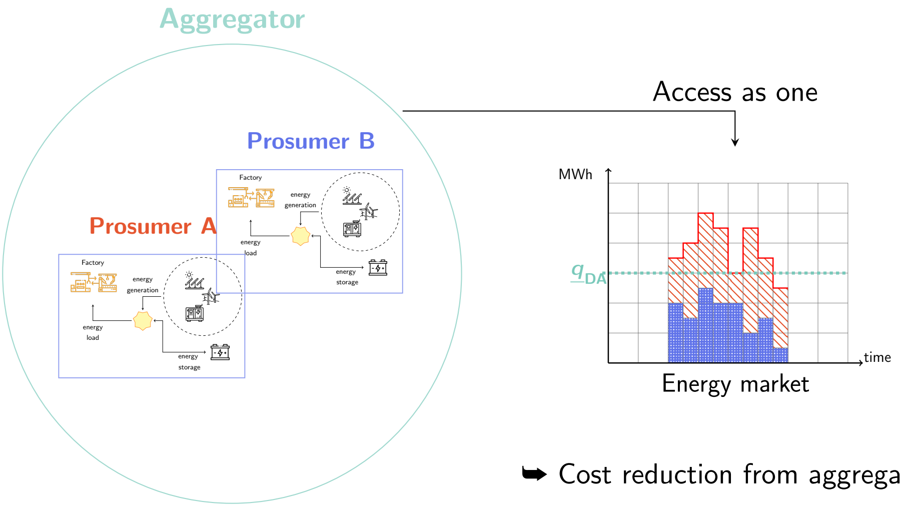

- ➥ Cost reduction from aggregation
- ➥ How to fairly allocate benefits?

PRESENTATION OUTLINE

DIFFERENT VISIONS OF FAIRNESS

Definition (Oxford Dictionary)

Fairness is the quality of treating people equally or in a way that is reasonable.

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Fairness is the quality of treating people equally or in a way that is reasonable.

- A take on fairness is necessarily subjective, as the definition is ambiguous.
- Moreover, are we looking for fair outcomes or for fair processes?
- Mathematic modeling requires a clear definition, leading to a particular model.
- Then we must make a choice which has consequences on the solution.

DIFFERENT VISIONS OF FAIRNESS

- **Egalitarism**: everyone gets the same share.
- **Rawl's theory (minimax)**: we should favor the least well-off.
- **The Need Principle**: first, we satisfy everyone's basic needs, then we can focus on efficiency.
- **Proportional fairness**: derived from Nash bargaining solution in Game theory, the allocation must satisfy some properties.
  - ➥ scale invariance, symmetry, Pareto optimality, independence of irrelevant alternatives

FAIRNESS CONSIDERATIONS: AN EXAMPLE

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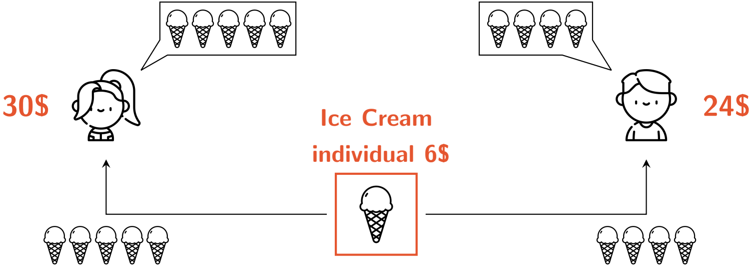
Individualist



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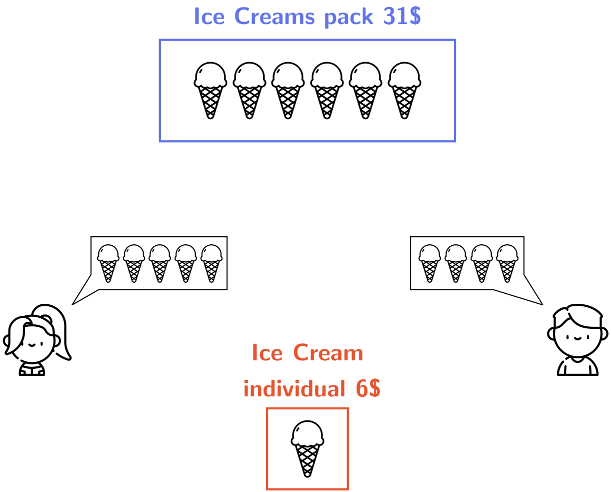
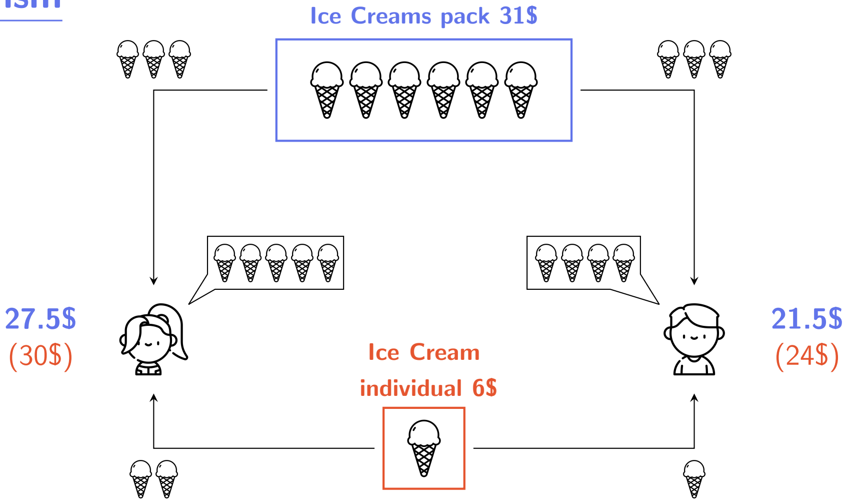


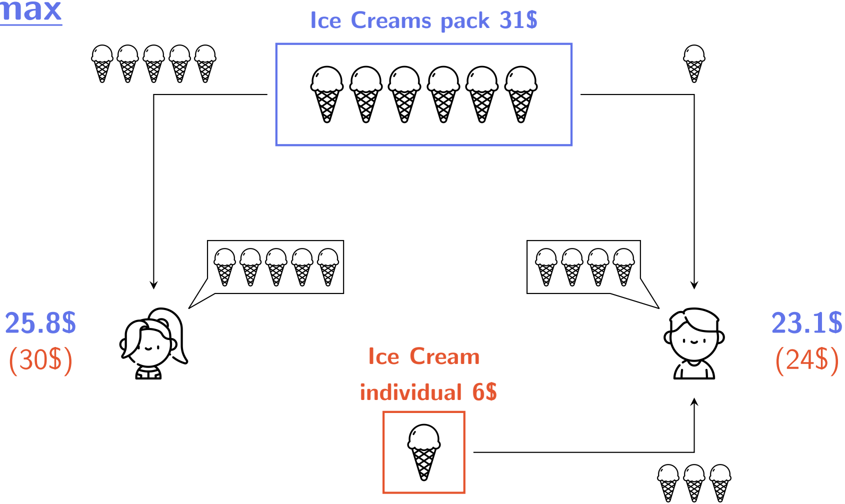
FAIRNESS CONSIDERATIONS: AN EXAMPLE

Egalitarism



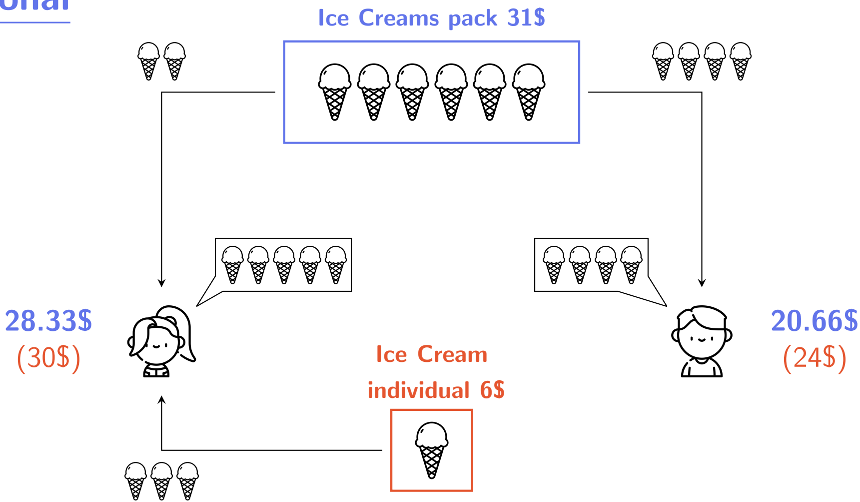
FAIRNESS CONSIDERATIONS: AN EXAMPLE

Minimax



FAIRNESS CONSIDERATIONS: AN EXAMPLE

Proportional



FAIRNESS BY DESIGN

- The literature tackles fairness considerations in various fields.
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- However, we focus on fairness by design: fairness is accommodated in the model.
  - ➥ In *A Guide to Formulating Equity and Fairness in an Optimization Model*, Violet (Xinying) Chen and J. N. Hooker review how to model fairness in an optimization model.

PRESENTATION OUTLINE

TOY EXAMPLE: CONTEXT

Prosumer A_1

- Big energy volume
- Fixed demand

Prosumer A_2

- Smaller volume
- Flexible

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Prosumer A_1

- Big energy volume
- Fixed demand

Prosumer A_2

- Smaller volume
- Flexible

- Balancing market (expensive prices)
- Day-ahead with energy volume requirements (cheap prices)

MODEL FOR ONE PROSUMER

Prosumer model

$$(A_i) := \min_{y^{A_i}, b} \quad f_i(y^{A_i}, b)$$

- y^{A_i} are the control variables (energy purchases) for A_i
- b represents the decision to buy in advance or not
- **Minimize energy costs**

$$f_i(y^{A_i}, b) = \sum_{t \in [T]} p_t^{\mathrm{DA}} q_{t,\mathrm{DA}}^{A_i} + p_t^{\mathrm{B}} q_{t,\mathrm{B}}^{A_i}$$

MODEL FOR ONE PROSUMER

Prosumer model

$$(A_i) := \min_{y^{A_i}, b} \quad f_i(y^{A_i}, b)$$
$$\text{s.t} \quad y^{A_i} \in \mathcal{Y}^{A_i},$$

$$\mathcal{Y}^{A_i} := \begin{cases} \underline{Q_i} \leq q^{A_i}_{t,\mathrm{DA}} + q^{A_i}_{t,\mathrm{B}} \leq \overline{Q_i}, \ t \in [T] & \textbf{bounded load} \\ \sum_{t=1}^{T} (q^{A_i}_{t,\mathrm{DA}} + q^{A_i}_{t,\mathrm{B}}) \geq L^i & \textbf{overall load requirements} \end{cases}$$

MODEL FOR ONE PROSUMER

Prosumer model

$$(A_i) \;:=\; \underset{y^{A_i}, b}{\text{Min}} \quad f_i(y^{A_i}, b)$$
$$\text{s.t} \quad y^{A_i} \in \mathcal{Y}^{A_i},$$
$$b \in \mathcal{B}(y^{A_i}).$$

$$\mathcal{B}(y^{A_i}) = \left\{ \underline{q_{t,\text{DA}}}\, b_t \leq q^{A_i}_{t,\text{DA}} \leq M b_t,\; b_t \in \{0,1\},\; t \in [T] \right\}$$

minimum day-ahead purchases

MODEL FOR A PROSUMER AGGREGATION

Aggregator modeling

$$(A) := \quad \underset{y,b}{\text{Min}} \quad f(y,b)$$
$$\text{s.t} \quad y^{A_i} \in \mathcal{Y}^{A_i} \qquad \forall i$$
$$b \in \mathcal{B}(y)$$

- f is the objective function
- $y := (y^{A_1}, \ldots, y^{A_N})$ are the control variables for all prosumer
-

$$\mathcal{B}(y) = \left\{ \underline{q_{t,\text{DA}}} b_t \leq \sum_{i=1}^{N} q_{t,\text{DA}}^{A_i} \leq M b_t, \ b_t \in \{0,1\}, \ t \in [T] \right\}$$

MODEL FOR A PROSUMER AGGREGATION

Aggregator modeling

$$(A) := \underset{y,b}{\text{Min}} \quad f(y,b)$$
$$\text{s.t} \quad y^{A_i} \in \mathcal{Y}^{A_i} \qquad \forall i$$
$$b \in \mathcal{B}(y)$$

- add constraints $c_{A_i} \leq \overline{c}_{A_i}$

where $c_{A_i} := \sum_{t=1}^{T} c_{A_i,t}$ is the cost of A_i in (A),

and $\overline{c}_{A_i} := \sum_{t=1}^{T} \overline{c}_{A_i,t}$ is the optimal value of (A_i).

We have two challenges with the aggregation :

1. Acceptability

MODEL FOR A PROSUMER AGGREGATION

Aggregator modeling

$$
\begin{aligned}
(A) \;:=\; \quad \underset{y,b}{\text{Min}} \quad & f(y,b) \\
\text{s.t} \quad & y^{A_i} \in \mathcal{Y}^{A_i} \qquad \forall i \\
& b \in \mathcal{B}(y)
\end{aligned}
$$

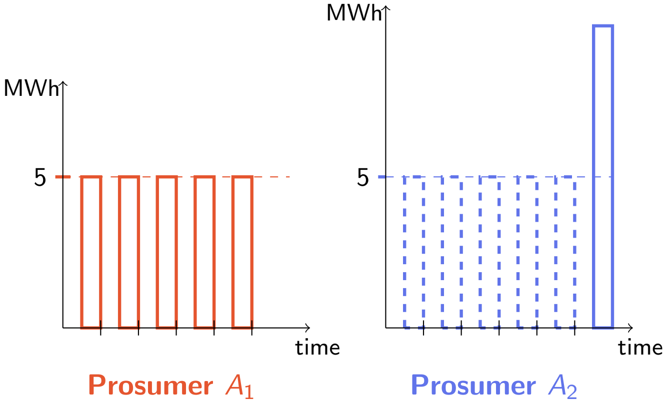
We have two challenges with the aggregation :

1. Acceptability
2. Fairness

- Utilitarian: $f(y) = \sum_{i=1}^{N} c_{A_i}$.
- Minimax proportional: $f(y) := \underset{i \in [\![1,N]\!]}{\text{Max}} \frac{\overline{c}_{A_i} - c_{A_i}}{\overline{c}_{A_i}}$.
- Proportional: $f(y) := \eta \sum_{i=1}^{N} \log(c_{A_i})$.

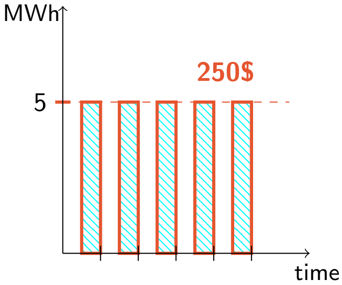
TOY EXAMPLE: DATA

Day-ahead ($/MWh)	2	5	12	2	5	$q_{min}^{DA} = 7MWh$
Balancing ($/MWh)	5	10	20	5	10	$q_{min}^{B} = 0MWh$

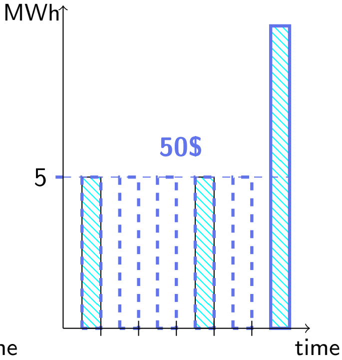


TOY EXAMPLE: INDIVIDUALIST

Day-ahead ($/MWh)	2	5	12	2	5	$q_{min}^{DA} = 7MWh$
Balancing ($/MWh)	5	10	20	5	10	$q_{min}^{B} = 0MWh$



Prosumer A_1

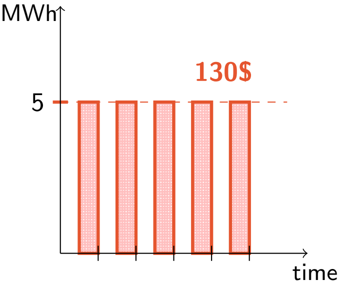


Prosumer A_2

	c_{A_1}	c_{A_2}	$c_{A_1} + c_{A_2}$
Individualist	250	50	300
Utilitarian			
Acceptable Utilitarian			
Proportional			
Minimax proportional			

TOY EXAMPLE: UTILITARIAN

Day-ahead (\$/MWh)	2	5	12	2	5	$q^{DA}_{min} = 7MWh$
Balancing (\$/MWh)	5	10	20	5	10	$q^{B}_{min} = 0MWh$



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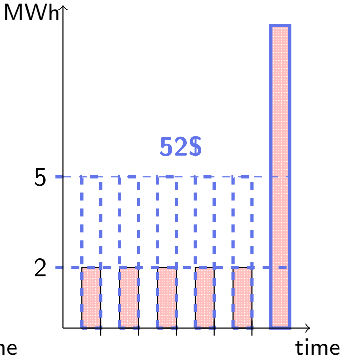


Prosumer A_2

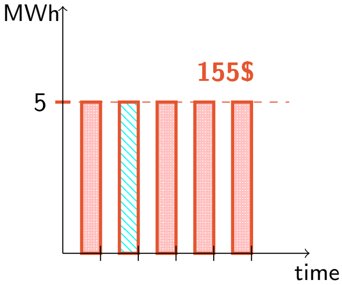
	c_{A_1}	c_{A_2}	$c_{A_1} + c_{A_2}$
Individualist	250	50	300
Utilitarian	130	52	182
Acceptable Utilitarian			
Proportional			
Minimax proportional			

TOY EXAMPLE: ACCEPTABLE UTILITARIAN

Day-ahead ($/MWh)	2	5	12	2	5
Balancing ($/MWh)	5	10	20	5	10

$q^{DA}_{min} = 7MWh$

$q^{B}_{min} = 0MWh$



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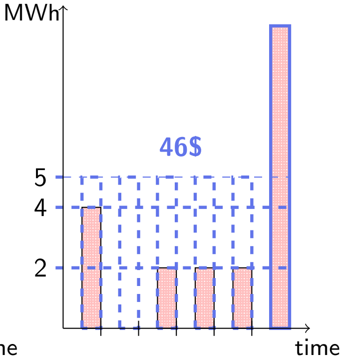

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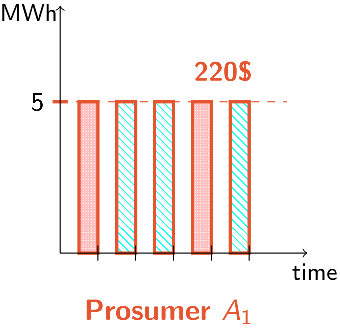
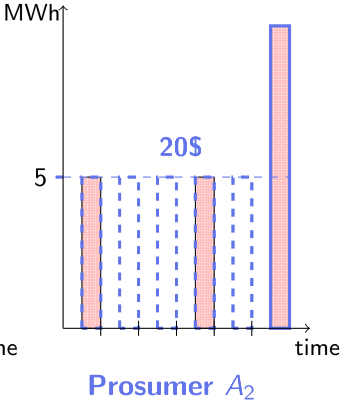
Acceptable Utilitarian	155	46	201
Proportional			
Minimax proportional			

TOY EXAMPLE: PROPORTIONAL

Day-ahead ($/MWh)	2	5	12	2	5	$q_{min}^{DA} = 7MWh$
Balancing ($/MWh)	5	10	20	5	10	$q_{min}^{B} = 0MWh$

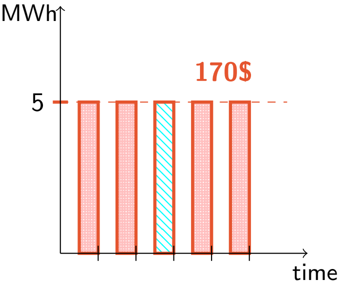




	c_{A_1}	c_{A_2}	$c_{A_1} + c_{A_2}$
Individualist	250	50	300
Utilitarian	130	52	182
Acceptable Utilitarian	155	46	201
Proportional	220	20	240
Minimax proportional			

TOY EXAMPLE: MINIMAX PROPORTIONAL

Day-ahead ($/MWh)	2	5	12	2	5	$q_{min}^{DA} = 7MWh$
Balancing ($/MWh)	5	10	20	5	10	$q_{min}^{B} = 0MWh$



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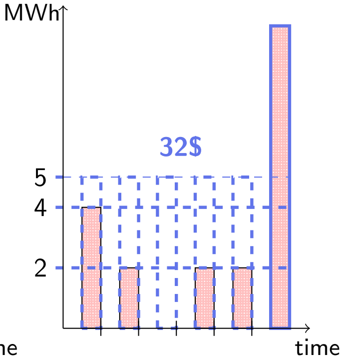

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Minimax proportional	170	32	202

CONCLUSIONS FROM THE ILLUSTRATION

- The utilitarian is the most efficient approach, but it can lead to unacceptable solutions for some prosumers.
- The proportional approach coming from a theory of bargaining favors smaller prosumers.
- The minimax approach derived from Rawl's theory on fairness: the solution finds a balance between both prosumers.

PRESENTATION OUTLINE

EXTENTION: THE DYNAMIC CASE

With long term problems in mind, we extend the previous model to the dynamic case.

We adapt acceptability constraint so that prosumers have no incentive to leave the aggregation between stages.

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We adapt acceptability constraint so that prosumers have no incentive to leave the aggregation between stages.

- Average Acceptability:

$$\sum_{t=1}^{T} c_{A_i,t} \leq \sum_{t=1}^{T} \overline{c}_{A_i,t}, \qquad \forall i$$

- Progressive Acceptability:

$$\sum_{\tau=1}^{t} c_{A_i,\tau} \leq \sum_{\tau=1}^{t} \overline{c}_{A_i,\tau}, \qquad \forall i, \forall t$$

- Stage-wise Acceptability:

$$c_{A_i,t} \leq \overline{c}_{A_i,t}, \qquad \forall i, \forall t$$

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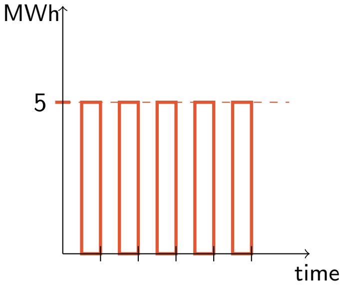

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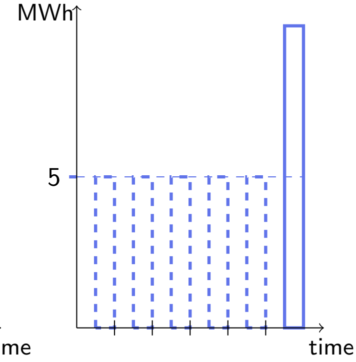

Prosumer A_2

We try those extensions of acceptability with the utilitarian objective.

TOY EXAMPLE: AVERAGE ACCEPTABILITY

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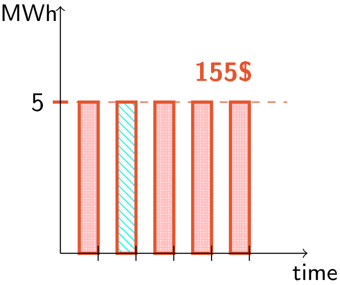

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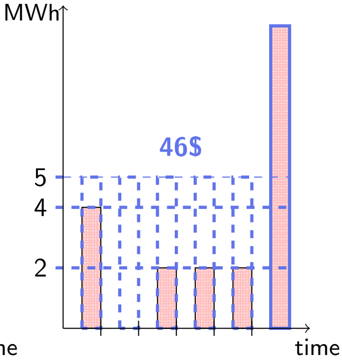

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Average Acceptability	155	46	201
Progressive Acceptability			
Stage-wise Acceptability			

TOY EXAMPLE: PROGRESSIVE ACCEPTABILITY

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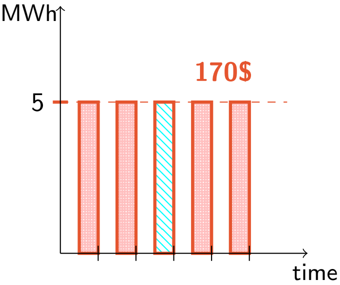
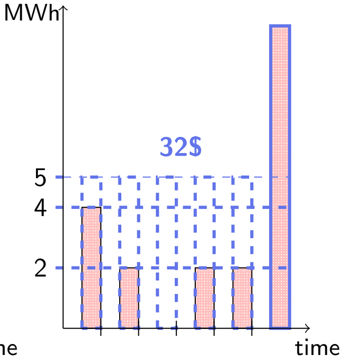


Prosumer A_1



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Stage-wise Acceptability			

TOY EXAMPLE: STAGE-WISE ACCEPTABILITY

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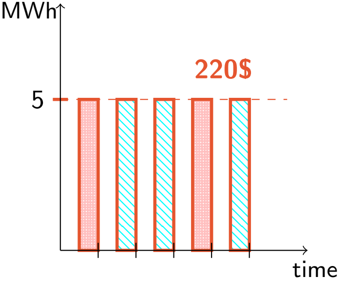
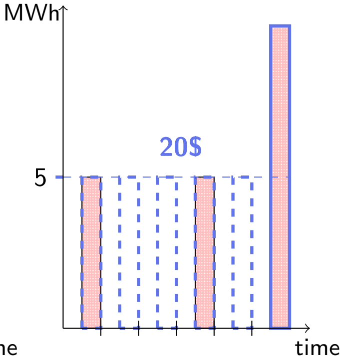


Prosumer A_1



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STOCHASTIC EXTENSION

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STOCHASTIC EXTENSION

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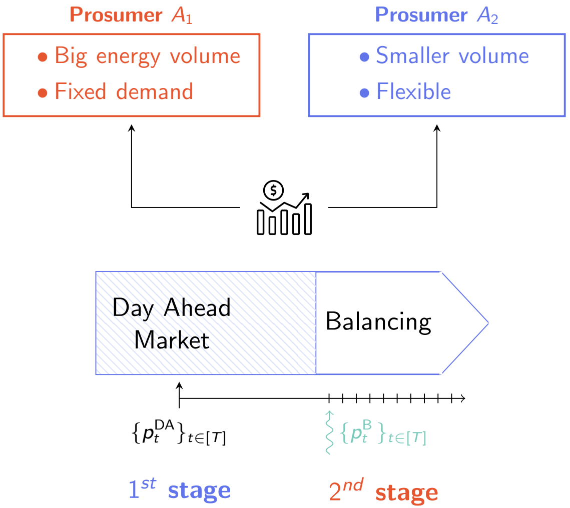
- In a 2 stage setting, we have:
  1. first-stage variables: day-ahead purchases $\{b_t, q^i_{t,\mathrm{DA}}\}_{t\in[T],i\in[N]}$
  2. recourse variables: balancing purchases $\{q^i_{t,\mathrm{B}}\}_{t\in[T],i\in[N]}$



STOCHASTIC EXTENSION

Considering uncertainties
raises 3 challenges:

STOCHASTIC EXTENSION

Considering uncertainties raises 3 challenges:

1. How to handle the uncertainties?

- Optimize expected costs:

$$\underset{q_{DA}, b, q_B}{\text{Min}} \quad \mathbb{E}_\omega \left[f(q_{DA}, b, q_B, \omega) \right]$$

- Optimize the worst case:

$$\underset{q_{DA}, b, q_B}{\text{Min}} \quad \underset{\omega \in \Omega}{\text{Max}} \left\{ f(q_{DA}, b, q_B, \omega) \right\}$$

- Optimize a risk measure:

$$\underset{q_{,\text{DA}}, b, q_{,\text{B}}}{\text{Min}} \quad \rho_\omega \left\{ f(q_{,\text{DA}}, b, q_{,\text{B}}, \omega) \right\}$$

STOCHASTIC EXTENSION

Considering uncertainties raises 3 challenges:

1. How to handle the uncertainties?
2. How to accommodate fairness into the model?

- Utilitarian:

$$f(y) = \sum_{i=1}^{N} c_{A_i}$$

- Minimax proportional:

$$f(y) := \operatorname*{Max}_{i \in [\![1,N]\!]} \frac{\overline{c}_{A_i} - c_{A_i}}{\overline{c}_{A_i}}.$$

STOCHASTIC EXTENSION

Considering uncertainties raises 3 challenges:

1. How to handle the uncertainties?
2. How to accommodate fairness into the model?
3. How to adapt the acceptability constraints?

ACCEPTABILITY CONSTRAINTS

- Expected Acceptability:

$$\boldsymbol{c}_{\boldsymbol{A}_i} \preceq_{\mathbb{E}} \overline{\boldsymbol{c}}_{\boldsymbol{A}_i} \iff \mathbb{E}[\boldsymbol{c}_{\boldsymbol{A}_i}] \leq \mathbb{E}[\overline{\boldsymbol{c}}_{\boldsymbol{A}_i}] \qquad \forall i$$

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- Almost sure Acceptability:

$$\boldsymbol{c_{A_i}} \preceq_{as} \boldsymbol{\overline{c}_{A_i}} \iff c_{A_i,\omega} \leq \overline{c}_{A_i,\omega}, \quad \forall \omega \qquad \forall i$$

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- 1^{st}order Acceptability:

$$\boldsymbol{c_{A_i}} \preceq_{(1)} \boldsymbol{\overline{c}_{A_i}} \iff \mathbb{P}(\boldsymbol{\overline{c}_{A_i}} \leq \eta) \leq \mathbb{P}(\boldsymbol{c_{A_i}} \leq \eta), \ \forall \eta \in \mathbb{R} \qquad \forall i$$

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- Increasing convex Acceptability:

$$\boldsymbol{c_{A_i}} \preceq_{ic} \boldsymbol{\overline{c}_{A_i}} \iff \mathbb{E}\left[(\boldsymbol{c_{A_i}} - \eta)^+\right] \leq \mathbb{E}\left[(\boldsymbol{\overline{c}_{A_i}} - \eta)^+\right], \ \forall \eta \in \mathbb{R} \qquad \forall i$$

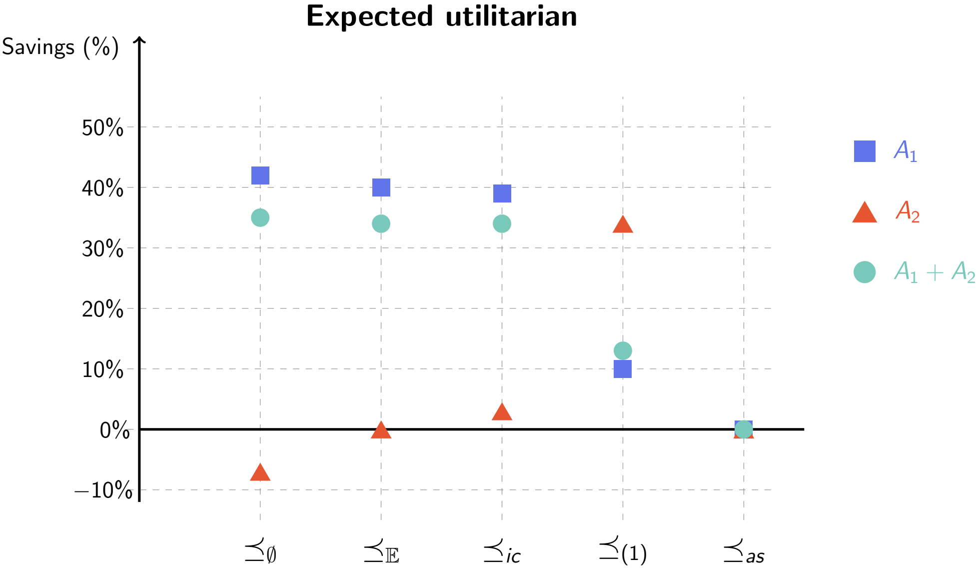
TOY EXAMPLE

With a similar example as the one presented in the deterministic case, we draw 100 scenarios for the balancing prices.

We test the small example with:

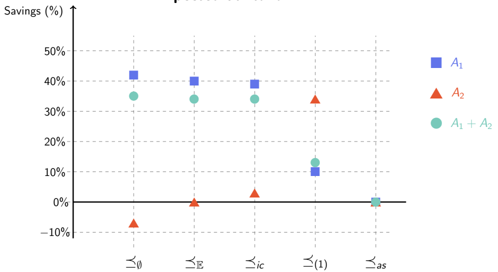
- different objective functions:
  - expected utilitarian costs
  - expected minimax costs
  - robust utilitarian costs
  - robust minimax costs
- the different acceptability constraints

TOY EXAMPLE: EXPECTED UTILITARIAN

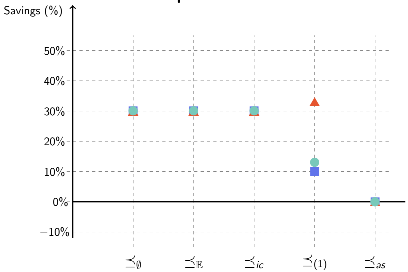


TOY EXAMPLE: ALL RESULTS

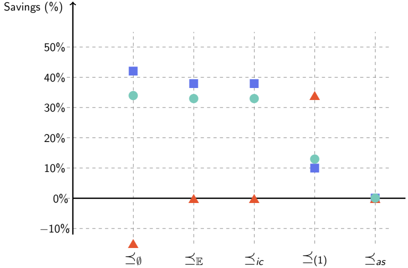
Expected utilitarian



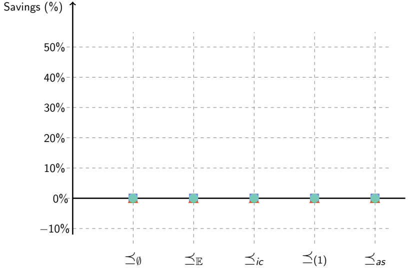
Expected minimax



Robust utilitarian



Robust minimax



PRESENTATION OUTLINE

IN A NUTSHELL

- Aggregation for prosumers saves costs, the question is how to fairly allocate them?

- We present two challenges in the problem:

  1. acceptability modeled through constraints;
  2. fair allocation modeled through the objective function.

- We extend fairness to dynamic and stochastic frameworks:

  - fairness can be derived to take into consideration cost distribution and risk aversion.