ETH zürich

Multi-agent maintenance scheduling based on the coordination between central operator and decentralized producers in an electricity market

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Outline

- Introduction
  - What is maintenance?
  - Types of maintenance
  - Smart grid system and maintenance
  - Solution methods
- Problem formulation and the proposed negotiation method
  - System’s modelling
  - Negotiation algorithm
- Simulation results
- Summary and future work

What is maintenance?

Maintenance is defined as engineering actions which are necessary for retaining or restoring an equipment, machine or system to the specified condition to achieve its maximum useful life.

Type of maintenance

Preventive maintenance

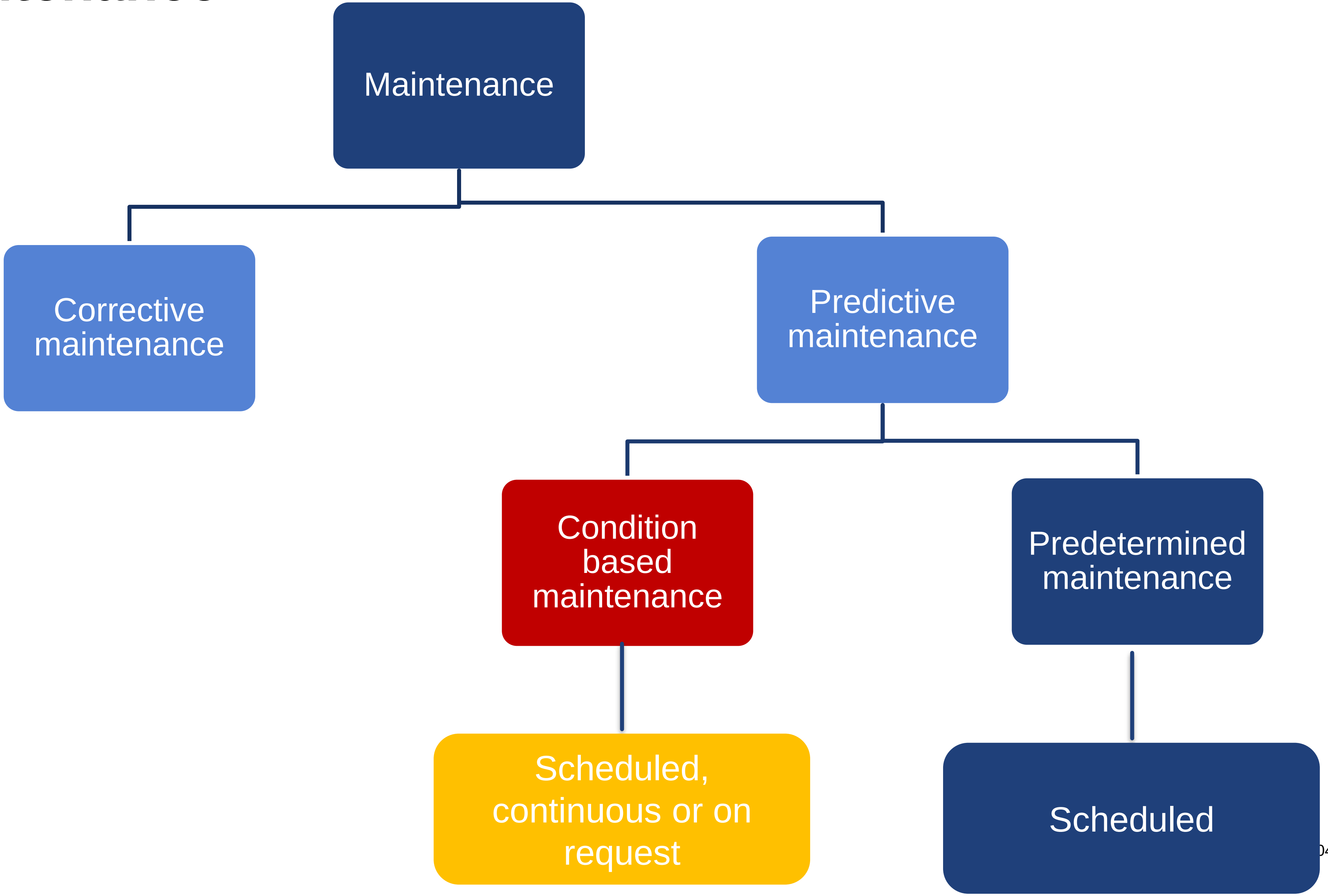
before a failure has occurred

VS

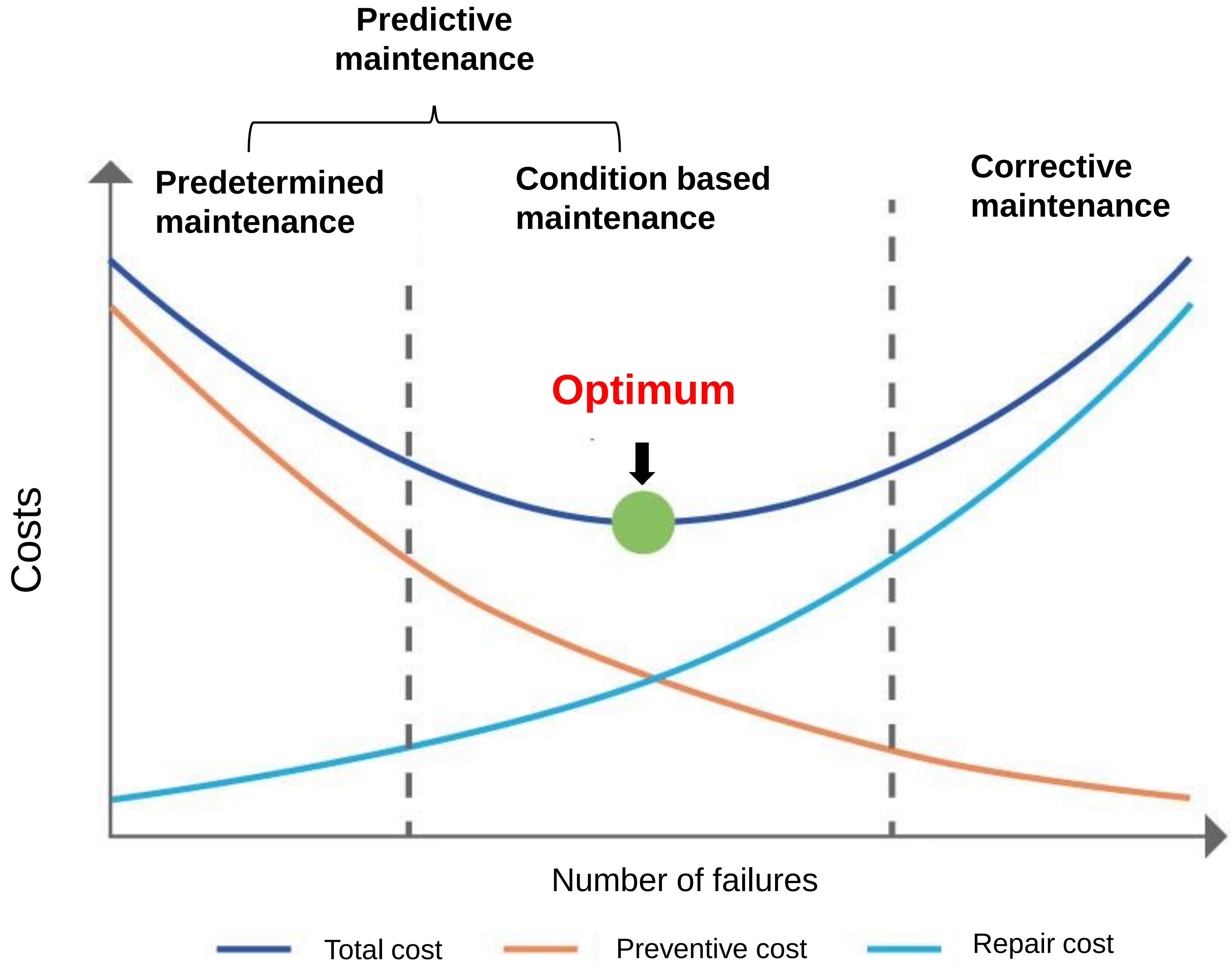
Corrective maintenance

after a failure has occurred

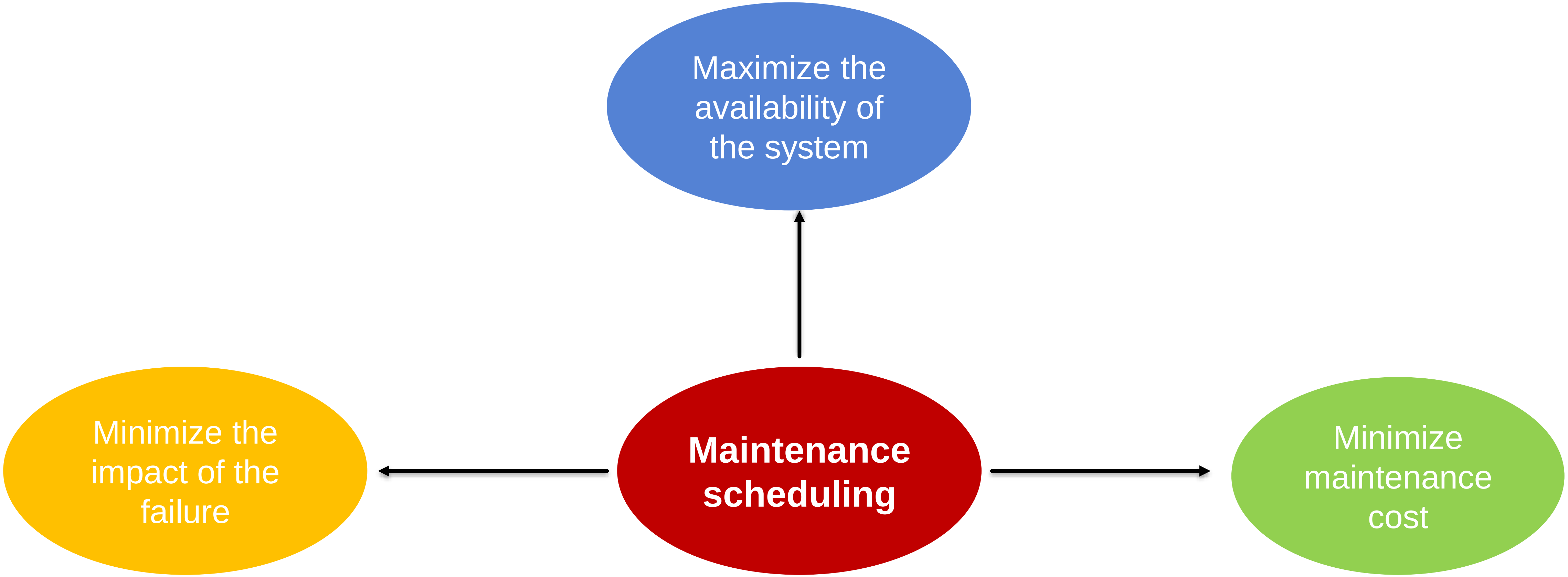
Type of maintenance



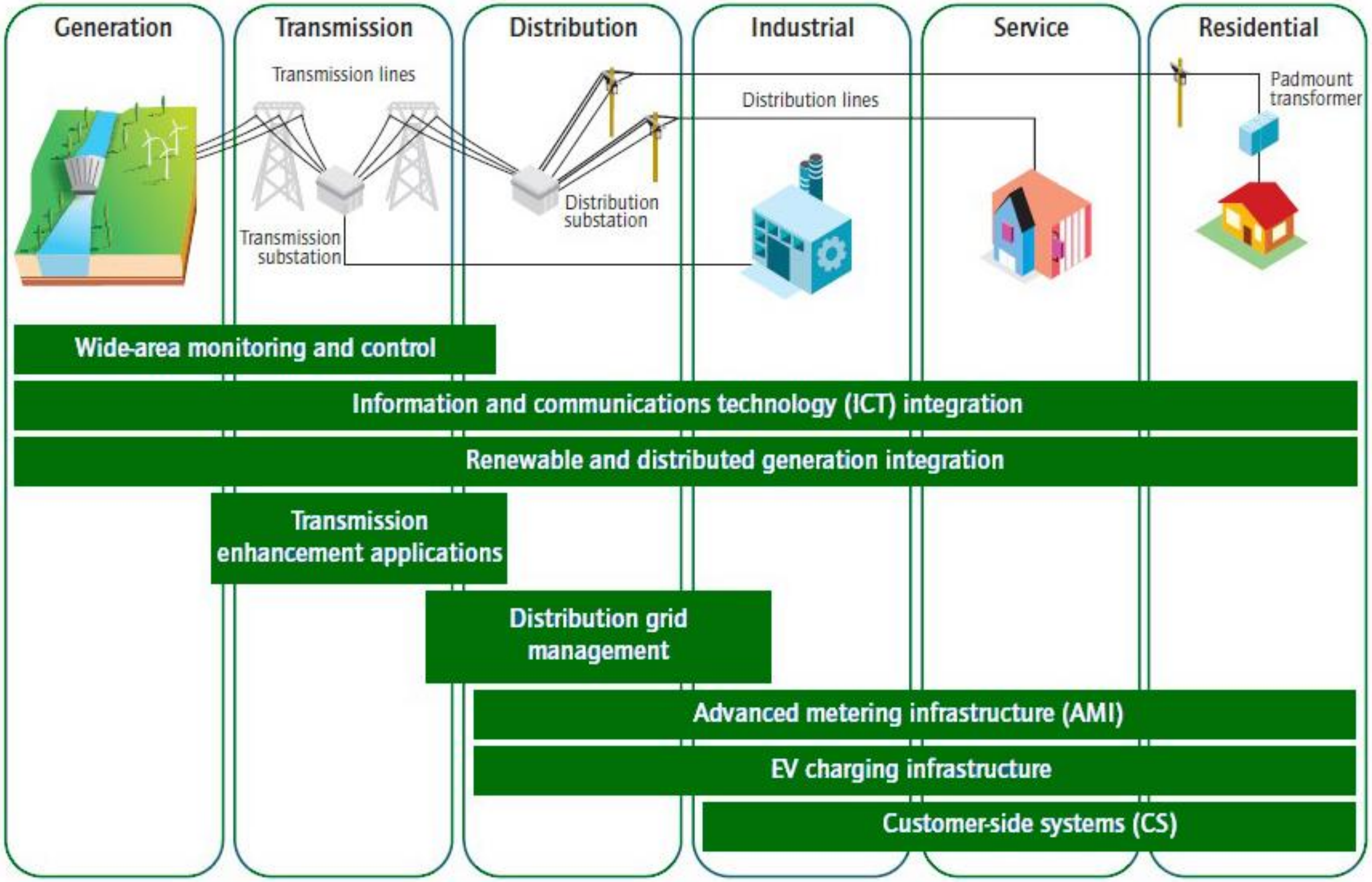
Cost of maintenance



Maintenance scheduling objective

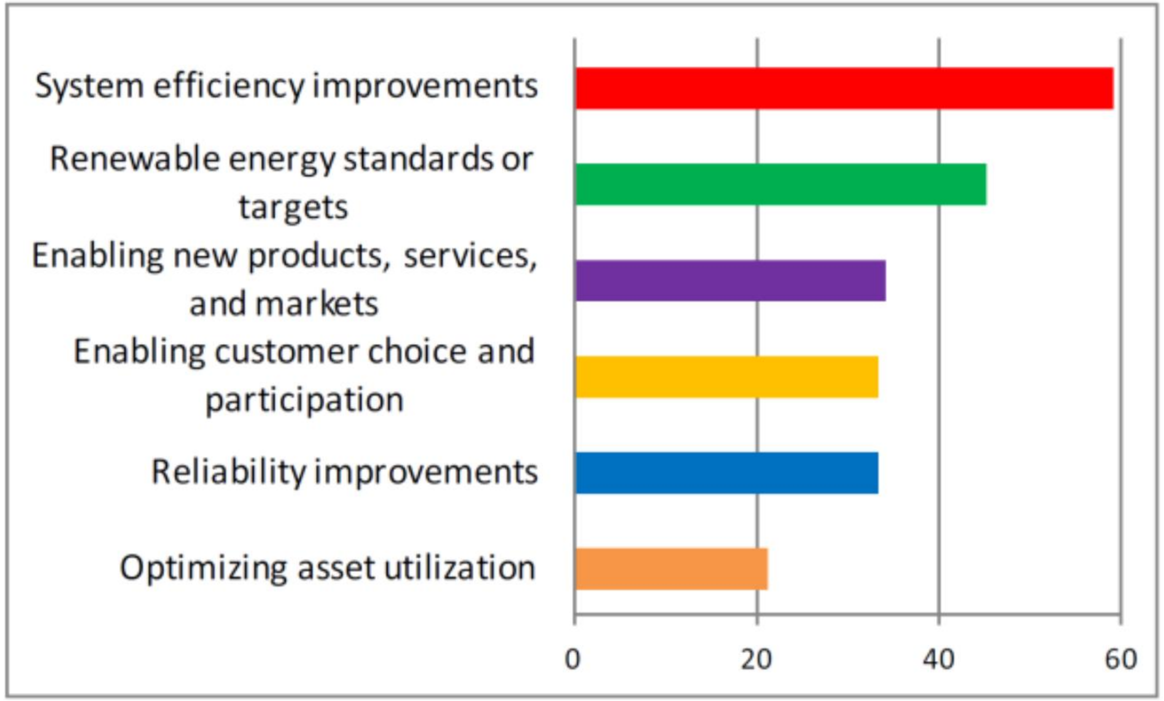


Smart grid technology and electrical market

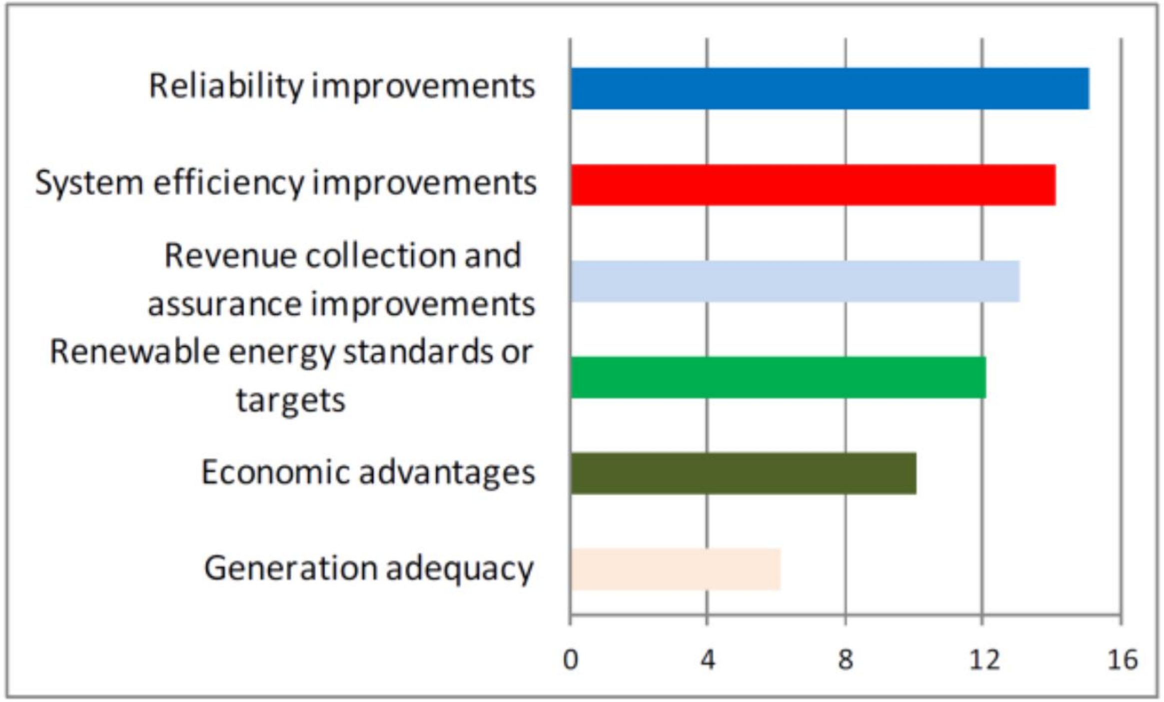


Comparison of the developed and developing countries

Developed Countries



Developing Countries



Generation maintenance challenges

- Maximize the system’s reliability
- Consider the system’s constraints
- Fulfillment of the energy demand

→ **Maintenance scheduling**

Solution methods for generation maintenance scheduling

- **Centralized optimization method**

  Very high computational cost

  Need the complete information of the system

- **Decentralized optimization method (Agent's based modelling)**

  Need the coordination procedure to fulfill the load

- **Solution: Decentralized method using negotiation algorithm**

Framework of the proposed negotiation mechanism

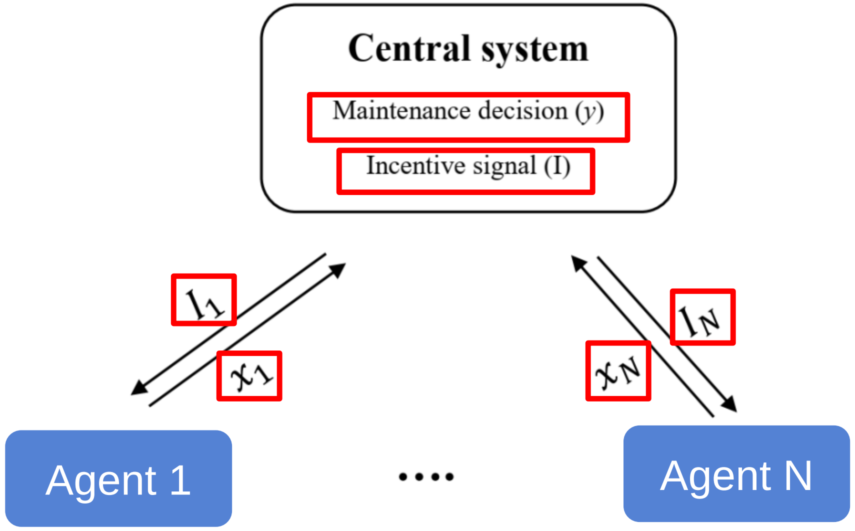
1) Each agent decides on the maintenance time slot

2) They submit their decisions (bids) to the central system (x)

3) The central coordinating system is responsible for the reliability at the network level and load fulfillment

4) In the case that the load cannot be fully supplied if all the decisions of the agents are accepted, the central system accepts the bids of the agents that are close to the failure time and rejects other bids (y)

5) The agents will fail if no maintenance is, hence the central system encourages them to change their decisions by providing an incentive signal *(I)*



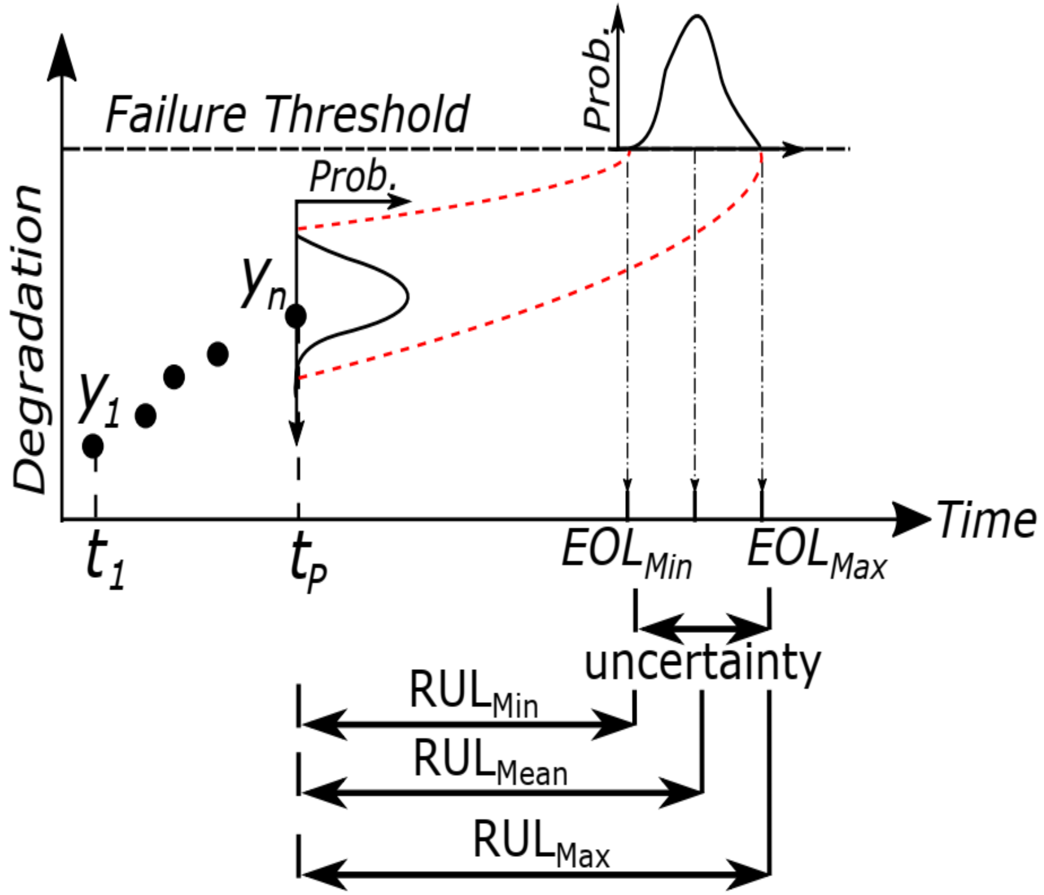
What matters in the negotiation solution?

- Agents' predictive maintenance modelling
- Modelling the central system's objective function to fulfill the load
- Incentive signal function

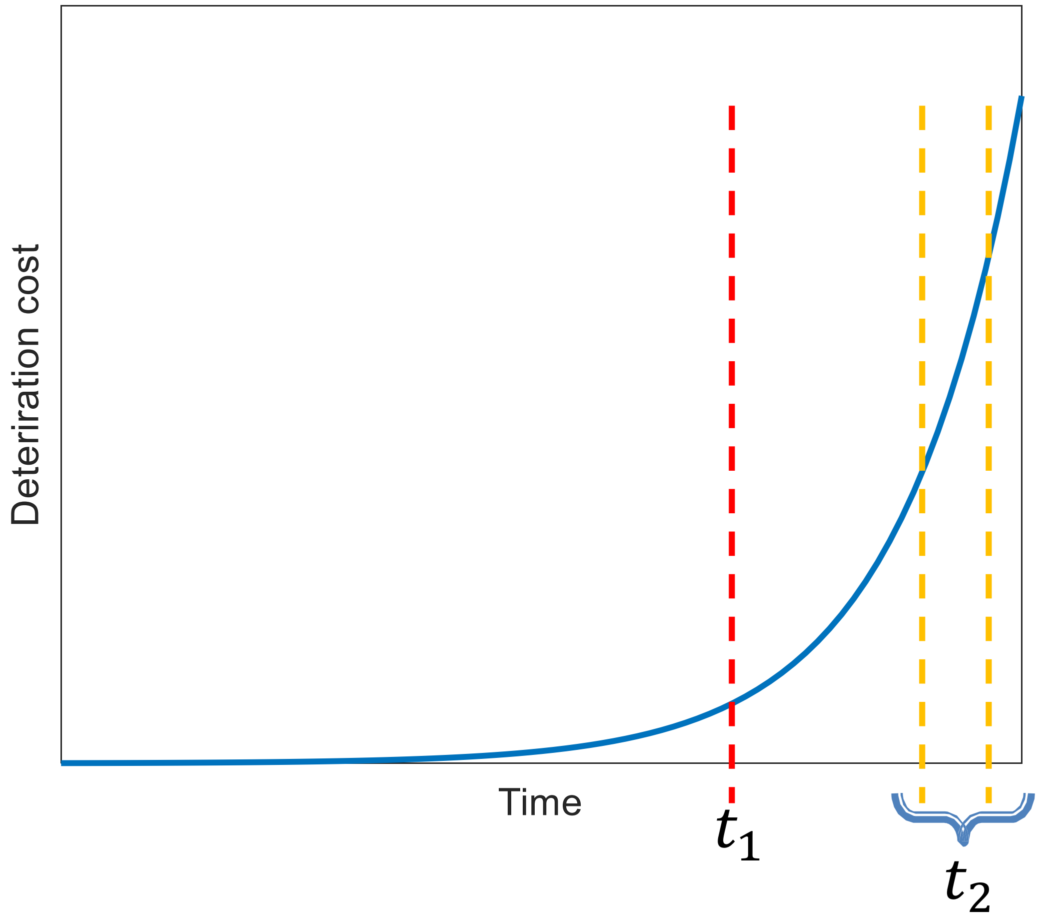
Remaining useful life (RUL)

RUL is the number of remaining time at the specific operation time that a system can operate without a failure

- Deterministic RUL value
- RUL values with confidence intervals RUL$\pm C$
- Probability density function



Agent deterioration cost



$$D_c = E\{\alpha_c e^{(t-t_1)}(sign(t-t_1) - sign(t-t_2)\}$$

Agents' objective function

- Agent expected reward function $\mathbb{E}\Big\{(1-x_n(t))\Big(\frac{1}{2}(1-\text{sign}(t-t_{2,n,k}))\Big)\ (P(t)q_n(t)-C_n(t))\Big\}$

- Agent deterioration cost $\mathbb{E}\Big\{(1-x_n(t))\alpha_n e^{(t-t_{1,n,k})}\Big(\text{sign}(t-t_{1,n,k})\ -\text{sign}(t-t_{2,n,k})\Big)\Big\}$

$$\max_{x_n} \sum_{k\in\mathcal{K}_n}\sum_{t\in\mathcal{T}_k}\mathbb{E}\Big\{(1-x_n(t))\Big(\frac{1}{2}(1-\text{sign}(t-t_{2,n,k}))(P(t)q_n(t)-C_n(t))$$

$$-\alpha_n e^{(t-t_{1,n,k})}(\text{sign}\,(t-t_{1,n,k})-\text{sign}(t-t_{2,n,k}))\Big)\Big\}$$

s.t $\mathrm{C}_1: \quad x_n(t)\in\{0,1\}, \quad t\in\mathcal{T}_k, k\in\mathcal{K}_n,$ → Maintenance decision

$\mathrm{C}_2: \quad x_n(t+1)-x_n(t)\le x_n(t+r_{n,k}-1), \quad t\in\mathcal{T}_k, k\in\mathcal{K}_n,$ → Maintenance repair time

$\mathrm{C}_3: \quad 1\le\sum_{t\in\mathcal{T}_k}x_n(t)\le r_{n,k}, \quad k\in\{2,\cdots,\mathcal{K}_n\},$ → Perform maintenance

Agents' objective function

$$\max_{x_n} \sum_{k\in\mathcal{K}_n} \sum_{t\in\mathcal{T}_k} \sum_{s\in\mathcal{S}_{n,k}} \Big\{ (1 - x_n(t)) \Big(\frac{\pi_{n,k,s}}{2} (1 - \mathrm{sign}(t - t_{2,n,k,s})) (P(t) q_n(t) - C_n(t))$$

$$- \alpha_n e^{(t - t_{1,n,k})} \big(\mathrm{sign}\,(t - t_{1,n,k}) - \pi_{n,k,s}\,\mathrm{sign}(t - t_{2,n,k,s}) \big) \Big) \Big\},$$

$$\text{s.t.} \quad \mathrm{C}_1, \quad \mathrm{C}_2, \quad \mathrm{C}_3.$$

Integer linear programming

Central system objective

- Maximizing the reliability → The priority is to accept the decision of the agents that are close to t_2
- Fully supplying the power demand

$$\max_{y,q,\theta} \sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}_n} \sum_{t\in\mathcal{T}_k} \sum_{s\in\mathcal{S}_{n,k}} \frac{\pi_{n,k,s}}{t_{2,n,k,s}-t+\epsilon} y_n(t),$$

s.t.

$$\mathrm{A}_1: \sum_{n\in\mathcal{N}_j} (1-y_n(t))q_n(t) - \sum_{r\in\Gamma_j} B_{j,r}(\theta_j(t)-\theta_r(t)) \geq L_j(t), \quad j\in\mathcal{J}, \quad t\in\{1,\cdots,T\},$$
→ Supplying power demand

$$\mathrm{A}_2: y_n(t)\in\{0,1\},$$
→ Maintenance decision

$$\mathrm{A}_3: y_n(t)\leq x_n(t),$$
→ Accept or reject the bid

$$\mathrm{A}_4: 0\leq q_n(t)\leq q_n^{\max}, \quad t\in\{1,\cdots,T\}$$
→ Maximum generation

$$\mathrm{A}_5: -F_{j,r}\leq B_{j,r}(\theta_j(t)-\theta_r(t))\leq F_{j,r}, \quad r\in\Gamma_j, j\in\mathcal{J}, t\in\{1,\cdots,T\}.$$
→ Line capacity limit

$$\max_{y,q,\theta} \sum_{n\in\mathcal{N}} \sum_{k\in\mathcal{K}_n} \sum_{t\in\mathcal{T}_k} \sum_{s\in\mathcal{S}_{n,k}} \frac{\pi_{n,k,s}}{t_{2,n,k,s} - t + \epsilon} y_n(t),$$

$$\text{s.t.} \quad \text{A}_1 : \sum_{n\in\mathcal{N}_j} (1 - y_n(t))q_n(t) - \sum_{r\in\Gamma_j} B_{j,r}(\theta_j(t) - \theta_r(t)) \geq L_j(t), \quad j \in \mathcal{J}, \quad t \in \{1, \cdots, T\},$$

$$\text{A}_2 : \quad y_n(t) \in \{0, 1\},$$

$$\text{A}_3 : \quad y_n(t) \leq x_n(t),$$

$$\text{A}_4 : 0 \leq q_n(t) \leq q_n^{\max}, \quad t \in \{1, \cdots, T\}$$

$$\text{A}_5 : -F_{j,r} \leq B_{j,r}(\theta_j(t) - \theta_r(t)) \leq F_{j,r}, \quad r \in \Gamma_j, j \in \mathcal{J}, t \in \{1, \cdots, T\}.$$

→ Nonlinear programming

Big M

$$Z_n(t) = (1 - y_n(t))q_n(t),$$

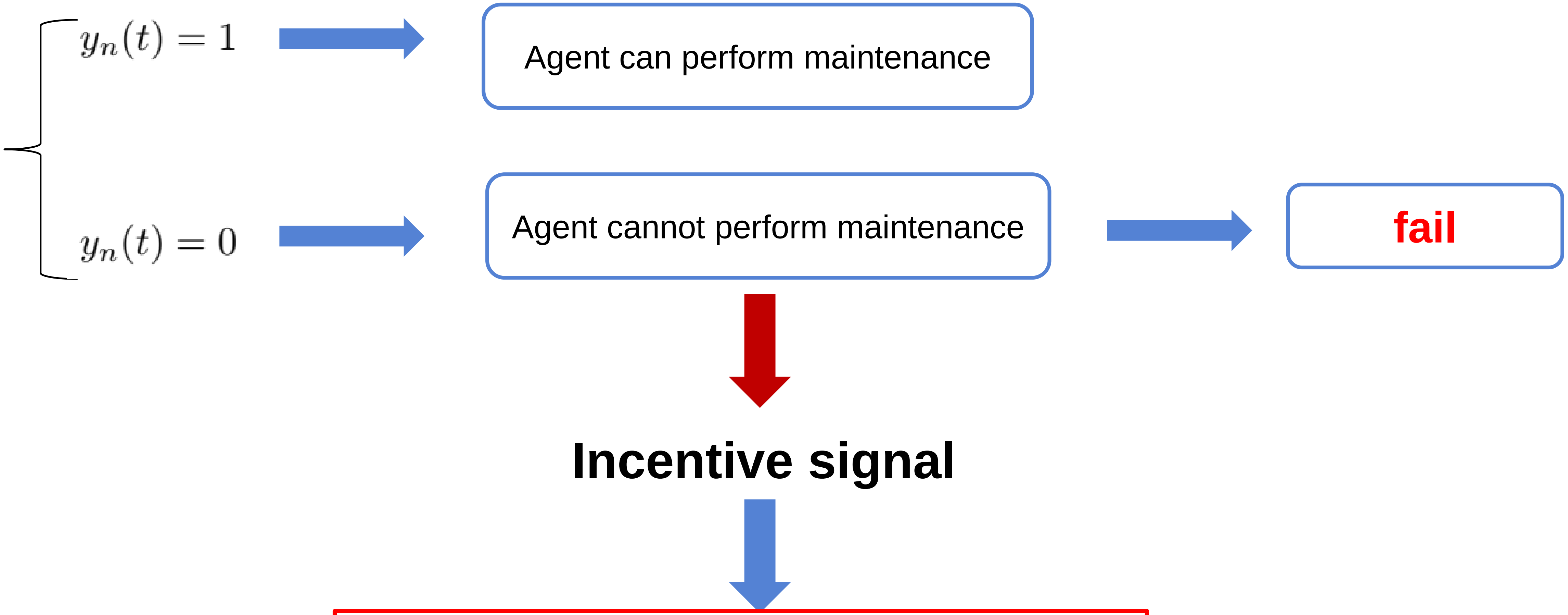
$$0 \leq Z_n(t) \leq (1 - y_n(t))M$$

$$Z_n(t) \geq q_n(t) - (1 - (1 - y_n(t)))M$$

$$Z_n(t) \leq q_n(t) + (1 - (1 - y_n(t)))M,$$

→ **Mixed-integer linear programming**

Coordination procedure using an incentive signal



$$I_n^i(t) = \gamma_n x_n^i(t)\,\mathrm{sign}\left(\sum_{o=1}^{i-1}\left(y_n^o(t) - x_n^o(t)\right)\right),$$

Agent objective at iteration i of the negotiation algorithm

$$\max_{x_n^i} \sum_{k\in\mathcal{K}_n} \sum_{t\in\mathcal{T}_k} \sum_{s\in\mathcal{S}_{n,k}} \Big\{ \big(1 - x_n^i(t)\big)\Big(\frac{\pi_{n,k,s}}{2}\big(1-\mathrm{sign}(t - t_{2,n,k,s})\big)\big(P(t)q_n(t) - C_n(t)\big)$$

$$- \alpha_n e^{(t-t_{1,n,k})}\big(\mathrm{sign}\,(t - t_{1,n,k}) - \pi_{n,k,s}\,\mathrm{sign}(t - t_{2,n,k,s})\big)\Big)\Big\} + \sum_{t=1}^{T} I_n^i(t),$$

$$\text{s.t.} \quad x_n^i(t) \in \{0,1\}, \quad t \in \{1,\cdots,T\},$$

$$x_n^i(t+1) - x_n^i(t) \le x_n^i(t + r_n(k) - 1), \quad t \in \{1,\cdots,T\}, \quad \mathcal{K}_n = \{1,\cdots,K_n\},$$

$$1 \le \sum_{t=t_{1,n}(k)}^{t_{2,n,k}} x_n^i(t) \le r_n(k), \quad \mathcal{K}_n = \{1,\cdots,K_n\},$$

Negotiation algorithm

Algorithm 1 Negotiation algorithm for maintenance decision

1: **Input**: $x_n^0(t) = 0, \quad y_n^0(t) = 0, n \in \mathcal{N}, t = \{1, \cdots, T\}$.

Iterate:

2: For $n \in \mathcal{N}$ repeat until convergence:

3: Obtain $x_n^i(t)$

4: Obtain $y_n^i(t)$

5: If $y_n^i(t) \neq x_n^i(t)$, $t = \{1, \cdots, T\}$, calculate incentive signal

6: $i \leftarrow i + 1$.

Rational of the proposed incentive signal

- Convergence of negotiation algorithm
- Budget balance
- Individual rationality

Negotiation algorithm convergence

Assumption 1. *We assume that the repair time* $(r_n(k), n \in \mathcal{N}, k \in \mathcal{K}_n)$ *is sufficiently small with respect to* $(t_{2,n,k} - t_{1,n,k}, n \in \mathcal{N}, k \in \mathcal{K}_n)$. *As in the worst case where* $t_{1,n,k}$ *and* $t_{2,n,k}$ *are equal for all the agents we have:*

$$t_{2,n,k} - t_{1,n,k} \geq N \max_{n \in \mathcal{N}} r_{n,k}.$$

Assumption 2. *We assume that at each time one agent can perform maintenance while the power demand is satisfied. In other words, if agent* m *in* $n \in \mathcal{N}$ *decides to perform maintenance at time* $t \in \{1, \cdots, T\}$, *we have*

$$\sum_{n \in \mathcal{N}, n \neq m} q_n^{\max} \geq L(t).$$

Negotiation algorithm convergence

Lemma 1. *Consider $x_n^i(t)$ and $y_n^i(t)$ as the maintenance decision of agent n and the central system at time t and iteration i of the algorithm. In the case that $x_n^i(t)$ is not equivalent to $y_n^i(t)$, $x_n^{i+1}(t)$ will not equal to $x_n^i(t)$ if we have:*

$$\gamma_n \geq \max\Big(0, \max_{t,k} \sum_{s\in\mathcal{S}_{n,k}} \Big\{\Big(-\frac{\pi_{n,k,s}}{2}(1-\operatorname{sign}(t-t_{2,n,k,s}))\big(P(t)q_n(t)-C_n(t)\big) + \alpha_n e^{(t-t_{1,n,k})}\big(\operatorname{sign}(t-t_{1,n,k})-\pi_{n,k,s}\operatorname{sign}(t-t_{2,n,k,s})\big)\Big)\Big\}\Big), \quad n\in\mathcal{N}.$$

Budget balance

The proposed incentive signal is budget balanced if the amount of money that the central system has to pay or receive from the negotiating agents would be equal to zero

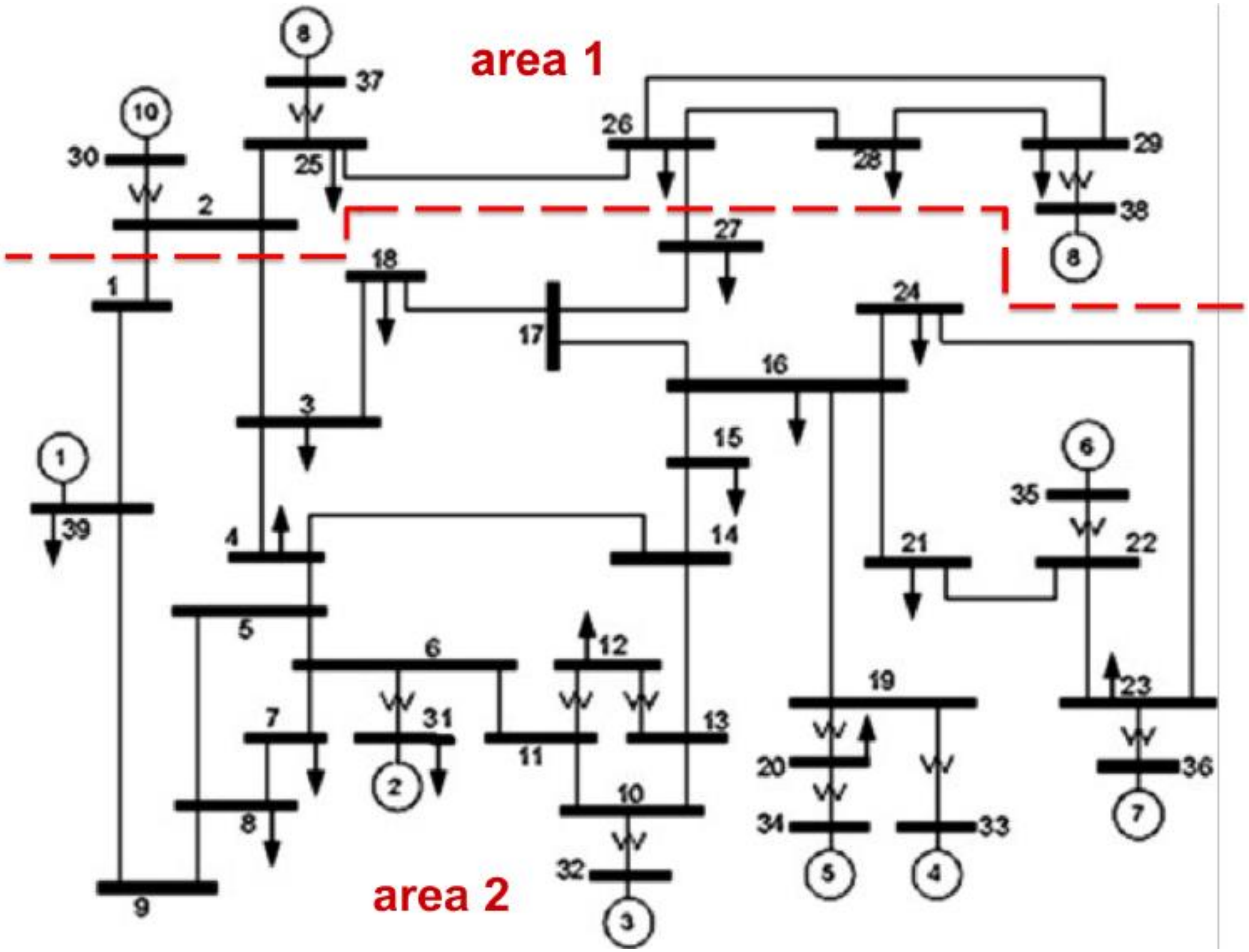
If the sum of the incentive signal given to the agents is less than zero then the mechanism is weak budget balance.

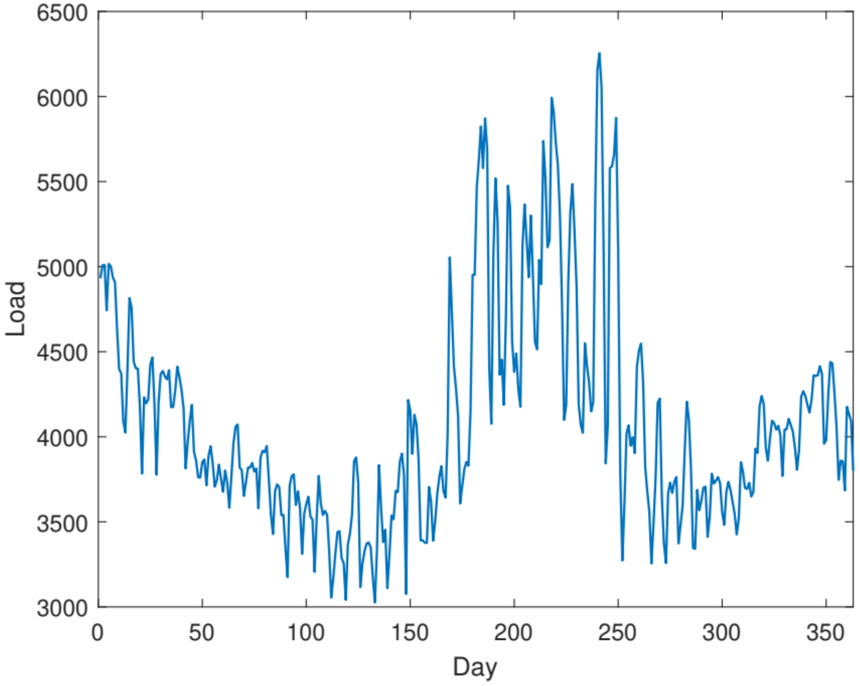
$$\sum_{n=1}^{N} I_n^i(t) < 0.$$

$$I_n^i(t) = \gamma_n x_n^i(t)\,\mathrm{sign}\left(\sum_{o=1}^{i-1}\left(y_n^o(t) - x_n^o(t)\right)\right) \xrightarrow{\;y_n^i(t) \le x_n^i(t)\;} I_n^i(t) \le 0 \longrightarrow$$

Weak Budget balance

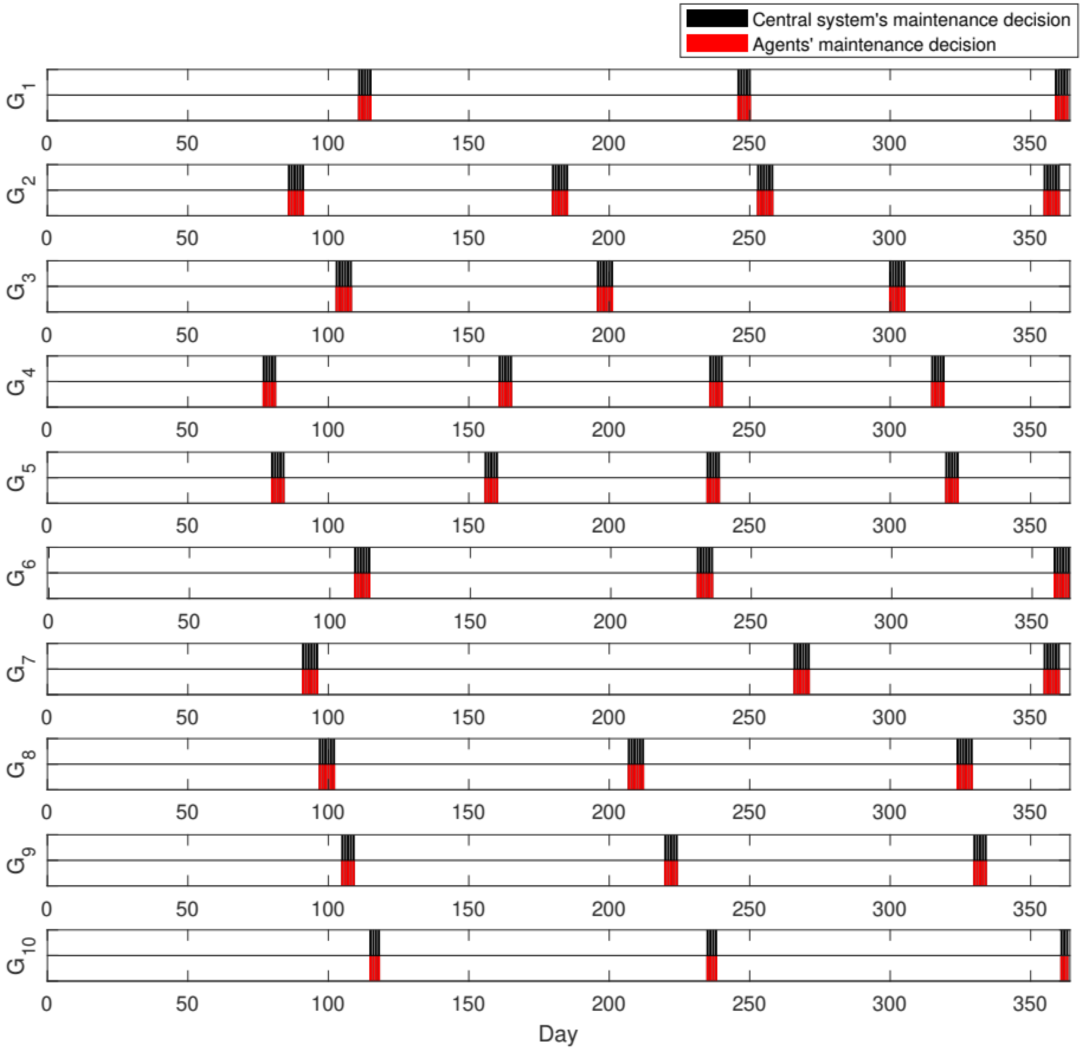
Case study


area 1
area 2

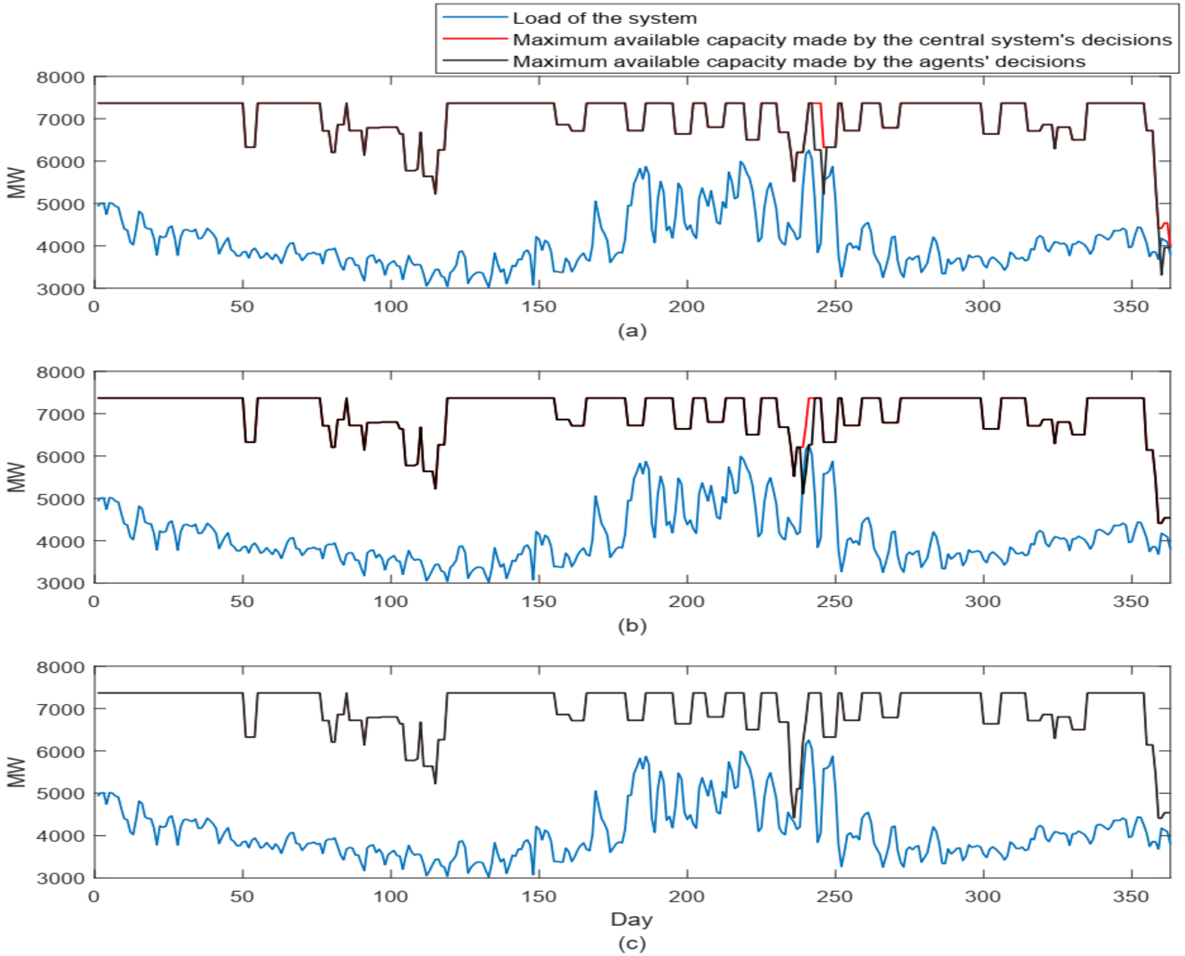

Load
Day
6500
6000
5500
5000
4500
4000
3500
3000
0
50
100
150
200
250
300
350

Maintenance decision during negotiation

Third iteration



Full-filled capacity during negotiation



Incentive signal and expected reward

Table 2: Incentive signals for agents [$]

Agent's number	Iteration 1	Iteration 2	Iteration 3
7	-200,000	0	0
10	-800,000	-400,000	0

Table 3: Rewards of the agents during negotiation [$]

Agent's number	Iteration 1	Iteration 2	Iteration 3
7	503,800	704,100	704,100
10	662,900	1,054,000	1,455,800

Individual rationality

Table 3: Rewards of the agents during negotiation [$]

Agent's number	Iteration 1	Iteration 2	Iteration 3
7	503,800	704,100	704,100
10	662,900	1,054,000	1,455,800

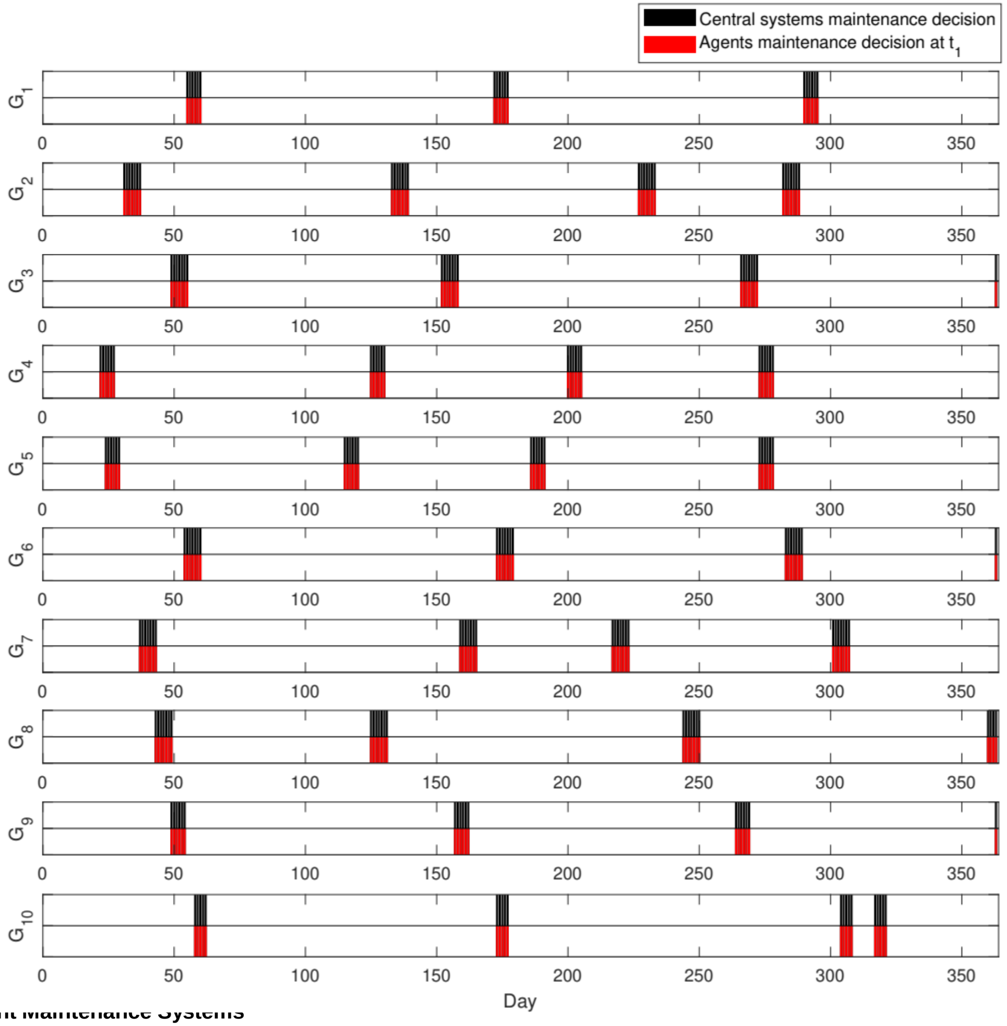
Rewards are positive

Agents participate in the negotiation algorithm voluntary

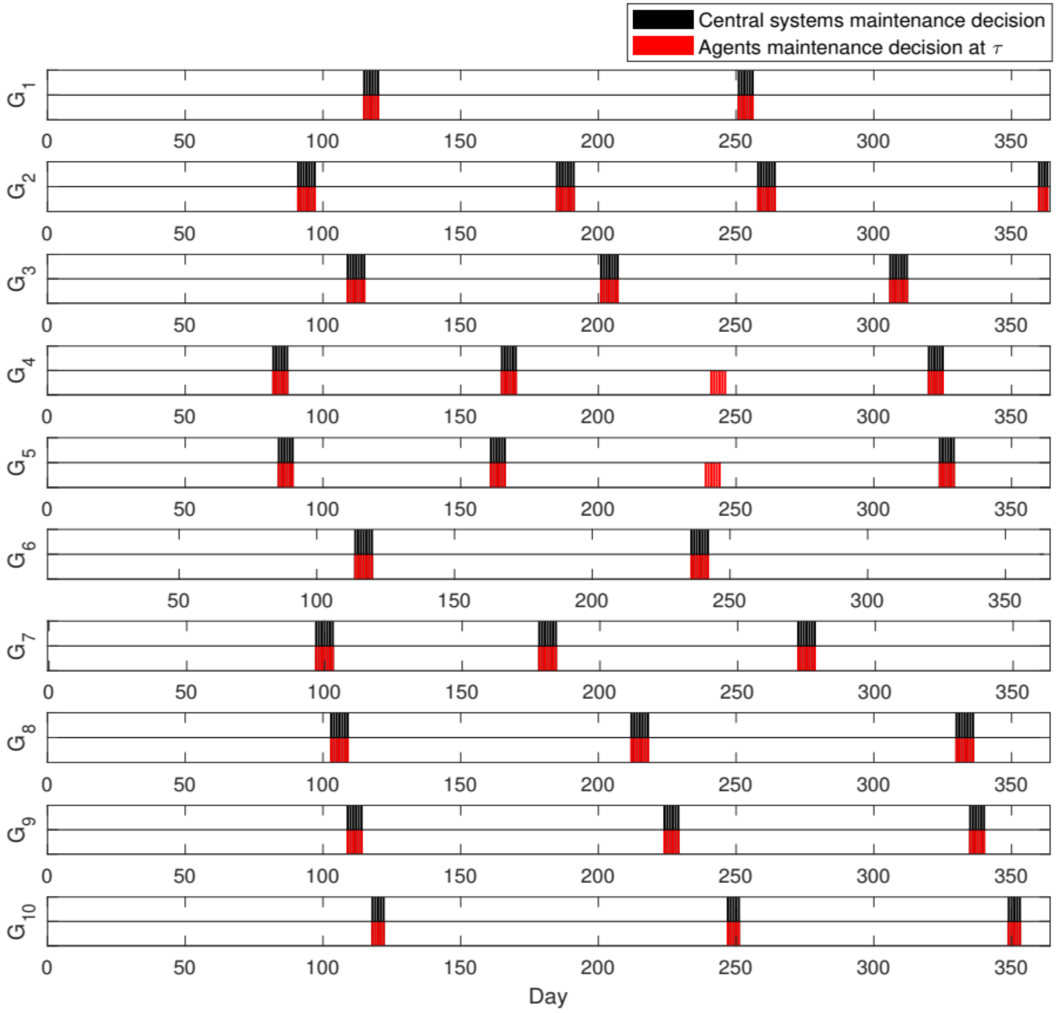
Negotiation mechanism is individual rational

Comparison of the proposed algorithm to the base line decision

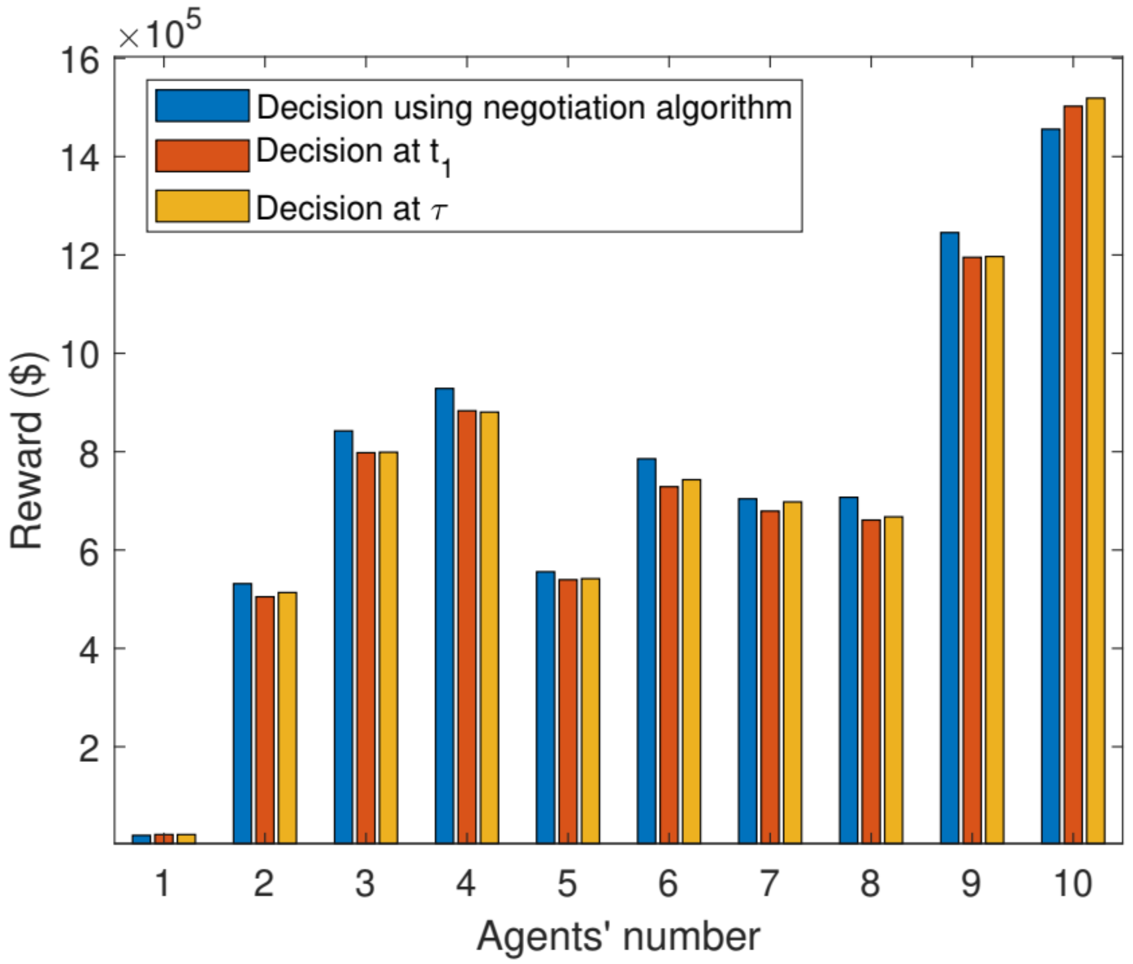
Agents decide at t_1

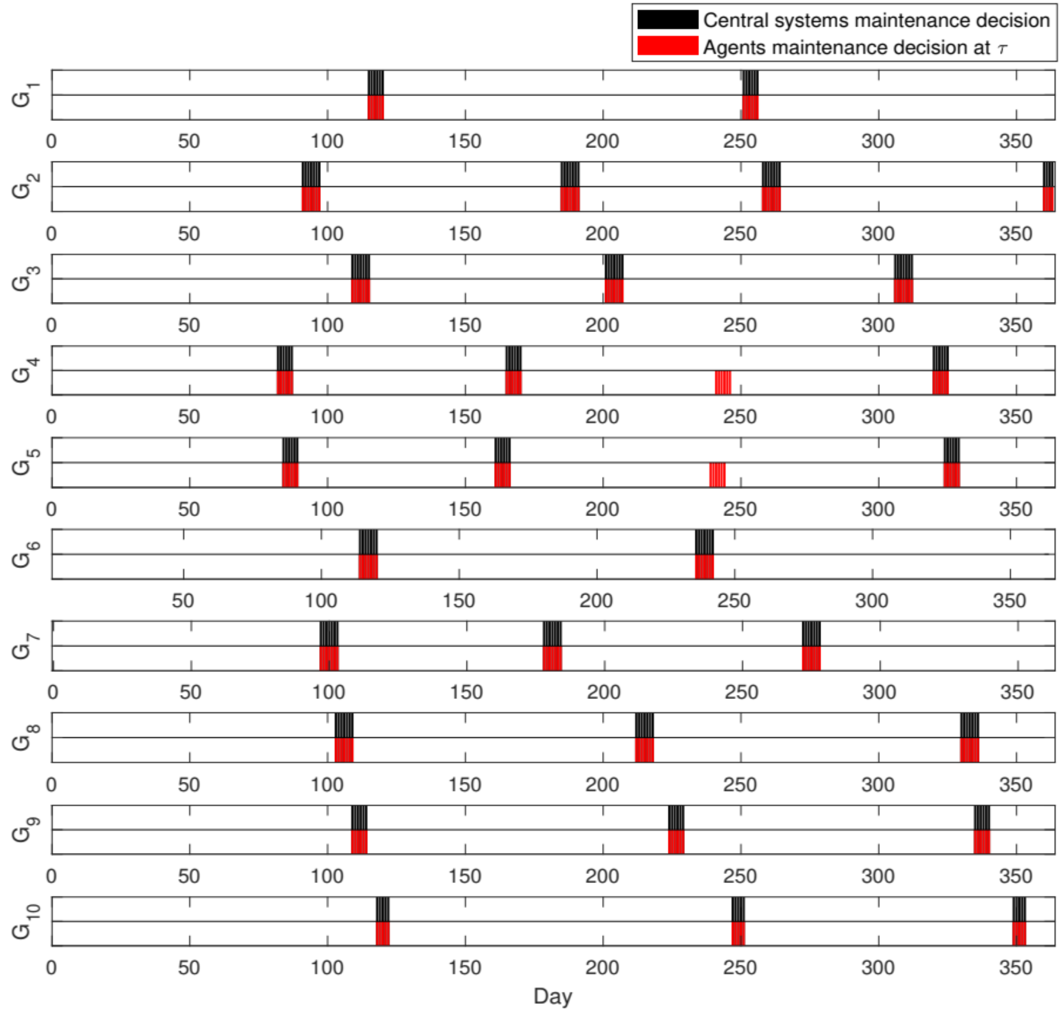


Agents decide at τ



Comparison of the proposed algorithm to the base line decision





Summary and conclusion

- We started with the maintenance scheduling and electrical market
- We propose a negotiation algorithm to solve the generation maintenance scheduling problem in the context of predictive maintenance.
- We propose incentive mechanism for power generators which makes sure that the agents' maintenance activities do not prevent power to be fully supplied to the demand.
- Our mechanism has the feature of a weak budget balance and is individually rational for each of the agents.

Future work

- Test the proposed algorithm in more extensive networks with more agents and more coordination requirements.

- Some assumptions on the generation units, such as ramp-up or down in their operation could be considered.

Q&A

Thanks for your attention