UNIVERSITY OF WASHINGTON
ELECTRICAL ENGINEERING

Bilevel Models of Transmission Line and Generating Unit Maintenance Scheduling

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2. Transmission Line Maintenance Scheduling
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Research Problem

- Problem: maintenance scheduling of transmission network components in competitive environment
- Research is divided into two parts:
  1. Maintenance scheduling of transmission lines
  2. Maintenance scheduling of generating units

Existing Maintenance Scheduling Models

- Significant number of papers in the literature
- Centralized decision making
- Network constraints included
- Usually fictive cost approach
- Lagrangian relaxation or Benders decomposition

Proposed Model

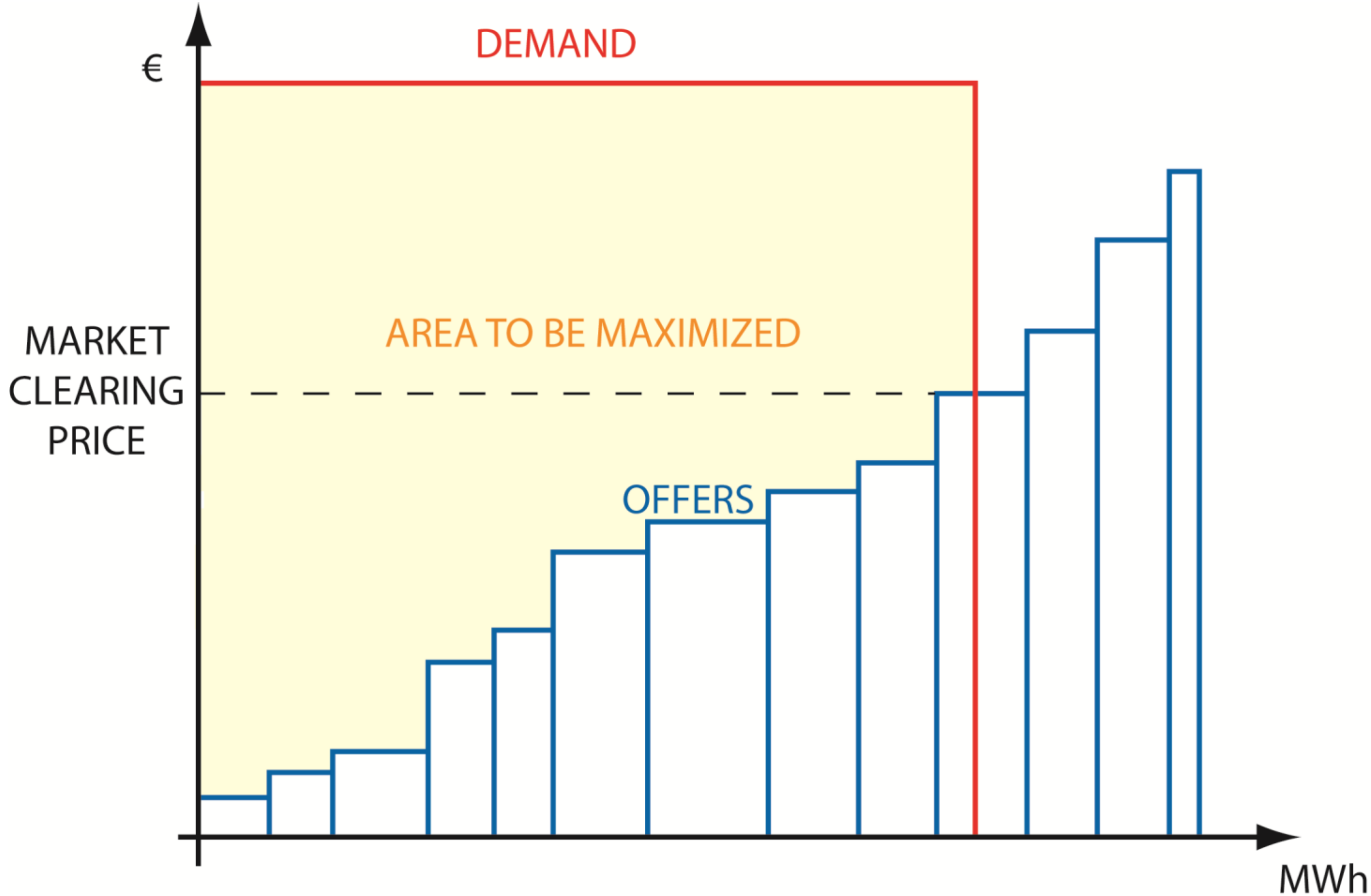
- Takes in account:
  - competitive environment (non-discriminatory approach of the System Operator)
  - goals of different market participants
  - conflicting sides (technical vs. economical)

1. Introduction
2. Transmission Line Maintenance Scheduling
3. Generating Unit Maintenance Scheduling

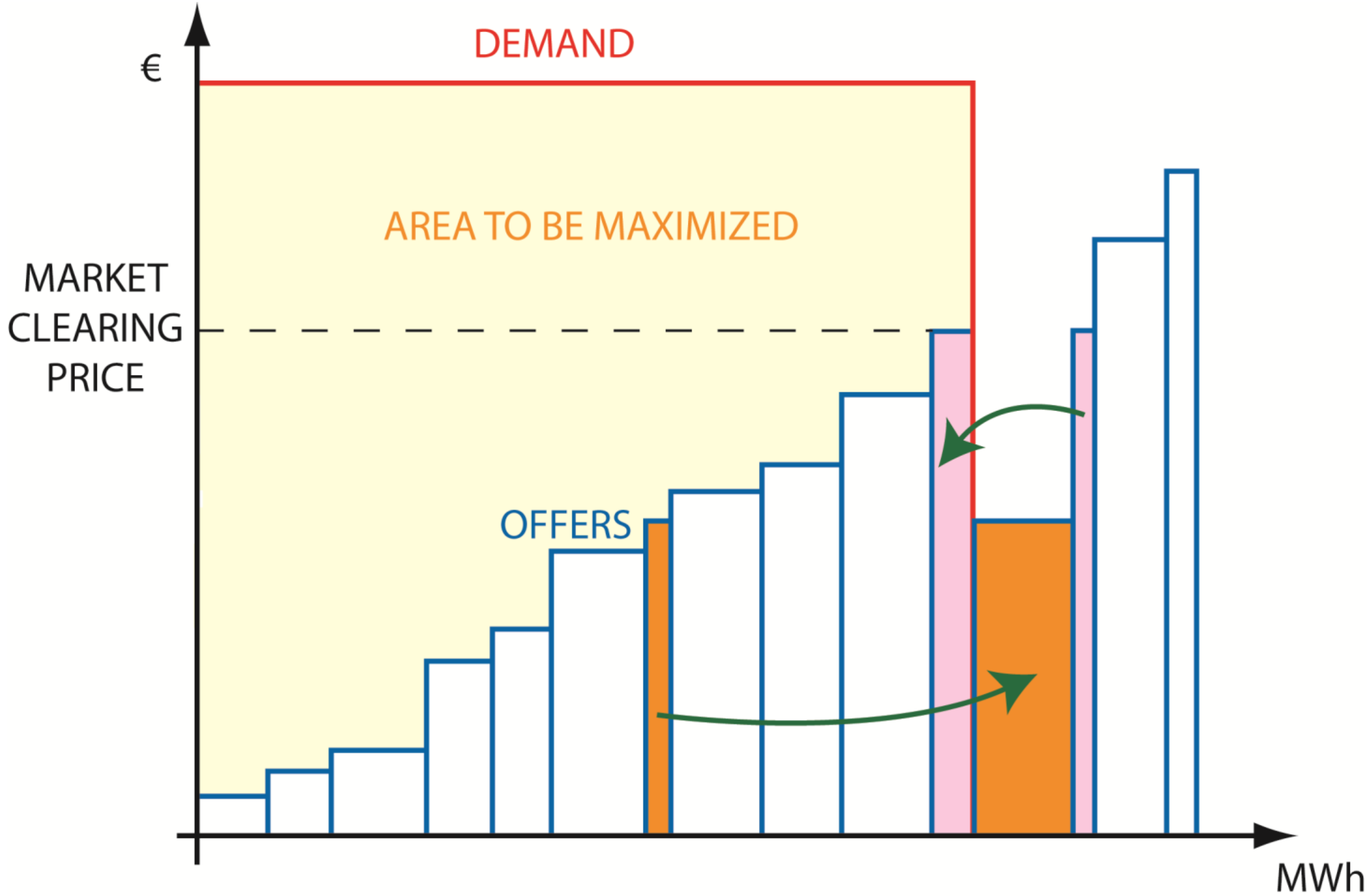
Model Description

- The purpose of the transmission line maintenance scheduling problem is to determine the optimal time interval for outage of the lines due for maintenance within a yearly time horizon
- TSO needs to preserve transmission system adequacy at all times -> maintenance should be carried out during time periods in which its effect on transmission network capacity margin is the least
- Additionally, transmission line maintenance outage should not have significant impact on the functioning of the electricity market

Model Description



Model Description



Model Description

- Bilevel approach: one hand, the maximization of the average transmission capacity margin, and, on the other hand, the minimization of the market-clearing impact
- The upper-level problem is constrained by a set of lower-level problems that represent the clearing of the market for all the time periods

Model Formulation

- Objective function:

$$\underset{\Delta_{\mathrm{U}}}{\text{Maximize}} \sum_{t=1}^{T} \left[\frac{\sum_{l \in \Omega^{\mathrm{NM}}} \left(\left(p_l^{\max} - \sum_{h \in \Phi} p_{lh}^{\mathrm{abs}}(t) \cdot U_h \right) \cdot k_l \right)}{\sum_{j \in \Omega^{\mathrm{D}}} \sum_{c \in \Omega_j} d_{jc}^{\max}(t)} + \frac{\sum_{l \in \Omega^{\mathrm{M}}} \left(\left((1 - x_l(t)) \cdot p_l^{\max} - \sum_{h \in \Phi} p_{lh}^{\mathrm{abs}}(t) \cdot U_h \right) \cdot k_l \right)}{\sum_{j \in \Omega^{\mathrm{D}}} \sum_{c \in \Omega_j} d_{jc}^{\max}(t)} \right]$$

Model Formulation

- Power flow constraints:

$$\sum_{h \in \Phi} p_{lh}^{\text{abs}}(t) = p_l^{\text{abs}}(t) \quad \forall l \in \{\Omega^{\text{M}} \cup \Omega^{\text{NM}}\}, \quad t \leq T$$

$$p_{lh}^{\text{abs}}(t) \leq V_h \cdot p_l^{\max} \quad \forall h \in \Phi, l \in \{\Omega^{\text{M}} \cup \Omega^{\text{NM}}\}, \quad t \leq T$$

$$p_l^{\text{abs}}(t) \geq p_l(t) \quad \forall l \in \{\Omega^{\text{M}} \cup \Omega^{\text{NM}}\}, \quad t \leq T$$

$$p_l^{\text{abs}}(t) \geq -p_l(t) \quad \forall l \in \{\Omega^{\text{M}} \cup \Omega^{\text{NM}}\}, \quad t \leq T$$

Model Formulation

- Scheduling constraints:

$$x_l(t) \in \{0,1\} \quad \forall l \in \Omega^{\mathrm{M}}, \quad t \leq T$$

$$\sum_{t=1}^{T/2} x_l(2t-1) = W d_l \quad \forall l \in \Omega^{\mathrm{M}}$$

$$\sum_{t=1}^{T/2} x_l(2t) = W e_l \quad \forall l \in \Omega^{\mathrm{M}}$$

Model Formulation

- Continuous maintenance constraints:

$$x_l(2t-1) - x_l(2t-3) \leq x_l(2t-1+(2Wd_l-2)) \quad \forall t \leq \frac{T}{2}$$

$$x_l(2t) - x_l(2t-2) \leq x_l(2t+(2We_l-2)) \quad \forall t \leq \frac{T}{2}$$

$$x_l(t) - x_l(t-1) \leq x_l(t+(Wd_l+We_l-1)) \quad \forall t \leq T$$

Model Formulation

- Number of lines undergoing maintenance, exclusion constraints and priority constraints:

$$\sum_{l \in \Omega^{\mathrm{M}}} x_l(t) \leq N \quad \forall t \leq T$$

$$x_{l_i}(t) + x_{l_j}(t) \leq 1 \quad \forall \{l_i, l_j\} \in \Omega^{\mathrm{E}} \quad \forall t \leq T$$

$$\sum_{r=1}^{t} x_{l_i}(r-1) - x_{l_j}(t) \geq 0 \quad \forall \{l_i, l_j\} \in \Omega^{\mathrm{P}}, t \leq T$$

Model Formulation

- Maintenance overlap constraints:

$$\sum_{r=1}^{t} x_{l_i}(r-(Wd_i+We_i)+O_{ij}) - x_{l_j}(t) \geq 0 \qquad \forall\{l_i,l_j\}\in\Omega^{O}, t\leq T$$

$$\sum_{r=1}^{t} \left[(Wd+We)_{ij}^{\min}\cdot x_{l_i}(r-(Wd_i+We_i)+O_{ij})\right] - \sum_{r=1}^{t}\left[(Wd+We)_{ij}^{\max}\cdot x_{l_j}(r)\right] \leq 0 \qquad \forall\{l_i,l_j\}\in\Omega^{O}, t\leq T$$

Model Formulation

- Lower level problem objective function:

3) lower-level problems:

$$p_l(t)\forall l \in \arg\left\{\underset{\Delta_{\mathrm{L\_P}}}{\text{Maximize}}\right.$$

$$\left[\sum_{j\in\Omega^{\mathrm{D}}}\sum_{c\in\Omega_j}\lambda_{Djc}(t)\cdot d_{jc}(t)\right.$$

$$\left.-\sum_{i\in\Omega^{\mathrm{G}}}\sum_{b\in\Omega_i}\lambda_{Gib}(t)\cdot g_{ib}(t)\right]$$

Model Formulation

- Lower level problem constraints:

$$\sum_{i \in \Psi_s^{\mathrm{G}}} \sum_{b \in \Omega_i} g_{ib}(t) - \sum_{l|o(l)=s} p_l(t) + \sum_{l|d(l)=s} p_l(t) = \sum_{i \in \Psi_s^{\mathrm{D}}} \sum_{c \in \Omega_j} d_{jc}(t) \quad : \alpha_s(t) \quad \forall s \in \Pi$$

$$p_l(t) = b_l(1 - x_l(t)) \cdot (\theta_{o(l)}(t) - \theta_{d(l)}(t)) : \beta_l(t) \quad \forall l \in \Omega^{\mathrm{M}}$$

$$p_l(t) \leq p_l^{\max} : \beta_l^{\max}(t) \quad \forall l \in \Omega^{\mathrm{M}}$$

$$p_l(t) \geq -p_l^{\max} : \beta_l^{\min}(t) \quad \forall l \in \Omega^{\mathrm{M}}$$

Model Formulation

- Lower level problem constraints:

$$p_l(t) = b_l \cdot \left(\theta_{o(l)}(t) - \theta_{d(l)}(t)\right) : \kappa_l(t) \quad \forall l \in \Omega^{\mathrm{NM}}$$

$$p_l(t) \leq p_l^{\max} : \kappa_l^{\max}(t) \quad \forall l \in \Omega^{\mathrm{NM}}$$

$$p_l(t) \geq -p_l^{\max} : \kappa_l^{\min}(t) \quad \forall l \in \Omega^{\mathrm{NM}}$$

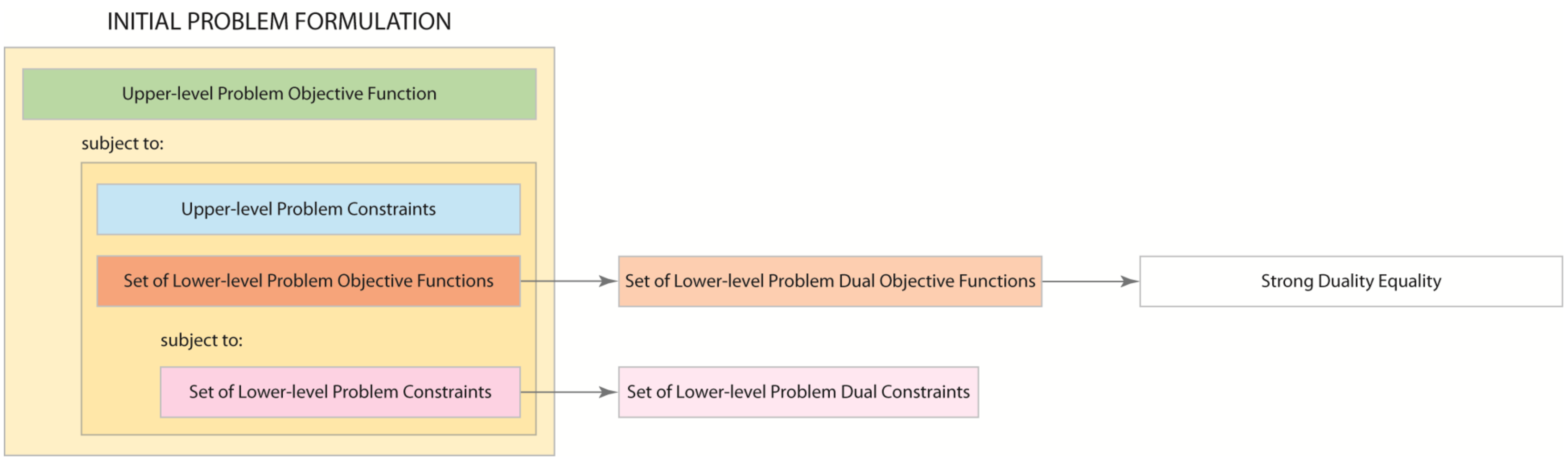
Model Formulation

- Lower level problem constraints:

$$
\left.
\begin{aligned}
& g_{ib}(t) \le g_{ib}^{\max}(t) : \gamma_{ib}^{\max}(t) \quad \forall b \in \Omega_i, i \in \Omega^{\mathrm{G}} \\
& d_{jc}(t) \le d_{jc}^{\max}(t) : \zeta_{jc}^{\max}(t) \quad \forall c \in \Omega_j, j \in \Omega^{\mathrm{D}} \\
& \theta_s(t) \le \pi : \eta_s^{\max}(t) \quad \forall s \in \Pi \backslash s : \text{reference bus} \\
& \theta_s(t) \ge -\pi : \eta_s^{\min}(t) \quad \forall s \in \Pi \backslash s : \text{reference bus} \\
& \theta_s(t) = 0 : \xi(t) s : \text{reference bus} \\
& g_{ib}(t) \ge 0 \quad \forall b \in \Omega_i, i \in \Omega^{\mathrm{G}} \\
& d_{jc}(t) \ge 0 \quad \forall c \in \Omega_j, j \in \Omega^{\mathrm{D}}
\end{aligned}
\right\} \quad \forall t \le T.
$$

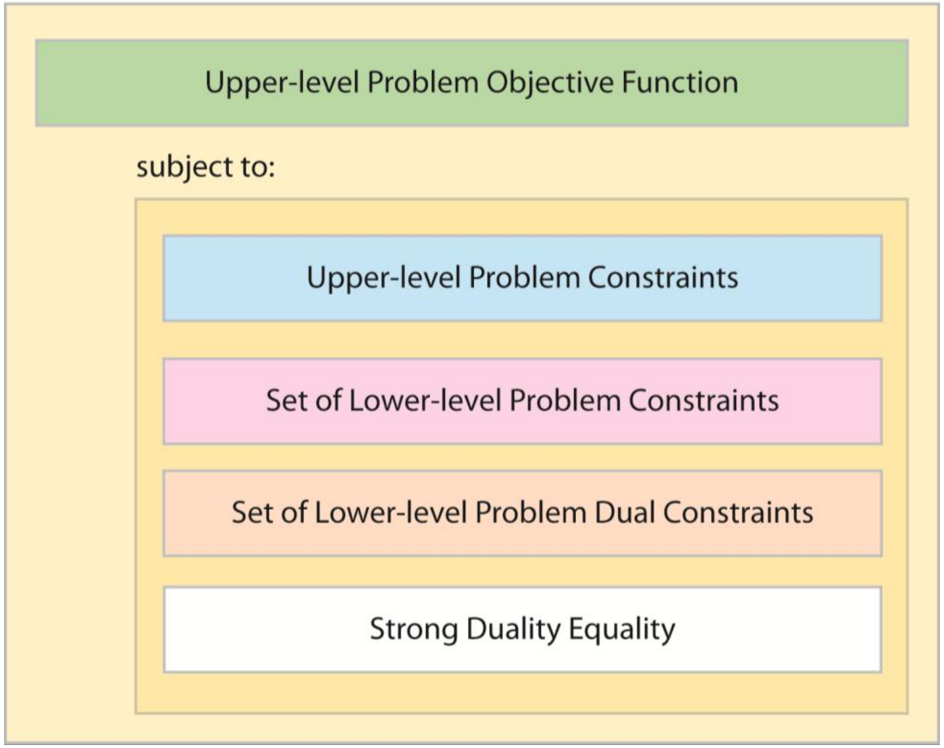
Solution Methodology

- How to solve this problem?



Solution Methodology

- Final MPEC:



MPEC

- Lower level problem dual objective function:

$$\underset{\Delta_{\mathrm{L\_D}}}{\text{Minimize}} \sum_{l\in\Omega^{\mathrm{M}}} \left(\beta_l^{\max}(t) - \beta_l^{\min}(t)\right)\cdot p_l^{\max}$$
$$+ \sum_{l\in\Omega^{\mathrm{NM}}} \left(\kappa_l^{\max}(t) - \kappa_l^{\min}(t)\right)\cdot p_l^{\max}$$
$$+ \sum_{i\in\Omega^{\mathrm{G}}} \sum_{b\in\Omega_i} \gamma_{ib}^{\max}(t)\cdot g_{ib}^{\max}(t)$$
$$+ \sum_{j\in\Omega^{\mathrm{D}}} \sum_{c\in\Omega_j} \zeta_{jc}^{\max}(t)\cdot d_{jc}^{\max}(t)$$
$$+ \sum_{s\in\Omega^{\mathrm{N}}} \left(\eta_s^{\max}(t) - \eta_s^{\min}(t)\right)\cdot \pi$$

MPEC

- Lower level problem dual constraints:

$$-\alpha_{s(j)}(t) + \zeta_{jc}^{\max} \geq \lambda_{Djc} \quad \forall c \in \Omega_j, j \in \Omega^{\mathrm{D}}$$

$$\alpha_{s(i)}(t) + \gamma_{ib}^{\max} \geq -\lambda_{Gib} \quad \forall b \in \Omega_i, i \in \Omega^{\mathrm{G}}$$

$$-\alpha_{o(l)}(t) + \alpha_{d(l)}(t) + \beta_l(t) + \beta_l^{\max}(t) + \beta_l^{\min}(t)$$
$$+ \kappa_l(t) + \kappa_l^{\max}(t) + \kappa_l^{\min}(t) = 0$$
$$\forall l \in \{\Omega^{\mathrm{M}} \cup \Omega^{\mathrm{NM}}\}$$

$$- \sum_{l|o(l)=s} b_l \cdot (1 - x_l(t)) \cdot \beta_l(t)$$
$$+ \sum_{l|d(l)=s} b_l \cdot (1 - x_l(t)) \cdot \beta_l(t)$$
$$- \sum_{l|o(l)=s} b_l \cdot \kappa_l(t) + \sum_{l|d(l)=s} b_l \cdot \kappa_l(t) + \eta_s^{\max}(t)$$

MPEC

- Lower level problem dual constraints:

$$
\begin{aligned}
&- \sum_{l|o(l)=s} b_l \cdot (1 - x_l(t)) \cdot \beta_l(t) \\
&\quad + \sum_{l|d(l)=s} b_l \cdot (1 - x_l(t)) \cdot \beta_l(t) \\
&\quad - \sum_{l|o(l)=s} b_l \cdot \kappa_l(t) + \sum_{l|d(l)=s} b_l \cdot \kappa_l(t) \\
&\quad + \xi_s(t) = 0 \quad s : \text{reference bus}
\end{aligned}
$$

MPEC

- Lower level problem dual constraints:

$$\alpha_s(t) \quad \text{free} \quad \forall s \in \Pi$$

$$\beta_l(t) \quad \text{free}; \quad \beta_l^{\max}(t) \geq 0; \quad \beta_l^{\min}(t) \leq 0 \qquad \forall l \in \Omega^{\mathrm{M}}$$

$$\kappa_l(t) \quad \text{free}; \quad \kappa_l^{\max}(t) \geq 0; \quad \kappa_l^{\min}(t) \leq 0 \qquad \forall l \in \Omega^{\mathrm{NM}}$$

$$\gamma_{ib}^{\max}(t) \geq 0 \quad \forall b \in \Omega_i, i \in \Omega^{\mathrm{G}}$$

$$\zeta_{jc}^{\max}(t) \geq 0 \quad \forall c \in \Omega_j, j \in \Omega^{\mathrm{D}}$$

$$\eta_s^{\max}(t) \geq 0; \quad \eta_s^{\min}(t) \leq 0 \qquad \forall s \in \Pi \backslash s : \text{reference bus}$$

$$\xi(t) \quad \text{free} \quad s : \text{reference bus.}$$

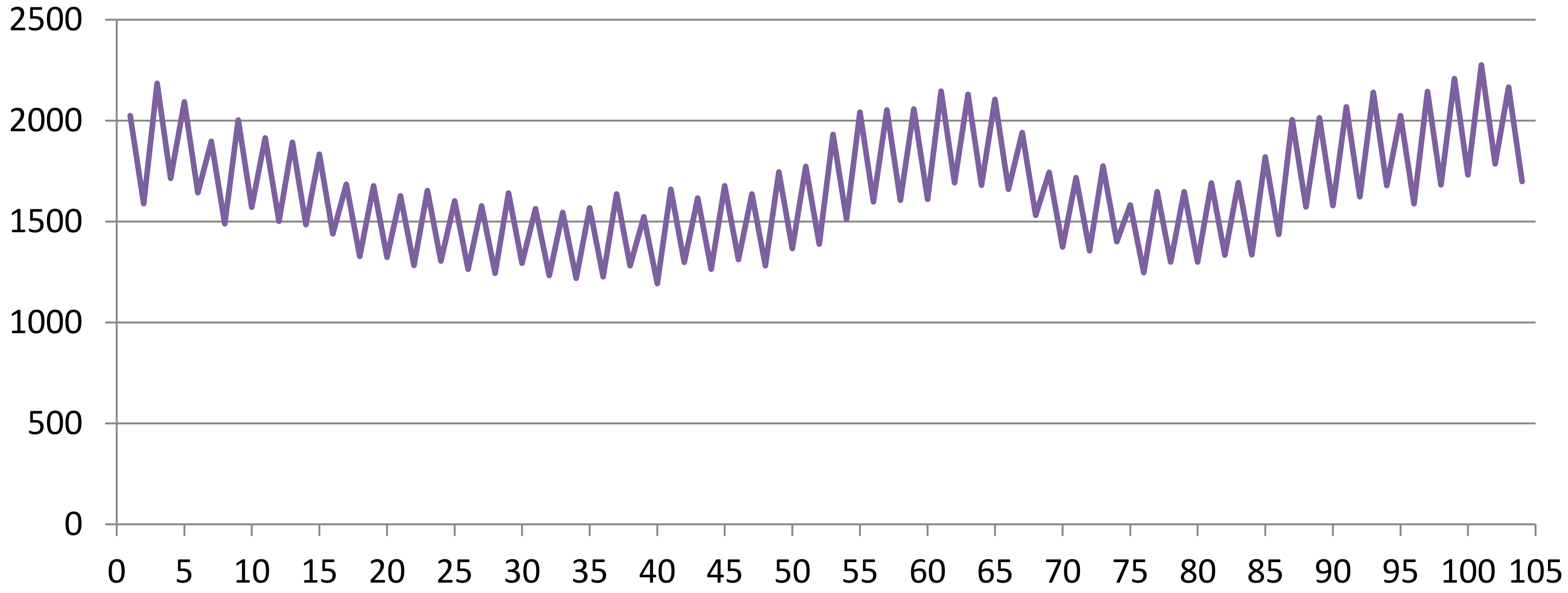
MPEC

- Strong duality equalities:

$$
\begin{aligned}
&\sum_{j\in\Omega^{\mathrm{D}}}\sum_{c\in\Omega_j}\lambda_{Djc}(t)\cdot d_{jc}(t)\\
&\quad-\sum_{i\in\Omega^{\mathrm{G}}}\sum_{b\in\Omega_i}\lambda_{Gib}(t)\cdot g_{ib}(t)\\
&\quad=\sum_{l\in\Omega^{\mathrm{M}}}\left(\beta_l^{\max}(t)-\beta_l^{\min}(t)\right)\cdot p_l^{\max}\\
&\qquad+\sum_{l\in\Omega^{\mathrm{NM}}}\left(\kappa_l^{\max}(t)-\kappa_l^{\min}(t)\right)\cdot p_l^{\max}\\
&\qquad+\sum_{i\in\Omega^{\mathrm{G}}}\sum_{b\in\Omega_i}\gamma_{ib}^{\max}(t)\cdot g_{ib}^{\max}(t)\\
&\qquad+\sum_{j\in\Omega^{\mathrm{D}}}\sum_{c\in\Omega_j}\zeta_{jc}^{\max}(t)\cdot d_{jc}^{\max}(t)\\
&\qquad+\sum_{s\in\Pi}\left(\eta_s^{\max}(t)-\eta_s^{\min}(t)\right)\cdot\pi.
\end{aligned}
$$

Case Study

- Slightly modified IEEE RTS-24
- Year is divided to 104 time periods (52 working week and 52 weekend time periods)



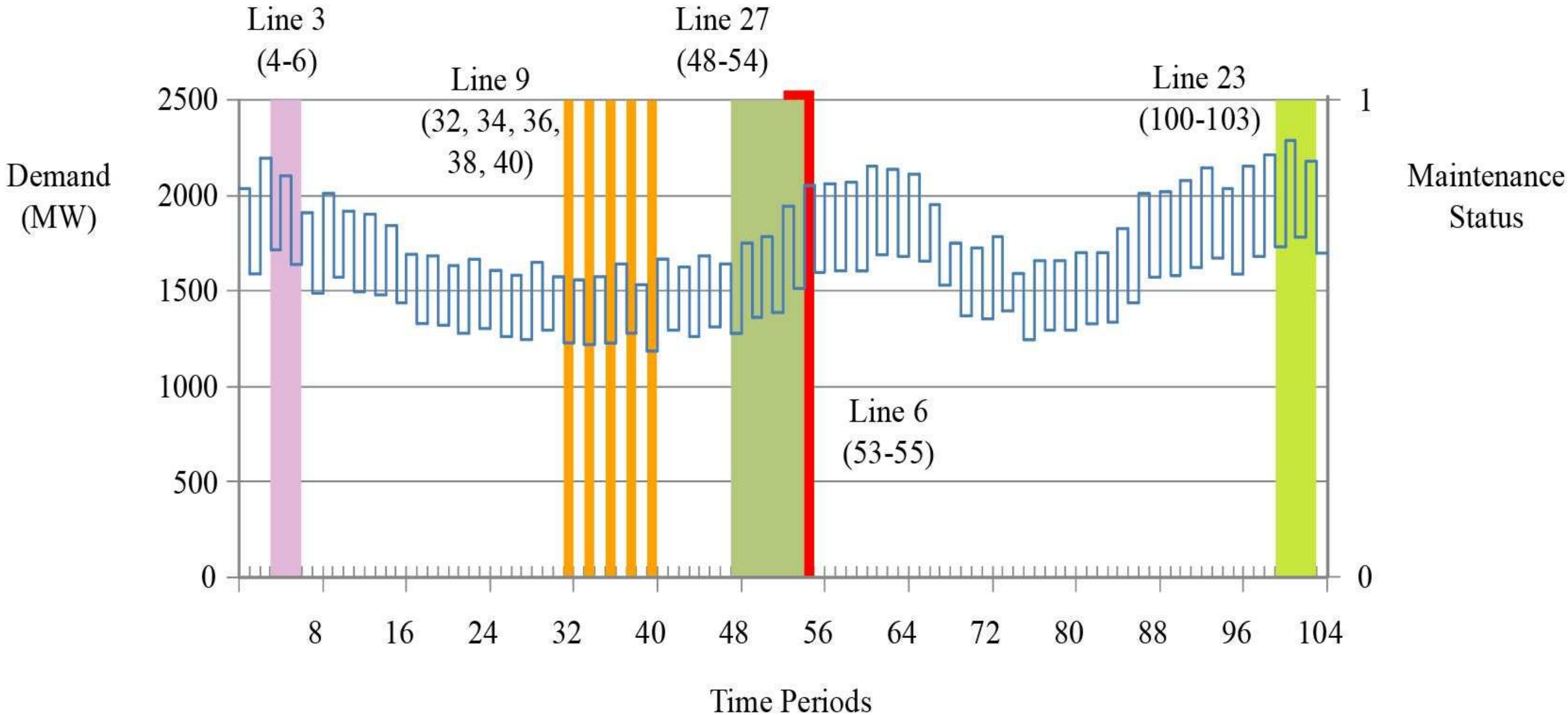
Case Study

- Maintenance requirements:

Line	3	6	9	23	27
Number of working week periods	1	2	0	2	3
Number of weekend periods	2	1	5	2	4
Exclusion constraints	-	-	-	-	-
Priority constraints	Before line 9	-	After line 3	-	-
Time periods overlap constraints	-	First 2 with line 27	-	-	Last 2 with line 6

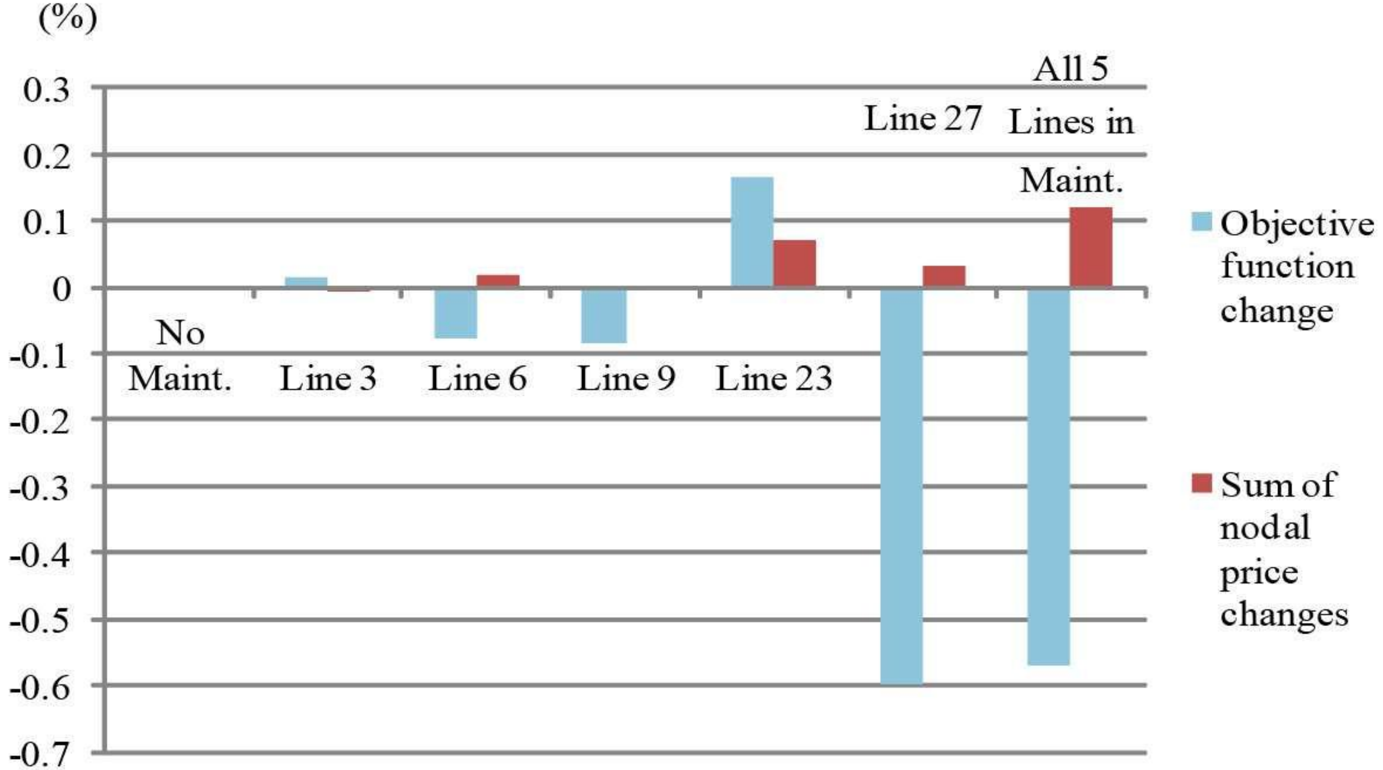
Case Study

- Results:



Case Study

- Analysis:



Computational Performance

- The required CPU time considering a single line in maintenance is around 2 min
- In case of 2 lines due for maintenance, the required CPU time increases up to 20 min
- To lighten the computational burden for the five-line case, we first obtain initial solutions for each line due for maintenance by solving a problem for each line separately
- Using the obtained results from the single-line problems as the initial solution for the five-line problem leads to a solution time of approximately 2.5 h

Computational Performance

- The computer burden is significantly lower if maintenance windows (specific periods for maintenance) are used since it reduces the number of binary variable combinations
- The problem under consideration is solved once a year, and thus, computational burden is not a primary concern

Conclusions

- In well-developed transmission systems, the maintenance outage of a single line has generally a small impact on the transmission capacity margin
- It is thus important to use transmission adequacy indices that mathematically recognize this fact

Conclusions

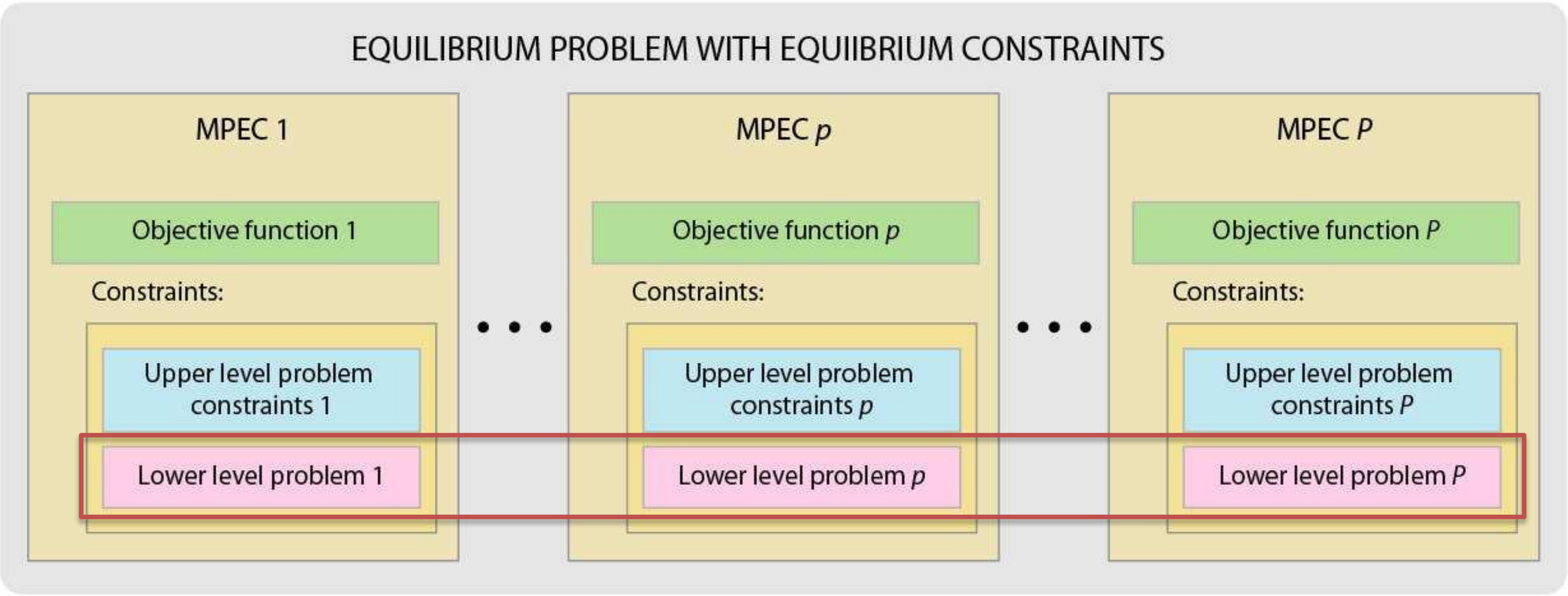
- The proposed model is computationally burdensome as a result of its MPEC structure and the low sensitivity of transmission capacity margin indices with the outage of a single line
- However, an appropriate objective function selection (for the upper-level problem), as the piece-wise one proposed in this paper, makes the problem computationally tractable

1. Introduction
2. Transmission Line Maintenance Scheduling
3. Generating Unit Maintenance Scheduling

Introduction

- Generator maintenance scheduling may significantly decrease the profit of generating company
- Since generating companies usually own more than one generator, scheduling maintenance to low load time periods may not be optimal
- Also, system constraints have to be taken into consideration

Problem Structure



EPEC

- Multiple MPECs which have the same lower level problem form an EPEC (Equilibrium Problem with Equilibrium Constraints)
- Stackelberg game: Multiple-leader-common-follower game

Single Producer Problem

- Objective function:

$$\underset{\Xi_{\mathrm{U}}}{\text{Maximize}} \quad \sum_{t=1}^{T} \sum_{i \in \mathrm{G}_p} \left[\alpha_s(t) \cdot \sum_{b \in \mathrm{I}} g_{ib}(t) \right]$$

Single Producer Problem

- Upper level problem constraints:

$$y_i(t) \in \{0,1\} \quad \forall i \in \mathrm{G}_p, t \leq T$$

$$y_i(t) = 0 \quad \forall i \in \mathrm{G}_p, t < w_i^{\mathrm{down}}$$

$$y_i(t) = 0 \quad \forall i \in \mathrm{G}_p, t > w_i^{\mathrm{up}}$$

Single Producer Problem

- Upper level problem constraints:

$$\sum_{t=1}^{T/2} y_i\,(2t-1) = Gwd_i \quad \forall i \in \mathrm{G}_p$$

$$\sum_{t=1}^{T/2} y_i\,(2t) = Gwe_i \quad \forall i \in \mathrm{G}_p$$

Single Producer Problem

- Upper level problem constraints:

$$y_i\,(2t-1) - y_i\,(2t-3) \leq y_i\,(2t-1+(2Gwd_i-2)) \quad \forall i \in \mathrm{G}_p, t \leq \frac{T}{2}$$

$$y_i\,(2t) - y_i\,(2t-2) \leq y_i\,(2t+(2Gwe_i-2)) \quad \forall i \in \mathrm{G}_p, t \leq \frac{T}{2}$$

$$y_i\,(t) - y_i\,(t-1) \leq y_i\,(t+(Gwd_i+Gwe_i-1)) \quad \forall i \in \mathrm{G}_p, t \leq T$$

Single Producer Problem

- Upper level problem constraints:

$$\sum_{i \in \mathrm{G}} \sum_{b \in \mathrm{I}} g_{ib}^{\max}(t) \cdot (1 - y_i(t)) \geq$$

$$\geq r(t) \cdot \sum_{j \in \mathrm{D}} \sum_{c \in \mathrm{J}} d_{jc}(t) \quad \forall t \leq T$$

EPEC Formulation

- Considering jointly the MPECs of all producers results in an EPEC formulated as follows:

$$\text{MPEC}_p \quad \forall p$$

- Generally, a diagonalization algorithm to solve an EPEC composed of *n* MPECs is implemented by sequentially solving one MPEC at a time
- MPEC_1 is solved considering fixed the decisions of MPEC_2, ..., MPEC_n, then MPEC_2 is solved considering fixed the decisions of MPEC_1, MPEC_3, ..., MPEC_n, and so on

EPEC Formulation

- Thus, when solving $MPEC_p$ the upper level problem constraints contain only binary variables $y_i\,(t)$, $i \in G_p$, while $y_i\,(t)$, $i \notin G_p$ are considered fixed parameters
- However, there are two problems with that approach:
  1. First producer gains significant advantage
  2. If a producer has lots of generating units, the computational burden is extremely high

EPEC Formulation

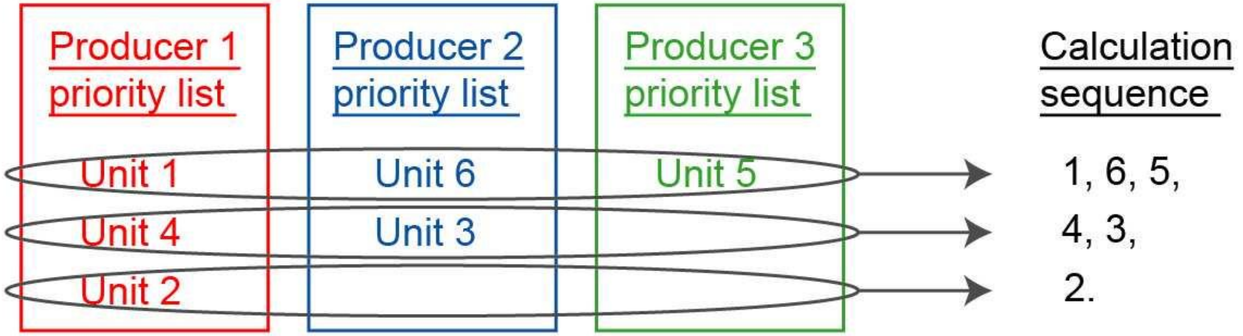
- In each iteration of the diagonalization algorithm finally implemented, one producer chooses the optimal maintenance schedule for one of its units taking the decisions made by other producers in previous iterations, as well as its own decisions in previous iterations, as fixed
- Once no producer has an incentive to change its decisions an equilibria has been found

Steps of the Algorithm

1. Collect the required information that for each generating unit include:
   - maintenance duration (number of working-week and weekend time periods),
   - maintenance windows,
   - initial desired maintenance periods (optional).

Steps of the Algorithm

2. Producers form own generating unit priority lists, which are used to determine the generating unit calculation sequence. Producer order is arbitrarily determined by the number of units they own. The higher the number of units a producers owns, the higher its priority. Once a producer "runs out" of units to schedule, the corresponding calculation is skipped.



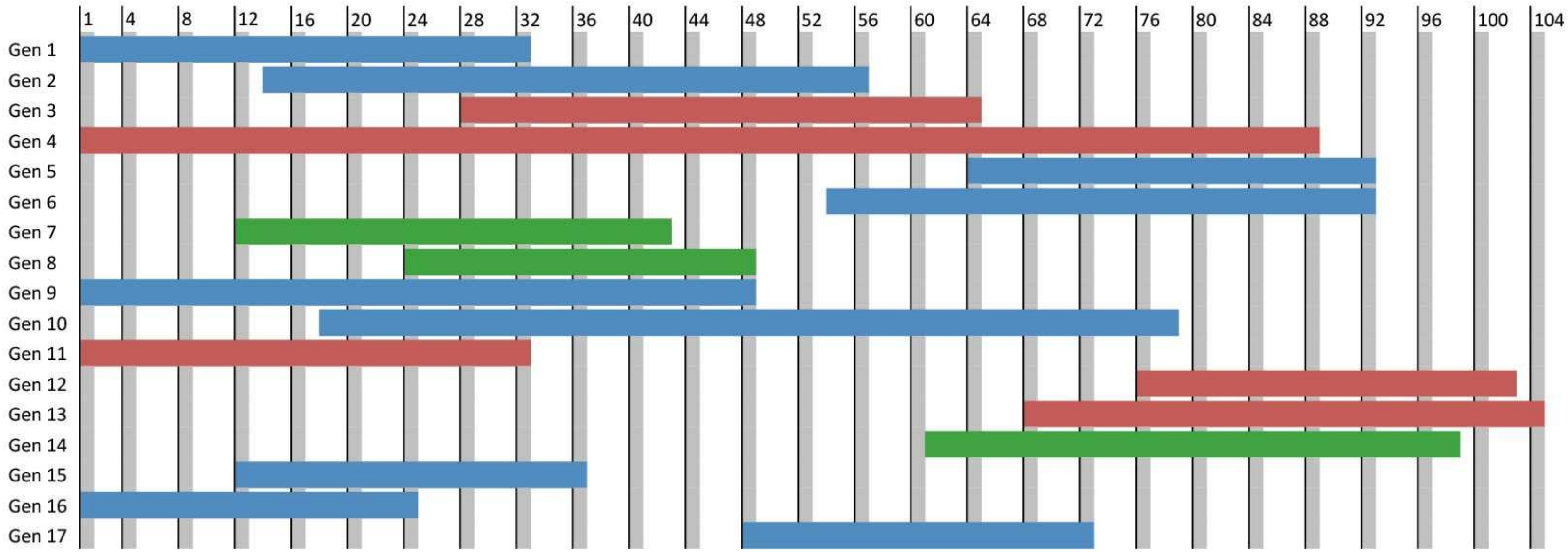
Steps of the Algorithm

3. The cycle described in the previous point is repeated until no producer changes its units' maintenance schedules throughout the cycle.
4. If an equilibrium is achieved, the procedure concludes. Otherwise, changing producer unit priorities results in a different calculation sequence possibly resulting in an alternative equilibrium.

Case Study

- IEEE 24 bus RTS system
- All calculations are done for both normal and 40% reduced line capacities in order to analyze the effect of congestion
- In order to illustrate the behavior of the proposed model a large number of simulations are carried out, changing the following parameters:
  - Initial maintenance schedule
  - Priority of producers' generating units
  - Improvement threshold of producers' objective functions
  - Transmission line capacities (in order to consider a congested and a non-congested network)

Case Study



Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Working-week Periods	1	3	4	3	2	6	5	4	0	4	3	2	3	6	5	4	4
Weekend Periods	2	4	4	3	3	5	4	4	6	5	4	3	3	6	5	5	5

Changing Initial Maintenance Periods

Seq.	1	3	7	2	4	8	5	11	14	6	12	9	13	10	15	16	17
Init.	2-4	50-57	25-33	44-50	14-19	30-37	78-82	6-12	75-86	67-77	98-102	28-38	91-96	38-46	20-29	10-18	62-70
Nor.	16-18	44-51	21-29	44-50	79-84	37-44	74-78	20-26	69-80	69-79	82-86	2-12	76-81	40-48	17-26	6-14	62-70
Red.	2-4	30-37	21-29	4-52	24-29	37-44	76-80	24-30	69-80	69-79	82-86	2-12	76-81	38-46	25-34	2-10	62-70
Init.	8-10	56-63	25-33	48-54	15-20	31-38	64-68	16-22	73-84	55-65	98-102	4-14	91-96	40-48	17-26	4-12	48-56
Nor.	16-18	54-61	**17-25**	42-48	16-21	37-44	80-84	16-22	69-80	55-65	98-102	2-12	80-85	26-34	17-26	**6-14**	48-56
Nor.	16-18	54-61	**15-23**	42-48	16-21	37-44	80-84	16-22	69-80	55-65	98-102	2-12	80-85	26-34	17-26	**6-14**	48-56
Nor.	16-18	54-61	**15-23**	42-48	16-21	37-44	80-84	16-22	69-80	55-65	98-102	2-12	80-85	26-34	17-26	**8-16**	48-56
Nor.	16-18	54-61	**17-25**	42-48	16-21	37-44	80-84	16-22	69-80	55-65	98-102	2-12	80-85	26-34	17-26	**8-16**	48-56
Red.	14-16	55-62	13-21	48-54	16-21	37-44	64-68	16-22	68-79	55-65	82-86	2-12	93-98	18-26	16-25	8-16	48-56

- Out of 66 simulations only one shows cyclic behavior

Changing Initial Maintenance Periods

	OF 1	OF 2	OF 3	Sum	No. of Iterations
Nor.	3035711	1953768	2144812	7134291	3
Red.	3048144	2006697	2182960	7237801	5
Nor.	3029366	1927348	2148004	7104718	-
Nor.	3033596	1932395	2149920	7115911	-
Nor.	3038218	1929151	2146114	7113483	-
Nor.	3026238	1929365	2147712	7103315	-
Red.	3076034	2033366	2206313	7315713	3

- Objective function values are higher in the case of congested network due to higher LMPs
- The fact that many different equilibria are obtained confirms that the considered maintenance scheduling problem is highly non-convex
- However, the obtained objective function values are very similar

	OF 1	OF 2	OF 3	Sum
Nor.	1.8%	3.4%	1.7%	1.9%
Red.	1.9%	2.7%	2.0%	1.4%

Changing Producer Priority Lists

Init.	28-30	56-63	25-33	40-46	21-26	27-34	86-90	20-26	69-80	69-79	82-86	24-34	91-96	20-28	12-21	2-10	50-58
Pr.	1	3	7	2	4	8	5	11	14	6	12	9	13	10	14	16	17
Nor.	16-18	42-49	13-21	40-46	15-20	37-44	80-84	16-22	69-80	55-65	98-102	26-36	80-85	24-32	15-24	4-12	52-60
Red.	2-4	42-49	13-21	48-54	14-19	37-44	82-86	16-22	71-82	55-65	80-84	26-36	93-98	18-26	15-24	2-10	52-60
Pr.	1	3	14	2	4	8	5	11	7	6	12	9	13	10	15	16	17
Nor.	28-30	42-49	69-80	26-32	26-31	37-44	80-84	22-28	21-29	55-65	98-102	20-30	80-85	46-54	25-34	8-16	52-60
Red.	4-6	49-56	**72-83**	48-54	12-17	37-44	**78-82**	10-16	25-33	55-65	82-86	20-30	**69-74**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**72-83**	48-54	12-17	37-44	**68-72**	10-16	25-33	55-65	82-86	20-30	**69-74**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**72-83**	48-54	12-17	37-44	**68-72**	10-16	25-33	55-65	82-86	20-30	**93-98**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**66-77**	48-54	12-17	37-44	**68-72**	10-16	25-33	55-65	82-86	20-30	**93-98**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**66-77**	48-54	12-17	37-44	**64-68**	10-16	25-33	55-65	82-86	20-30	**93-98**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**66-77**	48-54	12-17	37-44	**64-68**	10-16	25-33	55-65	82-86	20-30	**78-83**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**73-84**	48-54	12-17	37-44	**64-68**	10-16	25-33	55-65	82-86	20-30	**78-83**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**73-84**	48-54	12-17	37-44	**78-82**	10-16	25-33	55-65	82-86	20-30	**78-83**	46-54	13-22	2-10	52-60
Red.	4-6	49-56	**73-84**	48-54	12-17	37-44	**78-82**	10-16	25-33	55-65	82-86	20-30	**69-74**	46-54	13-22	2-10	52-60

- Again, out of 66 simulations only one shows cyclic behavior

Changing Producer Priority Lists

	OF 1	OF 2	OF 3	Sum	No. of Iterations
Nor.	3056730	1974277	2170959	7201966	6
Red.	3105472	2019062	2218662	7343196	2
Nor.	3005998	1947326	2152387	7105711	2
Red.	3069554	1989065	2215376	7273995	-
Red.	3073368	1980019	2213270	7266657	-
Red.	3083061	1987826	2227056	7297943	-
Red.	3102377	1988861	2229265	7320503	-
Red.	3109451	1997712	2233391	7340554	-
Red.	3065871	2007259	2218254	7291384	-
Red.	3090794	1973684	2222234	7286712	-
Red.	3104112	1970128	2212552	7286792	-
Red.	3067069	1985999	2212901	7265969	-

- Again, the obtained objective function values are very similar

	OF 1	OF 2	OF 3	Sum
Nor.	3.0%	3.6%	2.5%	3.0%
Red.	1.8%	1.4%	1.2%	1.3%

Computational Performance

- Elapsed time for a single iteration, in which a MILP problem is solved 17 times, is 3-5 minutes
- With a maximum of 8 iterations in the worst case scenario the problem is solved in 40 minutes
- In most cases the problem is solved in less than 20 minutes

Conclusions

- This EPEC formulation results in multiple equilibria due to non-convexities and discontinuities
- However, objective function values are rather similar
- The presented procedure could serve as a basis for non-discriminatory approach System Operator should exercise towards power producers

THE END

Thank you for attention