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A Rolling-Horizon Approach for Stochastic Mixed Complementarity Problems with Endogenous Learning: Application to Natural Gas Markets

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7. Supplementary Appendix

7.1. KKT Conditions for All the Producers' problems

7.1.1. Sales Variables

$$0 \leq -D_t \text{DAY} S_t (PROB_{pr}^s \pi_{mtr}^s) - \lambda_{pmtr}^{s,p1} + \begin{cases} \lambda_{pmtr}^{s,p12}, & t = r \\ \lambda_{pmtr}^{s,p13}, & t = r + 1 \\ 0, & t > r + 1 \end{cases}$$

$$\perp \text{sales}_{pmtr}^s \geq 0, \forall pmts \quad (1a)$$

$$0 \leq D_t \text{DAY} S_t RU_{pmr}^{\text{sales}} - \sum_s \lambda_{pmtr}^{s,p12} \perp \text{sales}_{pmtr}^{\text{adj}+} \geq 0, \forall pm, t = r \quad (1b)$$

$$0 \leq D_t \text{DAY} S_t RO_{pmr}^{\text{sales}} + \sum_s \lambda_{pmtr}^{s,p12} \perp \text{sales}_{pmtr}^{\text{adj}-} \geq 0, \forall pm, t = r \quad (1c)$$

$$0 \leq D_t \text{DAY} S_t (PROB_{pr}^s) RU_{pmr}^{\text{sales}} - \lambda_{pmtr}^{s,p13} \perp \text{sales}_{pmtr}^{SS+,s} \geq 0, \forall pms, t = r + 1 \quad (1d)$$

$$0 \leq D_t \text{DAY} S_t (PROB_{pr}^s) RO_{pmr}^{\text{sales}} + \lambda_{pmtr}^{s,p13} \perp \text{sales}_{pmtr}^{SS-,s} \geq 0, \forall pms, t = r + 1 \quad (1e)$$

$$0 \leq - \sum_s \lambda_{pmtr}^{s,p13} \perp \text{sales}_{pmtr}^{FS} \geq 0, \forall pm, t = r + 1 \quad (1f)$$

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7.1.2. Production Variables

$$0 \leq D_t DAY S_t (PROB_{pr}^s) \frac{\partial C_{pmtr}^{production}(prod_{pmtr}^s)}{\partial prod_{pmtr}^s} + \lambda_{pmtr}^{s,p1} + \lambda_{pmtr}^{s,p5} \\ + DAY S_t \lambda_{pmr}^{s,p7} + \begin{cases} \lambda_{pmtr}^{s,p20}, t = r \\ \lambda_{pmtr}^{s,p21}, t = r + 1 \\ 0, t > r + 1 \end{cases} \perp prod_{pmtr}^s \geq 0, \forall pmts \quad (2a)$$

$$0 \leq D_t DAY S_t RU_{pmr}^{prod} - \sum_s \lambda_{pmtr}^{s,p20} \perp prod_{pmtr}^{adj+} \geq 0, \forall pm, t = r \quad (2b)$$

$$0 \leq D_t DAY S_t RO_{pmr}^{prod} + \sum_s \lambda_{pmtr}^{s,p20} \perp prod_{pmtr}^{adj-} \geq 0, \forall pm, t = r \quad (2c)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RU_{pmr}^{prod} - \lambda_{pmtr}^{s,p21} \perp prod_{pmtr}^{SS+,s} \geq 0, \forall pms, t = r + 1 \quad (2d)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RO_{pmr}^{prod} + \lambda_{pmtr}^{s,p21} \perp prod_{pmtr}^{SS-,s} \geq 0, \forall pms, t = r + 1 \quad (2e)$$

$$0 \leq \lambda_{pmtr}^{p6} - \sum_s \lambda_{pmtr}^{s,p21} \perp prod_{pmtr}^{FS} \geq 0, \forall pm, t = r + 1 \quad (2f)$$

7.1.3. Flow Variables

$$0 \leq D_t DAY S_t (PROB_{pr}^s) (\tau_{at}^{REG} + \tau_{atr}^s) + \begin{cases} (1 - LOSS_a) \lambda_{pmtr}^{s,p1} & a \in a^{in}(m) \\ -\lambda_{pmtr}^{s,p1} & a \in a^{out}(m) \end{cases} \\ -\lambda_{patr}^{s,p4} + \begin{cases} \lambda_{patr}^{s,p18}, t = r \\ \lambda_{patr}^{s,p19}, t = r + 1 \\ 0, t > r + 1 \end{cases} \perp flow_{patr}^{s,prod} \geq 0, \forall pts, a \in A(p) \quad (3a)$$

$$0 \leq D_t DAY S_t RU_{par}^{flows} - \sum_s \lambda_{patr}^{s,p18} \perp flow_{patr}^{adj+,prod} \geq 0, \forall p, a \in A(p), t = r \quad (3b)$$

$$0 \leq D_t DAY S_t RO_{par}^{flows} + \sum_s \lambda_{patr}^{s,p18} \perp flow_{patr}^{adj-,prod} \geq 0, \forall p, a \in A(p), t = r \quad (3c)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RU_{par}^{flows} - \lambda_{patr}^{s,p19} \perp flow_{patr}^{SS+,s,prod} \geq 0, \forall ps, a \in A(p), t = r + 1 \quad (3d)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RO_{par}^{flows} + \lambda_{patr}^{s,p19} \perp flow_{patr}^{SS-,s,prod} \geq 0, \forall ps, a \in A(p), t = r + 1 \quad (3e)$$

$$0 \leq \sum_s -\lambda_{patr}^{s,p19} \perp flow_{patr}^{FS,prod} \geq 0, \forall p, a \in A(p), t = r + 1 \quad (3f)$$

7.1.4. Storage Injection Variables

$$\begin{aligned}
0 \leq D_t DAY S_t (PROB_{pr}^s) \frac{\partial C_{pmtr}^{storage}(inj_{pmtr}^s)}{\partial inj_{pmtr}^s} - \lambda_{pmtr}^{s,p1} + \lambda_{pmtr}^{s,p8} + \begin{cases} \lambda_{pmtr}^{s,p14}, t = r \\ \lambda_{pmtr}^{s,p15}, t = r + 1 \\ 0, t > r + 1 \end{cases} \\
- \sum_{e=t}^{r+H-1} DAY S_e (1 - LOSS_m) \lambda_{pmer}^{s,p2} \\
+ \sum_{e=t}^{r+H-1} DAY S_e (1 - LOSS_m) \lambda_{pmer}^{s,p3} + \perp inj_{pmtr}^s \geq 0, \forall pmts \quad (4a)
\end{aligned}$$

$$0 \leq D_t DAY S_t RU_{pmr}^{inj} - \sum_s \lambda_{pmtr}^{s,p14} \perp inj_{pmtr}^{adj+} \geq 0, \forall pm, t = r \quad (4b)$$

$$0 \leq D_t DAY S_t RO_{pmr}^{inj} + \sum_s \lambda_{pmtr}^{s,p14} \perp inj_{pmtr}^{adj-} \geq 0, \forall pm, t = r \quad (4c)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RU_{pmr}^{inj} - \lambda_{pmtr}^{s,p15} \perp inj_{pmtr}^{SS+,s} \geq 0, \forall pms, t = r + 1 \quad (4d)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RO_{pmr}^{inj} + \lambda_{pmtr}^{s,p15} \perp inj_{pmtr}^{SS-,s} \geq 0, \forall pms, t = r + 1 \quad (4e)$$

$$0 \leq \lambda_{pmtr}^{p9} - \sum_s \lambda_{pmtr}^{s,p15} \perp inj_{pmtr}^{FS} \geq 0, \forall pm, t = r + 1 \quad (4f)$$

7.1.5. Storage Extraction Variables

$$\begin{aligned}
0 \leq D_t DAY S_t (PROB_{pr}^s) \frac{\partial C_{pmtr}^{storage}(xtr_{pmtr}^s)}{\partial xtr_{pmtr}^s} + \lambda_{pmtr}^{s,p1} + \lambda_{pmtr}^{s,p10} + \begin{cases} \lambda_{pmtr}^{s,p16}, t = r \\ \lambda_{pmtr}^{s,p17}, t = r + 1 \\ 0, t > r + 1 \end{cases} \\
+ \sum_{e=t}^{r+H-1} DAY S_e \lambda_{pmer}^{s,p2} - \sum_{e=t}^{r+H-1} DAY S_e \lambda_{pmer}^{s,p3} \perp xtr_{pmtr}^s \geq 0, \forall pmts \quad (5a)
\end{aligned}$$

$$0 \leq D_t DAY S_t RU_{pmr}^{xtr} - \sum_s \lambda_{pmtr}^{s,p16} \perp xtr_{pmtr}^{adj+} \geq 0, \forall pm, t = r \quad (5b)$$

$$0 \leq D_t DAY S_t RO_{pmr}^{xtr} + \sum_s \lambda_{pmtr}^{s,p16} \perp xtr_{pmtr}^{adj-} \geq 0, \forall pm, t = r \quad (5c)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RU_{pmr}^{xtr} - \lambda_{pmtr}^{s,p17} \perp xtr_{pmtr}^{SS+,s} \geq 0, \forall pms, t = r + 1 \quad (5d)$$

$$0 \leq D_t DAY S_t (PROB_{pr}^s) RO_{pmr}^{xtr} + \lambda_{pmtr}^{s,p17} \perp xtr_{pmtr}^{SS-,s} \geq 0, \forall pms, t = r + 1 \quad (5e)$$

$$0 \leq \lambda_{pmtr}^{p11} - \sum_s \lambda_{pmtr}^{s,p17} \perp xtr_{pmtr}^{FS} \geq 0, \forall pm, t = r + 1 \quad (5f)$$

7.1.6. Storage Constraints

$$\begin{aligned}
0 &\leq INITSTOR_{mr} + \sum_{e=r}^t DAYSe[(1 - LOSS_m)inj_{pmer}^s - xtr_{pmer}^s] \\
&\quad - MINSTOR_m \perp \lambda_{pmtr}^{s,p2} \geq 0, \forall pmts, \tag{5g} \\
0 &\leq MAXSTOR_m - INITSTOR_{mr} \\
&\quad - \sum_{e=r}^t DAYSe[(1 - LOSS_m)inj_{pmer}^s - xtr_{pmer}^s] \perp \lambda_{pmtr}^{s,p3} \geq 0, \forall pmts, \tag{5h} \\
0 &\leq -inj_{pmtr}^s + DI_{pm}^{\max} \perp \lambda_{pmtr}^{s,p8} \geq 0, \forall pmts, \tag{5i} \\
0 &\leq -inj_{pmtr}^{FS} + DI_{pm}^{\max} \perp \lambda_{pmtr}^{p9} \geq 0, \forall pm, t = r + 1, \tag{5j} \\
0 &\leq -xtr_{pmtr}^s + DX_{pm}^{\max} \perp \lambda_{pmtr}^{s,p10} \geq 0, \forall pmts, \tag{5k} \\
0 &\leq -xtr_{pmtr}^{FS} + DX_{pm}^{\max} \perp \lambda_{pmtr}^{p11} \geq 0, \forall pm, t = r + 1, \tag{5l} \\
0 &= inj_{pmtr}^s - INJ_{pmt(r-1)}^{previous} - inj_{pmtr}^{adj+} + inj_{pmtr}^{adj-}, \lambda_{pmtr}^{s,p14} \text{ free}, \forall pms, t = r, \tag{5m} \\
0 &= inj_{pmtr}^s - inj_{pmtr}^{FS} - inj_{pmtr}^{SS+,s} + inj_{pmtr}^{SS-,s}, \lambda_{pmtr}^{s,p15} \text{ free}, \forall pms, t = r + 1, \tag{5n} \\
0 &= xtr_{pmtr}^s - XTR_{pmt(r-1)}^{previous} - xtr_{pmtr}^{adj+} + xtr_{pmtr}^{adj-}, \lambda_{pmtr}^{s,p16} \text{ free}, \forall pms, t = r, \tag{5o} \\
0 &= xtr_{pmtr}^s - xtr_{pmtr}^{FS} - xtr_{pmtr}^{SS+,s} + xtr_{pmtr}^{SS-,s}, \lambda_{pmtr}^{s,p17} \text{ free}, \forall pms, t = r + 1. \tag{5p}
\end{aligned}$$

7.1.7. Sales, Flow, and Production Constraints

$$\begin{aligned}
0 &= sales_{pmtr}^s - SALES_{pmt(r-1)}^{previous} - sales_{pmtr}^{adj+} + sales_{pmtr}^{adj-}, \lambda_{pmtr}^{s,p12} \text{ free}, \forall pms, t = r, \tag{5q} \\
0 &= sales_{pmtr}^s - sales_{pmtr}^{FS} - sales_{pmtr}^{SS+,s} + sales_{pmtr}^{SS-,s}, \lambda_{pmtr}^{s,p13} \text{ free}, \forall pms, t = r + 1, \tag{5r} \\
0 &= flows_{patr}^{s,prod} - FLOW_{pat(r-1)}^{previous,prod} - flows_{patr}^{adj+,prod} + flows_{patr}^{adj-,prod}, \lambda_{patr}^{s,p18} \text{ free}, \forall pas, t = r, \tag{5s} \\
0 &= flows_{patr}^{s,prod} - flows_{patr}^{FS,prod} - flows_{patr}^{SS+,s,prod} + flows_{patr}^{SS-,s,prod}, \lambda_{patr}^{s,p19} \text{ free}, \forall pas, t = r + 1, \tag{5t} \\
0 &= prod_{pmtr}^s - PROD_{pmt(r-1)}^{previous} - prod_{pmtr}^{adj+} + prod_{pmtr}^{adj-}, \lambda_{pmtr}^{s,p20} \text{ free}, \forall pms, t = r, \tag{5u} \\
0 &= prod_{pmtr}^s - prod_{pmtr}^{FS} - prod_{pmtr}^{SS+,s} + prod_{pmtr}^{SS-,s}, \lambda_{pmtr}^{s,p21} \text{ free}, \forall pms, t = r + 1, \tag{5v}
\end{aligned}$$

$$0 \leq flows_{patr}^{s,prod} - CONTRACTS_{pat} \perp \lambda_{patr}^{s,p4} \geq 0 \forall pats, \quad (5w)$$

$$0 \leq prod_{pmtr}^s - DP_{pm}^{\max} \perp \lambda_{pmtr}^{s,p5} \geq 0 \forall pmts, \quad (5x)$$

$$0 \leq prod_{pmtr}^{FS} - DP_{pm}^{\max} \perp \lambda_{pmtr}^{p6} \geq 0 \forall pm, t = r + 1. \quad (5y)$$

7.1.8. Balance Constraints

$$\begin{aligned} 0 = & prod_{pmtr}^s + \sum_{a \in a^{in}(m)} (1 - LOSS_a) flows_{patr}^{s,prod} + xtr_{pmtr}^s \\ & - sales_{pmtr}^s - \sum_{a \in a^{out}(m)} flows_{patr}^{s,prod} - inj_{pmtr}^s, \lambda_{pmtr}^{s,p1} \text{ free } \forall pmts. \end{aligned} \quad (6a)$$

7.2. KKT Conditions for TSO

7.2.1. Flow Variables

$$\begin{aligned} 0 \leq & D_t DAY S_t (PROB_r^s) \left[-(\tau_{atr}^s + \tau_{at}^{REG}) + \frac{\partial C^a (flows_{atr}^{s,tso})}{\partial flows_{atr}^{s,tso}} \right] \\ & + \begin{cases} \lambda_{atr}^{s,tso1}, t = r \\ \lambda_{atr}^{s,tso2}, t = r + 1 + \lambda_{atr}^{s,tso3} \perp flows_{atr}^{s,tso} \geq 0, \forall ats \\ 0, t > r + 1 \end{cases} \end{aligned} \quad (7a)$$

$$0 \leq D_t DAY S_t RU_{ar}^{flows} - \sum_s \lambda_{atr}^{s,tso1} \perp flows_{atr}^{adj+,tso} \geq 0, \forall a, t = r \quad (7b)$$

$$0 \leq D_t DAY S_t RO_{ar}^{flows} + \sum_s \lambda_{atr}^{s,tso1} \perp flows_{atr}^{adj-,tso} \geq 0, \forall a, t = r \quad (7c)$$

$$0 \leq \lambda_{atr}^{tso4} - \sum_s \lambda_{atr}^{s,tso2} \perp flows_{atr}^{FS,tso} \geq 0, \forall a, t = r + 1 \quad (7d)$$

$$0 \leq D_t DAY S_t (PROB_r^s) RU_{ar}^{flows} - \lambda_{atr}^{s,tso2} \perp flows_{atr}^{SS+,s,tso} \geq 0, \forall as, t = r + 1 \quad (7e)$$

$$0 \leq D_t DAY S_t (PROB_r^s) RO_{ar}^{flows} + \lambda_{atr}^{s,tso2} \perp flows_{atr}^{SS-,s,tso} \geq 0, \forall as, t = r + 1 \quad (7f)$$

7.2.2. TSO Constraints

$$0 = flows_{atr}^{s,tso} - FLOW S_{at(r-1)}^{previous,tso} - flows_{atr}^{adj+,tso} + flows_{atr}^{adj-,tso}, \lambda_{atr}^{s,tso1} \text{ free}, t = r, \forall as, \quad (8a)$$

$$0 = flows_{atr}^{s,tso} - flows_{atr}^{FS,tso} - flows_{atr}^{SS+,s,tso} + flows_{atr}^{SS-,s,tso}, \lambda_{atr}^{s,tso2} \text{ free}, t = r + 1, \forall as, \quad (8b)$$

$$0 \leq DA_a^{\max} - flows_{atr}^{s,tso} \perp \lambda_{atr}^{s,tso3} \geq 0, \forall ats, \quad (8c)$$

$$0 \leq DA_a^{\max} - flows_{atr}^{FS,tso} \perp \lambda_{atr}^{tso4} \geq 0, t = r + 1, \forall a. \quad (8d)$$