

Matrix Completion Methods for Causal Panel Data Models

Susan Athey et al. (2021), JASA

Naoki Eguchi

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Faculty of Medicine, Kyoto University

Introduction

Today's Agenda ; Keyword : Imputation

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Imputation

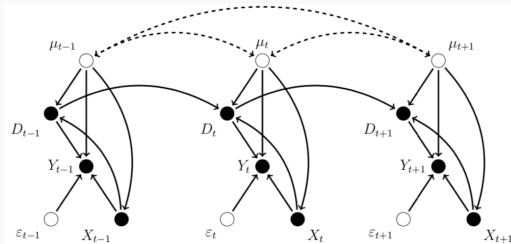
- As many panel data methods, we want to know ATT : $\mathbb{E}[Y_{it}(1) - Y_{it}(0)|W_i = 1]$.
- Thus, it boils down to estimate (impute) the counterfactual $Y_{it}(0)$.
 - Horizontal : Under unconfoundedness, we can impute counterfactual PO using observed outcomes for control units.
 - Vertical : By SCM, we can also impute it using weighted average outcomes for control units with most predictive weights trained with pre-treatment datas.

$$\mathbf{Y} = \begin{pmatrix} \checkmark & \checkmark & \checkmark \\ \vdots & \vdots & \vdots \\ \checkmark & \checkmark & \checkmark \\ \checkmark & \checkmark & ? \\ \vdots & \vdots & \vdots \\ \checkmark & \checkmark & ? \end{pmatrix}.$$

$$\mathbf{Y} = \begin{pmatrix} \checkmark & \checkmark & \dots & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \dots & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \dots & \checkmark & ? & \dots & ? \end{pmatrix}$$

Xu (2024): Counterfactual estimation

- functional form: $Y_{it}(0) = f(\mathbf{X}_{it}) + h(\mathbf{U}_{it}) + \epsilon_{it}$
→ No anticipation, carryover, feedback, LDV
- strict exogeneity: $\forall i, j \in \{1, \dots, N\}, \forall s, t \in \{1, \dots, T\}, \epsilon_{it} \perp\!\!\!\perp \{D_{js}, \mathbf{X}_{js}, \mathbf{U}_{js}\}$



- low-dimensional decomposition: $h(\mathbf{U}_{it}) = \{L_{it}\}, \text{rank}(\mathbf{L}_{N \times T}) \ll \min\{N, T\}$
→ The rank (= number of factors) is **FIXED !!**

Set Up

- Consider a setting with N units observed over T periods characterized by a binary treatment W_{it} and hence two POs $Y_{it}(1), Y_{it}(0)$.
 - $\mathbf{X} \in \mathbb{R}^{N \times P}$, $\mathbf{Z} \in \mathbb{R}^{T \times Q}$: observe (unit / time)-specific covariance matrix
- Estimand: $\mathbf{Y} = \{Y_{it}(0)^1\} = \begin{pmatrix} Y_{11}(0) & \cdots & Y_{1T}(0) \\ \vdots & \ddots & \vdots \\ Y_{N1}(0) & \cdots & Y_{NT}(0) \end{pmatrix}$ (\leftarrow Matrix!!)
- $W_{it} = \begin{cases} 1 & \text{if } (i, t) \in \mathcal{M} \\ 0 & \text{if } (i, t) \in \mathcal{O} \end{cases}$

¹以降は簡単のため, $Y_{it}(0) = Y_{it}$ とし, “(0)” を省略して表記する.

Patterns of data matrix

- Ordinary case (rich data wrt. units and times)

$$\mathbf{Y}_{N \times T} = \begin{pmatrix} \checkmark & \checkmark & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \checkmark & ? & \dots & ? \\ \checkmark & \checkmark & \checkmark & ? & \dots & ? \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \checkmark & \checkmark & \checkmark & ? & \dots & ? \end{pmatrix}$$

- Staggered adoption

$$\mathbf{Y}_{N \times T} = \begin{pmatrix} \checkmark & \checkmark & \checkmark & \checkmark & \dots & \checkmark & \text{(never adopter)} \\ \checkmark & \checkmark & \checkmark & \checkmark & \dots & ? & \text{(late adopter)} \\ \checkmark & \checkmark & ? & ? & \dots & ? & \\ \checkmark & \checkmark & ? & ? & \dots & ? & \text{(medium adopter)} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \\ \checkmark & ? & ? & ? & \dots & ? & \text{(early adopter)} \end{pmatrix}$$

Horizontal regression and unconfoundedness : thin matrix ($N \gg T$)

$$\mathbf{Y} = \begin{pmatrix} \checkmark & \checkmark & \checkmark \\ \vdots & \vdots & \vdots \\ \checkmark & \checkmark & \checkmark \\ \checkmark & \checkmark & ? \\ \vdots & \vdots & \vdots \\ \checkmark & \checkmark & ? \end{pmatrix}.$$

1. Regress the last period outcome on the lagged outcomes. (among untreated)
2. Predict the missing POs using the estimated regression.

$$\forall (i, T) \in \mathcal{M}, \hat{Y}_{iT} = \hat{\beta}_0 + \sum_{t=1}^{T-1} \hat{\beta}_t Y_{it}, \text{ where } \hat{\beta} = \arg \min_{\beta} \sum_{i:(i,T) \in \mathcal{O}} (Y_{iT} - \beta_0 - \sum_{t=1}^{T-1} \beta_t Y_{it})^2.$$

→ Nonparametrically,

Vertical regression and synthesis control : fat matrix ($T \gg N$)

$$\mathbf{Y} = \begin{pmatrix} \checkmark & \checkmark & \dots & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \dots & \checkmark & \checkmark & \dots & \checkmark \\ \checkmark & \checkmark & \dots & \checkmark & ? & \dots & ? \end{pmatrix}$$

1. Regress the outcomes for treated unit prior to the treatment on the outcomes for the control units in the same periods.
2. Predict the missing POs using the estimated regression.

$$\forall (N, t) \in \mathcal{M}, \hat{Y}_{Nt} = \hat{\gamma}_0 + \sum_{i=1}^{N-1} \hat{\gamma}_i Y_{it}, \text{ where } \hat{\gamma} = \arg \min_{\gamma} \sum_{t:(N,t) \in \mathcal{O}} (Y_{Nt} - \gamma_0 - \sum_{i=1}^{N-1} \gamma_i Y_{it})^2.$$

→ Vertical regression is generalization of ADH(2010) in that it relaxes two restrictions :

- the coefficients $\hat{\gamma}$ are nonnegative. (Interpretability ; What is a negative weight?)
- the intercept in this regression is 0. (This is seen to be plausible in recent literatures.)

Matrix Completion

- Under no covariates, we model the $N \times T$ matrix of complete matrix \mathbf{Y} as

$$\mathbf{Y} = \mathbf{L}^* + \epsilon, \text{ where } \mathbb{E}[\epsilon|\mathbf{L}^*] = 0.$$

Assumption 1

- ϵ is independent of \mathbf{L}^*
- The element of ϵ are σ -sub-Gaussian and independent each other.
 $\Leftrightarrow \forall t, \mathbb{E}[\exp(t\epsilon)] \leq \exp(\frac{\sigma^2 t^2}{2}).$

- The goal is to estimate the matrix \mathbf{L}^* . (low-rank assumption)

→ Note that two types² of fixed effects are included.

²これら以外にも Interactive fixed effect といったあらゆる factor を”少数まで”許容する

MC-NNM (Matrix Completion with Nuclear Norm Minimization) estimator

- MC-NNM estimator for \mathbf{L}^* is given by $\hat{\mathbf{L}} + \hat{\Gamma}\mathbf{1}'_T + \mathbf{1}_N\hat{\Delta}'$

$$(\hat{\mathbf{L}}, \hat{\Gamma}, \hat{\Delta}) = \arg \min_{\hat{\mathbf{L}}, \hat{\Gamma}, \hat{\Delta}} \left\{ \frac{1}{|\mathcal{O}|} \|\mathbf{P}_{\mathcal{O}}(\mathbb{Y} - \mathbf{L} - \Gamma\mathbf{1}'_T - \mathbf{1}_N\Delta')\|_F^2 + \lambda \|\mathbf{L}\|_* \right\}$$

- $\Gamma \in \mathbb{R}^N$: unit-varying (and time-fixed) effect (individual effect)
- $\Delta \in \mathbb{R}^T$: time-varying (and unit-fixed) effect (time effect)
- matrix indicator function : $\mathbf{P}_{\mathcal{O}}(\mathbf{A}) = \begin{cases} A_{it} & \text{if } (i, t) \in \mathcal{O} \\ 0 & \text{if } (i, t) \notin \mathcal{O} \end{cases}$ (NA is regarded as 0)
- Frobenius norm : $\|\mathbf{A}\|_F^2 = \sum_{i=1}^N \sum_{t=1}^T A_{it}^2$ (行列版の mean squared error を計算している)
- Regularization term $\lambda \|\mathbf{L}\|_*$ leads to **the low rank of \mathbf{L}** .
 \rightarrow minimize $\lambda \|\mathbf{L}\|_* \Leftrightarrow$ the sparsity of Singular value $\sigma_i(\mathbf{L})(> 0) \Leftrightarrow$ low rank of \mathbf{L}

- **Fact 1.** (Singular value decomposition) *Every real matrix $L \in \mathbb{R}^N \times \mathbb{R}^T$ can be decomposed using a onthogonal matrix $\mathbf{S} \in \mathbb{R}^N \times \mathbb{R}^{\min(N,T)}$, $\mathbf{R} \in \mathbb{R}^T \times \mathbb{R}^{\min(N,T)}$ by*

$$\mathbf{L} = \mathbf{S}\mathbf{\Sigma}\mathbf{R}', \text{ where } \mathbf{\Sigma} = \text{diag}(\sigma_1, \dots, \sigma_{\min(N,T)}), \mathbf{S}'\mathbf{S} = \mathbf{I}_{\min(\mathbf{N},\mathbf{T})} = \mathbf{R}'\mathbf{R}$$

- **Fact 2.** *The number of non-zero singular value = rank \mathbf{L}*

- Nuclear norm : $\|L\|_* = \sum_{i=1}^{\min(N,T)} \sigma_i(\mathbf{L})$

\rightarrow minimize $\lambda\|L\|_* \Leftrightarrow$ the sparsity of Singular value $\sigma_i(\mathbf{L})(> 0) \Leftrightarrow$ low rank of \mathbf{L}

- Since the rank of \mathbf{L} corresponds to **the number of factor**, this assumption of low rank is quite plausible.
- Although the law rank matrix CAN include two fixed effects, these "strong" factors are separately estimated for improving the quality of the practical imputations.

Algorithm for calculating $\hat{\mathbf{L}}$

- For simplicity, assume that there are no fixed effects. (only estimate \mathbf{L})
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The relationship with horizontal and vertical regressions

- Let the estimand \mathbf{Y} partition as $\begin{pmatrix} \mathbf{Y}_0 & \mathbf{y}_1 \\ \mathbf{y}_2' & ? \end{pmatrix}$,
where $\mathbf{Y}_0 \in \mathbb{R}^{N-1} \times \mathbb{R}^{T-1}$, $\mathbf{y}_1 \in \mathbb{R}^{N-1}$, $\mathbf{y}_2 \in \mathbb{R}^{T-1}$.
- For a given positive integer R , define an $N \times R$ matrix \mathbf{A} , an $T \times R$ matrix \mathbf{B} , a N -dim. vector γ and a R -dim. vector δ , then, the objective function w.r.t. MSE is

$$Q(\mathbf{Y}; R, \mathbf{A}, \mathbf{B}, \gamma, \delta) = \frac{1}{|\mathcal{O}|} \|\mathbf{P}_{\mathcal{O}}(\mathbb{Y} - \mathbf{A}\mathbf{B}' - \gamma\mathbf{1}_T' - \mathbf{1}_N\delta')\|_F^2$$

- Nuclear norm matrix completion

$$\begin{aligned} (R_\lambda^{\text{mc-nnm}}, \mathbf{A}_\lambda^{\text{mc-nnm}}, \mathbf{B}_\lambda^{\text{mc-nnm}}, \gamma_\lambda^{\text{mc-nnm}}, \delta_\lambda^{\text{mc-nnm}}) \\ = \arg \min_{R, \mathbf{A}, \mathbf{B}, \gamma, \delta} \left\{ Q(\mathbf{Y}; R, \mathbf{A}, \mathbf{B}, \gamma, \delta) + \frac{\lambda}{2} \|\mathbf{A}\|_F^2 + \frac{\lambda}{2} \|\mathbf{B}\|_F^2 \right\}. \end{aligned}$$

- **Fact 3.** $\|\mathbf{L}\|_* = \min_{\mathbf{A}, \mathbf{B}: \mathbf{L} = \mathbf{A}\mathbf{B}'} \frac{1}{2} (\|\mathbf{A}\|_F^2 + \|\mathbf{B}\|_F^2).$

Horizontal regression (thin matrix, $N > T$)

- Horizontal regression estimator

$$(R^{hr}, \mathbf{A}^{hr}, \mathbf{B}^{hr}, \gamma^{hr}, \delta^{hr}) = \arg \min_{R, \mathbf{A}, \mathbf{B}, \gamma, \delta} Q(\mathbf{Y}; R, \mathbf{A}, \mathbf{B}, \gamma, \delta),$$

$$\text{subject to } R = T - 1, \quad \mathbf{A} = \begin{pmatrix} \mathbf{Y}_0 \\ y_2^\top \end{pmatrix}, \quad \gamma = 0, \quad \delta_1 = \cdots = \delta_{T-1} = 0.$$

- The solution for \mathbf{B} is

$$\mathbf{B}^{hr\top} = \begin{pmatrix} E_{T-1} & \hat{\beta} \end{pmatrix}, \quad (\hat{\beta}, \hat{\delta}_T) = \arg \min_{\beta, \delta_T} \sum_{i=1}^{N-1} \left(Y_{iT} - \delta_T - \sum_{t=1}^{T-1} \beta_t Y_{it} \right)^2.$$

- Vertical regression, defined if $T > N$: fat matrix

(iv) (synthetic control),

$$(R^{\text{sc-adh}}, \mathbf{A}^{\text{sc-adh}}, \mathbf{B}^{\text{sc-adh}}, \gamma^{\text{sc-adh}}, \delta^{\text{sc-adh}}) \\ = \underset{R, \mathbf{A}, \mathbf{B}, \gamma, \delta}{\operatorname{argmin}} Q(\mathbf{Y}; R, \mathbf{A}, \mathbf{B}, \gamma, \delta),$$

subject to

$$R = N - 1, \quad \mathbf{B} = \begin{pmatrix} \mathbf{Y}_0^\top \\ \mathbf{y}_1^\top \end{pmatrix}, \quad \delta = 0, \quad \gamma = 0, \\ \forall i, A_{iT} \geq 0, \quad \sum_{i=1}^{N-1} A_{iT} = 1,$$

(v) (vertical regression, elastic net),

$$(R^{\text{vt-en}}, \mathbf{A}^{\text{vt-en}}, \mathbf{B}^{\text{vt-en}}, \gamma^{\text{vt-en}}, \delta^{\text{vt-en}}) \\ = \underset{R, \mathbf{A}, \mathbf{B}, \gamma, \delta}{\operatorname{argmin}} \left\{ Q(\mathbf{Y}; R, \mathbf{A}, \mathbf{B}, \gamma, \delta) \right. \\ \left. + \lambda \left[\frac{1-\alpha}{2} \left\| \begin{pmatrix} \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} \right\|_F^2 + \alpha \left\| \begin{pmatrix} \mathbf{a}_2 \\ \mathbf{a}_3 \end{pmatrix} \right\|_1 \right] \right\},$$

subject to

$$R = N - 1, \quad \mathbf{B} = \begin{pmatrix} \mathbf{Y}_0^\top \\ \mathbf{y}_1^\top \end{pmatrix}, \\ \gamma_1 = \gamma_2 = \dots = \gamma_{N-1} = 0, \quad \delta = 0,$$

where \mathbf{A} is partitioned as

$$\mathbf{A} = \begin{pmatrix} \tilde{\mathbf{A}} & \mathbf{a}_1 \\ \mathbf{a}_2^\top & \mathbf{a}_3 \end{pmatrix},$$

Theoretical Bounds for the Estimation Error

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Two illustrations

Comparing each method

- In a real data matrix \mathbf{Y} where **no units is treated**, we choose units as "hypothetical treated" units (=regard as missing) and aim to predict (impute) their value.
→ Technically, compare the average root-mean-squared-error(RMSE) to assess which of the algorithm generally perform well.
- The compared estimators (algorithms) are as follows.
 - DiD : 2 回差分により counterfactual を補完する
 - VT-EN : elastics net で vertical regression function を作り、その推定値で補完
 - HR-EN : elastics net で horizontal regression function を作り、その推定値で補完
 - SC-ADH : classical approach to construct "synthetic control".
 - MC-NNM : 本日の主役

ADH(2010): California smoking data

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References

References

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