

Topic 5: Two-Way Cluster-Robust (TWCR) Standard Errors

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Key points: The validity of Two-Way Cluster-Robust (TWCR) standard errors

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5.1 One-Way Clustering

First, consider the case of one-way clustering. The linear model with one-way clustering

$$y_{ig} = \mathbf{x}_{ig}\boldsymbol{\beta} + u_{ig}$$

where i denotes the i th of the N individuals in the sample, j denotes the g th of the G clusters, assume that

- $\mathbb{E}[u_{ig} | \mathbf{x}_{ig}] = 0$
- error independence across clusters: for $i \neq j$

$$\mathbb{E}[u_{ig}u_{jg'} | \mathbf{x}_{ig}, \mathbf{x}_{jg'}] = 0 \quad (5.1)$$

unless $g = g'$, that is, errors for individuals within the same cluster may be correlated.

Grouping observations by cluster, get

$$\mathbf{y}_g = \mathbf{X}_g\boldsymbol{\beta} + \mathbf{u}$$

where \mathbf{X}_g has dimension $N_g \times K$ and \mathbf{y}_g has dimension $N_g \times 1$, with N_g observations in cluster g . Stacking over cluster, get the matrix form of the model

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{u}$$

with \mathbf{y}, \mathbf{u} being $N \times 1$ vectors, \mathbf{X} being an $N \times K$ matrix. OLS estimator gives

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}'\mathbf{y} = \left(\sum_{g=1}^G \mathbf{X}_g' \mathbf{X}_g \right)^{-1} \sum_{g=1}^G \mathbf{X}_g' \mathbf{y}_g \quad (5.2)$$

then, by CLT, we have that $\sqrt{G}(\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}) \xrightarrow{d} \mathcal{N}(0, \boldsymbol{\Sigma})$ where the variance matrix of the limit normal distribution $\boldsymbol{\Sigma}$ is

$$\left(\lim_{G \rightarrow \infty} \frac{1}{G} \sum_{g=1}^G \mathbb{E}[\mathbf{X}_g' \mathbf{X}_g] \right)^{-1} \left(\lim_{G \rightarrow \infty} \frac{1}{G} \sum_{g=1}^G \mathbb{E}[\mathbf{X}_g' \mathbf{u}_g' \mathbf{u}_g \mathbf{X}_g] \right) \times \left(\lim_{G \rightarrow \infty} \frac{1}{G} \sum_{g=1}^G \mathbb{E}[\mathbf{X}_g' \mathbf{X}_g] \right)^{-1} \quad (5.3)$$

If the primary source of clustering is due to group-level common shocks, a useful approximation is that for the j th regressor, the default OLS variance estimate based on $s^2(\mathbf{X}'\mathbf{X})^{-1}$ should be inflated by $\tau_j \approx 1 + \rho_{x_j}\rho_u(\bar{N}_g - 1)$, where

- s is the estimated standard deviation of the error

- ρ_{x_j} is a measure of within-cluster correlation of x_j
- ρ_u is the within-cluster error correlation
- \bar{N}_g is the average cluster size

It's easy to see the τ_j can be large even with small ρ_u (Kloek, 1981; Scott and Holt, 1982; Moulton, 1990). If assume the model for the cluster error variance matrices $\mathbf{\Omega}_g = \mathbb{V}[\mathbf{u}_g | \mathbf{X}_g] = \mathbb{E}[\mathbf{u}_g \mathbf{u}_g' | \mathbf{X}_g]$, and there is a consistent estimate $\hat{\mathbf{\Omega}}_g$ of $\mathbf{\Omega}_g$, we can estimate $\mathbb{E}[\mathbf{X}_g' \mathbf{u}_g \mathbf{u}_g' \mathbf{X}_g] = \mathbb{E}[\mathbf{X}_g' \mathbf{\Omega}_g \mathbf{X}_g]$ via GLS.

Cluster-robust variance matrix estimate consider

$$\hat{\mathbb{V}}[\hat{\beta}] = (\mathbf{X}'\mathbf{X})^{-1} \left(\sum_{g=1}^G \mathbf{X}_g' \hat{\mathbf{u}}_g \hat{\mathbf{u}}_g' \mathbf{X}_g \right) (\mathbf{X}'\mathbf{X})^{-1} \quad (5.4)$$

where $\hat{\mathbf{u}}_g = \mathbf{y}_g - \mathbf{X}_g \hat{\beta}$. This estimate is consistent if

$$G^{-1} \sum_{g=1}^G \mathbf{X}_g' \hat{\mathbf{u}}_g \hat{\mathbf{u}}_g' \mathbf{X}_g - G^{-1} \sum_{g=1}^G \mathbb{E}[\mathbf{X}_g' \mathbf{u}_g \mathbf{u}_g' \mathbf{X}_g] \xrightarrow{P} \mathbf{0}$$

as $G \rightarrow \infty$. An informal presentation of Eq.(5.4) is to rewrite the central matrix as

$$\hat{\mathbf{B}} = \sum_{g=1}^G \mathbf{X}_g' \hat{\mathbf{u}}_g \hat{\mathbf{u}}_g' \mathbf{X}_g = \mathbf{X}' \begin{bmatrix} \hat{\mathbf{u}}_1 \hat{\mathbf{u}}_1' & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{u}}_2 \hat{\mathbf{u}}_2' & & \vdots \\ \vdots & & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & & \hat{\mathbf{u}}_G \hat{\mathbf{u}}_G' \end{bmatrix} \mathbf{X} = \mathbf{X}' (\hat{\mathbf{u}} \hat{\mathbf{u}}' \otimes \mathbf{S}^G) \mathbf{X} \quad (5.5)$$

where \otimes denotes element-wise multiplication. The (p, q) th element of this matrix is

$$\sum_{i=1}^N \sum_{j=1}^N x_{ia} x_{jb} \hat{u}_i \hat{u}_j \cdot \mathbf{1}(i, j \text{ in the same cluster})$$

with $\hat{u}_i = y_i - \mathbf{x}_i' \hat{\beta}$.

\mathbf{S}^G is an $N \times N$ indicator matrix with $\mathbf{S}_{ij}^G = 1$ only if the i th and j th observation belong to the same cluster: it zeros out a large amount of $\hat{\mathbf{u}} \hat{\mathbf{u}}'$ (asymptotically equivalently, $\mathbf{u} \mathbf{u}'$), specifically, only $\sum_{g=1}^G N_g^2$ out of $N^2 = \left(\sum_{g=1}^G N_g \right)^2$ terms are not zero (sub-matrices on the diagonal). Asymptotically

- for fixed N_g , $\frac{1}{N^2} \sum_{g=1}^G N_g^2 \xrightarrow{G \rightarrow \infty} 0$
- for balanced clusters $N_g = N/G$, $\frac{1}{N^2} \sum_{g=1}^G N_g^2 = \frac{1}{G} \xrightarrow{G \rightarrow \infty} 0$

A strand of literature popularizes this method:

- Liang and Zeger (1986): in a generalized estimatin equations setting
- Arellano (1987): fixed effects estimator in linear panel models
- Hansen (2007): asymptotic theory for panel data where $T \rightarrow \infty$ in addition to $N \rightarrow \infty$ (or $N_g \rightarrow \infty$ in addition to $G \rightarrow \infty$ in the notation above).

5.2 Two-Way Clustering

Now, consider the case of two-way clustering,

$$y_{i,gh} = \mathbf{x}'_{i,gh} \boldsymbol{\beta} + u$$

where each observation may belong to **two** dimension of groups: group $g \in \{1, \dots, G\}$ and $h \in \{1, \dots, H\}$, and for $i \neq j$

$$\mathbb{E} [u_{i,gh} u_{j,g'h'} \mid \mathbf{x}_{i,gh}, \mathbf{j}, \mathbf{g}'\mathbf{h}'] = 0 \quad (5.6)$$

unless $g = g'$ or $h = h'$, that is, errors for individuals within the same group (along either g or h) may be correlated.

Cluster-robust variance matrix estimate extending the one-way clustering case, keep elements of $\hat{\mathbf{u}}\hat{\mathbf{u}}'$ where the i th and j th observations share a cluster in **any** dimension, then similar to Eq.(5.5)

$$\hat{\mathbf{B}} = \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^{GH} \right) \mathbf{X} \quad (5.7)$$

here \mathbf{S}^{GH} is an $N \times N$ indicator matrix with $\mathbf{S}_{ij}^{GH} = 1$ only if the i th and j th observation share any cluster, the (p, q) th element of this matrix is

$$\sum_{i=1}^N \sum_{j=1}^N x_{ia} x_{jb} \hat{u}_i \hat{u}_j \cdot \mathbf{1}(i, j \text{ share any cluster})$$

$\hat{\mathbf{B}}$ can also be presented in one-way cluster-robust fashion:

$$\hat{\mathbf{B}} = \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^{GH} \right) \mathbf{X} = \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^G \right) \mathbf{X} + \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^H \right) \mathbf{X} - \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^{G \cap H} \right) \mathbf{X} \quad (5.8)$$

where $\mathbf{G}^{GH} = \mathbf{G}^G + \mathbf{G}^H - \mathbf{G}^{G \cap H}$, with

- \mathbf{G}^G : $\mathbf{G}_{ij}^G = 1$ only if the i th and j th observation belong to the same cluster $g \in \{1, 2, \dots, G\}$
- \mathbf{G}^H : $\mathbf{G}_{ij}^H = 1$ only if the i th and j th observation belong to the same cluster $h \in \{1, 2, \dots, H\}$
- $\mathbf{G}^{G \cap H}$: $\mathbf{G}_{ij}^{G \cap H} = 1$ only if the i th and j th observation belong to **both** the same cluster $g \in \{1, 2, \dots, G\}$ and the same cluster $h \in \{1, 2, \dots, H\}$

then, similar to one-way clustering case,

$$\begin{aligned} \hat{\mathbf{V}}[\hat{\boldsymbol{\beta}}] &= (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^G \right) \mathbf{X} (\mathbf{X}'\mathbf{X})^{-1} \\ &\quad + (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^H \right) \mathbf{X} (\mathbf{X}'\mathbf{X})^{-1} \\ &\quad - (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}' \left(\hat{\mathbf{u}}\hat{\mathbf{u}}' \otimes \mathbf{S}^{G \cap H} \right) \mathbf{X} (\mathbf{X}'\mathbf{X})^{-1} \end{aligned} \quad (5.9)$$

that is,

$$\hat{\mathbf{V}}[\hat{\boldsymbol{\beta}}] = \hat{\mathbf{V}}^G[\hat{\boldsymbol{\beta}}] + \hat{\mathbf{V}}^H[\hat{\boldsymbol{\beta}}] - \hat{\mathbf{V}}^{G \cap H}[\hat{\boldsymbol{\beta}}] \quad (5.10)$$

each of Eq.(5.10) can be separately computed by OLS of \mathbf{y} on \mathbf{X} , with variance matrix estimates $\hat{\mathbf{V}}$ based on

- clustering on $g \in \{1, 2, \dots, G\}$
- clustering on $h \in \{1, 2, \dots, H\}$
- clustering on $(g, h) \in \{(1, 1), \dots, (G, H)\}$

Practical considerations It is required to know what *ways* will be potentially important for clustering, which can be tested via checking the dimension of correlations in the errors. There are several ways to test

- estimate sample covariances of $\mathbf{X}'\hat{\mathbf{u}}$ within dimensions, test the null that the **average** of such covariances is 0: rejecting this null is sufficient (not necessary) to reject the null of no clustering (White, 1980)
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