

Module 9.3: Time Series Analysis

Fall Term 2022

Week 7:

Cointegration

Outline in Weeks

- ➊ Introduction; Descriptive Modelling
- ➋ Returns; Autocorrelation; Stationarity
- ➌ ARMA Models
- ➍ Unit Roots; Regressions between Time Series
- ➎ Volatility Modelling
- ➏ Value at Risk
- ➐ Cointegration
- ➑ Panel Data

Outline

- 1 Cointegration and Common Trends
- 2 Error Correction Models and the Engle-Granger Procedure
- 3 Johansen's Procedure
- 4 Epilogue

Cointegration and Common Trends

Suppose we have two time series Y_t and X_t , which are both $I(1)$, and we analyze a regression model of the form

$$Y_t = \beta_1 + \beta_2 X_t + U_t.$$

Here U_t has mean zero but may display autocorrelation. Two cases:

- $U_t \sim I(1)$: if U_t displays no mean-reversion, then Y_t does not revert to the explained part $\beta_1 + \beta_2 X_t$. Even if $\beta_2 = 0$, its t -statistic and R^2 will often seem significant (*spurious regressions*). To avoid this, one should estimate a model in differences, i.e., $\Delta Y_t = a_1 + a_2 \Delta X_t + \Delta U_t$.
- $U_t \sim I(0)$: now Y_t and X_t have a *common* stochastic trend, such that the linear combination $Y_t - \beta_2 X_t$ does not have a trend. This is called *cointegration*.

Example

- Consider the model

$$Y_t = \beta_1 + \beta_2 X_t + U_{1,t}$$
$$X_t = X_{t-1} + U_{2,t}$$

where $\beta_2 \neq 0$, $U_{1,t}, U_{2,t} \stackrel{\text{iid}}{\sim} (0, \sigma^2)$ independently of each other.

- X_t is a random walk and thus nonstationary. Y_t contains X_t and is thus also nonstationary. But

$$Y_t - \beta_2 X_t = \beta_1 + U_{1,t}$$

is stationary: the RHS is white noise plus a constant.

- $(1, -\beta_2)$ is called the *cointegrating vector*.

Cointegration and Common Trends, contd.

- The concept is easily extended to more than two series: if X_{2t}, \dots, X_{kt} are all $I(1)$ variables, and

$$Y_t = \beta_1 + \beta_2 X_{2t} + \dots + \beta_k X_{kt} + U_t,$$

then this is a spurious regression if $U_t \sim I(1)$ (and $\beta_i = 0$), and a cointegrating relation if U_t is stationary.

- In other words, cointegration between k integrated series means that there exists a *linear combination*¹ of them which is stationary.
- Examples of possibly cointegrated time series:
 - exchange rates and relative prices (*purchasing power parity*);
 - spot and futures prices of assets or exchange rates;
 - short- and long-term interest rates (*term structure models*);
 - stock prices and dividends (*present value relations*).

¹i.e., a weighted sum

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Testing for Cointegration

- For cointegrated series, one should exploit the long-run equilibrium relationship between variables for estimation rather than differencing. Differencing would *remove* that structure.
- Engle and Granger proposed the following procedure:
 - Conduct individual unit root tests to ensure all series are $I(1)$.
 - Estimate the regression model

$$Y_t = \beta_1 + \beta_2 X_{2t} + \dots + \beta_k X_{kt} + U_t$$

by ordinary least-squares. Estimates are (super)consistent, but standard errors are wrong because series are $I(1)$.

- Apply an ADF unit root test (with constant) to the residuals \hat{u}_t from this regression. This yields a test for $H_0 : U_t \sim I(1)$ (spurious regression) against $H_1 : U_t \sim I(0)$ (cointegration). The critical values depend on k . E.g., for $k = 2$ (X_{2t} and an intercept), the 5% c.v. is -3.41.
- If H_0 is rejected, estimate an *error correction model*.

Engle-Granger critical values

Number of series (w/o constant)	2	3	4	5	6
Critical value	-3.41	-3.80	-4.16	-4.49	-4.74

Error Correction Models

- Cointegration between Y_t and X_t implies that deviations ($Y_{t-1} - \beta_1 - \beta_2 X_{t-1}$) from the equilibrium level should be (partially) corrected in the next period, by Y_t , X_t , or both.
- This leads to a *vector error correction model* (VECM), which in the simplest form is

$$\begin{aligned}\Delta Y_t &= c_1 + \alpha_1(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + e_{1t}, \\ \Delta X_t &= c_2 + \alpha_2(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + e_{2t},\end{aligned}$$

where e_{1t} and e_{2t} are two white noise errors (possibly correlated), and where we expect $\alpha_1 < 0$ and/or $\alpha_2\beta_2 > 0$.

- We might need to add lags of ΔY_t and/or ΔX_t on RHS to combat autocorrelation.
- The *Granger representation theorem* states that cointegration implies an error correction model (possibly with more lags), and vice versa; see exercises.

Engle-Granger Procedure

- The VECM

$$\Delta Y_t = c_1 + \alpha_1(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + e_{1t},$$

$$\Delta X_t = c_2 + \alpha_2(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + e_{2t}.$$

is estimated by replacing $Y_{t-1} - \beta_1 - \beta_2 X_{t-1}$ by OLS residual $\hat{u}_{t-1} = Y_{t-1} - \hat{\beta}_1 - \hat{\beta}_2 X_{t-1}$, and estimating α_1 and α_2 by OLS.

- Note that \hat{u} is stationary, so this is a valid regression!
- If $\alpha_2 = 0$, then all correction is done by Y_t , and not by X_t . In that case it makes sense to treat X_t as exogenous and Y_t as endogenous, and consider the “single-equation” error correction model

$$\Delta Y_t = c + \alpha_1(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + e_t.$$

- In general, both Y_t and X_t are endogenous.

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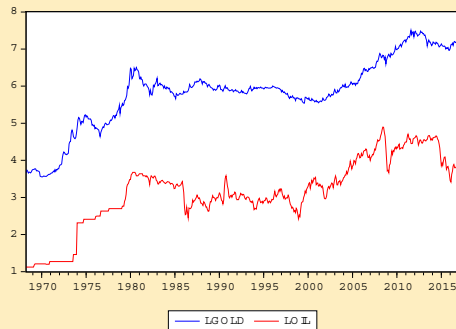
Example

- Until 1971, as part of the Bretton-Woods system of fixed exchange rates, the US dollar was convertible to gold, i.e., it was possible for foreign central banks to redeem US dollars for gold at a fixed rate of 35\$ per troy ounce, so that the price of gold was fixed.
- In 1971, US president Nixon unilaterally cancelled the direct convertibility, ultimately ending the Bretton-Woods agreement.
- Gold became a floating asset, and its price increased sharply; in other words, the US\$ was massively devalued.

Example continued

- We want to analyze the hypothesis that the increasing price (in US\$) of oil is not a consequence of an increased demand for (or a reduced supply of) oil, but rather of a continued devaluation of the US\$.
- We have at our disposal monthly data from April 1968 to January 2017 (586 observations) on the following variables:
 - gold_t , the spot price of one troy ounce of gold in US\$;
 - oil_t , the spot price of one barrel of WTI crude oil in US\$.
- Idea: if the relative price of oil expressed in units of gold $\text{oil}_t/\text{gold}_t$ is stationary, then this implies that $\log(\text{oil}_t) - \log(\text{gold}_t)$ is stationary, so that $\log(\text{oil}_t)$ and $\log(\text{gold}_t)$ must be cointegrated if the individual series are integrated.

$\log(\text{gold}_t)$ and $\log(\text{oil}_t)$



Example continued

Step 0 Take logs: `genr lgold = log(gold)`, `genr loil = log(oil)`.

Step 1 Test that the variables are integrated (ADF test with constant and trend)

Null Hypothesis: LOIL has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 1 (Automatic - based on SIC, maxlag=18)

	t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic	-2.552422	0.3027
Test critical values: 1% level	-3.973847	
5% level	-3.417533	
10% level	-3.131184	

*Mackinnon (1996) one-sided p-values.

Null Hypothesis: LGOLD has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 0 (Automatic - based on SIC, maxlag=18)

	t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic	-1.820648	0.6937
Test critical values: 1% level	-3.973820	
5% level	-3.417519	
10% level	-3.131176	

*Mackinnon (1996) one-sided p-values.

Neither test rejects, so the series are $I(1)$.

Example continued

Step 2 Estimate long-run relationship

$$\text{loil}_t = \beta_1 + \beta_2 \text{lgold}_t + U_t$$

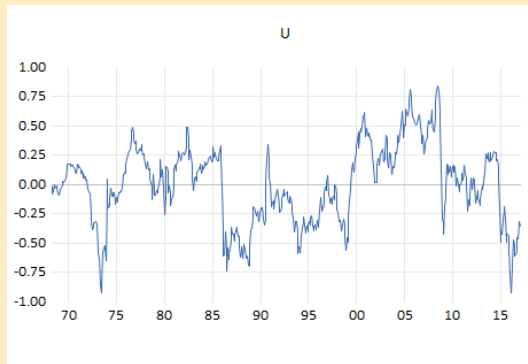
and save the residuals (Proc→Make Residual Series→Ordinary) as u.

Dependent Variable: LOIL				
Method: Least Squares				
Date: 11/30/20 Time: 16:50				
Sample: 1968M04 2017M01				
Included observations: 586				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-2.258963	0.086329	-26.16698	0.0000
LGOLD	0.926232	0.014618	63.36354	0.0000
R-squared	0.873014	Mean dependent var	3.141848	
Adjusted R-squared	0.872797	S.D. dependent var	0.929639	
S.E. of regression	0.331561	Akaike info criterion	0.633398	
Sum squared resid	64.20072	Schwarz criterion	0.648324	
Log likelihood	-183.5855	Hannan-Quinn criter.	0.639214	
F-statistic	4014.938	Durbin-Watson stat	0.074317	
Prob(F-statistic)	0.000000			

The cointegrating vector is $(1, -\beta_2) = (1, -0.926)$ (if the Engle-Granger test rejects).
Careful: standard errors are wrong, because variables are $I(1)$.

Example continued

Residuals (=equilibrium error) \hat{u}_t



Example continued

Step 3 Apply ADF test (with intercept) to u_t .

Null Hypothesis: u has a unit root
Exogenous: Constant
Lag Length: 1 (Automatic - based on SIC, maxlag=18)

	t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic	-3.724771	0.0040
Test critical values:		
1% level	-3.441318	
5% level	-2.866270	
10% level	-2.569348	

*MacKinnon (1996) one-sided p-values.

Careful: we need to use Engle-Granger 5% critical value of -3.41 , not the ones given by EViews. Conclusion: test rejects the null of “no cointegration”.

Example continued

Step 4 Estimate VECM. Note: I threw in a lag of the dependent variable in the equation for $d(\text{loil})$, as there was autocorrelation without it (cf. selected lag length in ADF test).

Dependent Variable: D(LOIL)
Method: Least Squares
Date: 11/30/20 Time: 17:09
Sample (adjusted): 1968M06 2017M01
Included observations: 584 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.003641	0.003278	1.110606	0.2672
U(-1)	-0.034971	0.009942	-3.517509	0.0005
D(LOIL(-1))	0.256547	0.040092	6.399038	0.0000
R-squared	0.077666	Mean dependent var	0.004862	
Adjusted R-squared	0.074491	S.D. dependent var	0.082210	
S.E. of regression	0.079089	Akaike info criterion	-2.231362	
Sum squared resid	3.634195	Schwarz criterion	-2.208914	
Log likelihood	654.5578	Hannan-Quinn criter.	-2.222613	
F-statistic	24.46179	Durbin-Watson stat	2.006622	
Prob(F-statistic)	0.000000			

Dependent Variable: D(LGOLD)
Method: Least Squares
Date: 11/30/20 Time: 17:17
Sample (adjusted): 1968M05 2017M01
Included observations: 585 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.005866	0.002342	2.504458	0.0125
U(-1)	0.008997	0.007077	1.271298	0.2041
R-squared	0.002765	Mean dependent var	0.005871	
Adjusted R-squared	0.001054	S.D. dependent var	0.056676	
S.E. of regression	0.056646	Akaike info criterion	-2.900562	
Sum squared resid	1.870743	Schwarz criterion	-2.885616	
Log likelihood	850.4143	Hannan-Quinn criter.	-2.894737	
F-statistic	1.616198	Durbin-Watson stat	1.932704	
Prob(F-statistic)	0.204130			

The adjustment coefficient α_2 in the equation for $d(\text{lgold})$ is insignificant. So all the adjustment is done by $\text{loil} \rightarrow$ single-equation ECM.

Example continued

- The final model is the single-equation ECM

$$\Delta \text{loil}_t = 0.0036 - 0.035(\text{loil}_{t-1} - 0.926 \text{lgold}_{t-1} + 2.26) + 0.25 \Delta \text{loil}_{t-1} + e_{1t}$$

In our earlier notation,

$$\Delta Y_t = c + \alpha_1(Y_{t-1} - \beta_1 - \beta_2 X_{t-1}) + \gamma \Delta Y_{t-1} + e_{1t},$$

with $c = 0.0036$, $\alpha_1 = -0.035 < 0$ as desired, $\beta_1 = -2.26$, $\beta_2 = 0.926$, and $\gamma = 0.25$.

- Interpretation: there is an equilibrium relationship between *loil* and *lgold*. In case of a disequilibrium, *loil* adjusts towards the equilibrium. The adjustment amounts to 3.5% per period.

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Limitations of Engle-Granger Procedure:

- Choice of the dependent variable Y_t in Engle-Granger test is arbitrary. Selecting another X_{it} as dependent variable should not matter asymptotically (as number of observations $T \rightarrow \infty$), but will make a difference in practice.
- Method can only be used if there is only a single unique cointegrating relation, which involves Y_t . So (X_{2t}, \dots, X_{kt}) are not allowed to be cointegrated without Y_t .
- Although the OLS estimators $\hat{\beta}_i$ are consistent under cointegration, they do not have an asymptotic normal distribution, so standard inference (t -tests) fails.

Johansen Procedure

- An alternative is to use *Johansen's procedure*.
- Johansen has derived the MLE of the general VECM with normally distributed errors \mathbf{u}_t and k variables.
- This facilitates likelihood ratio tests for H_{0r} : “ r or fewer cointegrating relationships” against the alternative “more than r ”
- The test is known as the *Johansen trace test*. The test statistics $\lambda_{trace}(r)$ can be expressed in terms of particular eigenvalues $\hat{\lambda}_j$. Their asymptotic distribution under the null is a multivariate version of the Dickey-Fuller distribution.
- We reject for large positive values of the test statistic; critical values and p -values are built into EViews and similar programs.

Johansen's cointegration test

These tests may be used to estimate the cointegrating rank r in the following way:

- 1 Start with $r = 0$;
- 2 Test H_{0r} with $\lambda_{trace}(r)$;
- 3 If H_{0r} is not rejected, then $\hat{r} = r$; if it is rejected, replace r by $r + 1$ and go back to step 2;
- 4 If H_{0r} is rejected for all $r = 0, 1, \dots, k - 1$, then conclude $\hat{r} = k$ (this corresponds to a stationary system).

Treatment of constant and linear trend

Just like with the Dickey-Fuller test, we have to allow for a constant and possibly a linear trend in the VECM. Eviews distinguishes five cases:

- 1 No constant, no trend. This implies that the variables have mean zero. Rarely applicable.
- 2 Constant in the cointegrating relations, no trend. Applicable when the data have no trend (interest rates, inflation, real exchange rates).
- 3 Constant in the VECM equation. This leads to a drift, so applicable for trending series (real gdp, stock prices). This is the default, for good reasons.
- 4 Constant in VECM, trend in cointegration relations. Similar to 3, but hard to interpret.
- 5 Trend in the VECM equation. Leads to a quadratic trend. Rarely applicable.

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Example continued

Step 1 Apply Johansen integration test.

Choose Option 3 (unrestricted constant) and one lagged Δ on RHS (lag specification 1), because that's what we found in the Engle-Granger approach.

Johansen test

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.024313	17.92430	15.49471	0.0211
At most 1	0.006060	3.549966	3.841465	0.0595
Trace test indicates 1 cointegrating eqn(s) at the 0.05 level				
* denotes rejection of the hypothesis at the 0.05 level				
**MacKinnon-Haug-Michelis (1999) p-values				

H_{00} : “No Cointegration” is rejected. H_{01} : “One cointegrating relationship” is not.
Conclusion: there is one cointegrating (=equilibrium) relationship.

Example continued

Step 2 Estimate VECM. Choose “1 cointegrating relationship”, and lag specification 1 1.

Vector Error Correction Estimates
Date: 11/30/20 Time: 17:32
Sample (adjusted): 1968M06 2017M01
Included observations: 584 after adjustments
Standard errors in () & t-statistics in []

Cointegrating Eq:		CointEq1
LOIL(-1)	1.000000	
LGOLD(-1)	-0.914126 (0.09263) [-9.86821]	
C	2.187722	
Error Correction:		D(LOIL) D(LGOLD)
CointEq1	-0.034498 (0.00997) [-3.46000]	0.007463 (0.00713) [1.04641]
D(LOIL(-1))	0.250758 (0.04063) [6.17135]	0.048515 (0.02906) [1.66924]
D(LGOLD(-1))	0.050704 (0.05870) [0.86374]	0.019596 (0.04199) [0.46668]
C	0.003354 (0.00329) [1.01839]	0.005412 (0.00236) [2.29777]

Example continued

- Final model is

$$\begin{aligned}\Delta \text{loil}_t &= 0.0034 - 0.034(\text{loil}_{t-1} - 0.914\text{lgold}_{t-1} + 2.19) + 0.25\Delta \text{loil}_{t-1} + 0.05\Delta \text{lgold}_{t-1} + e_{1t} \\ \Delta \text{lgold}_t &= 0.0054 - 0.007(\text{loil}_{t-1} - 0.914\text{lgold}_{t-1} + 2.19) + 0.049\Delta \text{loil}_{t-1} + 0.019\Delta \text{lgold}_{t-1} + e_{2t}\end{aligned}$$

- Note how similar the first equation is to what we found with Engle-Granger! Here, too, $\alpha_2 = -0.007$ is insignificant, so we could ignore the 2nd equation.
- The cointegrating vector is $(1, -0.914)$.
- Interpretation: there is an equilibrium relationship between loil and lgold . In case of a disequilibrium, loil adjusts towards the equilibrium. The adjustment amounts to 3.4% per period.

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Learning Goals

Students

- Understand the concept of cointegration,
- are able to test for cointegration using both the Engle-Granger procedure and the Johansen test,
- and are able to estimate an error correction model.

Homework

- Exercise 7
- Problem 6 from Chapter 8 of Brooks (2019)