02_arima_models

September 29, 2021

1 Univariate ARIMA Models

[1]:
```python
import warnings
warnings.filterwarnings('ignore')
```

[2]:
```python
%matplotlib inline

from tqdm import tqdm
from itertools import product
import pandas as pd
import pandas_datareader.data as web
import numpy as np
from numpy.linalg import LinAlgError

import statsmodels.tsa.api as tsa
from statsmodels.graphics.tsaplots import plot_acf, plot_pacf
from statsmodels.tsa.stattools import acf, q_stat, adfuller
from scipy.stats import probplot, moment
from sklearn.metrics import mean_squared_error

import matplotlib.pyplot as plt
import seaborn as sns
```

[3]:
```python
sns.set_style('whitegrid')
```

[4]:
```python
def plot_correlogram(x, lags=None, title=None):
    lags = min(10, int(len(x)/5)) if lags is None else lags
    fig, axes = plt.subplots(nrows=2, ncols=2, figsize=(14, 8))
    x.plot(ax=axes[0][0], title='Residuals')
    x.rolling(21).mean().plot(ax=axes[0][0], c='k', lw=1)
    q_p = np.max(q_stat(acf(x, nlags=lags), len(x))[1])
    stats = f'Q-Stat: {np.max(q_p):>8.2f}\nADF: {adfuller(x)[1]:>11.2f}'
    axes[0][0].text(x=.02, y=.85, s=stats, transform=axes[0][0].transAxes)
    probplot(x, plot=axes[0][1])
    mean, var, skew, kurtosis = moment(x, moment=[1, 2, 3, 4])
    s = f'Mean: {mean:>12.2f}\nSD: {np.sqrt(var):>16.2f}\nSkew: {skew:12.
↪2f}\nKurtosis:{kurtosis:9.2f}'
```

```
    axes[0][1].text(x=.02, y=.75, s=s, transform=axes[0][1].transAxes)
    plot_acf(x=x, lags=lags, zero=False, ax=axes[1][0])
    plot_pacf(x, lags=lags, zero=False, ax=axes[1][1])
    axes[1][0].set_xlabel('Lag')
    axes[1][1].set_xlabel('Lag')
    fig.suptitle(title, fontsize=14)
    sns.despine()
    fig.tight_layout()
    fig.subplots_adjust(top=.9)
```

1.1 Download Series

Load monthly industrial production and daily NASDAQ stock market index:

[5]:
```
industrial_production = web.DataReader('IPGMFN', 'fred', '1988', '2017-12').
 ↪squeeze().dropna()
nasdaq = web.DataReader('NASDAQCOM', 'fred', '1990', '2017-12-31').squeeze().
 ↪dropna()
```

1.1.1 Log Transformation

[6]:
```
nasdaq_log = np.log(nasdaq)
industrial_production_log = np.log(industrial_production)
```

1.1.2 Differencing

[7]:
```
nasdaq_log_diff = nasdaq_log.diff().dropna()

# seasonal differencing => yoy instantanteous returns
industrial_production_log_diff = industrial_production_log.diff(12).dropna()
```

1.2 Univariate Time Series Models

1.2.1 Autoregressive (AR) Model

Multiple linear-regression models expressed the variable of interest as a linear combination of predictors or input variables. Univariate time series models relate the value of the time series at the point in time of interest to a linear combination of lagged values of the series and possibly past disturbance terms. While exponential smoothing models are based on a description of the trend and seasonality in the data, ARIMA models aim to describe the autocorrelations in the data. ARIMA(p, d, q) models require stationarity and leverage two building blocks: - Autoregressive (AR) terms consisting of p-lagged values of the time series - Moving average (MA) terms that contain q-lagged disturbances

Chapter 8 introduces the ARIMA building blocks, simple autoregressive (AR) and moving average (MA) models, and explains how to combine them in autoregressive moving-average (ARMA) models that may account for series integration as ARIMA models or include exogenous variables as AR(I)MAX models.

Furthermore, we will illustrate how to include seasonal AR and MA terms to extend the toolbox to also include SARMAX models.

1.2.2 ARMA vs ARIMA

The ARMA model of the undifferenced series produces the same result as the ARIMA model of the differenced series.

[8]:
```
model1 = tsa.ARMA(endog=nasdaq_log_diff, order=(2,2)).fit()
model2 = tsa.ARIMA(endog=nasdaq_log, order=(2,1,2)).fit()
```

```
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```

[9]:
```
model1.params.sort_index() == model2.params.sort_index().values
```

[9]:
```
ar.L1.NASDAQCOM    True
ar.L2.NASDAQCOM    True
const              True
ma.L1.NASDAQCOM    True
ma.L2.NASDAQCOM    True
dtype: bool
```

1.2.3 Seasonal differencing vs SARIMAX

Seasonal differencing has same effect as using SARIMAX w seasonal order (0,1,0,12).

[10]:
```
model1 = tsa.statespace.SARIMAX(industrial_production_log, order=(2,0,2),␣
 ↪seasonal_order=(0,1,0,12)).fit()
model2 = tsa.statespace.SARIMAX(industrial_production_log_diff, order=(2,0,2),␣
 ↪seasonal_order=(0,0,0,12)).fit()
```

```
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packages/statsmodels/base/model.py:566: ConvergenceWarning: Maximum Likelihood
optimization failed to converge. Check mle_retvals
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```

[11]:

```python
model1.params.to_frame('SARIMAX').join(model2.params.to_frame('diff'))
```

[11]:

	SARIMAX	diff
ar.L1	1.765901	1.765978
ar.L2	-0.788175	-0.788255
ma.L1	-0.859266	-0.859608
ma.L2	0.352755	0.353158
sigma2	0.000101	0.000101

1.3 Finding the optimal ARMA lags

1.3.1 Run candidate models

We iterate over various (p, q) lag combinations and collect diagnostic statistics to compare the result.

[12]:

```python
train_size = 120
results = {}
y_true = industrial_production_log_diff.iloc[train_size:]
for p in range(5):
    for q in range(5):
        aic, bic = [], []
        if p == 0 and q == 0:
            continue
        print(p, q)
        convergence_error = stationarity_error = 0
        y_pred = []
        for T in range(train_size, len(industrial_production_log_diff)):
            train_set = industrial_production_log_diff.iloc[T-train_size:T]
            try:
                model = tsa.ARMA(endog=train_set, order=(p, q)).fit()
```

```python
            except LinAlgError:
                convergence_error += 1
            except ValueError:
                stationarity_error += 1

            forecast, _, _ = model.forecast(steps=1)
            y_pred.append(forecast[0])
            aic.append(model.aic)
            bic.append(model.bic)

        result = (pd.DataFrame({'y_true': y_true, 'y_pred': y_pred})
                  .replace(np.inf, np.nan)
                  .dropna())

        rmse = np.sqrt(mean_squared_error(
            y_true=result.y_true, y_pred=result.y_pred))

        results[(p, q)] = [rmse,
                           np.mean(aic),
                           np.mean(bic),
                           convergence_error,
                           stationarity_error]
```

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```
0 1
```

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packages/statsmodels/base/model.py:547: HessianInversionWarning: Inverting
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packages/statsmodels/base/model.py:547: HessianInversionWarning: Inverting
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information was provided, so inferred frequency MS will be used.
  warnings.warn('No frequency information was'
```

```
---------------------------------------------------------------------------
KeyboardInterrupt                         Traceback (most recent call last)
<ipython-input-12-42dd50b45734> in <module>
     13             train_set = industrial_production_log_diff.iloc[T-train_size:
 ↪T]
     14             try:
---> 15                 model = tsa.ARMA(endog=train_set, order=(p, q)).fit()
     16             except LinAlgError:
     17                 convergence_error += 1

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/
 ↪statsmodels/tsa/arima_model.py in fit(self, start_params, trend, method,
 ↪transparams, solver, maxiter, full_output, disp, callback, start_ar_lags,
 ↪**kwargs)
   1025             kwargs.setdefault('m', 12)
   1026             kwargs.setdefault('approx_grad', True)
-> 1027         mlefit = super(ARMA, self).fit(start_params, method=solver,

   1028                                        maxiter=maxiter,
   1029                                        full_output=full_output,
 ↪disp=disp,

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/
 ↪statsmodels/base/model.py in fit(self, start_params, method, maxiter,
 ↪full_output, disp, fargs, callback, retall, skip_hessian, **kwargs)
    517         warn_convergence = kwargs.pop('warn_convergence', True)
```

```
    518         optimizer = Optimizer()
--> 519         xopt, retvals, optim_settings = optimizer._fit(f, score,␣
↪start_params,
    520                                                        fargs, kwargs,
    521                                                        hessian=hess,

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/
↪statsmodels/base/optimizer.py in _fit(self, objective, gradient, start_params,␣
↪fargs, kwargs, hessian, method, maxiter, full_output, disp, callback, retall)
    222
    223         func = fit_funcs[method]
--> 224         xopt, retvals = func(objective, gradient, start_params, fargs,␣
↪kwargs,
    225                              disp=disp, maxiter=maxiter,␣
↪callback=callback,
    226                              retall=retall, full_output=full_output,

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/
↪statsmodels/base/optimizer.py in _fit_lbfgs(f, score, start_params, fargs,␣
↪kwargs, disp, maxiter, callback, retall, full_output, hess)
    627         func = f
    628
--> 629     retvals = optimize.fmin_l_bfgs_b(func, start_params, maxiter=maxiter,

    630                                      callback=callback, args=fargs,
    631                                      bounds=bounds, disp=disp,

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/lbfgsb.py in fmin_l_bfgs_b(func, x0, fprime, args, approx_grad,␣
↪bounds, m, factr, pgtol, epsilon, iprint, maxfun, maxiter, disp, callback,␣
↪maxls)
    195             'maxls': maxls}
    196
--> 197     res = _minimize_lbfgsb(fun, x0, args=args, jac=jac, bounds=bounds,

    198                            **opts)
    199     d = {'grad': res['jac'],

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/lbfgsb.py in _minimize_lbfgsb(fun, x0, args, jac, bounds, disp,␣
↪maxcor, ftol, gtol, eps, maxfun, maxiter, iprint, callback, maxls,␣
↪finite_diff_rel_step, **unknown_options)
    358             # until the completion of the current minimization iteration.
    359             # Overwrite f and g:
--> 360             f, g = func_and_grad(x)
    361         elif task_str.startswith(b'NEW_X'):
    362             # new iteration

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/_differentiable_functions.py in fun_and_grad(self, x)
```

```
    259                 self._update_x_impl(x)
    260             self._update_fun()
--> 261             self._update_grad()
    262             return self.f, self.g
    263 

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/_differentiable_functions.py in _update_grad(self)
    229         def _update_grad(self):
    230             if not self.g_updated:
--> 231                 self._update_grad_impl()
    232                 self.g_updated = True
    233 

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/_differentiable_functions.py in update_grad()
    149                     self._update_fun()
    150                     self.ngev += 1
--> 151                     self.g = approx_derivative(fun_wrapped, self.x, f0=self
↪f,
    152                                                **finite_diff_options)
    153 

~/.pyenv/versions/miniconda3-latest/envs/ml4t/lib/python3.8/site-packages/scipy/
↪optimize/_numdiff.py in approx_derivative(fun, x0, method, rel_step, abs_step ␣
↪f0, bounds, sparsity, as_linear_operator, args, kwargs)
    463             else:
    464                 # user specifies an absolute step
--> 465                 sign_x0 = (x0 >= 0).astype(float) * 2 - 1
    466                 h = abs_step
    467 

KeyboardInterrupt:
```

[ ]:
```python
arma_results = pd.DataFrame(results).T
arma_results.columns = ['RMSE', 'AIC', 'BIC', 'convergence', 'stationarity']
arma_results.index.names = ['p', 'q']
arma_results.info()
```

[ ]:
```python
with pd.HDFStore('arima.h5') as store:
    store.put('arma', arma_results)
```

We aim to minimize both RMSE and BIC:

[ ]:
```python
arma_results.nsmallest(5, columns=['RMSE'])
```

[ ]:
```python
arma_results.nsmallest(5, columns=['BIC'])
```

[ ]:
```
fig, axes = plt.subplots(ncols=2, figsize=(10,4), sharex=True, sharey=True)
sns.heatmap(arma_results[arma_results.RMSE<.5].RMSE.unstack().mul(10), fmt='.
↪3f', annot=True, cmap='Blues', ax=axes[0], cbar=False);
sns.heatmap(arma_results.BIC.unstack(), fmt='.2f', annot=True, cmap='Blues',␣
↪ax=axes[1], cbar=False)
axes[0].set_title('Root Mean Squared Error')
axes[1].set_title('Bayesian Information Criterion')
fig.tight_layout();
```

[ ]:
```
arma_results.rank().loc[:, ['RMSE', 'BIC']].mean(1).nsmallest(5)
```

1.3.2 Estimating the best ARMA Model

ARMA(4,0) and ARMA(4,1) are close, so we chose the more parsimonious (4,0) configuration:

[ ]:
```
best_p, best_q = arma_results.rank().loc[:, ['RMSE', 'BIC']].mean(1).idxmin()
```

[ ]:
```
best_arma_model = tsa.ARMA(endog=industrial_production_log_diff, order=(best_p,␣
↪best_q)).fit()
print(best_arma_model.summary())
```

1.3.3 Check Residual Correlogram

[ ]:
```
plot_correlogram(best_arma_model.resid)
```

1.4 SARIMAX

[ ]:
```
sarimax_model = tsa.SARIMAX(endog=industrial_production_log_diff.dropna().
↪values,
                    order=(2, 0, 2),
                    seasonal_order=(1, 0, 1, 12)).fit(start_params=[0, 0, 0, 0,␣
↪0, 0, 1])
```

[ ]:
```
print(sarimax_model.summary())
```

[ ]:
```
plot_correlogram(pd.Series(sarimax_model.resid))
```

We will build a SARIMAX model for monthly data on an industrial production time series for the 1988-2017 period. As illustrated in the first section on analytical tools, the data has been log-transformed, and we are using seasonal (lag-12) differences. We estimate the model for a range of both ordinary and conventional AR and MA parameters using a rolling window of 10 years of training data, and evaluate the RMSE of the 1-step-ahead forecast.

1.4.1 Finding the optimal number of lags

This takes a while…

[ ]:
```python
l3 = list(range(3))
l4 = list(range(4))
params = [t for t in product(l4, l4, l3, l3) if t[0] > 0 and t[1] >  0]
len(params)
```

[ ]:
```python
train_size = 120 # 10 years of training data
results = {}
test_set = industrial_production_log_diff.iloc[train_size:]

for p1, q1, p2, q2 in tqdm(params):
    preds = test_set.copy().to_frame('y_true').assign(y_pred=np.nan)
    aic, bic = [], []
    if p1 == 0 and q1 == 0:
        continue
    convergence_error = stationarity_error = 0
    y_pred = []
    for i, T in enumerate(range(train_size,␣
 ↪len(industrial_production_log_diff))):
        train_set = industrial_production_log_diff.iloc[T-train_size:T]
        try:
            with warnings.catch_warnings():
                warnings.filterwarnings("ignore")
                model = tsa.SARIMAX(endog=train_set.values,
                                order=(p1, 0, q1),
                                seasonal_order=(p2, 0, q2, 12)).fit(disp=0)
        except LinAlgError:
            convergence_error += 1
        except ValueError:
            stationarity_error += 1

        preds.iloc[i, 1] = model.forecast(steps=1)[0]
        aic.append(model.aic)
        bic.append(model.bic)

    preds.dropna(inplace=True)
    mse = mean_squared_error(preds.y_true, preds.y_pred)
    results[(p1, q1, p2, q2)] = [np.sqrt(mse),
                                      preds.y_true.sub(preds.y_pred).pow(2).
 ↪std(),
                                      np.mean(aic),
                                      np.std(aic),
                                      np.mean(bic),
                                      np.std(bic),
                                      convergence_error,
                                      stationarity_error]
```

1.4.2 Compare model metrics

[ ]:
```
sarimax_results = pd.DataFrame(results).T
sarimax_results.columns = ['RMSE', 'RMSE_std', 'AIC', 'AIC_std', 'BIC',␣
 ↪'BIC_std', 'convergence', 'stationarity']
sarimax_results['CV'] = sarimax_results.RMSE_std.div(sarimax_results.RMSE)
sarimax_results.index.names = ['p1', 'q1', 'p2', 'q2']
sarimax_results.info()
```

[ ]:
```
with pd.HDFStore('arima.h5') as store:
    store.put('sarimax', sarimax_results)
```

[ ]:
```
with pd.HDFStore('arima.h5') as store:
    sarimax_results = store.get('sarimax')
```

[ ]:
```
sarimax_results.nsmallest(5, columns='RMSE')
```

We also collect the AIC and BIC criteria that show a very high rank correlation coefficient of 0.94, with BIC favoring models with slightly fewer parameters than AIC. The best five models by RMSE are:

[ ]:
```
sarimax_results[['RMSE', 'AIC', 'BIC']].sort_values('RMSE').head()
```

[ ]:
```
sarimax_results[['RMSE', 'AIC', 'BIC']].corr('spearman')
```

[ ]:
```
sns.jointplot(y='RMSE', x='BIC', data=sarimax_results[['RMSE', 'BIC']].rank());
```

[ ]:
```
sarimax_results[(sarimax_results.RMSE < sarimax_results.RMSE.quantile(.05)) &
                (sarimax_results.BIC < sarimax_results.BIC.quantile(.1))].
 ↪sort_values('RMSE')
```

1.4.3 Train best model

[ ]:
```
p1, q1, p2, q2 = 2, 3, 1, 2
```

[ ]:
```
best_model = tsa.SARIMAX(endog=industrial_production_log_diff.values,␣
 ↪order=(p1, 0, q1),
                         seasonal_order=(p2, 0, q2, 12)).fit()
```

[ ]:
```
print(best_model.summary())
```

1.4.4 Check Residual Correlogram

[ ]:
```
plot_correlogram(pd.Series(best_model.resid),
                 lags=20,
                 title=f'SARIMAX ({p1}, 0, {q1}) x ({p2}, 0, {q2}, 12) | Model␣
 ↪Diagnostics')
```