

# **ETC3550**

## **Applied forecasting for business and economics**

Ch11. Advanced forecasting methods

[OTexts.org/fpp3/](https://OTexts.org/fpp3/)



# Outline

- 1 Complex seasonality
- 2 Vector autoregression
- 3 Neural network models
- 4 Bootstrapping and bagging

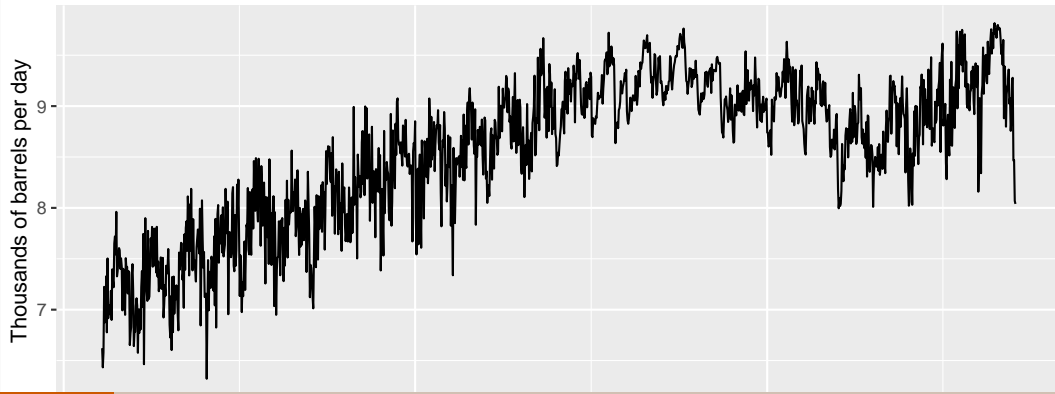
# Outline

- 1 Complex seasonality
- 2 Vector autoregression
- 3 Neural network models
- 4 Bootstrapping and bagging

# Examples

```
us_gasoline %>% autoplot(Barrels) +  
  labs(x = "Year", y = "Thousands of barrels per day",  
        title = "Weekly US finished motor gasoline products")
```

Weekly US finished motor gasoline products



# Examples

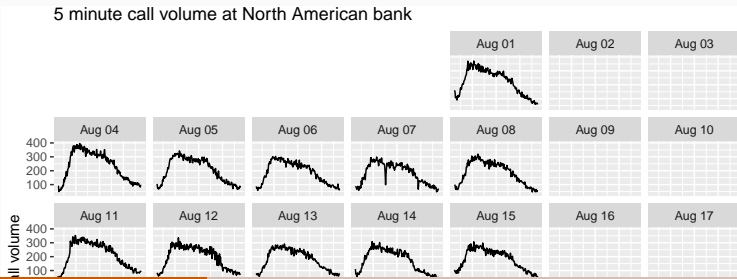
```
calls <- read_tsv("http://robjhyndman.com/data/callcenter.txt") %>%
  rename(time = `...1`) %>%
  pivot_longer(-time, names_to="date", values_to="volume") %>%
  mutate(
    date = as.Date(date, format = "%d/%m/%Y"),
    datetime = as_datetime(date) + time
  ) %>%
  as_tsibble(index = datetime)
calls %>%
  fill_gaps() %>%
  autoplot(volume) +
  labs(x = "Weeks", y = "Call volume",
       title = "5 minute call volume at North American bank")
```

5 minute call volume at North American bank



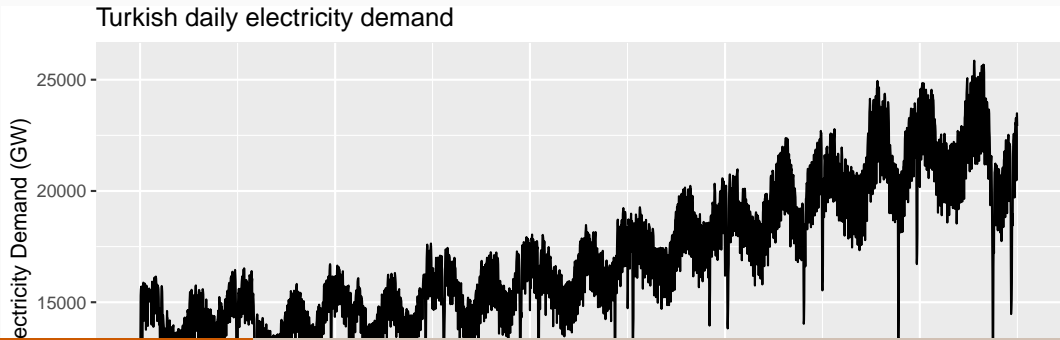
# Examples

```
library(sugrrants)
calls %>%
  filter(yearmonth(date) == yearmonth("2003 August")) %>%
  ggplot(aes(x = time, y = volume)) +
  geom_line() +
  facet_calendar(date) +
  labs(x = "Weeks", y = "Call volume",
       title = "5 minute call volume at North American bank")
```



# Examples

```
turkey_elec <- read_csv("data/turkey_elec.csv", col_names = "Demand") %>%  
  mutate(Date = seq(ymd("2000-01-01"), ymd("2008-12-31"), by = "day")) %>%  
  as_tsibble(index = Date)  
turkey_elec %>% autoplot(Demand) +  
  labs(title = "Turkish daily electricity demand",  
       x = "Year", y = "Electricity Demand (GW)")
```



## TBATS

**T**rigonometric terms for seasonality

**B**ox-Cox transformations for heterogeneity

**A**RMA errors for short-term dynamics

**T**rend (possibly damped)

**S**easonal (including multiple and

non-integer periods)



# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad \begin{aligned} s_{j,t}^{(i)} &= s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} + \gamma_1^{(i)} d_t \\ s_{j,t}^{(i)} &= -s_{j,t-1}^{(i)} \sin \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \cos \lambda_j^{(i)} + \gamma_2^{(i)} d_t \end{aligned}$$

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad \begin{aligned} s_{j,t}^{(i)} &= s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} + \gamma_1^{(i)} d_t \\ s_{j,t}^{(i)} &= -s_{j,t-1}^{(i)} \sin \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \cos \lambda_j^{(i)} + \gamma_2^{(i)} d_t \end{aligned}$$

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$M$  seasonal periods

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad \begin{aligned} s_{j,t}^{(i)} &= s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} + \gamma_1^{(i)} d_t \\ s_{j,t}^{(i)} &= -s_{j,t-1}^{(i)} \sin \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \cos \lambda_j^{(i)} + \gamma_2^{(i)} d_t \end{aligned}$$

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$M$  seasonal periods

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

global and local trend

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad \begin{aligned} s_{j,t}^{(i)} &= s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} + \gamma_1^{(i)} d_t \\ s_{i,t}^{(i)} &= -s_{i,t-1}^{(i)} \sin \lambda_i^{(i)} + s_{i,t-1}^{*(i)} \cos \lambda_i^{(i)} + \gamma_2^{(i)} d_t \end{aligned}$$

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$M$  seasonal periods

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

global and local trend

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

ARMA error

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad \begin{aligned} s_{j,t}^{(i)} &= s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} + \gamma_1^{(i)} d_t \\ s_{i,t}^{(i)} &= -s_{i,t-1}^{(i)} \sin \lambda_i^{(i)} + s_{i,t-1}^{*(i)} \cos \lambda_i^{(i)} + \gamma_2^{(i)} d_t \end{aligned}$$

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ \log y_t & \text{if } \omega = 0. \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_{t-1} + \phi b_{t-1} + \sum_{i=1}^M s_{t-m_i}^{(i)} + d_t$$

$M$  seasonal periods

$$\ell_t = \ell_{t-1} + \phi b_{t-1} + \alpha d_t$$

global and local trend

$$b_t = (1 - \phi)b + \phi b_{t-1} + \beta d_t$$

$$d_t = \sum_{i=1}^p \phi_i d_{t-i} + \sum_{j=1}^q \theta_j \varepsilon_{t-j} + \varepsilon_t$$

ARMA error

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad s_{j,t}^{(i)} = s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} - s_{j,t-1}^{*(i)} \sin \lambda_j^{(i)} \quad s_{j,t-1}^{*(i)} = s_{j,t-1}^{(i)} \sin \lambda_j^{(i)} + s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} + \gamma_2^{(i)} d_t$$

Fourier-like seasonal terms

# TBATS model

$y_t$  = observation at time  $t$

$$y_t^{(\omega)} = \begin{cases} (y_t^\omega - 1)/\omega & \text{if } \omega \neq 0; \\ 1 & \text{if } \omega = 0; \end{cases}$$

Box-Cox transformation

$$y_t^{(\omega)} = \ell_t + b_t + d_t$$

$M$  seasonal periods

$$\ell_t = \ell_t$$

global and local trend

$$b_t = (1 - \alpha) b_{t-1} + \alpha \ell_t$$

ARMA error

$$d_t = \sum_{i=1}^M s_{j,t}^{(i)}$$

Fourier-like seasonal terms

$$s_t^{(i)} = \sum_{j=1}^{k_i} s_{j,t}^{(i)} \quad s_{j,t}^{(i)} = s_{j,t-1}^{(i)} \cos \lambda_j^{(i)} - s_{j,t-1}^{(i)*} \sin \lambda_j^{(i)} + s_{j,t-1}^{*(i)} \cos \lambda_j^{(i)} + \gamma_2^{(i)} d_t$$

# Complex seasonality

```
gasoline %>% tbats() %>% forecast() %>% autoplot()
```



# Complex seasonality

```
calls %>% tbats() %>% forecast() %>% autoplot()
```

# Complex seasonality

```
telec %>% tbats() %>% forecast() %>% autoplot()
```

## TBATS

**T**rigonometric terms for seasonality

**B**ox-Cox transformations for heterogeneity

**A**RMA errors for short-term dynamics

**T**rend (possibly damped)

**S**easonal (including multiple and non-integer periods)

- Handles non-integer seasonality, multiple seasonal periods.
- Entirely automated
- Prediction intervals often too wide
- Very slow on long series

# Outline

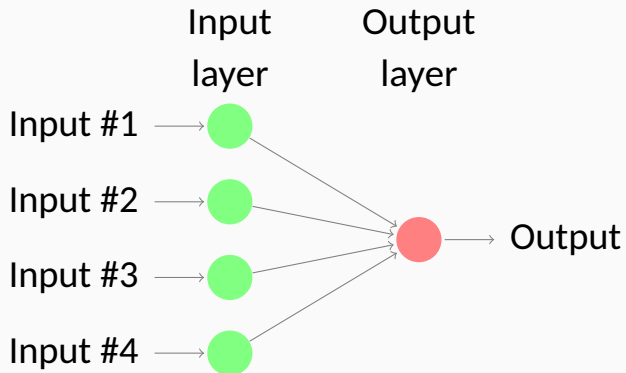
- 1 Complex seasonality
- 2 Vector autoregression
- 3 Neural network models
- 4 Bootstrapping and bagging

# Outline

- 1 Complex seasonality
- 2 Vector autoregression
- 3 Neural network models
- 4 Bootstrapping and bagging

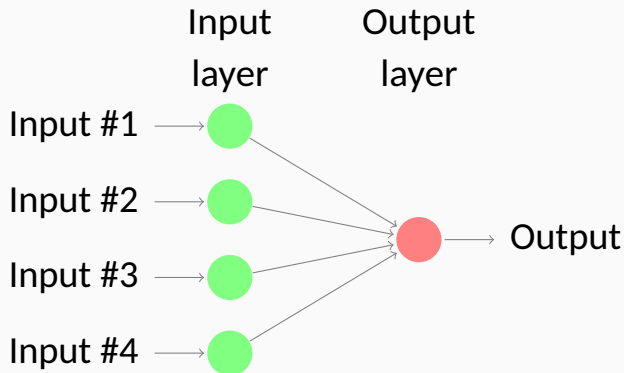
# Neural network models

## Simplest version: linear regression



# Neural network models

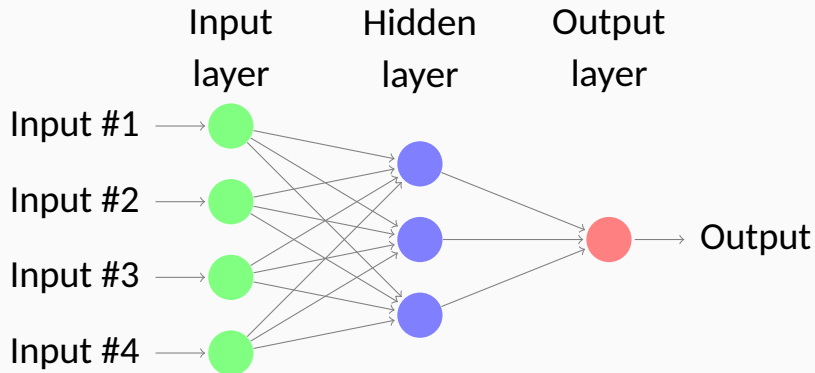
## Simplest version: linear regression



- Coefficients attached to predictors are called “weights”.
- Forecasts are obtained by a linear combination of inputs.

# Neural network models

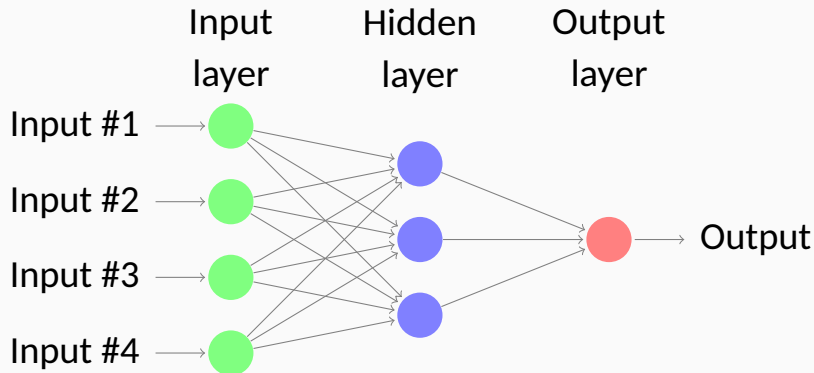
## Nonlinear model with one hidden layer





# Neural network models

## Nonlinear model with one hidden layer



- A **multilayer feed-forward network** where each layer of nodes receives inputs from the previous layers.

# Neural network models

Inputs to hidden neuron  $j$  linearly combined:

$$z_j = b_j + \sum_{i=1}^4 w_{i,j} x_i.$$

Modified using nonlinear function such as a sigmoid:

$$s(z) = \frac{1}{1 + e^{-z}},$$

This tends to reduce the effect of extreme input values, thus making the network somewhat robust to outliers.

# Neural network models

- Weights take random values to begin with, which are then updated using the observed data.
- There is an element of randomness in the predictions. So the network is usually trained several times using different random starting points, and the results are averaged.
- Number of hidden layers, and the number of nodes in each hidden layer, must be specified in advance.

# NNAR models

- Lagged values of the time series can be used as inputs to a neural network.
- NNAR( $p, k$ ):  $p$  lagged inputs and  $k$  nodes in the single hidden layer.
- NNAR( $p, 0$ ) model is equivalent to an ARIMA( $p, 0, 0$ ) model but without stationarity restrictions.
- Seasonal NNAR( $p, P, k$ ): inputs  $(y_{t-1}, y_{t-2}, \dots, y_{t-p}, y_{t-m}, y_{t-2m}, y_{t-Pm})$  and  $k$  neurons in the hidden layer.
- NNAR( $p, P, 0$ ) <sub>$m$</sub>  model is equivalent to an ARIMA( $p, 0, 0$ )( $P, 0, 0$ ) <sub>$m$</sub>  model but without stationarity restrictions.

# NNAR models in R

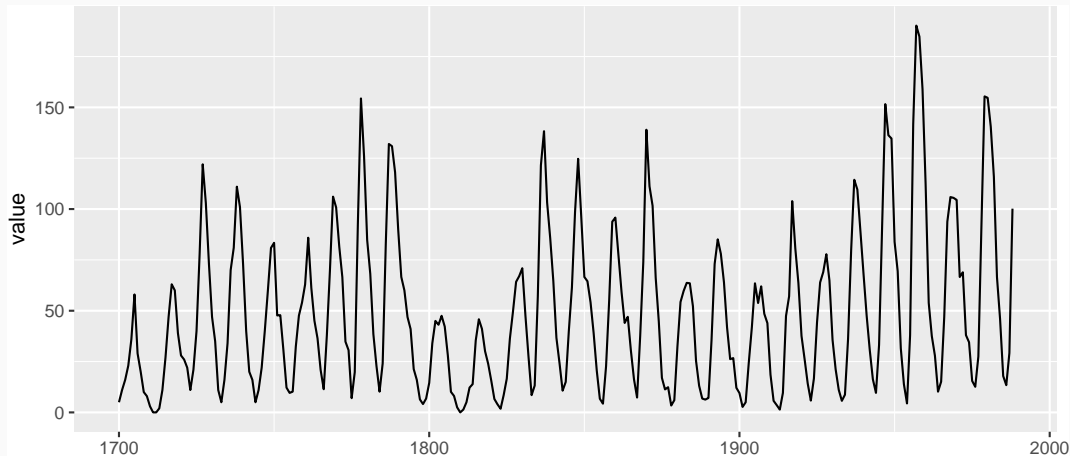
- The `nnetar()` function fits an  $\text{NNAR}(p, P, k)_m$  model.
- If  $p$  and  $P$  are not specified, they are automatically selected.
- For non-seasonal time series, default  $p$  = optimal number of lags (according to the AIC) for a linear  $\text{AR}(p)$  model.
- For seasonal time series, defaults are  $P = 1$  and  $p$  is chosen from the optimal linear model fitted to the seasonally adjusted data.
- Default  $k = (p + P + 1)/2$  (rounded to the nearest integer).

# Sunspots

- Surface of the sun contains magnetic regions that appear as dark spots.
- These affect the propagation of radio waves and so telecommunication companies like to predict sunspot activity in order to plan for any future difficulties.
- Sunspots follow a cycle of length between 9 and 14 years.

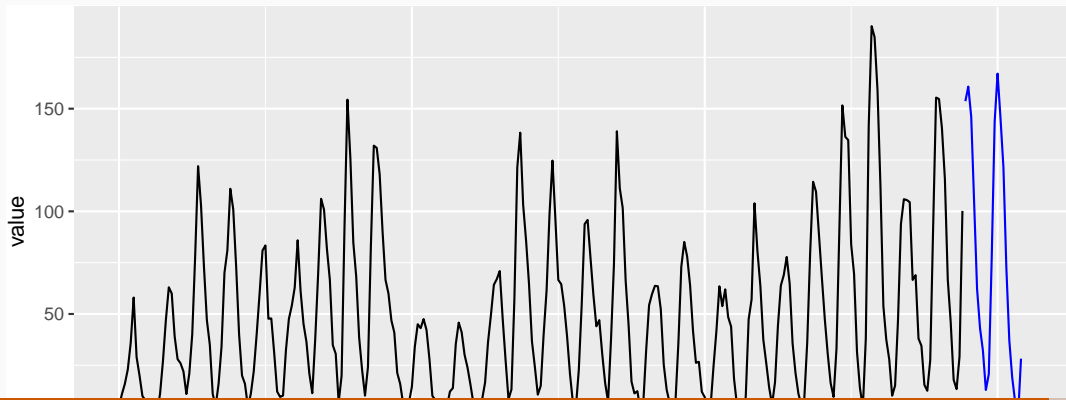
# Sunspots

```
sunspots <- sunspot.year %>% as_tsibble()  
sunspots %>% autoplot(value)
```



# NNAR(9,5) model for sunspots

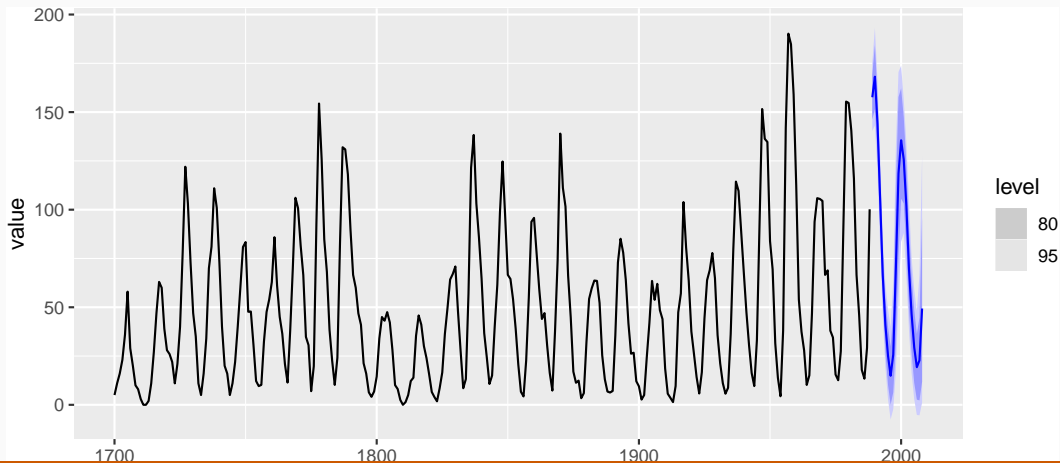
```
sunspots <- sunspot.year %>% as_tsibble()  
fit <- sunspots %>% model(NNETAR(value))  
fit %>% forecast(h=20, times = 1) %>%  
  autoplot(sunspots, level = NULL)
```





# Prediction intervals by simulation

```
fit %>% forecast(h=20) %>%  
  autoplot(sunspots)
```



# Outline

- 1 Complex seasonality
- 2 Vector autoregression
- 3 Neural network models
- 4 Bootstrapping and bagging