

Time Series Analysis Methods and Applications

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Abstract The goal of this project is to discover Time Series analysis. We start with the data loading and creation of different types of object including `ts`, `xts` and `zoo` and proceed with data manipulation, conversion and visualization. Then we discover different algorithms of time series analysis like decomposition, forecasting and clustering. At the end we develop a practical example and build a Shiny application.

Introduction

The goal of this project is to discover Time Series analysis. We start with the data loading and creation of different types of object including `ts`, `xts` and `zoo` and proceed with data manipulation, conversion and visualization. Then we discover different algorithms of time series analysis like decomposition, forecasting and clustering. At the end we develop a practical example and build a Shiny application.

Background

The function `ts` for the core package `stats` (R Core Team, 2012) is used to create time-series objects. These are vector or matrices with class of “`ts`” (and additional attributes) which represent data which has been sampled at equispaced points in time. In the matrix case, each column of the matrix data is assumed to contain a single (univariate) time series. Time series must have at least one observation, and although they need not be numeric there is very limited support for non-numeric series.

An `xts` object from package `xts` (Ryan and Ulrich, 2018) extends the S3 class `zoo` from the package of the same name (Zeileis and Grothendieck, 2005). Package `zoo` is the creator for an S3 class of indexed totally ordered observations which includes irregular time series.

Similar to `zoo` objects, `xts` objects must have an ordered index. While `zoo` indexes cannot contain duplicate values, `xts` objects have optionally supported duplicate index elements since version 0.5-0. The `xts` class has one additional requirement, the index must be a time-based class. Currently supported classes include: ‘Date’, ‘POSIXct’, ‘timeDate’, as well as ‘yearmon’ and ‘yearqtr’ where the index values remain unique.

Ethical Consideration for the Time Series ML Framework

As the goal of this report is only to research the time series methods, many aspects of the ethical ML framework do not directly apply. The time series data used here is open source and we can assume was collected in transparent ways. That being said, there is likely a large segment of the populace that can’t take advantage of analysis presented in this report - we assume a low income population with limited access to internet and not STEM educated. If the outcome of this system were to be of more social impact, this would need to be use more appropriate datasets, analysis of which could be more advantageous to that population.

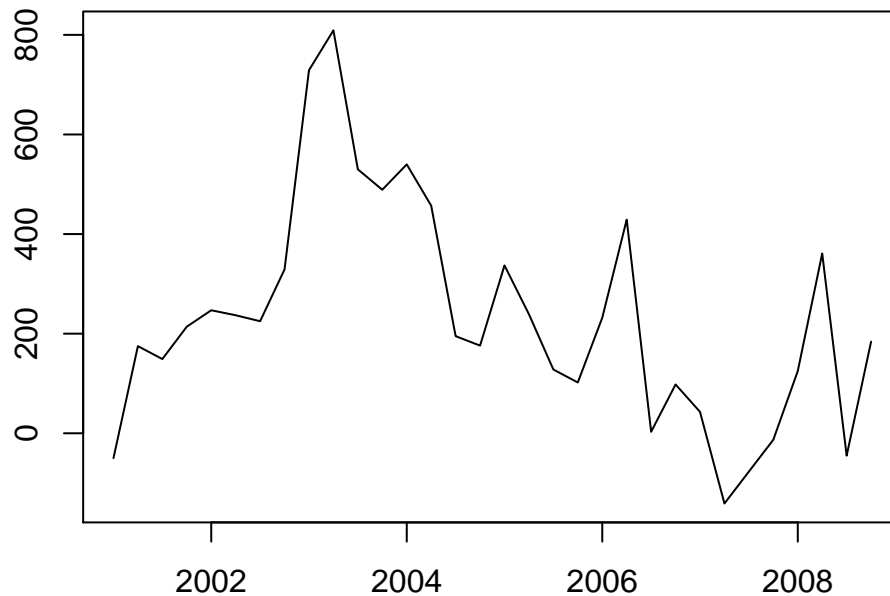


Figure 1: Time Series ts class Example Plot

Time Series Data Manipulating and Visualizing

Constructing TS object

In the following example (Fig 1) we construct and plot a simple TS class:

```
simpleTS <- c(-50, 175, 149, 214, 247, 237, 225, 329, 729, 809,
             530, 489, 540, 457, 195, 176, 337, 239, 128, 102, 232, 429, 3,
             98, 43, -141, -77, -13, 125, 361, -45, 184)
simpleTS <- ts(simpleTS, start = c(2001, 1), end = c(2008, 4), frequency = 4)
print(simpleTS)

#>      Qtr1 Qtr2 Qtr3 Qtr4
#> 2001  -50  175  149  214
#> 2002  247  237  225  329
#> 2003  729  809  530  489
#> 2004  540  457  195  176
#> 2005  337  239  128  102
#> 2006  232  429   3   98
#> 2007   43 -141  -77  -13
#> 2008  125  361  -45  184

plot(simpleTS, ylab="", xlab="")
```

Loading Stock Data

There are many ways to load times data, but the fastest is to use [zoo](#) that has many convinient utilities to manipulate times series data. This is especially convinient when dealing with complex stock data.

This is an example of loading and presenting of stock data using [Historical stock data for all current S&P 500 companies](#). Stock market data can be interesting to analyze and as a further incentive, strong predictive models can have large financial payoff. Data has the following columns:

- Date - in format: yy-mm-dd
- Open - price of the stock at market open (this is NYSE data so all in USD)
- High - Highest price reached in the day
- Low Close - Lowest price reached in the day
- Volume - Number of shares traded
- Name - the stock's ticker name

First we load the whole dataset as data frame:

```
stocks5 <- read_csv(file="../../data/all_stocks_5yr.csv.zip", col_names = TRUE)
stocks5$Name <- as.factor(stocks5$Name)
head(stocks5$Name)
```

```
#> [1] AAL AAL AAL AAL AAL AAL
#> 505 Levels: A AAL AAP AAPL ABBV ABC ABT ACN ADBE ADI ADM ADP ADS ... ZTS
```

As the name suggests we should have 500 (505 to be correct) stock names in the dataset. The code below extracts stock data of AAL (American Airlines Group Inc), converts it to **zoo** object and plots it as multi-variate time series (Fig 2).

```
stocks5_aal <- stocks5[stocks5$Name=="AAL",c(1:6)]
stocks5_aal <- zoo(stocks5_aal[,2:6], stocks5_aal$date)
print(paste("Start date: ", start(stocks5_aal)))

#> [1] "Start date: 2013-02-08"

print(paste("Last date: ", end(stocks5_aal)))

#> [1] "Last date: 2018-02-07"

str(stocks5_aal)

#> 'zoo' series from 2013-02-08 to 2018-02-07
#> Data: num [1:1259, 1:5] 15.1 14.9 14.4 14.3 14.9 ...
#> - attr(*, "dimnames")=List of 2
#> ..$ : NULL
#> ..$ : chr [1:5] "open" "high" "low" "close" ...
#> Index: Date[1:1259], format: "2013-02-08" "2013-02-11" "2013-02-12" "2013-02-13" "2013-02-14" ...

plot(stocks5_aal, xlab = "", nc = 1, main = "")
```

Additional time series data sets

Yahoo Science labeled time series

Yahoo Science labeled time series is a big Synthetic and real time-series with labeled anomalies, it should be downloaded and used locally. [Yahoo Science labeled time series](#)

NAB Data Corpus

[NAB Data Corpus](#) is a large dataset of ordered, timestamped, single-valued metrics. All data files contain anomalies, unless otherwise noted. This data better be loaded from github directly to R script.

Time Series Methods Showcase

Time series decomposition

Time series decomposition is to decompose a time series into trend, seasonal, cyclical and irregular components. Frequency represents data which has been sampled at equispaced points in time:

- frequency=7: a weekly series
- frequency=12: a monthly series
- frequency=4: a quarterly series

To decompose a time series into components:

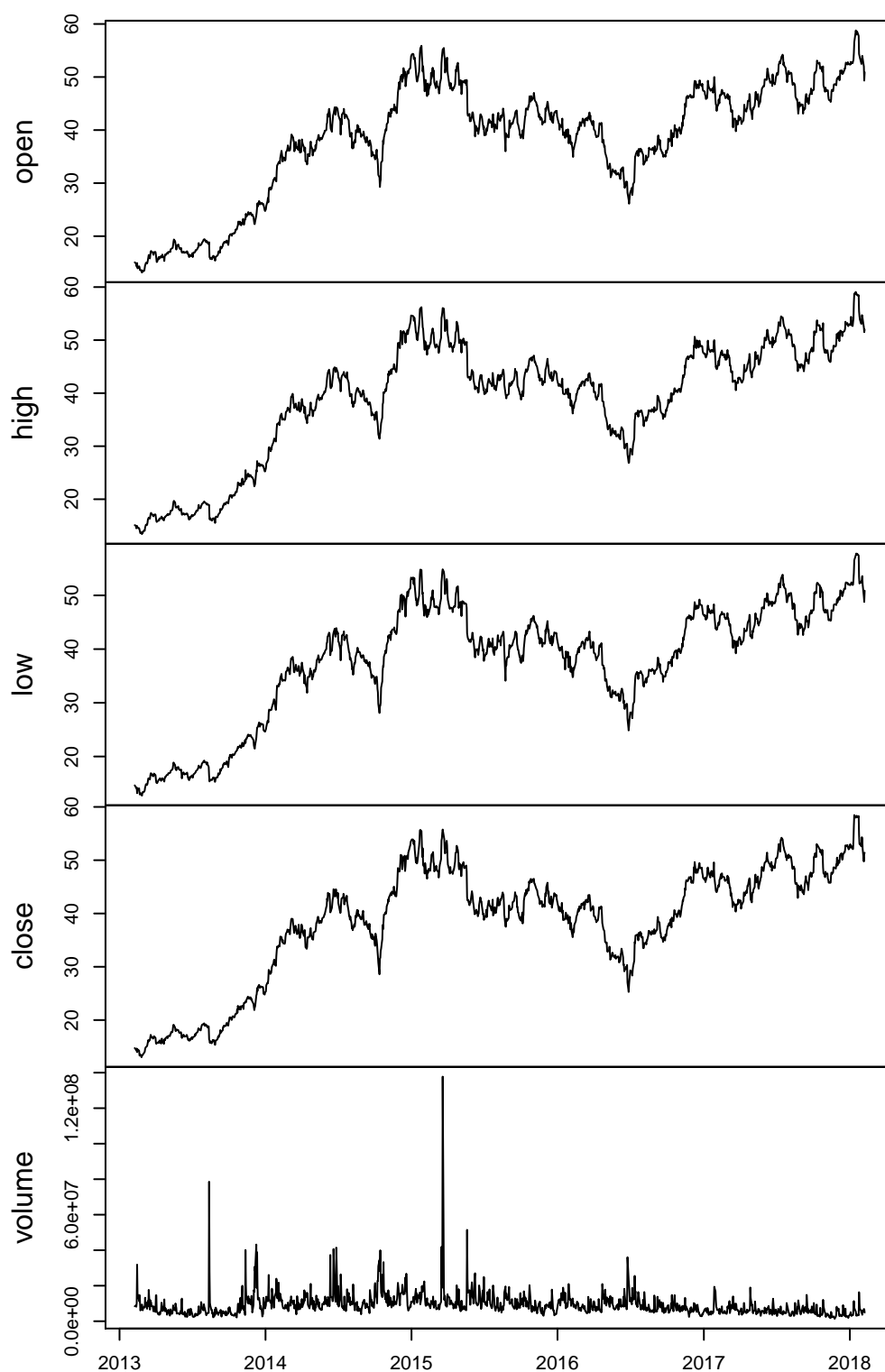


Figure 2: Multi-variate time series visualization of AAL stock

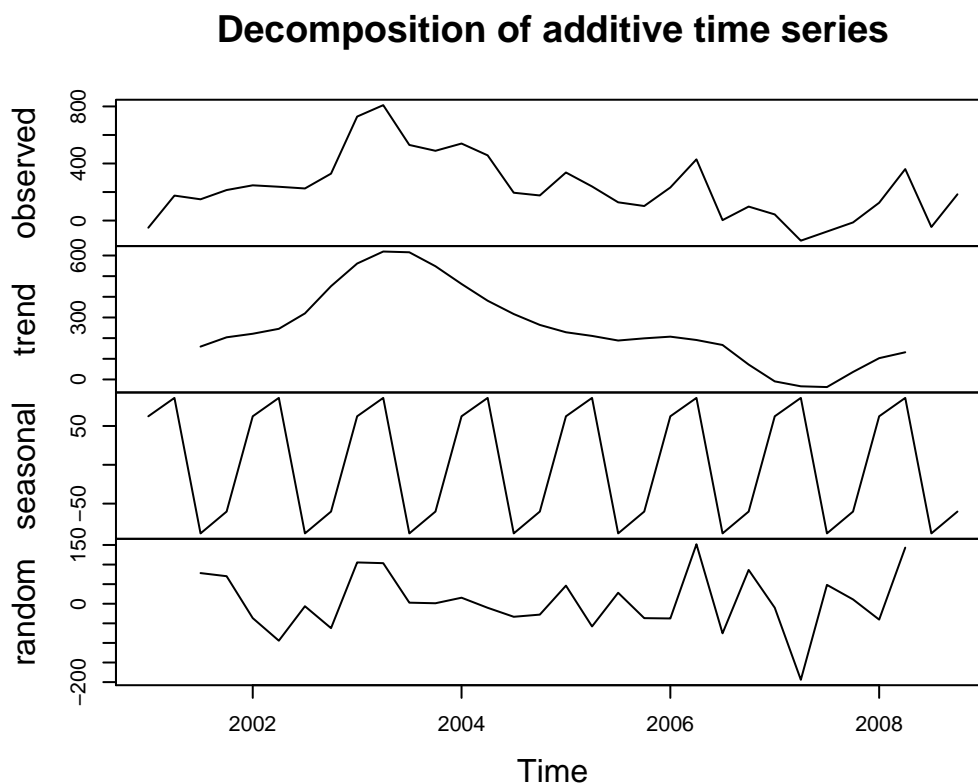


Figure 3: Decomposition of cyclic object example

- Trend component: long term trend
- Seasonal component: seasonal variation
- Cyclical component: repeated but non-periodic fluctuations
- Irregular component: the residuals

A `simpleTS` time series object was constructed in section [Constructing TS object](#). It is used below as an example to demonstrate time series decomposition (Fig 3). It was constructed to have quarterly data and will be decomposed with frequency 4.

```
m <- decompose(simpleTS)
plot(m)
```

A more complex and realistic example of time series manipulation and decomposition is presented below. We will use 'open' series of the AAL stock taken directly from Yahoo Finance using `tseries` (Trapletti and Hornik, 2018) package instead of data created in section [Loading Stock Data](#). The full daily chart of this series is presented on (Fig. 4). To decompose the series, code below calculates yearly cycles of the last years since 2010, data aggregated monthly (Fig. 5).

```
library("tseries")
AAL <- get.hist.quote(instrument = "AAL", start = "2010-01-01")

#> time series starts 2010-01-04
#> time series ends 2019-02-20

plot(AAL, xlab = "")

require(xts)
last8 <- window(AAL$Open, start=as.Date("2010-01-01"), end=as.Date("2017-12-31"))
last8_mo <- aggregate(last8, as.yearmon, tail, 1)
m <- decompose(ts(last8_mo, frequency = 12))
years <- seq(2010, 2020, 1)
plot(m, xlab="", xaxt="n")
axis(1, at=1:9, labels=years[1:9], pos = -6.6)
```

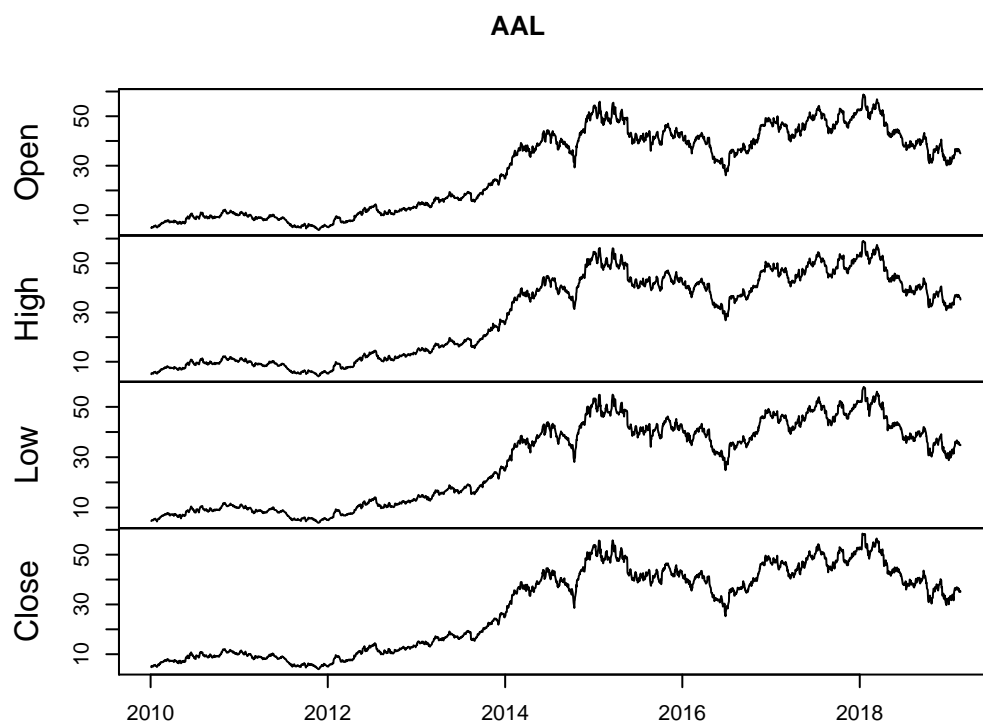


Figure 4: AAL daily stock data since 2010

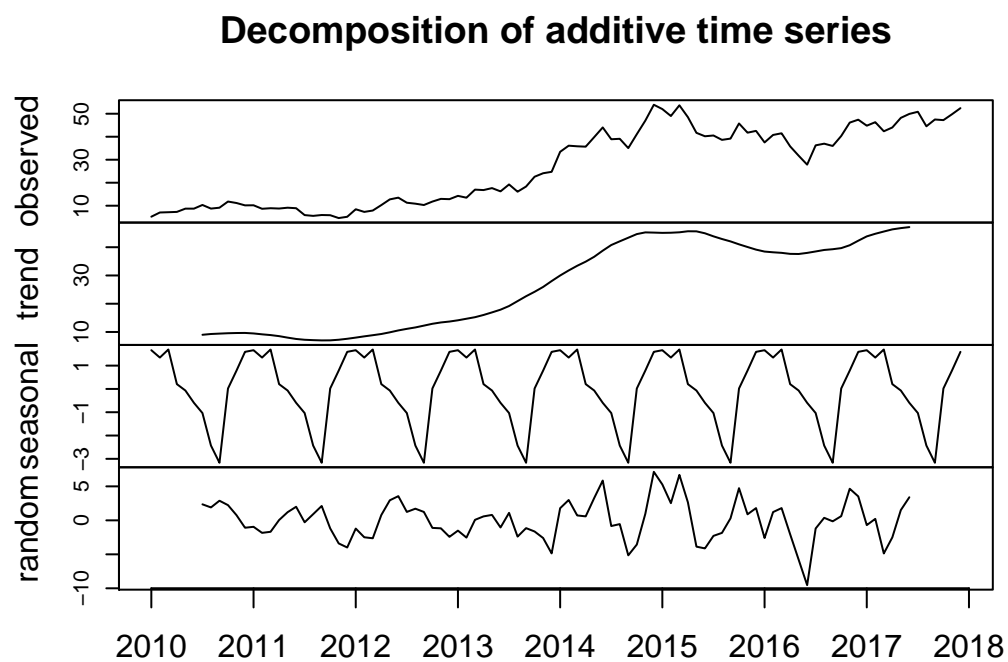


Figure 5: Decomposition of 8 years AAL 'open' series

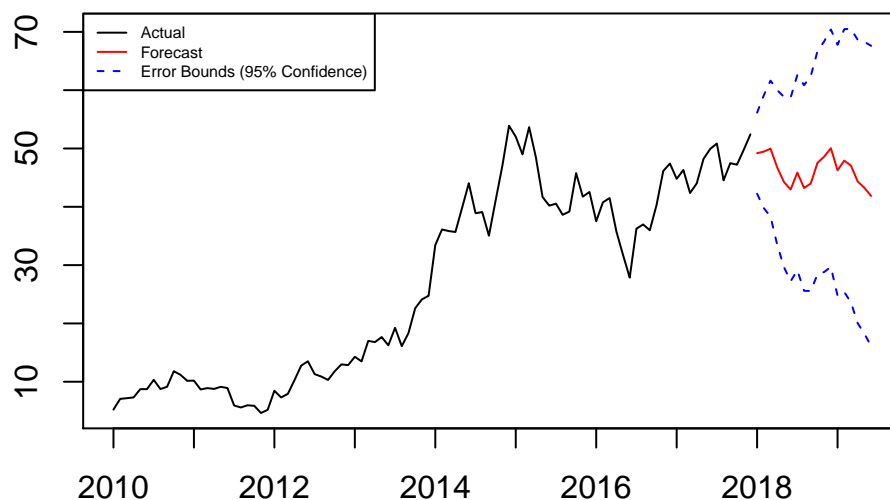


Figure 6: Cyclic Time Series Forecasting with ARIMA model

Time series forecasting

Time series forecasting is to forecast future events based on known past data. To forecast future events based on known past data For example, to predict the price of a stock based on its past performance. Popular models are:

- Autoregressive moving average (ARMA)
- Autoregressive integrated moving average (ARIMA)

Example on Fig. 6 shows forecasting using ARIMA model.

```
ff <- ts(last8_mo)
fit <- arima(ff, order=c(1,0,0), list(order=c(2,1,0), period=12))
fore <- predict(fit, n.ahead=18)

# error bounds at 95% confidence level
U <- fore$pred + 2*fore$se
L <- fore$pred - 2*fore$se

ts.plot(ff, fore$pred, U, L, col=c(1,2,4,4), lty = c(1,1,2,2),
        xlab="", gpars = list(xaxt="n"))
axis(1, at=seq(from=1, to=121, by=12), labels=years[1:11])
legend("topleft", c("Actual", "Forecast", "Error Bounds (95% Confidence)"),
      col=c(1,2,4), lty=c(1,1,2), cex=0.5)
```

Time series forecasting with forecast package

It is common practice to split the data into two parts, training and test data, where the training data is used to estimate any parameters of a forecasting method and the test data is used to evaluate its accuracy. To perform this task and also to test several additional forecasting methods we used package **forecast** (Hyndman and Khandakar, 2008).

Code below creates train and test data from the the previously obtained 'open' stock data for the last 8 years aggregated monthly. Then it fits the train data using several models and plots the fitting results in the Fig.7. It also plots the test portion in red for easy comparison of prediction and real data.

```

library(forecast)

# test data
test_x <- window(last8, start=as.Date("2016-12-20"))
test_x <- test_x[endpoints(test_x, "month")]
test_x <- ts(test_x, frequency = 12)
str(test_x)

#> Time-Series [1:13] from 1 to 2: 47.4 44.8 46.3 42.4 44 ...
#> - attr(*, "index")= Date[1:13], format: "2016-12-30" "2017-01-31" ...

#train data
x <- window(last8, end=as.Date("2016-12-31"))
x <- x[endpoints(x, "month")]
x <- ts(x, frequency = 12)
str(x)

#> Time-Series [1:84] from 1 to 7.92: 5.23 7.06 7.18 7.31 8.73 ...
#> - attr(*, "index")= Date[1:84], format: "2010-01-29" "2010-02-26" ...

library(forecast)
if(!file.exists("./models.Rds")) {
  models <- list(
    mod_arima = auto.arima(x, ic='aicc', stepwise=FALSE),
    mod_exp = ets(x, ic='aicc', restrict=FALSE),
    mod_neural = nnetar(x, p=12, size=25),
    mod_tbars = tbars(x, ic='aicc', seasonal.periods=12),
    mod_bars = bars(x, ic='aicc', seasonal.periods=12),
    mod_stl = stlm(x, s.window=12, ic='aicc', robust=TRUE, method='ets'),
    mod_sts = StructTS(x)
  )
  saveRDS(models, file = "./models.Rds")
} else {
  models <- readRDS("./models.Rds")
}

forecasts <- lapply(models, forecast, 12)
forecasts$naive <- naive(x, 12)
par(mfrow=c(4, 2))
for(f in forecasts){
  plot(f, xlab="", xaxt="n")
  lines(y=test_x[1:13], x=seq(from=(8-1/12), to=9, by=1/12)[1:13], col='red')
  axis(1, at=1:10, labels=years[1:10])
}

```

Evaluating forecast accuracy

Because the test data is not used in determining the forecasts, it should provide a reliable indication of how well the model is likely to forecast on new data. The metrics used below are described in (Hyndman and Athanasopoulos, 2014), also available online [here](#). The metrics are:

- ME - Mean absolute error
- RMSE - Root mean squared error
- MAE - mean absolute error
- MPE - mean percentage error
- MAPE - Mean absolute percentage error
- MASE - mean absolute scaled error
- Theil's U - Uncertainty coefficient

Code below (adaptation of [Timeseries analysis procedure and methods using R](#)) calculates common forecast errors of the predictions made in the previous section.

```

test_xx <- ts(test_x[2:13], start=c(8,1), frequency = 12)
acc <- lapply(forecasts, function(f){
  accuracy(f, test_xx)[2,,drop=FALSE]
})

```

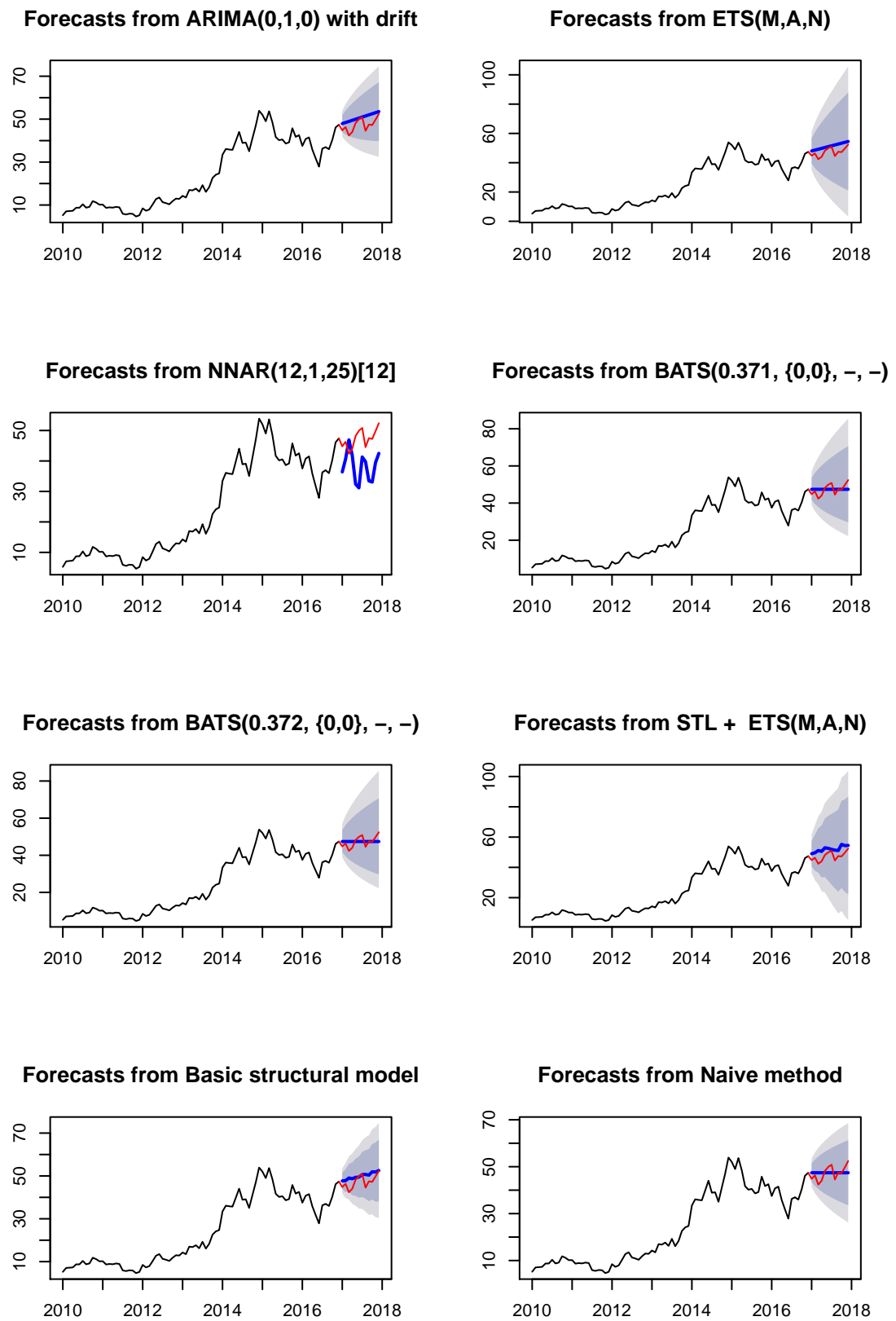



Figure 7: AAL stock prediction vs reality using different forecasting methods

```

}))
acc <- Reduce(rbind, acc)
row.names(acc) <- names(forecasts)
acc <- acc[order(acc[, 'MASE']),]
round(acc, 2)

#>           ME  RMSE  MAE    MPE  MAPE  MASE  ACF1  Theil's U
#> mod_t bats -0.08  2.92  2.45  -0.56  5.21  0.28  0.33    0.96
#> mod_bats -0.08  2.92  2.45  -0.56  5.21  0.28  0.33    0.96
#> naive -0.09  2.92  2.45  -0.58  5.21  0.28  0.33    0.96
#> mod_sts -2.68  3.55  2.79  -5.94  6.16  0.32  0.08    1.19
#> mod_arima -3.40  4.07  3.40  -7.45  7.45  0.39  0.13    1.37
#> mod_exp -3.93  4.52  3.93  -8.55  8.55  0.45  0.15    1.53
#> mod_stl -4.70  5.23  4.70 -10.20 10.20  0.54 -0.06    1.77
#> mod_neural 9.08 10.97 9.84  18.68 20.47  1.13  0.38    3.69

```

Time series clustering

Time series clustering partitioning time series data into groups based on similarity or distance, so that time series in the same cluster are similar. For time series clustering with R, the first step is to work out an appropriate distance/similarity metric, and then, at the second step, use existing clustering techniques, such as k-means, hierarchical clustering, density-based clustering or subspace clustering, to find clustering structures.

Measure of distance/dissimilarity - Euclidean distance - Manhattan distance - Maximum norm - Hamming distance - The angle between two vectors (inner product) - Dynamic Time Warping (DTW) distance

Example: Grouping together time series of similar types

The [dataset](#) contains 600 examples of control charts synthetically generated by the process developed by [Alcock and Manolopoulos \(1999\)](#). Each control chart is a time series with 60 values. The classes are organized as follows:

- 1-100 Normal
- 101-200 Cyclic
- 201-300 Increasing trend
- 301-400 Decreasing trend
- 401-500 Upward shift
- 501-600 Downward shift

Code below reads the series and shows example of each type of series (Fig. 8):

```

controlCharts <- read.csv(
  "http://kdd.ics.uci.edu/databases/synthetic_control/synthetic_control.data",
  header=F, sep="")

idx <- c(1, 101, 201, 301, 401, 501)
sample1 <- t(controlCharts[idx, ])
plot.ts(sample1, main = "")

```

Now we randomly sample n cases from each class, to make it easy for plotting:

```

n <- 5
s <- sample(1:100, n)
idx <- c(s, 100+s, 200+s, 300+s, 400+s, 500+s)
sample2 <- controlCharts[idx,]
observedLabels <- c(rep(1,n), rep(2,n), rep(3,n), rep(4,n), rep(5,n), rep(6,n))

```

Next step is to compute DTW distances between the sample series and perform hierarchical clustering (Fig. 9).

```

library(dtw)
distMatrix <- dist(sample2, method="DTW")
hc <- hclust(distMatrix, method="average")
plot(hc, labels=observedLabels, main="")

```

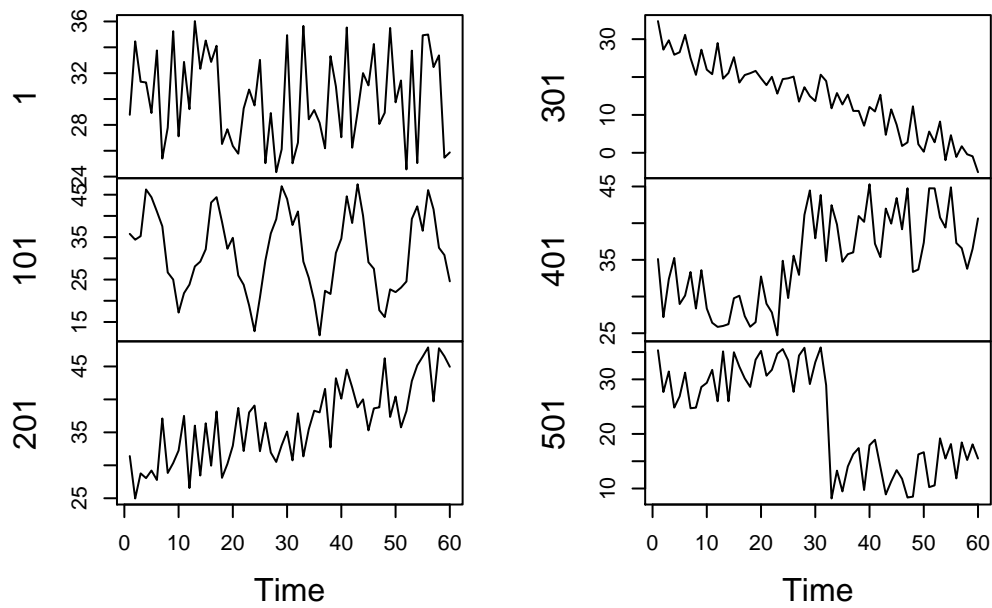


Figure 8: Different types of syntetic time series

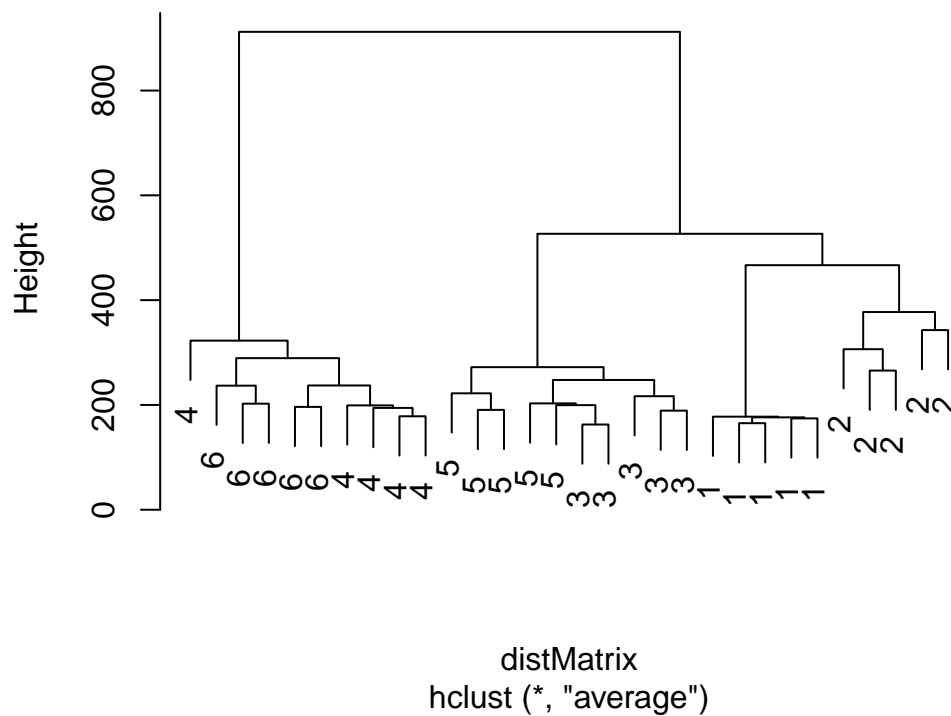


Figure 9: Hierarhical clustering of syntetic time series using DTW distances

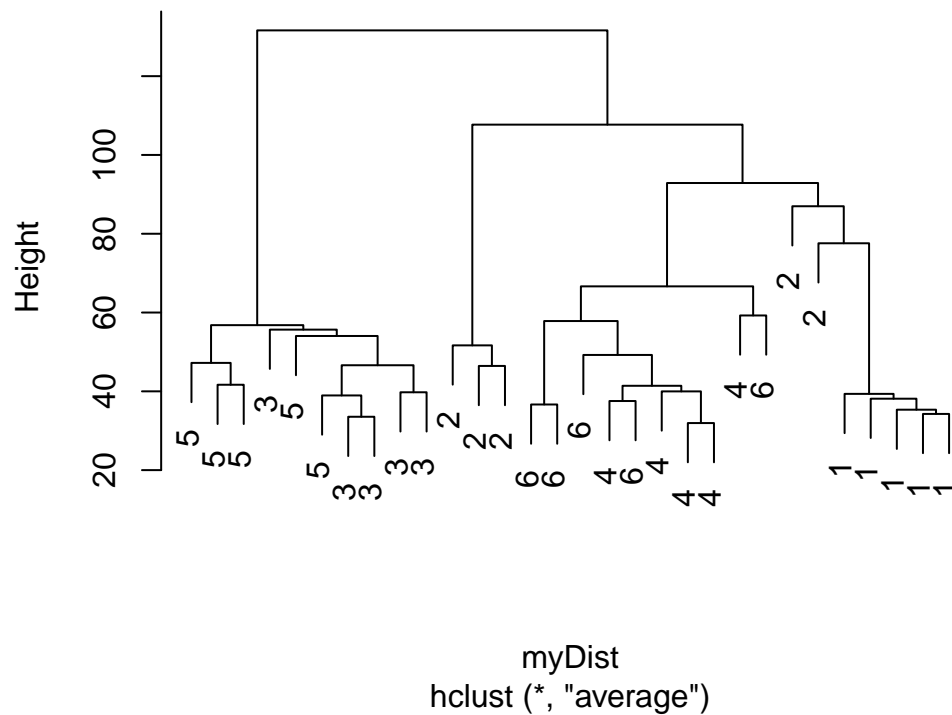


Figure 10: Hierarchical clustering of synthetic time series using Euclidean distances

```
memb <- cutree(hc, k = 8)
table(observedLabels, memb)

#>      memb
#> observedLabels 1 2 3 4 5 6 7 8
#>      1 5 0 0 0 0 0 0
#>      2 0 1 1 2 1 0 0
#>      3 0 0 0 0 0 5 0
#>      4 0 0 0 0 0 0 1 4
#>      5 0 0 0 0 0 5 0
#>      6 0 0 0 0 0 0 0 5
```

Hierarchical clustering with Euclidean distance

```
myDist <- dist(sample2)
hc <- hclust(myDist, method = "ave")
plot(hc, labels = observedLabels, main = "")
```

Cut tree to get 8 clusters

```
memb <- cutree(hc, k = 8)
table(observedLabels, memb)

#>      memb
#> observedLabels 1 2 3 4 5 6 7 8
#>      1 5 0 0 0 0 0 0
#>      2 0 1 1 3 0 0 0
#>      3 0 0 0 0 5 0 0
#>      4 0 0 0 0 0 1 4
#>      5 0 0 0 0 5 0 0
#>      6 0 0 0 0 0 0 4 1
```

Time series classification

Time series classification problem is a classification model based on labelled time series and then use the model to predict the label of unlabelled time series. The way for time series classification with R is to extract and build features from time series data first, and then apply existing classification techniques, such as SVM, k-NN, neural networks, regression and decision trees, to the feature set. Feature Extraction is done by the following methods:

- Singular Value Decomposition (SVD)
- Discrete Fourier Transform (DFT)
- Discrete Wavelet Transform (DWT)
- Piecewise Aggregate Approximation (PAA)
- Perpetually Important Points (PIP)
- Piecewise Linear Representation
- Symbolic Representation

Below is the example of Decision Tree model use for time series classification (Fig. 11):

```
classId <- rep(as.character(1:6), each = 100)
newSc <- data.frame(cbind(classId, controlCharts))

library(party)
ct <- ctree(classId ~ ., data = newSc,
  controls = ctree_control(minsplit = 20,
  minbucket = 5, maxdepth = 5))
plot(ct)
```

Let's estimate the accuracy of the prediction:

```
pClassId <- predict(ct)
table(classId, pClassId)

#>      pClassId
#> classId  1   2   3   4   5   6
#>      1 100   0   0   0   0   0
#>      2   1  97   2   0   0   0
#>      3   0   0  99   0   1   0
#>      4   0   0   0 100   0   0
#>      5   4   0   8   0  88   0
#>      6   0   3   0  90   0   7

(sum(classId == pClassId))/nrow(controlCharts)

#> [1] 0.8183333
```

Time Series feature extraction with Discrete Wavelet Transform

Discrete Wavelet Transform (DWT) provides a multi-resolution representation using wavelets and is used in the example below. Another popular feature extraction technique is Discrete Fourier Transform (DFT). [Haar Wavelet Transform](#) is a simplest DWT. The code below extracting DWT coefficients (with Haar filter).

```
library(wavelets)

wtData <- NULL
for (i in 1:nrow(controlCharts)) {
  a <- t(controlCharts[i,])
  wt <- dwt(a, filter="haar", boundary="periodic")
  wtData <- rbind(wtData, unlist(c(wt@W,wt@V[[wt@level]])))
}
wtData <- as.data.frame(wtData)
```

Now It's set class labels into categorical values:

```
classId <- c(rep("1",100), rep("2",100), rep("3",100),
  rep("4",100), rep("5",100), rep("6",100))
wtSc <- data.frame(cbind(classId, wtData))
```

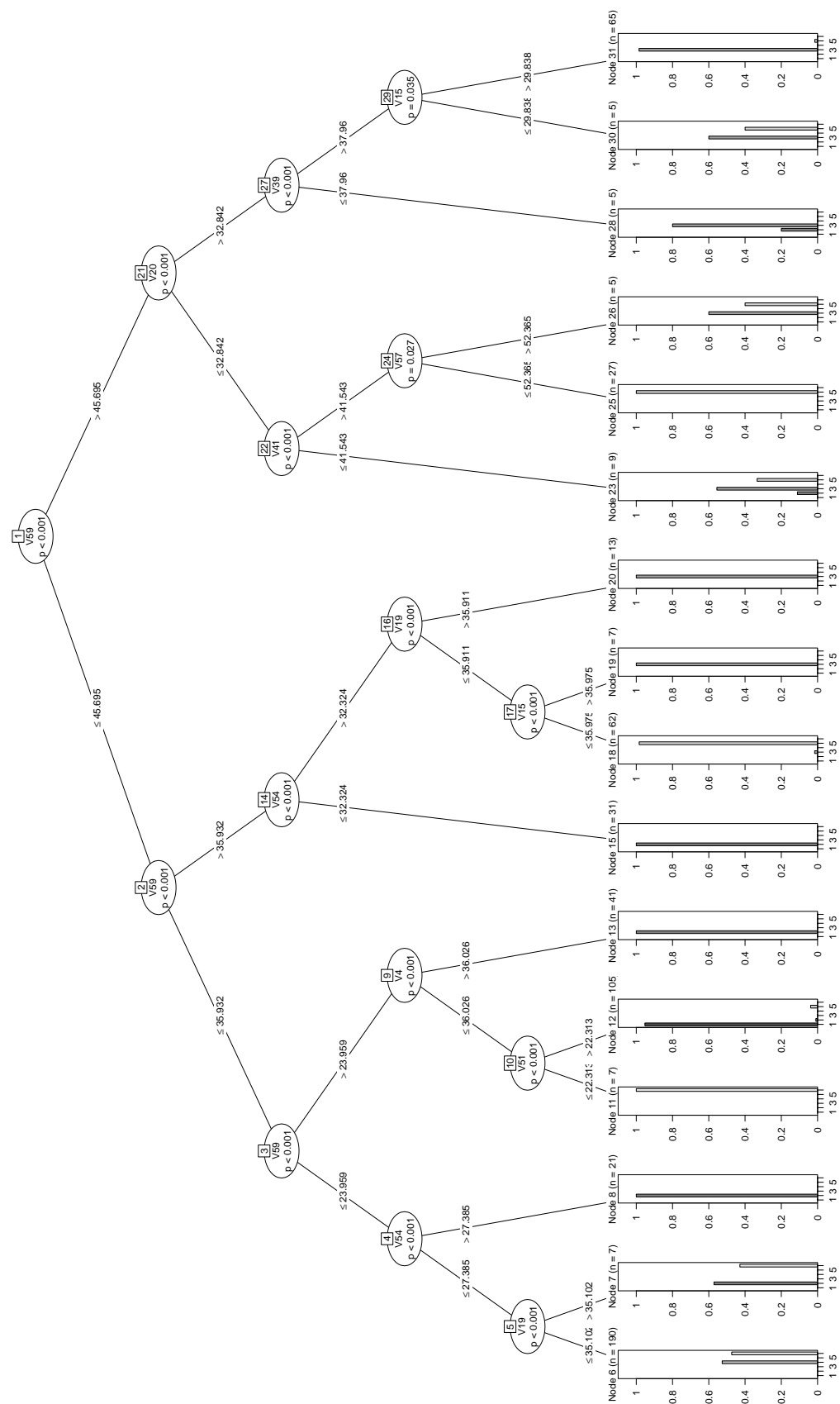


Figure 11: Decision Tree model use for time series classification

Now let's build a decision tree with **ctree** from package **party**, check predicted classes against original class labels and calculate accuracy. The resulting decision tree is presented in Fig. 12.

```
library(party)

ct <- ctree(classId ~ ., data=wtSc,
controls = ctree_control(minsplit=30, minbucket=10, maxdepth=5))
pClassId <- predict(ct)
table(classId, pClassId)

#>      pClassId
#> classId 1  2  3  4  5  6
#>      1 97  3  0  0  0  0
#>      2  1 99  0  0  0  0
#>      3  0  0 81  0 19  0
#>      4  0  0  0 63  0 37
#>      5  0  0 16  0 84  0
#>      6  0  0  0  1  0 99

(sum(classId==pClassId)) / nrow(wtSc)

#> [1] 0.8716667

plot(ct, ip_args = list(pval = F), ep_args = list(digits = 0))
```

KNN model - Find the k nearest neighbours

To find the k nearest neighbours first we generate a new series as a deviation series 501, then calculate and sort distances and display 20 closest series:

```
set.seed(22)
k <- 20
newTS <- controlCharts[501, ] + runif(100) * 15
distances <- dist(newTS, controlCharts, method = "DTW")
s <- sort(as.vector(distances), index.return = TRUE)

#Distances and indexes of the closest series
str(s)

#> List of 2
#> $ x : num [1:600] 331 332 333 339 340 ...
#> $ ix: int [1:600] 577 530 377 512 598 511 349 504 589 306 ...

#Class IDs of k nearest neighbours out of 20 closest
table(classId[s$ix[1:k]])

#>
#>  4  6
#>  4 16
```

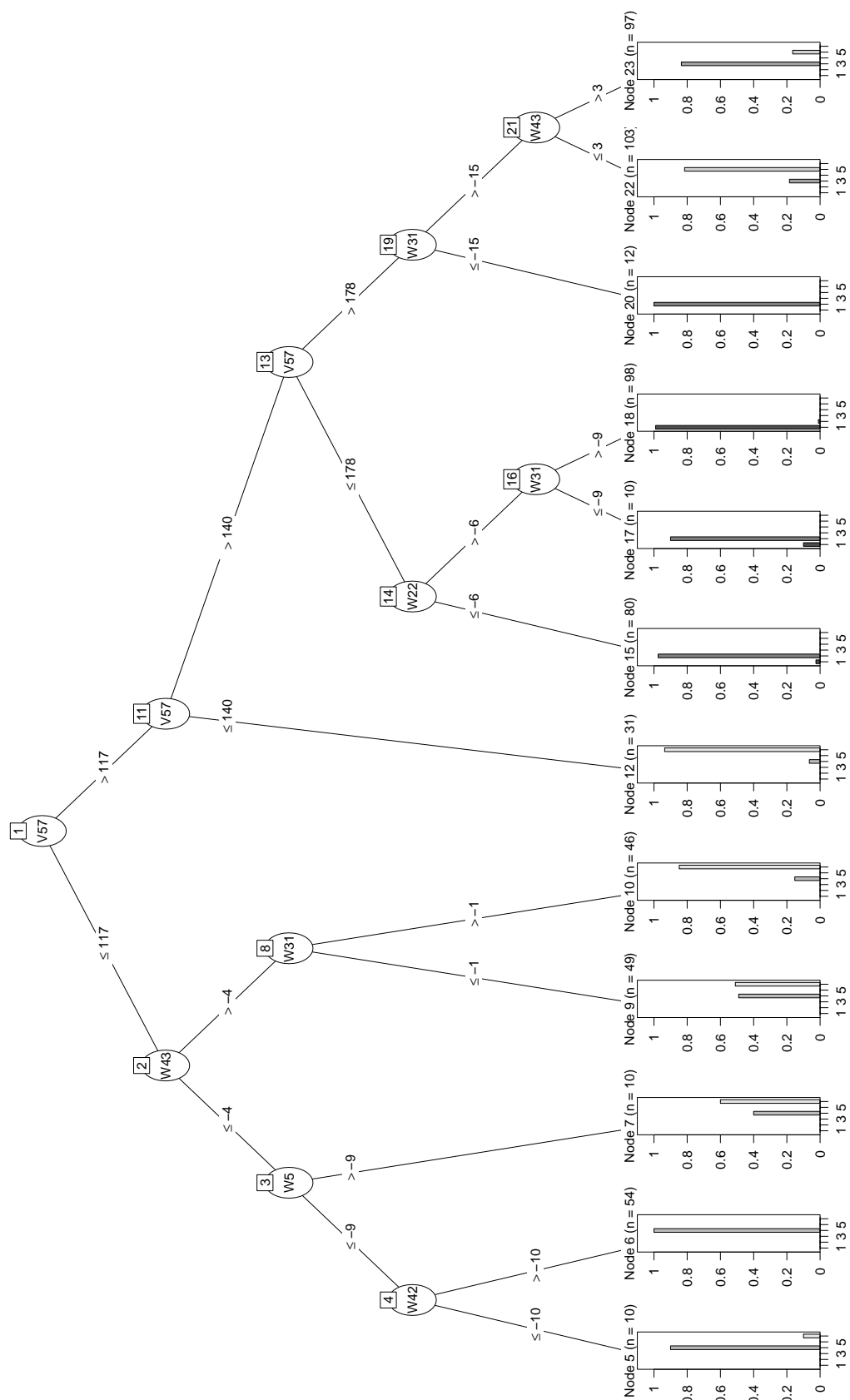


Figure 12: Hierarchical clustering of synthetic time series using Discrete Wavelet Transform

Example of Time-Series Analysis Practical Application

Prepare Shiny App for Deployment

Saving recommender data objects

```
#saveRDS(rcmnd_ub, file = "jokeRecommender.Rds")  
#saveRDS(jokes, file = "jokes.Rds")
```

Deployment Discussion

This model is currently not of much use given its accuracy but it will serve as a proof of concept. This model could be used to help writers of movies/tv shows write jokes appropriate for a specific or large audience.

More data should be collected from this userbase to fill a training dataset. The dataset in its current state is quite sparse. The data would need to be updated every 3-5 years as people's taste changes and people within certain age groups mature. The Shiny app developed would be a deployment method to collect more data.

Further analysis could be done (with the appropriate data) to see how similar taste in humor is related to age.

The model developed in this project was used to create Shiny application currently deployed at ivbsoftware.shinyapps.io/JokeRecommender/. Code of the application could be found in [Github](#).

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Note from the Authors

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