

Example Stochastic Reserving

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9/6/2019

```
library(mvtnorm)
library(MASS)
library(abind)
library(stochasticreserver)
```

Initialize Triangle

Input (B0) is a development array of cumulative averages with a the exposures (claims) used in the denominator appended as the last column. Assumption is for the same development increments as exposure increments and that all development lags with no development have # been removed. Data elements that are not available are indicated as such. This should work (but not tested for) just about any subset of an upper triangular data matrix.

Another requirement of this code is that the matrix contain no columns that are all zero.

```
B0 = matrix(c(670.25868,1480.24821,1938.53579,2466.25469,2837.84888,3003.52391,
3055.38674,3132.93838,3141.18638,3159.72524,
767.98833,1592.50266,2463.79447,3019.71976,3374.72689,3553.61387,3602.27898,
3627.28386,3645.5656,NA,
740.57952,1615.79681,2345.85028,2910.52511,3201.5226,3417.71335,3506.58672,
3529.00243,NA,NA,
862.11956,1754.90405,2534.77727,3270.85361,3739.88962,4003.00219,4125.30694,
NA,NA,NA,
840.94172,1859.02531,2804.54535,3445.34665,3950.47098,4185.95298,NA,NA,NA,NA,
848.00496,2052.922,3076.13789,3861.03111,4351.57694,NA,NA,NA,NA,NA,
901.77403,1927.88718,3003.58919,3881.41744,NA,NA,NA,NA,NA,NA,
935.19866,2103.97736,3181.75054,NA,NA,NA,NA,NA,NA,NA,
759.32467,1584.91057,NA,NA,NA,NA,NA,NA,NA,NA,
723.30282,NA,NA,NA,NA,NA,NA,NA,NA),10,10,byrow = TRUE)
dnom = c(39161.,38672.4628,41801.048,42263.2794,41480.8768,40214.3872,43598.5056,
42118.324,43479.4248,49492.4106)

size <- nrow(B0)
# Identify model to be used
# Berquist for the Berquist-Sherman Incremental Severity
# CapeCod for the Cape Cod
# Hoerl for the Generalized Hoerl Curve Model with trend
# Wright for the Generalized Hoerl Curve with individual accident year levels
# Chain for the Chain Ladder model
#model = "Berquist"
#model = "CapeCod"
model = "Hoerl"
#model = "Wright"
#model = "Chain"
# Toggle graphs off if desired
graphs = TRUE
```

```

# Toggle simulations off if desired
simulation = TRUE

# Set tau to have columns with entries 1 through size
tau = t(array((1:size), c(size, size)))

# Calculate incremental average matrix
A0 = cbind(B0[, 1], (B0[, (2:size)] + 0 * B0[, (1:(size - 1))]) -
           (B0[, (1:(size - 1))] + 0 * B0[, (2:size)]))

# Generate a matrix to reflect exposure count in the variance structure
logd = log(matrix(dnom, size, size))

# Set up matrix of rows and columns, makes later calculations simpler
rowNum = row(A0)
colNum = col(A0)

#. msk is a mask matrix of allowable data, upper triangular assuming same
#' development increments as exposure increments
#' msn is a mask matrix that picks off the first forecast diagonal
#' msd is a mask matrix that picks off the to date diagonal
msk = (size - rowNum) >= colNum - 1
msn = (size - rowNum) == colNum - 2
msd = (size - rowNum) == colNum - 1

# Amount paid to date
paid_to_date = rowSums(B0 * msd, na.rm = TRUE)

```

START OF MODEL SPECIFIC CODE

```

if (model == "Berquist") {
  model_lst <- berquist(tau, B0, paid_to_date, msk)
} else if (model == "CapeCod") {
  model_lst <- capecod(tau, B0, paid_to_date, msk)
} else if (model == "Hoerl") {
  model_lst <- hoerl(tau, B0, paid_to_date, msk)
} else if (model == "Wright") {
  model_lst <- wright(tau, B0, paid_to_date, msk)
} else if (model == "Chain") {
  model_lst <- chain(tau, B0, paid_to_date, msk)
}
g_obj <- model_lst$g_obj
g_grad <- model_lst$g_grad
g_hess <- model_lst$g_hess
a0 <- model_lst$a0

```

Negative Loglikelihood Function to be Minimized

Note that the general form of the model has parameters in addition to those in the loss model, namely the power for the variance and the constant of proportionality that varies by column. So if the original model has k parameters with size columns of data, the total objective function has $k + \text{size} + 1$ parameters

```

l.obj = function(a, A) {
  npar = length(a) - 2
  e = g_obj(a[1:npar])
  v = exp(-outer(logd[, 1], rep(a[npar + 1], size), "-")) * (e^2)^a[npar + 2]
  t1 = log(2 * pi * v) / 2
  t2 = (A - e) ^ 2 / (2 * v)
  sum(t1 + t2, na.rm = TRUE)
}

# Gradient of the objective function
l.grad = function(a, A) {
  npar = length(a) - 2
  p = a[npar + 2]
  Av = aperm(array(A, c(size, size, npar)), c(3, 1, 2))
  e = g_obj(a[1:npar])
  ev = aperm(array(e, c(size, size, npar)), c(3, 1, 2))
  v = exp(-outer(logd[, 1], rep(a[npar + 1], size), "-")) * (e^2)^p
  vv = aperm(array(v, c(size, size, npar)), c(3, 1, 2))
  dt = rowSums(g_grad(a[1:npar]) * ((p / ev) + (ev - Av) / vv - p *
                                     (Av - ev)^2 / (vv * ev)),
               na.rm = TRUE,
               dims = 1)
  yy = 1 - (A - e) ^ 2 / v
  dk = sum(yy / 2, na.rm = TRUE)
  dp = sum(yy * log(e ^ 2) / 2, na.rm = TRUE)
  c(dt, dk, dp)
}

```

Hessian of the objective function

- e is the expectedated value matrix
- v is the matrix of variances
- A, e, v all have shape c(size, size)
- The variables `_v` are copies of the originals to shape c(npar,size,size), paralleling the gradient of g.
- The variables `_m` are copies of the originals to shape c(npar,npar,size,size), paralleling the hessian of g

```

l.hess = function(a, A) {
  npar = length(a) - 2
  p = a[npar + 2]
  Av = aperm(array(A, c(size, size, npar)), c(3, 1, 2))
  Am = aperm(array(A, c(size, size, npar, npar)), c(3, 4, 1, 2))
  e = g_obj(a[1:npar])
  ev = aperm(array(e, c(size, size, npar)), c(3, 1, 2))
  em = aperm(array(e, c(size, size, npar, npar)), c(3, 4, 1, 2))
  v = exp(-outer(logd[, 1], rep(a[npar + 1], size), "-")) * (e ^ 2) ^ p
  vv = aperm(array(v, c(size, size, npar)), c(3, 1, 2))
  vm = aperm(array(v, c(size, size, npar, npar)), c(3, 4, 1, 2))
  g1 = g_grad(a[1:npar])
  gg = aperm(array(g1, c(npar, size, size, npar)), c(4, 1, 2, 3))
  gg = gg * aperm(gg, c(2, 1, 3, 4))
  gh = g_hess(a[1:npar])
  dtt = rowSums(
    gh * (p / em + (em - Am) / vm - p * (Am - em) ^ 2 / (vm * em)) +
    gg * (

```

```

      1 / vm + 4 * p * (Am - em) / (vm * em) + p * (2 * p + 1) * (Am - em) ^ 2 /
      (vm * em ^ 2) - p / em ^ 2
    ),
    dims = 2,
    na.rm = TRUE
  )
  dkt = rowSums((g1 * (Av - ev) + p * g1 * (Av - ev) ^ 2 / ev) / vv, na.rm = TRUE)
  dtp = rowSums(g1 * (1 / ev + (
    log(ev ^ 2) * (Av - ev) + (p * log(ev ^ 2) - 1) * (Av - ev) ^ 2 / ev
  ) / vv),
    na.rm = TRUE)
  dkk = sum((A - e) ^ 2 / (2 * v), na.rm = TRUE)
  dpk = sum(log(e ^ 2) * (A - e) ^ 2 / (2 * v), na.rm = TRUE)
  dpp = sum(log(e ^ 2) ^ 2 * (A - e) ^ 2 / (2 * v), na.rm = TRUE)
  m1 = rbind(array(dkt), c(dtp))
  rbind(cbind(dtt, t(m1)), cbind(m1, rbind(cbind(dkk, c(
    dpk
  )), c(dpk, dpp))))
}

```

End of function specifications now on to the minimization

Minimization

Get starting values for kappa and p parameters, default 10 and 1

```
ttt = c(10, 1)
```

For starting values use fitted objective function and assume variance for a cell is estimated by the square of the difference between actual and expected averages. Note since $\log(0)$ is $-\text{Inf}$ we need to go through some machinations to prep the y values for the fit

```

E = g_obj(a0)
yyy = (A0 - E)^2
yyy = logd + log(((yyy != 0) * yyy) - (yyy == 0))
sss = na.omit(data.frame(x = c(log(E^2)), y = c(yyy)))
ttt = array(coef(lm(sss$y ~ sss$x)))[1:2]
a0 = c(a0, ttt)

set.seed(1) # to check reproducibility with original code
max = list(iter.max = 10000, eval.max = 10000)

```

Actual minimization

```

mle = nlminb(a0, l.obj, gradient = l.grad, hessian = l.hess,
  scale = abs(1 / (2 * ((a0 * (a0 != 0)) + (1 * (a0 == 0))))),
  A = A0, control = max)

```

Model statistics

- **mean** and **var** are model fitted values

- **stres** is the standardized residuals

```

npar = length(a0) - 2
p = mle$par[npar + 2]
mean = g_obj(mle$par[1:npar])
var = exp(-outer(logd[, 1], rep(mle$par[npar + 1], size), "-")) * (mean ^
                                                                    2) ^ p

stres = (A0 - mean) / sqrt(var)
g1 = g_grad(mle$par[1:npar])
gg = aperm(array(g1, c(npar, size, size, npar)), c(4, 1, 2, 3))
gg = gg * aperm(gg, c(2, 1, 3, 4))
meanv = aperm(array(mean, c(size, size, npar)), c(3, 1, 2))
meanm = aperm(array(mean, c(size, size, npar, npar)), c(3, 4, 1, 2))
varm = aperm(array(var, c(size, size, npar, npar)), c(3, 4, 1, 2))

```

Masks to screen out NA entries in original input matrix

```

s = 0 * A0
sv = aperm(array(s, c(size, size, npar)), c(3, 1, 2))
sm = aperm(array(s, c(size, size, npar, npar)), c(3, 4, 1, 2))

```

Calculate the information matrix

- Using second derivatives of the log likelihood function Second with respect to theta parameters

```
tt = rowSums(sm + gg * (1 / varm + 2 * p ^ 2 / (meanm ^ 2)), dims = 2, na.rm = TRUE)
```

Second with respect to theta and kappa

```
kt = p * rowSums(sv + g1 / meanv, na.rm = TRUE)
```

Second with respect to p and theta

```
tp = p * rowSums(sv + g1 * log(meanv ^ 2) / meanv, na.rm = TRUE)
```

Second with respect to kappa

```
kk = (1 / 2) * sum(1 + s, na.rm = TRUE)
```

Second with respect to p and kappa

```
pk = (1 / 2) * sum(s + log(mean ^ 2), na.rm = TRUE)
```

Second with respect to p

```
pp = (1 / 2) * sum(s + log(mean ^ 2) ^ 2, na.rm = TRUE)
```

Create information matrix in blocks

```

m1 = rbind(array(kt), c(tp))
inf = rbind(cbind(tt, t(m1)), cbind(m1, rbind(c(kk, pk), c(pk, pp))))

```

Variance-covariance matrix for parameters, inverse of information matrix

```
vcov = solve(inf)
```

Simulation

Initialize simulation array to keep simulation results

```
sim = matrix(0, 0, 11)
smn = matrix(0, 0, 11)
spm = matrix(0, 0, npar + 2)
```

Simulation for distribution of future amounts

Want 10,000 simulations, but exceeds R capacity, so do in batches of 5,000

```
nsim = 5000
msk = aperm(array(c(msk), c(size, size, nsim)), c(3, 1, 2))
msn = aperm(array(c(msn), c(size, size, nsim)), c(3, 1, 2))

if (simulation) {
  for (i in 1:5) {
    # Randomly generate parameters from multivariate normal
    spar = rmvnorm(nsim, mle$par, vcov)

    # Arrays to calculate simulated means
    esim = g_obj(spar)

    # Arrays to calculate simulated variances
    ksim = exp(aperm(outer(array(
      spar[, c(npar + 1)], c(nsim, size)
    ), log(dnom), "-"), c(1, 3, 2)))
    psim = array(spar[, npar + 2], c(nsim, size, size))
    vsim = ksim * (esim ^ 2) ^ psim

    # Randomly simulate future averages
    temp = array(rnorm(nsim * size * size, c(esim), sqrt(c(vsim))), c(nsim, size, size))

    # Combine to total by exposure period and in aggregate
    # notice separate array with name ending in "n" to capture
    # forecast for next accounting period
    sdnm = t(matrix(dnom, size, nsim))
    fore = sdnm * rowSums(temp * !msk, dims = 2)
    forn = sdnm * rowSums(temp * msn, dims = 2)

    # Cumulate and return for another 5,000
    sim = rbind(sim, cbind(fore, rowSums(fore)))
    smn = rbind(smn, cbind(forn, rowSums(forn)))
    spm = rbind(spm, spar)
  }
}
```

Print Results

```
model
```

```
## [1] "Hoerl"
```

```
model_description(model)
```

```
## [1] "Generalized Hoerl Curve Model with Trend"
```

```
summary(sim)
```

```
##           V1           V2           V3           V4
## Min.      :0      Min.    :-2208490      Min.    :-3804527      Min.    :-5992989
## 1st Qu.:0      1st Qu.: -21117      1st Qu.: 367584      1st Qu.: 1840551
## Median :0      Median : 182624      Median : 832281      Median : 2737909
## Mean     :0      Mean     : 187219      Mean     : 852369      Mean     : 2764779
## 3rd Qu.:0      3rd Qu.: 392581      3rd Qu.: 1324325      3rd Qu.: 3665383
## Max.     :0      Max.     : 2337207      Max.     : 5463162      Max.     : 9796623
##           V5           V6           V7
## Min.      :-2673996      Min.      : 2973114      Min.      :18415004
## 1st Qu.: 5895531      1st Qu.:15056985      1st Qu.:36558098
## Median : 7417472      Median :17391073      Median :40191121
## Mean     : 7433759      Mean     :17428167      Mean     :40198575
## 3rd Qu.: 8952586      3rd Qu.:19775174      3rd Qu.:43786949
## Max.     :17823691      Max.     :33324982      Max.     :64044023
##           V8           V9           V10
## Min.      : 42635180      Min.      : 84602187      Min.      :147458026
## 1st Qu.: 67656581      1st Qu.:117555956      1st Qu.:197239795
## Median : 72765035      Median :124469665      Median :207118943
## Mean     : 72769286      Mean     :124641424      Mean     :207451820
## 3rd Qu.: 77764124      3rd Qu.:131567817      3rd Qu.:217428116
## Max.     :106540770      Max.     :173366354      Max.     :271965621
##           V11
## Min.      :348584519
## 1st Qu.:453264017
## Median :473033240
## Mean     :473727397
## 3rd Qu.:493480419
## Max.     :606557866
```

```
summary(smn)
```

```
##           V1           V2           V3           V4
## Min.      :0      Min.    :-2208490      Min.    :-3115594      Min.    :-3068350
## 1st Qu.:0      1st Qu.: -21117      1st Qu.: 237639      1st Qu.: 1158427
## Median :0      Median : 182624      Median : 630842      Median : 1853083
## Mean     :0      Mean     : 187219      Mean     : 640646      Mean     : 1857638
## 3rd Qu.:0      3rd Qu.: 392581      3rd Qu.: 1043496      3rd Qu.: 2560199
## Max.     :0      Max.     : 2337207      Max.     : 3971738      Max.     : 6843497
##           V5           V6           V7
## Min.      :-4249322      Min.      : 672065      Min.      : 6333106
## 1st Qu.: 3487607      1st Qu.: 8249938      1st Qu.:18143629
## Median : 4616366      Median : 9867620      Median :20452592
## Mean     : 4606687      Mean     : 9879531      Mean     :20497593
## 3rd Qu.: 5722689      3rd Qu.:11498718      3rd Qu.:22806770
```

```
## Max.      :11746388    Max.      :19262639    Max.      :35413380
##          V8              V9              V10
## Min.      :12362698    Min.      :23576556    Min.      :33066545
## 1st Qu.   :29265167    1st Qu.   :42456948    1st Qu.   :54880593
## Median    :32271226    Median    :46051469    Median    :59310793
## Mean      :32277564    Mean      :46118371    Mean      :59372552
## 3rd Qu.   :35256668    3rd Qu.   :49811006    3rd Qu.   :63722832
## Max.      :53006982    Max.      :72609638    Max.      :86736032
##          V11
## Min.      :129752423
## 1st Qu.   :167087821
## Median    :175382878
## Mean      :175437801
## 3rd Qu.   :183644510
## Max.      :230595466
```

Scatter plots of residuals & Distribution of Forecasts

```
if (graphs) {
  #x11(title = model_description(model))

  # Prep data for lines for averages in scatter plots of standardized residuals
  ttt = array(cbind(c(rowNum + colNum - 1), c(stres)),
              c(length(c(stres)), 2, 19))
  sss = t(array((1:19), c(19, length(c(stres))))))

  # Plotting
  par(mfrow = c(2, 2))
  plot(
    na.omit(cbind(c(rowNum + colNum - 1), c(stres))),
    main = "Standardized Residuals by CY",
    xlab = "CY",
    ylab = "Standardized Residual",
    pch = 18
  )
  lines(na.omit(list(
    x = (1:19),
    y = colSums(ttt[, 2, ] *
                 (ttt[, 1, ] == sss), na.rm = TRUE) /
        colSums((ttt[, 1, ] == sss) +
                 0 *
                 ttt[, 2, ], na.rm = TRUE)
  )), col = "red")
  plot(
    na.omit(cbind(c(colNum), c(stres))),
    main = "Standardized Residuals by Lag",
    xlab = "Lag",
    ylab = "Standardized Residual",
    pch = 18
  )
  lines(na.omit(list(
    x = colNum[1, ],
```

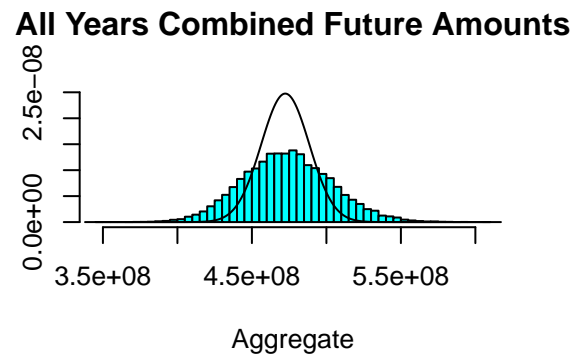
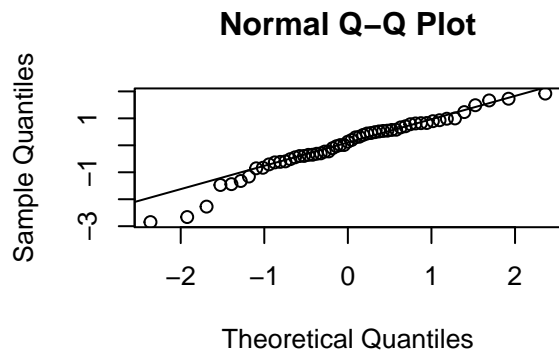
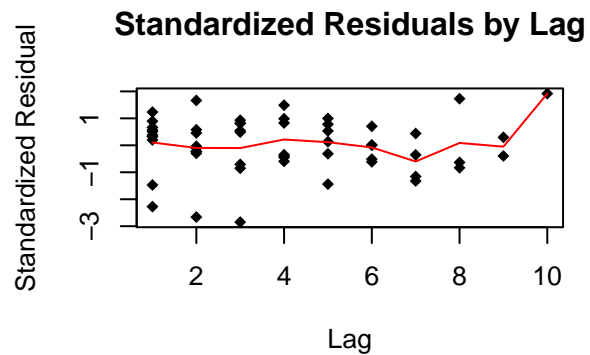
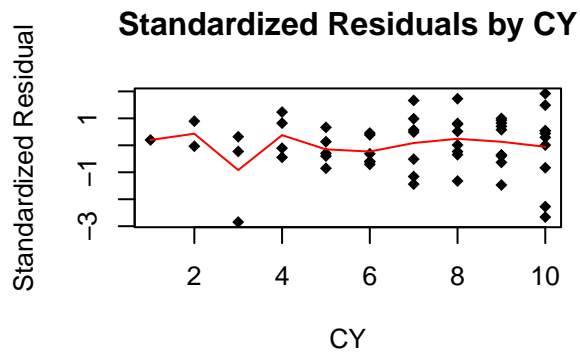


```

y = colSums(stres, na.rm = TRUE) /
  colSums(1 + 0 * stres, na.rm = TRUE)
)), col = "red")
qqnorm(c(stres))
qqline(c(stres))
if (simulation) {
  proc = list(x = (density(sim[, 11]))$x,
              y = dnorm((density(sim[, 11]))$x,
                        sum(matrix(c(
                          dnom
                        ), size, size) * mean * !msk),
                        sqrt(sum(
                          matrix(c(dnom), size, size) ^ 2 * var * !msk
                        ))))

  truehist(sim[, 11],
            ymax = max(proc$y),
            main = "All Years Combined Future Amounts",
            xlab = "Aggregate")
  lines(proc)
}
}

```



Summary From Simulation

Summary of mean, standard deviation, and 90% confidence interval from simulation, similar for one-period forecast

```

sumr = matrix(0, 0, 4)
sumn = matrix(0, 0, 4)

```

```

for (i in 1:11) {
  sumr = rbind(sumr, c(mean(sim[, i]), sd(sim[, i]), quantile(sim[, i], c(.05, .95))))
  sumn = rbind(sumn, c(mean(smn[, i]), sd(smn[, i]), quantile(smn[, i], c(.05, .95))))
}
sumr

```

```

##
##      [1,]      0.0      0.0      0.0      0.0
##      [2,]  187218.8  353761.7 -369841.5  771157.4
##      [3,]   852369.4   772535.9 -380479.7  2139129.1
##      [4,]  2764779.0  1423821.4   477583.3  5125608.7
##      [5,]  7433758.5  2324640.2   3648857.0 11230492.1
##      [6,] 17428166.6  3534255.6 11707287.6 23288978.3
##      [7,] 40198575.3  5398539.0 31437358.2 49159689.5
##      [8,] 72769285.8  7522855.3 60449526.0 85209982.7
##      [9,]124641423.8 10528687.6 107631732.4 142319135.4
##     [10,]207451819.6 15348515.7 182707406.7 233387503.6
##     [11,]473727396.8 29753777.6 426184913.1 523884658.5

```

sumn

```

##
##      [1,]      0.0      0.0      0.00      0.0
##      [2,]  187218.8  353761.7 -369841.53  771157.4
##      [3,]   640646.4   650084.5 -414251.81  1707212.6
##      [4,]  1857638.2 1084140.1   97447.16  3637977.1
##      [5,]  4606686.8 1674886.5  1854988.61  7323039.9
##      [6,]  9879531.2 2435095.3  5867670.36 13873959.3
##      [7,] 20497593.0 3517316.7 14703500.28 26303795.5
##      [8,] 32277564.1 4510385.1 24954391.59 39750930.9
##      [9,] 46118371.0 5547381.1 37074538.57 55339176.1
##     [10,] 59372551.6 6615812.4 48611660.50 70333442.5
##     [11,]175437801.1 12401775.7 155072276.37 195956054.9

```