

Empirical Analysis of the Role of Energy in Economic Growth

Caleb Reese^a, Lucas Timmer^a, Matthew Kuperus Heun^{a,*}

^a*Engineering Department, Calvin College, Grand Rapids, MI 49546, USA*

Abstract

***** Add abstract *****

Keywords: economic growth, energy, cobb-douglas, CES, LINEX

```
fileName <- "data/USData.txt"

# Read the data file as a table with a header.
## dataTable is a poor name. Name it after contents, unless this is the
## start of a script where this will be provided at the command line.
dataTable <- read.table(fileName, header = TRUE)

# Identifies the header names associated with dataTable
names(dataTable)

[1] "Year"
[2] "GDP.Millionsofreal2005USdollars."
[3] "Labour.Millionsofhoursworked."
[4] "CapitalStock.Millionsofreal2005USdollars."
[5] "Thermalenergy.TJ."
[6] "Exergy.TJ."
[7] "UsefulWork.TJ."
[8] "iYear"
[9] "iGDP"
```

*Corresponding author

Email address: mkh2@calvin.edu, tel: +1 (616) 526-6663, fax: +1 (616) 526-6501 (Matthew Kuperus Heun)

Preprint submitted to Energy Economics

January 18, 2013

```
[10] "iLabor"
[11] "iCapStk"
[12] "iQ"
[13] "iX"
[14] "iU"
```

1. Cobb-Douglas Without Energy

```
# Establish guess values for alpha and lambda.
lambdaGuess <- 0.0 # guessing lambda = 0 means there is no technological progress.
alphaGuess <- 0.3 # a typical value for alpha, the coefficient on capital stock

# Runs a non-linear least squares fit to the data. We've replaced beta with 1-alpha
modelCD <- nls(iGDP ~ exp(lambda*iYear) * iCapStk^alpha * iLabor^(1 - alpha),
               start=(list(lambda=lambdaGuess,alpha=alphaGuess)),
               data=dataTable)

# Checks validity of the model. AIC stands for Akaike's Information Criterion.
aicCD <- AIC(modelCD, k=2); aicCD

[1] -163

summaryCD <- summary(modelCD) # Gives the nls summary table.
print(summaryCD)

Formula: iGDP ~ exp(lambda * iYear) * iCapStk^alpha * iLabor^(1 - alpha)

Parameters:
      Estimate Std. Error t value Pr(>|t|)
lambda 0.010256  0.000682   15.03 1.7e-15
alpha  0.270030  0.028311    9.54 1.4e-10

Residual standard error: 0.0178 on 30 degrees of freedom

Number of iterations to convergence: 4
Achieved convergence tolerance: 3.81e-07
```

```

ciCD <- confint(modelCD, level = 0.95); ciCD # Displays confidence intervals for t

Waiting for profiling to be done...

              2.5%   97.5%
lambda 0.008862 0.01164
alpha  0.212405 0.32785

# Calculate beta and its confidence interval and report it.
alpha <- as.numeric(coef(modelCD)["alpha"])
beta <- 1.0 - alpha
beta.est <- deltaMethod(modelCD, "1 - alpha"); beta.est # Estimates beta and its s

              Estimate      SE
1 - alpha      0.73 0.02831

# Now calculate a confidence interval on beta
dofCD <- summaryCD$df[2]; dofCD # Gives the degrees of freedom for the model.

[1] 30

tvalCD <- qt(0.975, df = dofCD); tvalCD

[1] 2.042

betaCICD <- with(beta.est, Estimate + c(-1.0, 1.0) * tvalCD * SE); betaCICD # Give

[1] 0.6722 0.7878

coef(modelCD)

lambda  alpha
0.01026 0.27003

```

```

# Combine all estimates and their confidence intervals into data frames with intervals
estCD <- data.frame(lambda = coef(modelCD)["lambda"], alpha = coef(modelCD)["alpha"],
row.names(estCD) <- "Cobb-Douglas"
#row.names(estCD) <- "Cobb-Douglas: $y = e^{\lambda t}k^{\alpha}l^{\beta}$"
# The [1] subscripts pick off the lower confidence interval
lowerCD <- data.frame(lambda = ciCD["lambda", "2.5%"], alpha = ciCD["alpha", "2.5%"],
row.names(lowerCD) <- "- 95% CI"
# The [2] subscripts pick off the lower confidence interval
upperCD <- data.frame(lambda = ciCD["lambda", "97.5%"], alpha = ciCD["alpha", "97.5%"],
row.names(upperCD) <- "+ 95% CI"

# Now create the data for a table.
dataCD <- rbind(lowerCD, estCD, upperCD); dataCD

      lambda  alpha  beta gamma
- 95% CI    0.008862 0.2124 0.6722    NA
Cobb-Douglas 0.010256 0.2700 0.7300    NA
+ 95% CI    0.011645 0.3279 0.7878    NA

colnames(dataCD) <- c("$\\lambda$", "$\\alpha$", "$\\beta$", "$\\gamma$")
tableCD <- xtable(dataCD)

Warning: provided 3 variables to replace 1 variables

```

```
print(xtable(dataCD), floating=FALSE)
```

	λ	α	β	γ
- 95% CI	0.01	0.21	0.67	
Cobb-Douglas	0.01	0.27	0.73	
+ 95% CI	0.01	0.33	0.79	

```

# According to http://cran.r-project.org/web/packages/xtable/vignettes/xtableGallery.html
# be able to use the "sanitize.text.function" parameter to allow markup in column
# line is not working at the present time. --MKH, 18 Jan 2012.
# print(tableCD, sanitize.text.function = function(x){x})

```

2. Cobb-Douglas With Q

```
# Establish guess values for alpha, beta, and lambda.
# lambdaGuess <- 0.0 # guessing lambda = 0 means there is no technological progress
# alphaGuess <- 0.2 # a typical value for alpha
# betaGuess <- 0.6 # a typical value for beta

# Runs a non-linear least squares fit to the data.
# modelCDQ <- nls(iGDP ~ exp(lambda*iYear) * iCapStk^alpha * iLabor^beta * iQ^(1.0)
#               start=(list(lambda=lambdaGuess,alpha=alphaGuess,beta=betaGuess))
#               data=dataTable)

# Reparameterize to ensure that we meet the constraint that alpha + beta + gamma = 1
# 0 < a < 1
# 0 < b < 1
# alpha = min(a, b)
# beta = b - a
# gamma = 1 - max(a, b)

lambdaGuess <- 0.0 # guessing lambda = 0 means there is no technological progress.
alphaGuess <- 0.2 # a typical value for alpha
betaGuess <- 0.8 # a typical value for beta
modelCDq <- nls(iGDP ~ exp(lambda*iYear) *
               iCapStk^min(a,b) * iLabor^abs(b-a) *
               iQ^(1.0 - max(a,b)),
               algorithm = "port",
               start = list(lambda=lambdaGuess, a=alphaGuess, b=alphaGuess+betaGuess),
               lower = list(lambda=-Inf, a=0, b=0),
               upper = list(lambda=Inf, a=1, b=1),
               data = dataTable)

aicCDq <- AIC(modelCDq, k=2); aicCDq # Checks validity of the model. AIC stands for Akaike Information Criterion

[1] -161.1

summaryCDq <- summary(modelCDq); summaryCDq # Gives the nls summary table
```

```
Formula: iGDP ~ exp(lambda * iYear) * iCapStk^min(a, b) * iLabor^abs(b -
a) * iQ^(1 - max(a, b))
```

Parameters:

	Estimate	Std. Error	t value	Pr(> t)
lambda	0.01049	0.00108	9.67	1.4e-10
a	0.26322	0.03795	6.94	1.3e-07
b	0.97890	0.07647	12.80	1.9e-13

Residual standard error: 0.0181 on 29 degrees of freedom

Algorithm "port", convergence message: relative convergence (4)

```
# Provides confidence intervals on lambda, a, and b. But, we need CIs on alpha and
ciCDq <- confint(modelCDq, level = 0.95); ciCDq
```

Waiting for profiling to be done...

	2.5%	97.5%
lambda	0.00885	0.0127
a	0.18580	0.3283
b	0.82175	NA

```
a <- as.numeric(coef(modelCDq)["a"])
b <- as.numeric(coef(modelCDq)["b"])
lambda <- as.numeric(coef(modelCDq)["lambda"])
alpha <- a
beta <- b - a
gamma <- 1.0 - alpha - beta
```

```
# Report results with SE
```

```
beta.est <- deltaMethod(modelCDq, "b-a"); beta.est # Reports results for beta, bec
```

	Estimate	SE
b - a	0.7157	0.05916

```

gamma.est <- deltaMethod(modelCDq, "1-b"); gamma.est # Reports results for gamma,

      Estimate      SE
1 - b    0.0211 0.07647

# Now calculate confidence intervals.
dofCDq <- summaryCDq$df[2]; dofCDq # Gives the degrees of freedom for the model.

[1] 29

tvalCDq <- qt(0.975, df = dofCDq); tvalCDq

[1] 2.045

betaCICDq <- with(beta.est, Estimate + c(-1.0, 1.0) * tvalCDq * SE); betaCICDq # C

[1] 0.5947 0.8367

gammaCICDq <- with(gamma.est, Estimate + c(-1.0, 1.0) * tvalCDq * SE); gammaCICDq

[1] -0.1353 0.1775

# Combine all estimates and their confidence intervals into data frames with intel
estCDq <- data.frame(lambda = lambda, alpha = alpha, beta = beta, gamma = gamma);

      lambda  alpha  beta  gamma
1 0.01049 0.2632 0.7157 0.0211

#row.names(estCDq) <- "Cobb-Douglas with q: $y = e^{\lambda t}k^{\alpha}l^{\beta}$"
row.names(estCDq) <- "CobbDouglas with q"
# The [1] subscripts pick off the lower confidence interval
lowerCDq <- data.frame(lambda = ciCDq["lambda", "2.5%"], alpha = ciCDq["a", "2.5%"])
row.names(lowerCDq) <- "- 95% CI"
# The [2] subscripts pick off the lower confidence interval
upperCDq <- data.frame(lambda = ciCDq["lambda", "97.5%"], alpha = ciCDq["a", "97.5%"])
row.names(upperCDq) <- "+ 95% CI"

# Now create the data for a table.
dataCDq <- rbind(lowerCDq, estCDq, upperCDq); dataCDq

```

```

      lambda  alpha  beta  gamma
- 95% CI      0.00885 0.1858 0.5947 -0.1353
CobbDouglas with q 0.01049 0.2632 0.7157 0.0211
+ 95% CI      0.01270 0.3283 0.8367 0.1775

```

```

colnames(dataCDq) <- c("$\\lambda$", "$\\alpha$", "$\\beta$", "$\\gamma$")
tableCDq <- xtable(dataCDq)

```

```

dataAll <- rbind(dataCD, dataCDq); dataAll

```

```

      $\\lambda$ $\\alpha$ $\\beta$ $\\gamma$
- 95% CI      0.008862 0.2124 0.6722      NA
Cobb-Douglas 0.010256 0.2700 0.7300      NA
+ 95% CI      0.011645 0.3279 0.7878      NA
- 95% CI1     0.008850 0.1858 0.5947 -0.1353
CobbDouglas with q 0.010486 0.2632 0.7157 0.0211
+ 95% CI1     0.012700 0.3283 0.8367 0.1775

```

```

print(xtable(dataCDq), floating=FALSE)

```

	λ	α	β	γ
- 95% CI	0.01	0.19	0.59	-0.14
CobbDouglas with q	0.01	0.26	0.72	0.02
+ 95% CI	0.01	0.33	0.84	0.18

```

# According to http://cran.r-project.org/web/packages/xtable/vignettes/xtableGalle
# be able to use the "sanitize.text.function" parameter to allow markup in column
# line is not working at the present time. --MKH, 18 Jan 2012.
# print(tableCDq, sanitize.text.function = function(x){x})

```

```

print(xtable(dataAll, floating=FALSE))

```

3. Cobb-Douglas With X

	λ	α	β	γ
- 95% CI	0.01	0.21	0.67	
Cobb-Douglas	0.01	0.27	0.73	
+ 95% CI	0.01	0.33	0.79	
- 95% CI1	0.01	0.19	0.59	-0.14
CobbDouglas with q	0.01	0.26	0.72	0.02
+ 95% CI1	0.01	0.33	0.84	0.18

```

# Establish guess values for alpha, beta, and lambda.
lambdaGuess <- 0.0 # guessing lambda = 0 means there is no technological progress.
alphaGuess <- 0.2 # a typical value for alpha
betaGuess <- 0.6 # a typical value for beta

# Runs a non-linear least squares fit to the data.
modelCDX <- nls(iGDP ~ exp(lambda*iYear) * iCapStk^alpha * iLabor^beta * iX^(1.0 -
               start=(list(lambda=lambdaGuess,alpha=alphaGuess,beta=betaGuess)),
               data=dataTable)

# Gives the nls summary table
summary(modelCDX)

Formula: iGDP ~ exp(lambda * iYear) * iCapStk^alpha * iLabor^beta * iX^(1 -
      alpha - beta)

Parameters:
      Estimate Std. Error t value Pr(>|t|)
lambda  0.01071   0.00105  10.16  4.6e-11
alpha    0.25689   0.03666   7.01  1.0e-07
beta     0.70011   0.05916  11.83  1.3e-12

Residual standard error: 0.018 on 29 degrees of freedom

Number of iterations to convergence: 4
Achieved convergence tolerance: 2.88e-06

confint(modelCDX, level = 0.95)

```

Waiting for profiling to be done...

```
          2.5%   97.5%  
lambda 0.008559 0.01287  
alpha   0.182137 0.33181  
beta    0.578423 0.82111
```

```
# Calculate gamma and report it.  
alpha <- coef(modelCDX)["alpha"]  
beta <- coef(modelCDX)["beta"]  
gamma <- as.numeric(1.0 - alpha - beta)  
c(coef(modelCDX), gamma=gamma)
```

```
lambda  alpha    beta  gamma  
0.01071 0.25689 0.70011 0.04300
```

```
# Checks validity of the model. AIC stands for Akaike's Information Criterion  
AIC(modelCDX, k=2)
```

```
[1] -161.4
```

4. Cobb-Douglas With U

An issue arises in this example because constraining α and β is not sufficient to guarantee that γ is properly constrained.

```
# Establish guess values for alpha, beta, and lambda.  
lambdaGuess <- 0.0 # guessing lambda = 0 means there is no technological progress.  
alphaGuess <- 0.2 # a typical value for alpha  
betaGuess <- 0.6 # a typical value for beta  
gammaGuess <- 0.01 # a nice low value  
  
# Runs a non-linear least squares fit to the data with constraints  
modelCDU <- nls(iGDP ~ exp(lambda*iYear) * iCapStk^alpha * iLabor^beta * iU^(1.0 -  
  algorithm="port",
```

```

start = list(lambda=lambdaGuess, alpha=alphaGuess, beta=betaGuess),
lower = list(lambda=-Inf, alpha=0, beta=0),
upper = list(lambda=Inf, alpha=1, beta=1),
data=dataTable)

# Gives the nls summary table
summary(modelCDU)

Formula: iGDP ~ exp(lambda * iYear) * iCapStk^alpha * iLabor^beta * iU^(1 -
alpha - beta)

Parameters:
      Estimate Std. Error t value Pr(>|t|)
lambda  0.00920   0.00129   7.11  1.2e-06
alpha   0.32389   0.07187   4.51  0.00027
beta    0.71425   0.07641   9.35  2.5e-08

Residual standard error: 0.00994 on 18 degrees of freedom

Algorithm "port", convergence message: relative convergence (4)
(11 observations deleted due to missingness)

confint(modelCDU, level = 0.95)

Waiting for profiling to be done...

      2.5%   97.5%
lambda 0.00649 0.01192
alpha  0.17289 0.47457
beta   0.55373 0.87481

# Checks validity of the model. AIC stands for Akaike's Information Criterion
AIC(modelCDU, k=2)

[1] -129.3

```

The problem here is that $\hat{\gamma} < 0$.

```
# Calculate gamma and report it.
alpha <- coef(modelCDU)["alpha"]
beta <- coef(modelCDU)["beta"]
gamma <- as.numeric(1.0 - alpha - beta)
c(coef(modelCDU), gamma=gamma)
```

	lambda	alpha	beta	gamma
	0.009203	0.323887	0.714248	-0.038135

Our $\hat{\gamma}$ is not much below 0. Let's compute the standard error.

```
require(car) # the methods in alr3 have been deprecated. Use car instead.
gamma.est <- deltaMethod(modelCDU, "1-alpha-beta"); gamma.est
```

	Estimate	SE
1 - alpha - beta	-0.03813	0.03055

```
# crude CI (using 2 as a rough estimate for critical value)
with(gamma.est, Estimate + c(-1,1) * 2 * SE)

[1] -0.09924  0.02297
```

So no real cause for concern: our data don't convince us that the real γ is different from 0.

4.1. Forcing $\gamma \geq 0$

We can force α , β , and γ to be in $[0, 1]$ by a reparameterization:

$$a \in [0, 1], b \in [0, 1], \alpha = \min(a, b), \beta = |b - a|, \gamma = 1 - \max(a, b)$$

```
modelCDUforced <- nls(iGDP ~ exp(lambda*iYear) *
                      iCapStk^min(a,b) * iLabor^abs(b-a) *
                      iU^(1.0 - max(a,b)),
  algorithm="port",
  start = list(lambda=lambdaGuess, a=alphaGuess, b=alphaGuess + betaGuess),
  lower = list(lambda=-Inf, a=0, b=0),
  upper = list(lambda=Inf, a=1, b=1),
```

```

data=dataTable)

coef(summary(modelCDUforced))

      Estimate Std. Error t value Pr(>|t|)
lambda 0.009299   0.001349   6.893 1.908e-06
a       0.318805   0.074953   4.253 4.780e-04
b       1.000000   0.031938  31.310 3.765e-17

with( as.data.frame(t(coef(modelCDUforced))), c(alpha=min(a,b), beta=abs(b-a), gamma=1-b))

      alpha  beta  gamma
0.3188 0.6812 0.0000

```

But the naive delta method to calculate significance information fails because R doesn't know how to calculate the derivatives for the minimum and maximum functions. So we need to be clever, using the fact that we know now that $a < b$:

```

# alpha = a
deltaMethod( modelCDUforced, "a")

      Estimate      SE
a    0.3188 0.07495

# beta = b - a
deltaMethod( modelCDUforced, "b-a")

      Estimate      SE
b - a    0.6812 0.07972

# gamma = 1-b
deltaMethod( modelCDUforced, "1-b")

      Estimate      SE
1 - b         0 0.03194

```

So this seems to give us what we want for this case: We have parameter estimates and standard errors subject to all of our constraints.

It may be that we can avoid using min and max and just use a , $b - a$ and $1 - b$. If that works, then this generalizes fairly easily to any number of parameters that must be bounded by 0 and 1 and sum to 1. (Else we have to “sort” the dummy parameters first, which is OK but makes the coding a bit uglier.)

5. CES With Q

```
# Establish guess values for alpha, beta, and lambda.
phiGuess <- -20
betaGuess <- 0.5 # a typical value for beta (exponent on labor)
zetaGuess <- 0.0004 # a small value
lambda_LGuess <- 0.007 #assuming no technical progress on the labor-capital portion
lambda_EGuess <- 0.008 #assuming no technical progress on the energy portion of the

# Runs a non-linear least squares fit to the data with constraints
modelCESQ <- nls(iGDP ~ ((1-zeta) * (exp(lambda_L*iYear) * iLabor^beta * iCapStk^(1 -
    + zeta*(exp(lambda_E*iYear) * iQ)^phi)^(1/phi),
    algorithm = "port",
    control = nls.control(maxiter = 500, tol = 1e-06, minFactor = 1/1024,
        printEval = FALSE, warnOnly = FALSE),
    start = list(phi=phiGuess, beta=betaGuess, zeta=zetaGuess, lambda_L=lambda_LGuess,
        lambda_E=lambda_EGuess),
    lower = list(phi=-Inf, beta=0, zeta=0, lambda_L=-Inf, lambda_E=-Inf),
    upper = list(phi=0, beta=1, zeta=1, lambda_L=Inf, lambda_E=Inf),
    data=dataTable)

# Gives the nls summary table
summary(modelCESQ)

Formula: iGDP ~ ((1 - zeta) * (exp(lambda_L * iYear) * iLabor^beta * iCapStk^(1 -
    beta))^phi + zeta * (exp(lambda_E * iYear) * iQ)^phi)^(1/phi)

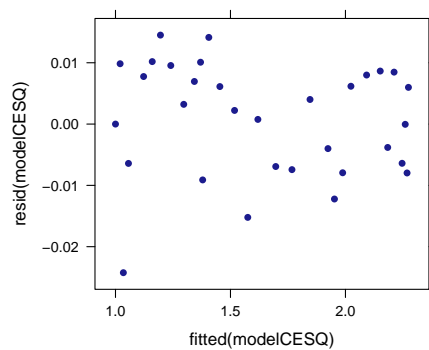
Parameters:
      Estimate Std. Error t value Pr(>|t|)
phi      -2.22e+01   1.50e+01  -1.48   0.1512
```

beta	5.82e-01	5.20e-02	11.19	1.2e-11
zeta	3.51e-04	1.38e-03	0.25	0.8014
lambda_L	7.62e-03	8.30e-04	9.18	8.5e-10
lambda_E	8.05e-03	2.84e-03	2.84	0.0085

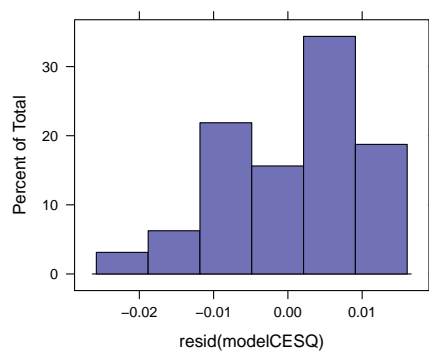
Residual standard error: 0.00993 on 27 degrees of freedom

Algorithm "port", convergence message: relative convergence (4)

```
xyplot( resid(modelCESQ) ~ fitted(modelCESQ) )
```



```
histogram( ~resid(modelCESQ) )
```



```
qqmath( ~resid(modelCESQ) )
```

