

DIY Macroeconomic Model Simulation

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Welcome



Warning

This website is under construction and will be regularly updated and extended.

This platform provides an open source code repository and online script for macroeconomic model simulation. It follows a “do-it-yourself” (DIY) approach, empowering users to numerically simulate key macroeconomic models on their own using the open-source programming languages *R* and *Python*. Whether you are a university teacher, student, researcher, or an economics enthusiast, our platform offers resources to deepen your understanding of both macroeconomic modelling and coding.

The platform covers an array of macroeconomic models, including canonical textbook models, models from different economic paradigms, and seminal models from the history of economic thought. It bridges a gap between intermediate and advanced level macroeconomics by providing detailed yet accessible treatments of seminal macroeconomic models. Most intermediate macroeconomics textbooks focus on graphical analysis, while advanced level materials are often more mathematical and less accessible. Our platform offers a hands-on and approachable resource for users to build both a solid foundation in modelling and macroeconomic intuition.

The platform’s DIY-approach aims to foster reproducibility and open-source principles in macroeconomic research and education by providing learning materials that are freely available and modifiable by everyone. The platform’s content will expand over time through new entries added by the project team.

Project team

Contact

We welcome any feedback. If you encounter any issues, find typos or mistakes, or have questions/thoughts on the content, please do get in touch.

1. If you are Github user, you can [report an issue](#) in our repository
2. You can also email us directly: franz.prante@wiwi.tu.chemnitz.de and k.kohler@leeds.ac.uk



(a) Franz Prante



(b) Karsten Kohler

Franz is a research associate at Chemnitz Uni-Karsten is an Associate Professor in Economics
versity of Technology, where he is currently at Leeds University Business School, where he
working on the macroeconomic effects of money and the interaction between fi-
tary policy and price effects on energy demand and the real economy, especially sources
He is also a PhD student at Université Sorbonne Paris Nord. of cyclical dynamics, instability, and rising in-
equality.

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Acknowledgements

We are grateful for helpful comments from Adam Aboobaker, Chandni Dwarkasing, Giuseppe
Fontana, Alex Guschanski, Eckhard Hein, and Rafael Wildauer on various sections of this
website. All errors are ours.

1 Getting Started

1.1 Structure of platform

The platform starts off with a general introduction the numerical simulation of economic models (Chapter 2). After that, it jumps right into a series of macroeconomic models. These models are grouped into static and dynamic models. In static models, time plays no role and all variables adjust instantaneously. By contrast, dynamic models characterise the adjustment of variables over time.

The model entries are largely self-contained and can be read independently of each other. For each model, the chapters provide three main components:

1. **Model descriptions** that concisely explain the key ideas, assumptions, and equations of each model. This helps users grasp the underlying concepts and intuition behind the models.
2. **Annotated code** that allows users to numerically simulate the models, examine their results under different scenarios, and produce visualisations to better understand the models' structure and output. This hands-on approach enables users to gain practical coding skills while exploring different macroeconomic theories.
3. **Analytical discussions** for users who are interested in delving deeper into the mathematical properties of the models.

To further facilitate the understanding of dynamic models, Chapter 9 of the section on dynamic models begins with a general introduction into the mathematical analysis of dynamic models (this is mostly relevant for the analytical discussions of dynamic models).

All simulation codes are written in the open-source programming languages *R* and *Python*. *R* codes are presented in the main text (and images and results in the text are the output of the shown *R* codes), while the corresponding *Python* codes are available by clicking on the callout blocks underneath the *R* codes.

1.2 Access and introduction to *R* and *Python*

To be able to manipulate the codes on this platform on your own machine, you first need to download and install *R* and *RStudio*. For Python, there are different options. One of them

is to download and install *Spyder* via the [Anaconda Python distribution](#). *Spyder* provides an interface for *Python* (like *RStudio* for *R*). If you install it via *Anaconda*, it will install *Python* automatically.

Besides being free, a key advantage of both *R* and *Python* is their huge and growing functionality due to new user-written libraries and packages continuously being added. In addition, a large amount of learning material is freely available on the web, e.g. [here](#) and [here](#) for *R* and [here](#), and [here](#) for *Python*. However, to get started in can be best to directly delve into some of the codes on this platform and learn by doing. To this end, the following “cheatsheets” that provide a concise overview of key functions are useful:

- [R Studio Cheatsheet](#)
- [Base R Cheatsheet](#)
- [more R cheatsheets here](#)
- [Python Basics Cheatsheet](#)
- [Python for Data Science Cheatsheet](#)
- [Python Cheatsheet for NumPy library](#)

Once you have installed *R* or *Python*, you can play with the codes on this platform yourself by copy and pasting them into the script panel of your local interface (IDE) and hitting CTRL + Enter to execute them. Don’t forget to always comment your code using the “#” symbol and to save your scripts to make sure your future self can seamlessly continue working on it.

The codes below covers some basic operations.¹ If you are new to *R* or *Python* and keen to get started, do the following:

- copy the codes below into the script panel of *RStudio* or *Spyder* on your machine
- adjust the working directory to your personal folder
- then run the code
- make sure you understand what it does

```
##### R Basics #####
#In the R script you write code and comments
#any line starting with # is a comment and it is NOT executed

## First things first: set the working directory to the the folder in which your R files are
# note that you need to separate folders by slashes /
```

¹We are grateful to Rafael Wildauer for permission to reproduce a slightly modified version of his learning materials. In addition, some of the material below is taken from [here](#).

```

#Let's define some variables
s = 0.05
Y = 10

#We can also assign several variables the same value at once
C = I = R = 2

#For displaying them we simply call the name of the object and execute the relevant line
Y
C

#We can define new variables using existing ones
W = Y - R
W

#R has a vast amount of built in functions, for example
max(10,2,100,-3)
sqrt(9)
abs(-13)

#you can find out more about these by using the help function, e.g.:?max()

#How can you delete stuff? Use the remove function rm()
#for individual objects
rm(Y)
#if you want to remove everything
rm(list=ls(all=TRUE))

#You can also assign text (a string) to a variable
text1 = 'Reggaeton'
text2 = "Bad Bunny"
#note "text" is the same as 'text' and a string can contain spaces
#You use the paste function to combine strings
paste(text1, text2)

#R uses standard operators like +, -, *
#for exponents use ^
3^2

#####
##### if statements and loops #####
#####

```

```

#sometimes we need to introduce if conditions into our code
#The syntax is
#if condition { do something }
a = 10
b = 13
if (b>a) {
  print("b is bigger")
}
#we can also tell R what to do in case the condition is not fulfilled
b=10
if (b>a) {
  print("b is bigger")
} else {
  print("b not bigger")
}

#Next we will look at loops which are a key tool to repeat tasks such as solving
#a theoretical model again and again to find its equilibrium.
#The basic structure is:
for (i in 1:5){
  print(i)
}

#Let's use it to solve a simple Keynesian cross model of the form
#Y=C+I
#C=c0+c1Y
#define exogenous parameters
c0=2
c1=0.8
I=10
#set initial values for two endogenous variable
Y=C=1
#Use a for loop to solve it
C
Y
for (i in 1:100){
  Y = C+I
  C = c0+c1*Y
}
C
Y

```

```

#solution is Y=(I+c0)/(1-c1)=60

#What is special about this loop is that it uses the values from the previous iteration
#to define the values of the next, because it starts with assigning a value to Y
#and then uses that value to assign a new value to C and in the next iteration it
#uses this new value for C to define a new value for Y etc.

#####
# Data structures #####
#In most applications we produce outputs which do not consist of a single number.
#Often we have an entire stream of results, or we want to analyse data and have to store large
#R has a variety of data structures for this purpose.
#let's clean up first
rm(list=ls(all=TRUE))

#####Vectors
#We can create an empty vector and fill it later (with results of our model for example)
vec1 = vector(length=3)
#we can define vectors explicitly using the c() function (c for column?)
vec2 = c(1,2,3)
vec3 = c(6,7,8)
#we can also use the sequence operator
vec4 = 1:10
#and we can define the step size
vec5 = seq(1,2,0.1)
vec5
#we can call specific entries using square brackets
vec5[4]
#if we want to access more elements at once
vec5[c(4,1)]

#####Matrices
#define a matrix: 3 rows and 2 columns, all elements equal to 0
mat1 = matrix(0, nrow=3, ncol=2)
mat1
#we can also fill it with specific values
mat2 = matrix(c(1,2,3,4,5,6), nrow = 3, ncol = 2)
mat2
#access specific elements (columns,rows)
mat2[3,1]
#access entire rows or columns
mat2[,1]

```

```
mat2[1,]
#access sub matrices
mat2[c(1,2),]
## Combine two column vectors in a matrix
mat3=cbind(vec1, vec2)
mat3
## Combine two row vectors in a matrix
mat4=rbind(vec1, vec2)
mat4
```

 Python code

1.3 Simple exercise

1.

 Solution

```
[1] 1.000000 1.250000 1.361111 1.423611 1.463611 1.491389 1.511797 1.527422  
[9] 1.539768 1.549768
```

2.

 Solution

	x	y
[1,]	1.000000	1.000000
[2,]	1.250000	1.125000
[3,]	1.361111	1.162037
[4,]	1.423611	1.177662
[5,]	1.463611	1.185662
[6,]	1.491389	1.190292
[7,]	1.511797	1.193207
[8,]	1.527422	1.195160
[9,]	1.539768	1.196532
[10,]	1.549768	1.197532

2 How to Simulate Economic Models

2.1 Introduction: economic models

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[1](#)

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¹That raises the question of whether an equilibrium is stable or unstable, which is discussed in Chapter [9](#).

2.2 Solving economic models numerically

the Gauss-Seidel method

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9

2.2.1 Solving economic models numerically: examples

2.2.1.1 A static model

```

### Simulate Keynesian goods market model via iteration

#Clear the environment
rm(list=ls(all=TRUE))

# Set number of parameterisations that will be considered
S=2

# Set fixed parameter values
c0=3
c1=0.8

#Create vector in which equilibrium solutions from different parameterisations will be stored
Y_eq=vector(length=S)
C_eq=vector(length=S)

#Create vector with parameter that will change
I0=vector(length=S)
I0[1]=5
I0[2]=6

# Initialise endogenous variables at arbitrary positive value
Y=C=1

#Solve this system numerically through 1000 iterations based on the initialisation
for (i in 1:S){
  for (iteration in 1:1000){
    Y = C + I0[i]
    C = c0 + c1*Y
  } # close iterations loop

  #Save results for different parameterisations in vector
}

```

```
Y_eq[i]=Y  
C_eq[i]=C  
} # close parameterisations loop  
  
# Display solutions  
Y_eq
```

```
C_eq
```

```
# Verify solutions for Y  
(c0+I0[])/(1-c1)
```

 Python code

```

### Simulate Keynesian goods market model via iteration

# Load NumPy library
import numpy as np

# Set the number of parameterisations that will be considered
S = 2

# Set fixed parameter values
c0 = 3
c1 = 0.8

# Create numpy arrays in which equilibrium solutions from different parameterisations will
Y_eq = np.zeros(S)
C_eq = np.zeros(S)

# Create a numpy array with the parameter that will change
I0 = np.zeros(S)
I0[0] = 5
I0[1] = 6

# Initialize endogenous variables at an arbitrary positive value
Y = C = 1

# Solve this system numerically through 1000 iterations based on the initialization
for i in range(S):
    for iteration in range(1000):
        Y = C + I0[i]
        C = c0 + c1 * Y

        # Save results for different parameterisations in the numpy arrays
        Y_eq[i] = Y
        C_eq[i] = C

# Display solutions
Y_eq
C_eq

# Verify solutions for Y
(c0+I0)/(1-c1)

```

•
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9

```
### Parameterisation for which method of iteration fails

#Clear the environment
rm(list=ls(all=TRUE))

# Set number of parameterisations that will be considered
S=2

# Set fixed parameter values
c0=3
c1=1.2

#Create vector in which equilibrium solutions from different parameterisations will be stored
```

```

Y_eq=vector(length=S)
C_eq=vector(length=S)

#Create vector with parameter that will change
I0=vector(length=S)
I0[1]=5
I0[2]=6

# Initialise endogenous variables at arbitrary positive value
Y=C=1

#Solve this system numerically through 1000 iterations based on the initialisation
for (i in 1:S){
  for (iteration in 1:1000){
    Y = C + I0[i]
    C = c0 + c1*Y
  } # close iterations loop

  #Save results for different parameterisations in vector
  Y_eq[i]=Y
  C_eq[i]=C
} # close parameterisations loop

# Display solutions
Y_eq

# Verify solutions for Y
(c0+I0[])/(1-c1)

```

 Python code

```
### Parameterisation for which method of iteration fails
c1 = 1.2

# Initialize endogenous variables at an arbitrary positive value
Y = C = 1

# Solve this system numerically through 1000 iterations based on the initialization
for i in range(S):
    for iteration in range(1000):
        Y = C + I0[i]
        C = c0 + c1 * Y

    # Save results for different parameterisations in the numpy arrays
    Y_eq[i] = Y
    C_eq[i] = C

# Display solutions for Y_eq
Y_eq

# Verify solutions for Y
(c0+I0)/(1-c1)
```

2.2.1.2 A dynamic model (in discrete time)

```

### Simulate Samuelson 1939

#Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods for which you want to simulate
Q=100

# Set number of parameterisations that will be considered
S=2

# Set period in which shock or shift in an will occur
s=15

# Set fixed parameter values
c1=0.8
beta=0.6

# Construct (S x Q) matrices in which values for different periods will be stored; initialise
C=matrix(data=1, nrow=S, ncol=Q)
I=matrix(data=1, nrow=S, ncol=Q)

#Construct matrices for exogenous variable or parameter that will change over time to capture
G0=matrix(data=5, nrow=S, ncol=Q)

# Set parameter values for different scenarios
G0[2,s:Q]=6      # scenario: permanent increase in government spending from I0=5 to I0=6 from

#Solve this system recursively based on the initialisation
for (i in 1:S){
  for (t in 2:Q){
    C[i,t] = c1*(C[i,t-1] + I[i,t-1] + G0[i,t])
  }
}

```

```
I[i,t] = beta*(c1*(C[i,t-1] + I[i,t-1] + G0[i,t]) - C[i,t-1])
} # close time loop
} # close scenarios loop

# Calculate output
Y=C+G0+I

# Display solution
Y[,Q]
```

```
# Verify solutions for Y
(G0[,Q])/(1-c1)
```

 Python code

```

### Simulate Samuelson 1939

# Set the number of periods for which you want to simulate
Q = 100

# Set the number of parameterisations that will be considered
S = 2

# Set the period in which a shock or shift in 'an' will occur
s = 15

# Set fixed parameter values
c1 = 0.8
beta = 0.6

# Construct (S x Q) matrices in which values for different periods will be stored; initialise at 5
C = np.ones((S, Q))
I = np.ones((S, Q))

# Construct matrices for exogenous variables or parameters that will change
# over time to capture different scenarios, initialise at 5
G0 = np.ones((S, Q))*5

# Set parameter values for different scenarios
G0[1, s:Q] = 6 # scenario: permanent increase in government spending from I0=5 to I0=6 from period s onwards

# Solve this system recursively based on the initialization
for i in range(S):
    for t in range(1, Q):
        C[i, t] = c1 * (C[i, t - 1] + I[i, t - 1] + G0[i, t])
        I[i, t] = beta * (c1 * (C[i, t - 1] + I[i, t - 1] + G0[i, t]) -
                           C[i, t - 1])

# Calculate output
Y = C + G0 + I

# Display the solutions at time Q
Y[:, Q - 1]

# Verify solutions for Y
(G0[:, Q - 1])/(1-c1)

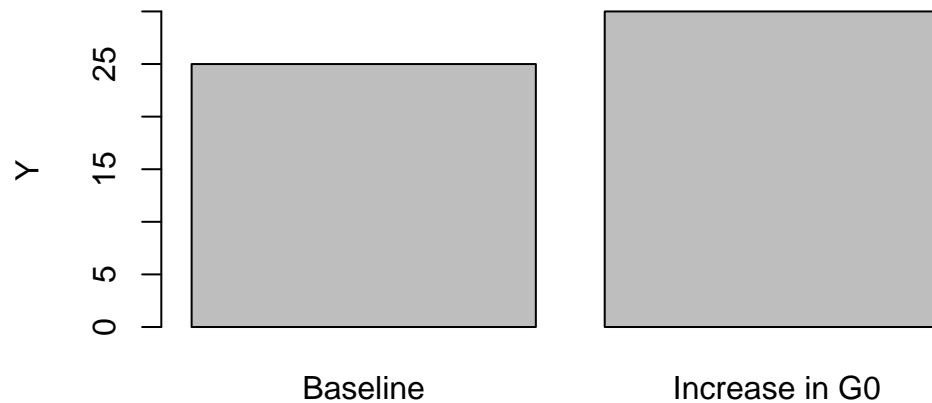
```

-
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2.3 How to plot the results of a model

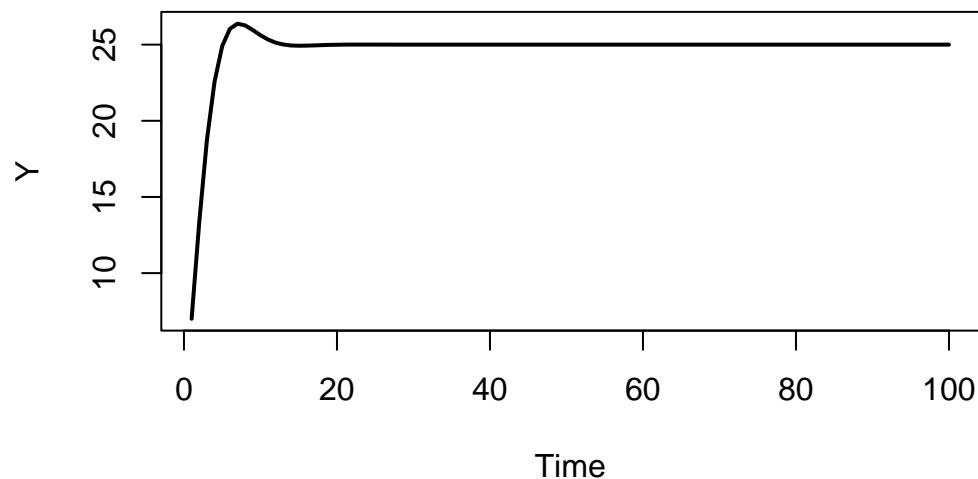
```
# Bar chart of different equilibrium solutions of Samuelson (1939) model  
barplot(Y[,Q], ylab="Y", main="Output", names.arg=c("Baseline", "Increase in G0"))
```

Output



```
# Time series chart of output dynamics in Samuelson (1939) model
plot(Y[1, 1:100], type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="Y")
title(main="Output", cex=0.8)
```

Output

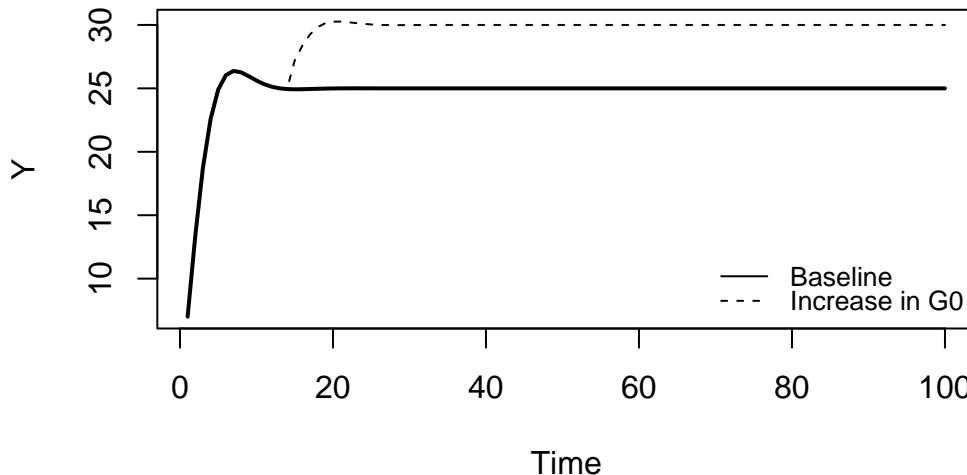


```

# Time series chart of output dynamics for different scenarios in Samuelson (1939) model
plot(Y[1, 1:100], type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="Y", ylim=range(min(Y[1,]),
title(main="Output under different scenarios", cex=0.8)
lines(Y[2, 1:100], lty=2)
legend("bottomright", legend=c("Baseline", "Increase in G0"),
      lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)

```

Output under different scenarios

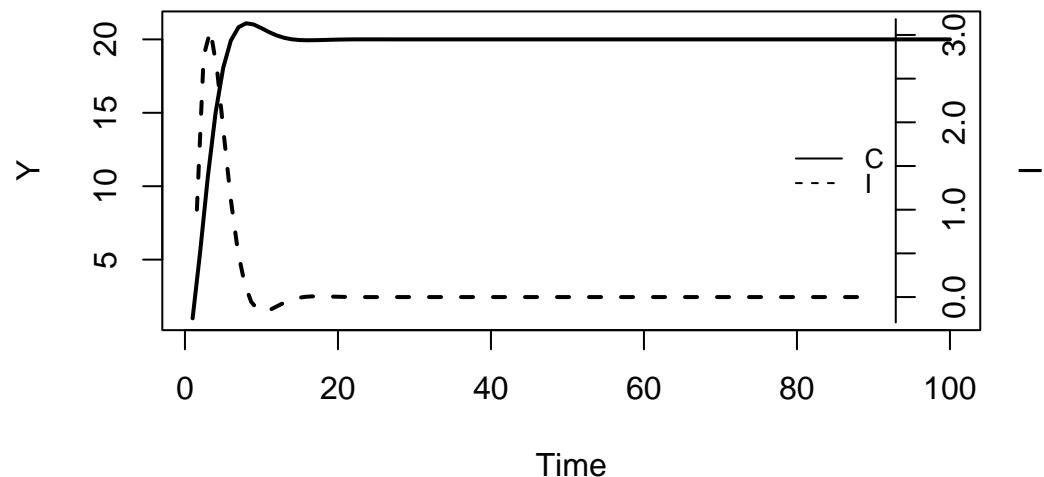


```

# Time series chart of Samuelson (1939) model with separate axes for consumption and investment
plot(C[1, 1:100], type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="Y")
title(main="Consumption and Investment", cex=0.8)
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(I[1, 1:100], type="l", col=1, lwd=2, lty=2, font.main=1, cex.main=1, ylab = '',
      axes=FALSE,
      xlab = '', ylim = range(I[1, 1:100]), cex=0.8)
axis(side = 4, at=pretty(range(I[1, 1:100])))
mtext("I", side = 4, line = 3)
legend("right", legend=c("C", "I"),
      lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)

```

Consumption and Investment



 Python code

```

##### Plots

# Load matplot library
import matplotlib.pyplot as plt

# Bar chart of different equilibrium solutions of Samuelson (1939) model
scenario_labels = ["Baseline", "Increase in G0"]
plt.bar(scenario_labels, Y[:, Q - 1])
plt.xlabel("Scenario")
plt.ylabel("Y")
plt.title("Output")
plt.show()

# Time series chart of output dynamics in Samuelson (1939) model
plt.plot(range(1, Q), Y[0, 0:Q - 1], color='black', linewidth=2, linestyle='--')
plt.xlabel("Time")
plt.ylabel("Y")
plt.title("Output", fontsize=10)
plt.show()

# Time series chart of output dynamics for different scenarios in Samuelson
#(1939) model
plt.plot(range(1, Q), Y[0, 0:Q - 1], color='black', linewidth=1, linestyle='--')
plt.plot(range(1, Q), Y[1, 0:Q - 1], color='black', linewidth=1, linestyle='---')
plt.xlabel("Time")
plt.ylabel("Y")
plt.title("Output under different scenarios", fontsize=10)
plt.legend(["Baseline", "Increase in G0"], loc='lower right')
plt.show()

# Time series chart of Samuelson (1939) model with separate axes for consumption
# and investment
fig, ax1 = plt.subplots()
ax1.plot(range(1, Q), C[0, 0:Q - 1], color='black', linewidth=2, linestyle='--',
          label='C')
ax1.set_xlabel("Time")
ax1.set_ylabel("C", color='black')
ax1.tick_params(axis='y', labelcolor='black')
ax2 = ax1.twinx()
ax2.plot(range(1, Q), I[0, 0:Q - 1], color='black', linewidth=2, linestyle='---',
          label='I')
ax2.set_ylabel("I", color='black')
ax2.tick_params(axis='y', labelcolor='black')
plt.title("Consumption and Investment", fontsize=10)
lines, labels = ax1.get_legend_handles_labels()
lines2, labels2 = ax2.get_legend_handles_labels()
ax2.legend(lines + lines2, labels + labels2, loc='right')
plt.show()

```

2.4 How to create a directed graph of a model

²

³

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 4 variables:
# endogenous: (1) Y, (2) C, (3) I
# exogenous: (4) GO
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged

#1 2 3 4
M_mat=matrix(c(0,1,1,1, #1
              1,0,0,0, #2
              0,1,0,0, #3
              0,0,0,0), #4
              4, 4, byrow=TRUE)
```

²See Fennell et al. (2015) for a neat exposition.

³To create the directed graph, we rely on external libraries which you may have to install first. In R, this can be accomplished with `install.packages("igraph")` and in Python with `pip install networkx`. Once that library is installed, you only need to activate it in each session before you use it. In R, you can do this by executing `library(igraph)` and in Python through `import networkx`.

```

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat=t(M_mat)

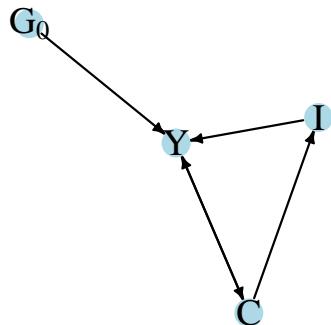
# Create directed graph from adjacency matrix
library(igraph)
dg=graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y", "C", "I", expression(G[0]))

# Plot directed graph matrix
plot(dg, main="Directed graph of Samuelson model", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

Directed graph of Samuelson model



 Python code

```
#Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Construct auxiliary Jacobian matrix for 4 variables
# endogenous: (1) Y, (2) C, (3) I
# exogenous: (4) G0
# where non-zero elements in regular Jacobian are set to 1 and zero elements are
# unchanged
M_mat = np.array([[0, 1, 1, 1],
                  [1, 0, 0, 0],
                  [0, 1, 0, 0],
                  [0, 0, 0, 0]])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "Y", 1: "C", 2: "I", 3: "$G_0$"}

# Plot the directed graph
pos = nx.spring_layout(G, seed=42)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=500, node_color='lightblue', font_color='black')
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.title("Directed graph of Samuelson model", fontsize=12)
plt.axis('off')
plt.show()
```

1.

2.

3.

2.5 Appendix: How to simulate dynamic model in continuous time

```
### Simulate continuous time version of Keynesian goods market model

#Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods for which you want to simulate
Q=800

# Set number of parameterisations that will be considered
S=1

# Set fixed parameter values
c0=3
c1=0.8
```

```

k=8
delta=0.01

# Construct matrices in which values for different periods will be stored; initialise at 1
Y=matrix(data=1, nrow=S, ncol=Q)
C=matrix(data=1, nrow=S, ncol=Q)

#Construct matrices for exogenous variable
I0=matrix(data=5, nrow=S, ncol=Q)

#Solve this system recursively based on the initialisation
for (t in 2:Q){
  for (iterations in 1:1000){
    Y[1,t] = Y[1,t-1] + delta*(k*(C[1,t-1] + I0[1,t-1] - Y[1,t-1]))
    C[1,t] = c0 + c1*Y[1,t]
  } # close within-period loop
} # close time loop

# Verify solutions for Y
(c0+I0[1,Q])/(1-c1)

```

```
Y[1,Q]
```

Python code

```
### Simulate continuous time version of Keynesian goods market model

# Load NumPy
import numpy as np

# Set number of periods for which you want to simulate
Q = 800

# Set number of parameterizations that will be considered
S = 1

# Set fixed parameter values
c0 = 3
c1 = 0.8
k = 8
delta = 0.01

# Initialize matrices to store values for different periods
Y = np.ones((S, Q))
C = np.ones((S, Q))

# Initialize the matrix for the exogenous variable
IO = np.full((S, Q), 5)

# Solve this system recursively based on the initialization
for t in range(1, Q):
    for iterations in range(1000):
        Y[0, t] = Y[0, t - 1] + delta * (k * (C[0, t - 1] + IO[0, t - 1] - Y[0, t - 1]))
        C[0, t] = c0 + c1 * Y[0, t]

# Verify the solution for Y at time Q
(c0 + IO[0, Q - 1]) / (1 - c1)

Y[0, Q - 1]
```

2.6 References

Part I

Static Models

3 A Neoclassical Macro Model

3.1 Overview

3.2 The Model

3.1

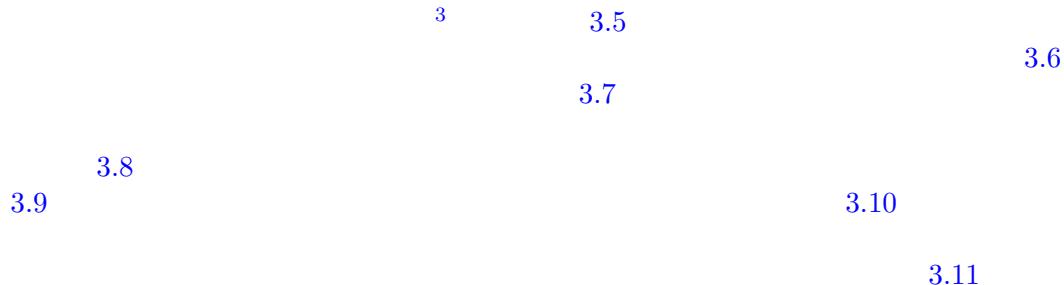
3.2

1

3.3

3.4

¹See the analytical discussion below for a derivation of equations Equation 3.2 -Equation 3.5 and Equation 3.10 from optimising microfoundations.



3.3 Simulation

3.3.1 Parameterisation

²Households are assumed to form rational expectations. In a deterministic setting, this implies perfect foresight so that expected and actual future income coincide.

³See the analytical discussion below for more details on Ricardian Equivalence.

3.3.2 Simulation code

```
# Clear the environment  
rm(list=ls(all=TRUE))
```

```

# Set number of scenarios (including baseline)
S=6

#Create vector in which equilibrium solutions from different parameterisations will be stored
Y_star=vector(length=S) # Income/output
w_star=vector(length=S) # Real wage
C_star=vector(length=S) # Consumption
I_star=vector(length=S) # Investment
r_star=vector(length=S) # Real interest rate
rn_star=vector(length=S) # Nominal interest rate
N_star=vector(length=S) # Employment
P_star=vector(length=S) # Price level

# Create and parameterise exogenous variables/parameters that will be shifted
M0=vector(length=S) # money supply
G0=vector(length=S) # government expenditures
A=vector(length=S) # productivity
Yf=vector(length=S) # expected future income
b1=vector(length=S) # household preference for leisure
M0 []=5
G0 []=1
A []=2
Yf []=1
b1 []=0.4

# Set parameter values for different scenarios
M0[2]=6 # scenario 2: monetary expansion
G0[3]=2 # scenario 3: fiscal expansion
A[4]=2.5 # scenario 4: productivity boost
Yf[5]=0.2 # scenario 5: lower expected future income
b1[6]=0.8 # scenario 6: increased preference for leisure

#Set constant parameter values
a=0.3 # Capital elasticity of output
b2=0.9 # discount rate
b3=0.6 # household preference for money
K=5 # Exogenous capital stock
pe=0.02 # Expected rate of inflation
Gf=1 # Future government spending

# Initialise endogenous variables at arbitrary positive value
w = C = I = Y = r = N = P = 1

```

```

#Solve this system numerically through 1000 iterations based on the initialisation
for (i in 1:S){

  for (iterations in 1:1000){

    #Model equations

    #(1) Cobb-Douglas production function
    Y = A[i]*(K^a)*N^(1-a)

    #(2) Labour demand
    w = A[i]*(1-a)*(K^a)*N^(-a)

    #(3) Labour supply
    N = 1 - (b1[i])/w

    #(4) Consumption demand
    C = (1/(1+b2+b3))*(Y - G0[i] + (Yf[i]-Gf)/(1+r) - b1[i]*(b2+b3)*log(b1[i]/w))

    #(5) Investment demand, solved for r
    r=(I^(a-1))*a*A[i]*N^(1-a)

    #(6) Goods market equilibrium condition, solved for I
    I = Y - C - G0[i]

    #(7) Nominal interest rate
    rn = r + pe

    #(8) Price level
    P = (M0[i]*rn)/((1+rn)*b3*C)

  }

  #Save results for different parameterisations in vector
  Y_star[i]=Y
  w_star[i]=w
  C_star[i]=C
  I_star[i]=I
  r_star[i]=r
  N_star[i]=N
  P_star[i]=P
  rn_star[i]=rn
}

```

}

 Python code

```

import numpy as np

# Set the number of scenarios (including baseline)
S = 6

# Create arrays to store equilibrium solutions from different parameterizations
Y_star = np.empty(S) # Income/output
w_star = np.empty(S) # Real wage
C_star = np.empty(S) # Consumption
I_star = np.empty(S) # Investment
r_star = np.empty(S) # Real interest rate
rn_star = np.empty(S) # Nominal interest rate
N_star = np.empty(S) # Employment
P_star = np.empty(S) # Price level

# Create and parameterize exogenous variables/parameters that will be shifted
M0 = np.zeros(S) # Money supply
G0 = np.zeros(S) # Government expenditures
A = np.zeros(S) # Productivity
Yf = np.zeros(S) # Expected future income
b1 = np.zeros(S) # Household preference for leisure

# Baseline parameterisation
M0[:] = 5
G0[:] = 1
A[:] = 2
Yf[:] = 1
b1[:] = 0.4

# Set parameter values for different scenarios
M0[1] = 6 # Scenario 2: monetary expansion
G0[2] = 2 # Scenario 3: fiscal expansion
A[3] = 2.5 # Scenario 4: productivity boost
Yf[4] = 0.2 # Scenario 5: lower expected future income
b1[5] = 0.8 # Scenario 6: increased preference for leisure

# Set constant parameter values
a = 0.3 # Capital elasticity of output
b2 = 0.9 # Discount rate
b3 = 0.6 # Household preference for money
K = 5 # Exogenous capital stock
pe = 0.02 # Expected rate of inflation
Gf = 1 # Future government spending

# Initialize endogenous variables at arbitrary positive values
w = C = I = Y = r = N = P = 1

# Solve this system numerically through 1000 iterations based on the initialization
for i in range(S):
    for iterations in range(1000):
        # Model equations

```

3.3.3 Plots

3.1 3.3

3.2

```
barplot(Y_star, ylab="Y", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Decrease in Y0", "5: Decrease in Yf"))
```

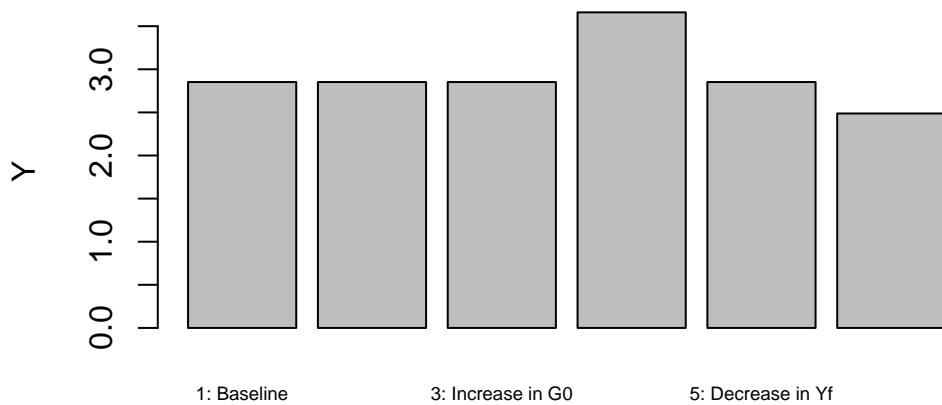


Figure 3.1: Output

```
barplot(P_star, ylab="P", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Decrease in Y0", "5: Decrease in Yf"))
```

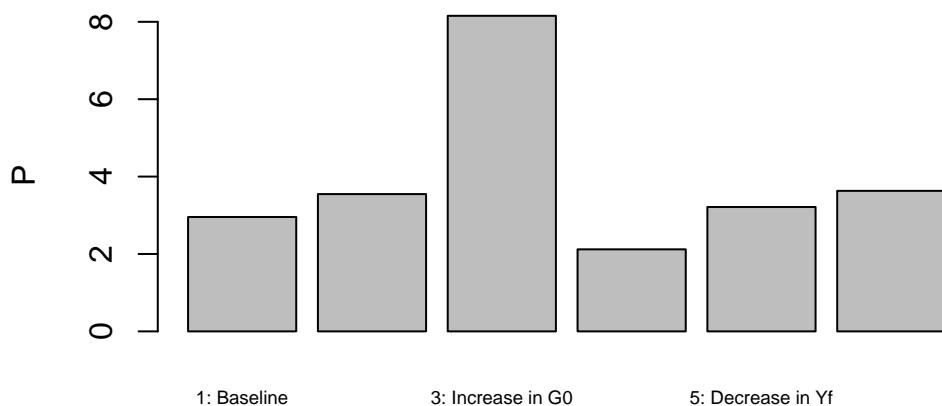


Figure 3.2: Price level

3.4 3.5

3.6 3.5

```
barplot(N_star, ylab="N", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Increase in Yf", "5: Decrease in Yf"))
```

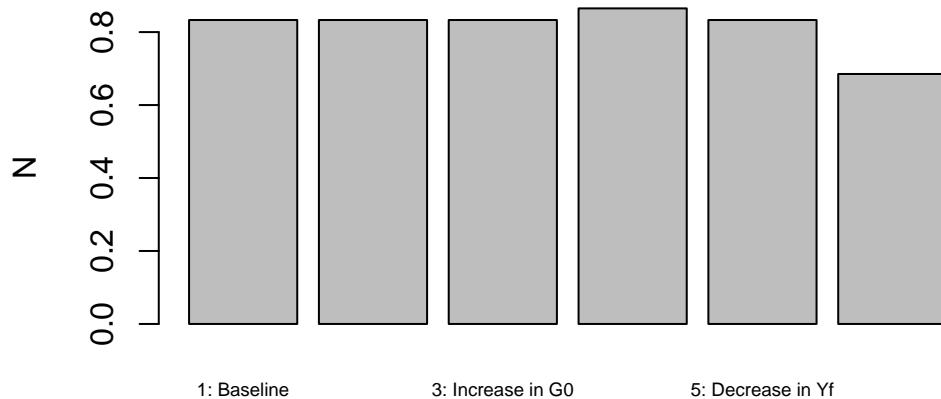


Figure 3.3: Employment

```
barplot(C_star, ylab="C", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Increase in Yf", "5: Decrease in Yf"))
```

⁴This result is partly driven by the use of a non-separable utility function, see analytical discussion below. With a separable utility function, the increase in government spending would increase labour supply and thereby have effects on employment and output.

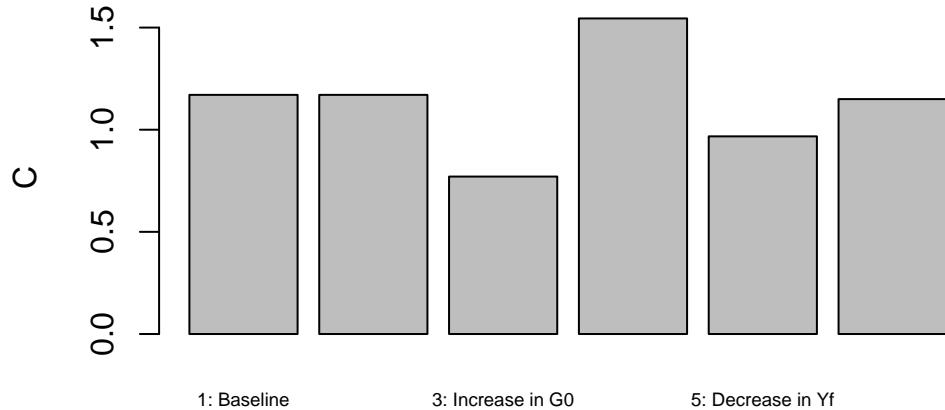


Figure 3.4: Consumption

```
barplot(I_star, ylab="I", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Decrease in G0", "5: Decrease in Yf"))
```

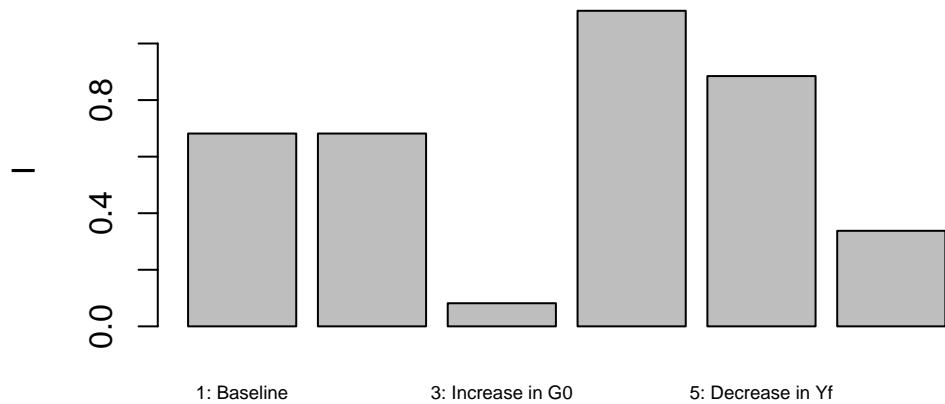


Figure 3.5: Investment

3.4

3.5

3.6

```
barplot(r_star, ylab="r", names.arg=c("1: Baseline", "2: Increase in M0", "3: Increase in G0", "4: Decrease in G0", "5: Decrease in Yf"))
```

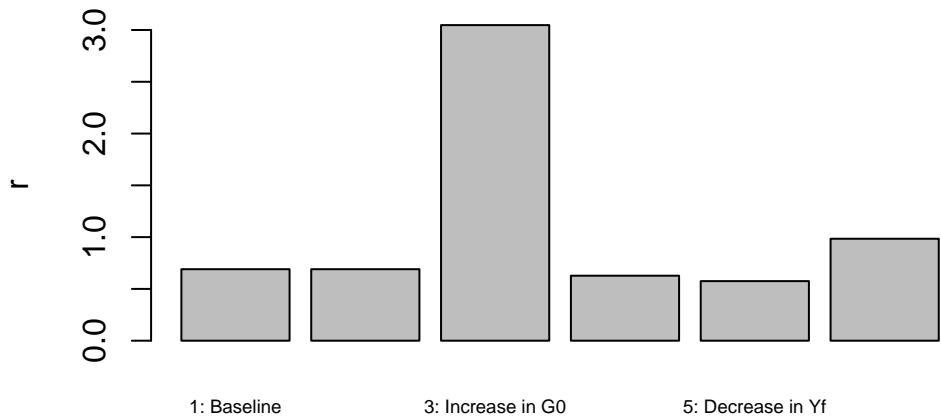


Figure 3.6: Interest rate

i Python code

```
# Plot results (here for output only)
import matplotlib.pyplot as plt

scenario_names = ["1: Baseline", "2: Increase in M0", "3: Increase in G0",
                   "4: Increase in A", "5: Decrease in Yf", "6: Increase in b1"]

# Output
plt.bar(scenario_names , Y_star)
plt.ylabel('Y')
plt.xticks(rotation=45, ha="right") # Rotate x-axis labels for better readability
plt.tight_layout() # Ensure the labels fit within the plot area
plt.show()
```

3.4 Directed graph

```

## Create directed graph
# Construct auxiliary Jacobian matrix for 13 variables:
# Y w N C I r P rn M0 G0 A Yf Md
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged

M_mat=matrix(c(0,0,1,0,0,0,0,0,0,0,1,0,0,
              0,0,1,0,0,0,0,0,0,0,1,0,0,
              0,1,0,0,0,0,0,0,0,0,0,0,0,
              1,1,0,0,0,1,0,0,0,1,0,1,0,
              0,0,1,0,0,1,0,0,0,0,0,0,0,
              1,0,0,1,1,0,0,0,0,1,0,0,0,
              0,0,0,0,0,0,0,0,1,0,0,0,1,
              0,0,0,0,0,1,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,1,0,0,1,1,0,0,0,0,0),
              13, 13, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y","w","N","C","I","r","P", expression(r[n]), expression(M[0]),expression(G[0]))

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

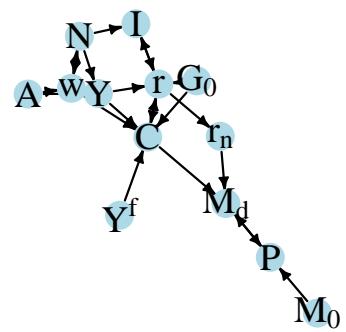


Figure 3.7: Directed graph

 Python code

```

# Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Construct the auxiliary Jacobian matrix
M_mat = np.array([
    [0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0],
    [0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0],
    [0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0],
    [0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 1, 1, 0, 0, 0, 0, 1, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1],
    [0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 1, 0, 1, 1, 0, 0, 0, 0, 0]
])
])
```

Create adjacency matrix from transpose of auxiliary Jacobian and add column names

```

A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {
    0: "Y",
    1: "w",
    2: "N",
    3: "C",
    4: "I",
    5: "r",
    6: "P",
    7: r"$r_n$",
    8: r"$M_0$",
    9: r"$G_0$",
    10: "A",
    11: r"$Y^f$",
    12: r"$M_d$"
}
```

Plot the directed graph

```

pos = nx.spring_layout(G, seed=42)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()
```

3.7

3.5 Analytical discussion: derivation of behavioural functions

3.5.1 The firm's problem: profit maximisation

5

3.15 3.2

⁵See Garín, Lester, and Sims (2021, chap. 12) for a more elaborate version where the firm maximises its lifetime value. The resulting investment function is very similar.

3.5.2 The government's budget constraint

6

3.5.3 The household's problem: intertemporal utility maximisation and Ricardian Equivalence

7

⁶See Garín, Lester, and Sims (2021, chap. 13) for a more detailed discussion of the government's budget constraints.

⁷See Garín, Lester, and Sims (2021), pp.280-289), on the differences between a separable and a non-separable preference specification. Note also that for simplicity, the utility function omits the utility from future leisure.

⁸See Garín, Lester, and Sims (2021, chap. 14) for a more detailed discussion of the household's budget constraints.

3.25

3.28 3.26 3.3 3.25 3.28 3.10 3.26 3.27
3.26 3.25 3.4

References

4 An IS-LM Model

4.1 Overview

The General Theory of Employment, Interest and Money

4.2 The Model

4.1
4.2
4.3
4.4 4.5
 4.6 4.7
 4.9
 4.10

4.3 Simulation

4.3.1 Parameterisation

4.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of scenarios (including baseline)
S=6

#Create vector in which equilibrium solutions from different parameterisations will be stored
Y_star=vector(length=S) # Income/output
C_star=vector(length=S) # Consumption
I_star=vector(length=S) # Investment
r_star=vector(length=S) # Real interest rate
N_star=vector(length=S) # Employment
U_star=vector(length=S) # Unemployment rate

# Set exogenous variables that will be shifted
i0=vector(length=S) # autonomous investment
m0=vector(length=S) # Autonomous demand for money
M0=vector(length=S) # money supply
G0=vector(length=S) # government spending
T0=vector(length=S) # taxes
i0 []=2
m0 []=6
M0 []=5
G0 []=1
T0 []=1
```

```

## Construct scenarios
# scenario 2: fall in animal spirits
i0[2]=1

#scenario 3: increase in liquidity preference
m0[3]=7

# scenario 4: monetary expansion
M0[4]=6

# scenario 5: reduction in tax rate
T0[5]=0

# scenario 6: fiscal expansion
G0[6]=2

#Set constant parameter values
c0=2      # Autonomous consumption
c1=0.6    # Sensitivity of consumption with respect to the income (marginal propensity to consume)
i1=0.1    # Sensitivity of investment with respect to the interest rate
m1=0.2    # Sensitivity of money demand with respect to income
m2=0.4    # Sensitivity of money demand with respect to interest rate
a=1.5     # labour coefficient
Nf=18     # Full employment/labour force

# Initialise endogenous variables at some arbitrary positive value
Y = C = I = r = N = U = 1

#Solve this system numerically through 1000 iterations based on the initialisation

for (i in 1:S){

  for (iterations in 1:1000){

    #Model equations

    # Goods market equilibrium
    Y = C + I + G0[i]

    # Consumption demand
    C = c0 + c1*(Y-T0[i])
  }
}

```

```

# Investment demand
I = i0[i] - i1*r

# Money market, solved for interest rate
r = (m0[i] - M0[i])/m2 + m1*Y/m2

# Employment
N = a*Y

#Unemployment rate
U = (1 - N/Nf)

}

#Save results for different parameterisations in vector
Y_star[i]=Y
C_star[i]=C
I_star[i]=I
r_star[i]=r
N_star[i]=N
U_star[i]=U
}

```

 Python code

```

import numpy as np

# Set the number of scenarios (including baseline)
S = 6

# Create arrays to store equilibrium solutions from different parameterizations
Y_star = np.empty(S) # Income/output
C_star = np.empty(S) # Consumption
I_star = np.empty(S) # Investment
r_star = np.empty(S) # Real interest rate
N_star = np.empty(S) # Employment
U_star = np.empty(S) # Unemployment rate

# Set exogenous variables that will be shifted
i0 = np.zeros(S) # Autonomous investment
m0 = np.zeros(S) # Autonomous demand for money
M0 = np.zeros(S) # Money supply
G0 = np.zeros(S) # Government spending
T0 = np.zeros(S) # Taxes

# Baseline parameterisation
i0[:] = 2
m0[:] = 6
M0[:] = 5
G0[:] = 1
T0[:] = 1

# Construct scenarios
# scenario 2: fall in animal spirits
i0[1] = 1

# scenario 3: increase in liquidity preference
m0[2] = 7

# scenario 4: monetary expansion
M0[3] = 6

# scenario 5: reduction in tax rate
T0[4] = 0

# scenario 6: fiscal expansion
G0[5] = 2

# Set constant parameter values      73
c0 = 2 # Autonomous consumption
c1 = 0.6 # Sensitivity of consumption with respect to income (marginal propensity to consume)
i1 = 0.1 # Sensitivity of investment with respect to the interest rate
m1 = 0.2 # Sensitivity of money demand with respect to income
m2 = 0.4 # Sensitivity of money demand with respect to the interest rate
a = 1.5 # labor coefficient
Nf = 18 # Full employment/labor force

```

4.3.3 Plots

15.1 4.2

4.3
15.1
1

```
barplot(Y_star, ylab="Y", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pref.", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."), cex.names=1)
```

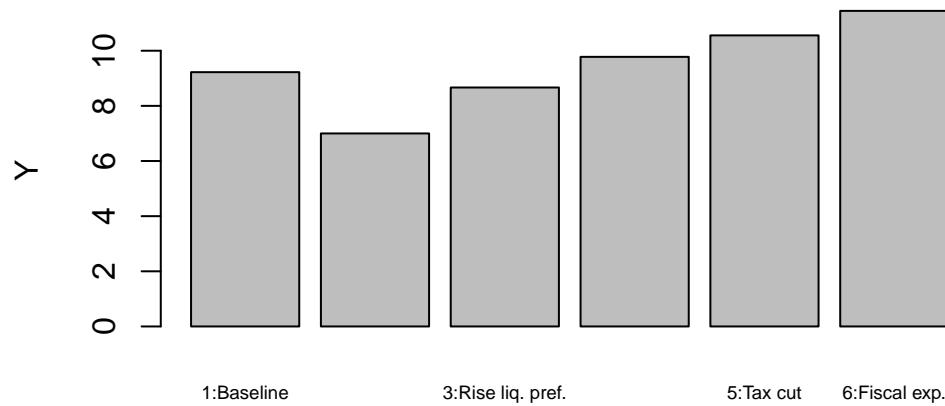


Figure 4.1: Output

```
barplot(r_star, ylab="r", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pref.", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."), cex.names=1)
```

¹The analytical discussion below shows formally that fiscal policy is more effective than monetary policy if $m_2 > i_2$.

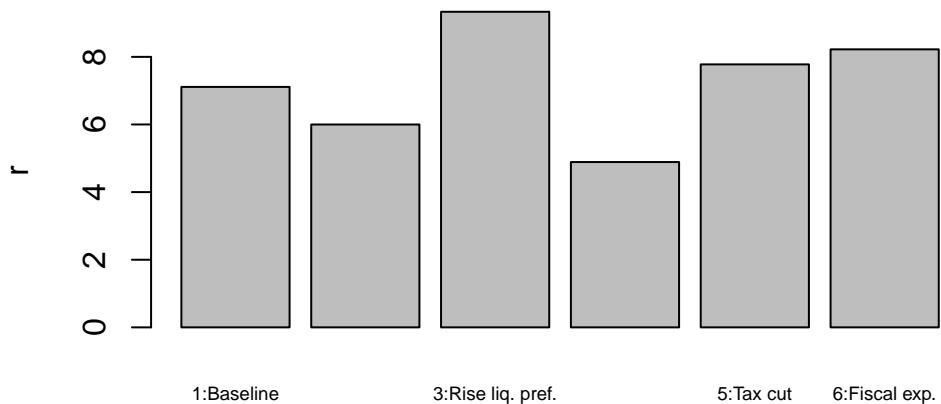


Figure 4.2: Interest rate

```
barplot(U_star*100, ylab="U (%)", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pref.", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."))
```

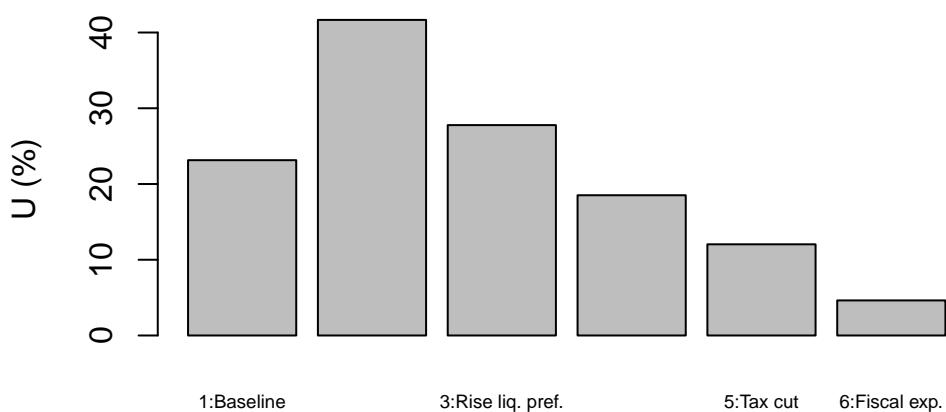


Figure 4.3: Unemployment

4.4

4.5

```
barplot(I_star, ylab="I", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pref.", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."), cex.names=1.5)
```

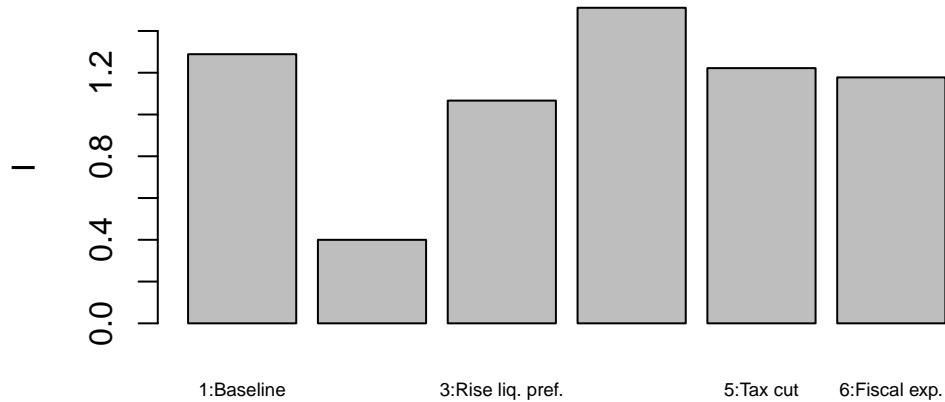


Figure 4.4: Investment

```
barplot(C_star, ylab="C", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pr", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."), cex.1
```

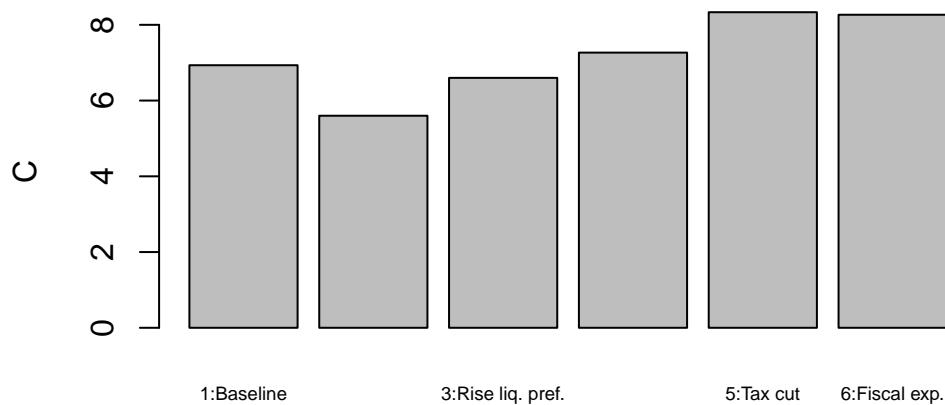


Figure 4.5: Consumption

```
barplot(N_star, ylab="N", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise liq. pr", "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."), cex.1
```

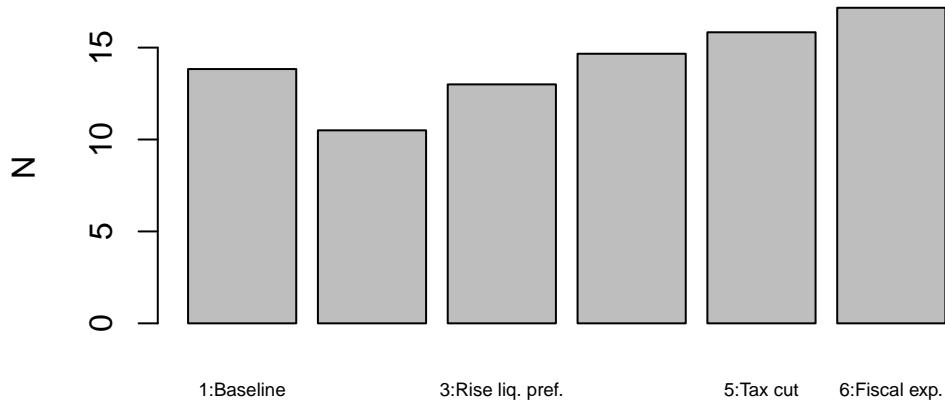


Figure 4.6: Employment

i Python code

```
# Plot results (here only for output)
import matplotlib.pyplot as plt

scenario_names = ["1:Baseline", "2:Fall animal spirits", "3:Rise liq. pref.",
                   "4:Monetary exp.", "5:Tax cut", "6:Fiscal exp."]

plt.bar(scenario_names, Y_star)
plt.ylabel('Y')
plt.xticks( scenario_names, rotation=45, fontsize=6)
plt.show()
```

4.4 Directed graph

```
# Construct auxiliary Jacobian matrix for 11 variables: Y, C, I, G, T, r, M0, N, i0, m0, Md
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged

M_mat=matrix(c(0,1,1,1,0,0,0,0,0,0,0,
              1,0,0,0,1,0,0,0,0,0,0,
              0,0,0,0,0,1,0,0,1,0,0,
```

```

0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,1,0,0,0,1,
0,0,0,0,0,0,0,0,0,0,0,
1,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,
1,0,0,0,0,1,0,0,0,1,0), 11, 11, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y", "C", "I", expression(G[0]), expression(T[0]), "r", expression(M[0]), "N", e

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

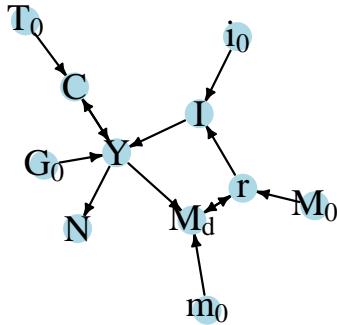


Figure 4.7: Directed graph of IS-LM model

 Python code

```

# Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the auxiliary Jacobian matrix
M_mat = np.array([
    [0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 0, 1, 0, 0, 0, 1, 0]
])
# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {
    0: "Y",
    1: "C",
    2: "I",
    3: r"$G_0$",
    4: r"$T_0$",
    5: "r",
    6: r"$M_0$",
    7: "N",
    8: r"$i_0$",
    9: r"$m_0$",
    10: r"$M_d$"
}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()

```

4.5 Analytical discussion

- 4.2
- 4.5
- 4.1
- 4.6
- 4.7
- 4.8
- 4.11
- 4.12
-
-
-

4.5.1 Calculate equilibrium fiscal multiplier

```
Y_star[6]-Y_star[1] # numerical approach
```

```
m2/((1-c1)*m2+i1*m1) # analytical approach
```

 Python code

```
Y_star[5]-Y_star[0] # numerical approach
```

```
m2/((1-c1)*m2+i1*m1) # analytical approach
```

References

5 A Neoclassical Synthesis Model (IS-LM-AS-AD)

5.1 Overview

The General Theory of Employment, Interest and Money
4

5.2 The Model

5.1

5.2

5.3

5.4

5.5

5.6

5.7

1

5.8

5.9

5.10

5.11

5.3 Simulation

5.3.1 Parameterisation

¹See the notes on the Classical Model ([here](#)) for a formal derivation of the labour demand and supply curves from optimisation. A minor modification is that here we work with a normalisation of the term for leisure in the household's log-utility function, $\ln(1 - \frac{N}{N_f})$, to allow N to be larger than unity.

5.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of scenarios (including baseline)
S=6

#Create vector in which equilibrium solutions from different parameterisations will be stored
Y_star=vector(length=S) # Income/output
C_star=vector(length=S) # Consumption
I_star=vector(length=S) # Investment
r_star=vector(length=S) # Real interest rate
N_star=vector(length=S) # Employment
U_star=vector(length=S) # Unemployment rate
P_star=vector(length=S) # Price level
w_star=vector(length=S) # Real wage
W_star=vector(length=S) # Nominal wage

# Set exogenous variables that will be shifted
i0=vector(length=S) # autonomous investment (animal spirits)
M0=vector(length=S) # money supply
G0=vector(length=S) # government spending
```

```

P0=vector(length=S) # expected price level
A=vector(length=S) # Exogenous productivity

#### Construct different scenarios
# baseline
A[] = 2
i0[] = 2
M0[] = 5
G0[] = 1
P0[] = 1

# scenario 2: fall in animal spirits
i0[2] = 1.5

# scenario 3: increase in productivity
A[3] = 3

# scenario 4: increase in expected price level
P0[4] = 1.5

# scenario 5: monetary expansion
M0[5] = 6

# scenario 6: fiscal expansion
G0[6] = 2

#Set constant parameter values
c0=2 # Autonomous consumption
c1=0.6 # Sensitivity of consumption with respect to the income (marginal propensity to consume)
i1=0.1 # Sensitivity of investment with respect to the interest rate
m1=0.2 # Sensitivity of money demand with respect to income
m2=0.4 # Sensitivity of money demand with respect to interest rate
Nf=5 # Full employment/labour force
K=4 # Exogenous capital stock
a=0.3 # Capital elasticity of output
b=0.4 # household preference for leisure
T0=1 # tax revenues
m0=6 # liquidity preference

# Initialise endogenous variables at some arbitrary positive value
Y = C = I = r = P = w = N = W = 1

```

```

#Solve this system numerically through 1000 iterations based on the initialisation

for (i in 1:S){

  for (iterations in 1:1000){

    #Model equations

    # Goods market equilibrium
    Y = C + I + G0[i]

    # Consumption demand
    C = c0 + c1*(Y-T0)

    # Investment demand
    I = i0[i] - i1*r

    # Money market, solved for interest rate
    r = (m0 - (M0[i]/P))/m2 + m1*Y/m2

    #Unemployment rate
    U = (1 - N/Nf)

    #Real wage
    w = A[i]*(1-a)*(K^a)*N^(-a)

    #Nominal wage
    W= (P0[i]*b*C)/(1- (N/Nf))

    #Price level
    P = W/w

    #Employment
    N = (Y/(A[i]*(K^a)))^(1/(1-a))

  }

  #Save results for different parameterisations in vector
  Y_star[i]=Y
  C_star[i]=C
  I_star[i]=I
  r_star[i]=r
}

```

```
N_star[i]=N  
U_star[i]=U  
P_star[i]=P  
w_star[i]=w  
W_star[i]=W  
}
```

 Python code

```
import numpy as np

# Set the number of scenarios (including baseline)
S = 6

# Create arrays to store equilibrium solutions from different parameterizations
Y_star = np.empty(S) # Income/output
C_star = np.empty(S) # Consumption
I_star = np.empty(S) # Investment
r_star = np.empty(S) # Real interest rate
N_star = np.empty(S) # Employment
U_star = np.empty(S) # Unemployment rate
P_star = np.empty(S) # Price level
w_star = np.empty(S) # Real wage
W_star = np.empty(S) # Nominal wage

# Set exogenous variables that will be shifted
i0 = np.zeros(S) # Autonomous investment (animal spirits)
M0 = np.zeros(S) # Money supply
G0 = np.zeros(S) # Government spending
P0 = np.zeros(S) # Expected price level
A = np.empty(S) # Exogenous productivity

# Construct different scenarios
# baseline
A[:] = 2
i0[:] = 2
M0[:] = 5
G0[:] = 1
P0[:] = 1

# scenario 2: fall in animal spirits
i0[1] = 1.5

# scenario 3: increase in productivity
A[2] = 3

# scenario 4: increase in expected price level
P0[3] = 1.5
```

5.3.3 Plots

15.1 5.5

```
barplot(Y_star, ylab="Y", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product  
"4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp.
```

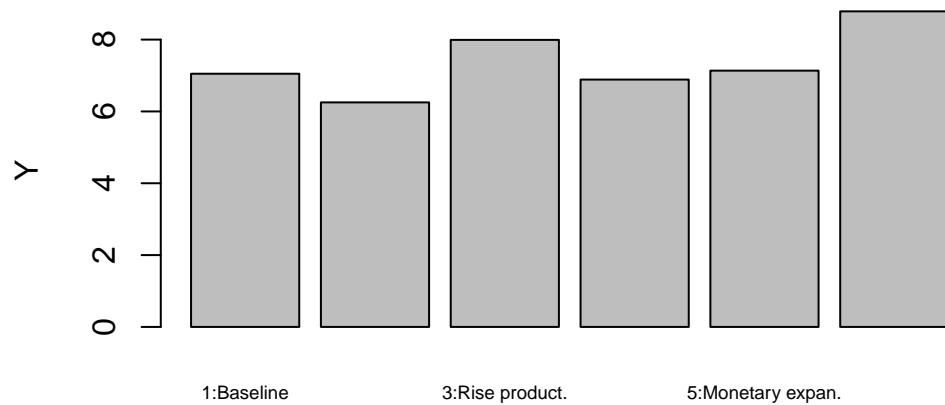


Figure 5.1: Output

```
barplot(P_star, ylab="P", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product  
"4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp.
```

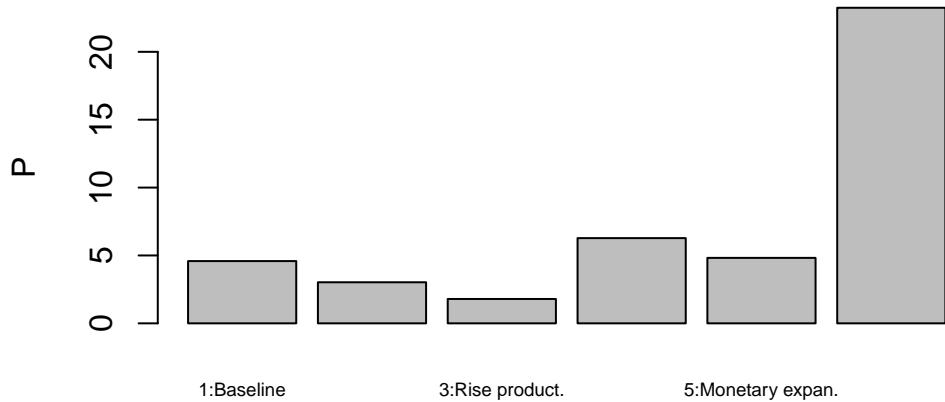


Figure 5.2: Price level

```
barplot(r_star, ylab="r", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product.", "4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp."))
```

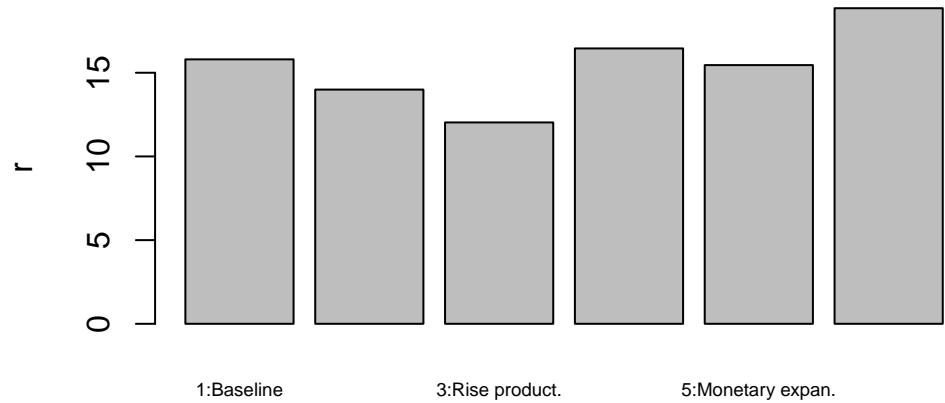


Figure 5.3: Interest rate

```
barplot(U_star*100, ylab="U (%)", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product.", "4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp."))
```

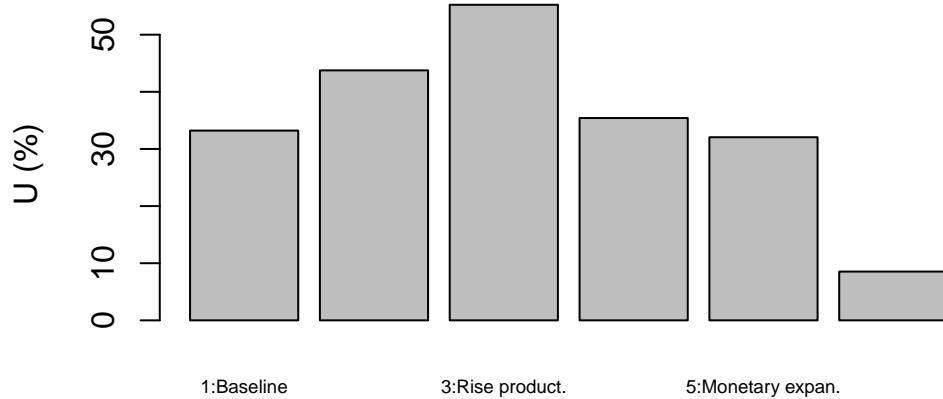


Figure 5.4: Unemployment rate

```
barplot(W_star, ylab="W", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product.", "4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp."))
```

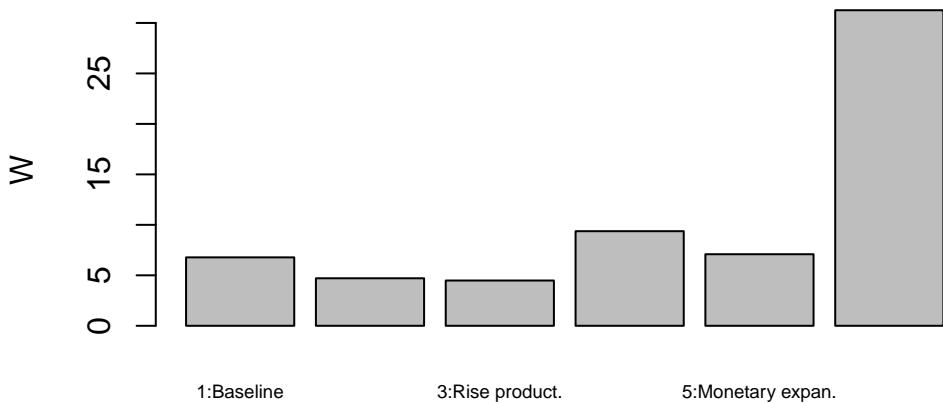


Figure 5.5: Nominal wage

```
barplot(w_star, ylab="w", names.arg=c("1:Baseline", "2:Fall animal spirits", "3:Rise product.", "4:Rise exp. price", "5:Monetary expan.", "6:Fiscal exp."))
```

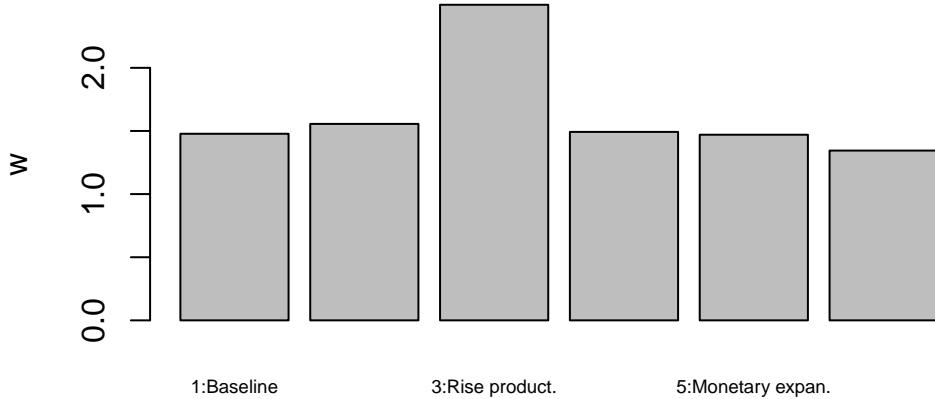


Figure 5.6: Real wage

i Python code

```
# Plot results (here only for output)
import matplotlib.pyplot as plt

scenario_names = ["1:Baseline", "2:Fall animal spirits", "3:Rise product.",
                  "4:Rise exp. price", "5:Monetary expan.", "6:Fiscal expan."]

plt.bar(scenario_names, Y_star)
plt.ylabel('Y')
plt.xticks(scenario_names, rotation=45, fontsize=6)
plt.show()
```

5.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 15 variables: Y, C, I, G, T, r, w, W, P, M0, N, i0

M_mat=matrix(c(0,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,
              1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,1,0,0,0,0,0,0,1,0,0,0,
```

```

0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
1,0,0,0,0,0,0,0,1,1,0,0,0,0,1,
0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,
0,1,0,0,0,0,0,0,0,0,1,0,0,1,0,
0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
1,0,0,0,0,0,0,0,0,0,0,0,1,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
1,0,0,0,0,1,0,0,1,0,0,0,0,0,0,0),
15, 15, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y", "C", "I", expression(G[0]), expression(T[0]), "r", "w", "W", "P", expression(G[1]),
expression(T[1]), "M_0", "i_0", "A", "N", "C", "W", "P", "r", "w", "T_0", "G_0", "I", "M_1", "i_1", "Y")

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

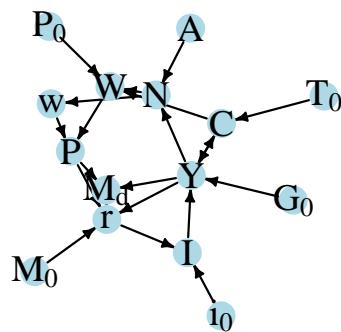


Figure 5.7: Directed graph of Neoclassical Synthesis model

 Python code

```

# Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the Jacobian matrix
M_mat = np.array([
    [0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 1],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0],
    [0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0],
    [0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {
    0: "Y",
    1: "C",
    2: "I",
    3: r"$G_0$",
    4: r"$T_0$",
    5: "r",
    6: "w",
    7: "W",
    8: "P",
    9: r"$M_0$",
    10: "N",
    11: r"$i_0$",
    12: "A",
    13: r"$P_0$",
    14: r"$M_d$",
}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)

```

5.7

5.5 Analytical discussion

5.2

5.3

5.1

5.4

5.5

5.6

5.2

5.9

5.7

5.8

5.10

References

6 A Post-Keynesian Macro Model with Endogenous Money

6.1 Overview

Synthesis

¹

Neoclassical

¹See Lavoie (2006), chap.1 and [Exploring Economics](#) for introductions. Lavoie (2014) and Hein (2014) provide more advanced treatments.

6.2 The Model

6.1				
6.2				
	6.3			
2				6.4
5		6.5		
	6.6			
			6.7	
	6.8			
6.9				
6.13		6.11		6.9
	6.12			
			6.13	

²For simplicity, it is assumed that all autonomous demand is debt-financed, i.e. there is no spending out of wealth.

6.3 Simulation

6.3.1 Parameterisation

6.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of scenarios (including baseline)
S=6

#Create vector in which equilibrium solutions from different parameterisations will be stored
Y_star=vector(length=S) # income/output
D_star=vector(length=S) # (notional) credit-financed aggregate demand
ND_star=vector(length=S) # income-financed aggregate demand
r_star=vector(length=S) # lending rate
```

```

N_star=vector(length=S) # employment
U_star=vector(length=S) # unemployment
P_star=vector(length=S) # price level
w_star=vector(length=S) # real wage
W_star=vector(length=S) # nominal wage
i_star=vector(length=S) # central bank rate
dL_star=vector(length=S) # change in loans
dM_star=vector(length=S) # change in bank deposits
dR_star=vector(length=S) # change in bank reserves

# Set exogenous variables that will be shifted
c=vector(length=S) # share of credit demand that is accommodated
d0=vector(length=S) # autonomous component of debt-financed aggregate demand
m=vector(length=S) # mark-up on lending rate
n=vector(length=S) # mark-up on prices
a=vector(length=S) # productivity

# Baseline parameterisation
c []=0.8
d0 []=5
m []=0.15
n []=0.15
a []=0.8

## Construct scenarios

# scenario 2: increase in credit rationing
c[2]=0.4

# scenario 3: increase in autonomous demand
d0[3]=10

# scenario 4: increase in interest rate mark-up
m[4]=0.3

# scenario 5: increase in price mark-up
n[5]=0.3

# scenario 6: increase in productivity
a[6]=0.4

```

```

#Set constant parameter values
b=0.5    # propensity to spend out of income
d1=0.8   # sensitivity of demand with respect to the interest rate
i0=0.01  # discretionary component of central bank rate
i1=0.5   # sensitivity of central bank rate with respect to price level
Nf=12    # full employment/labour force
h=0.8    # sensitivity of nominal wage with respect to unemployment
k=0.3    # desired reserve ratio
W0=2     # exogenous component of nominal wage

# Initialise endogenous variables at some arbitrary positive value
Y = D = ND = r = N = U = P = w = W = i = dL = dR = dM = 1

#Solve this system numerically through 1000 iterations based on the initialisation
for (j in 1:S){

  for (iterations in 1:1000){

    #Model equations

    # (1) Goods market
    Y = ND + c[j]*D

    # (2) Not-debt financed component of aggregate demand
    ND = b*Y

    # (3) Debt-financed component of aggregate demand
    D= d0[j] - d1*r

    # (4) Policy rate
    i = i0 + i1*P

    # (5) Lending rate
    r = (1+m[j])*i

    # (6) Change in loans
    dL = c[j]*D

    # (7) Change in deposits
    dM = dL

    # (8) Change in reserves
  }
}

```

```

dR = k*dM

# (9) Price level
P = (1+n[j])*a[j]*W

# (10) Nominal wage
W = W0 - h*(U)

# (11) Real wage
w = 1/((1+n[j])*a[j])

# (12) Employment
N = a[j]*Y

# (13) Unemployment rate
U = (Nf - N)/Nf

}

#Save results for different parameterisations in vector
Y_star[j]=Y
D_star[j]=D
ND_star[j]=ND
r_star[j]=r
N_star[j]=N
U_star[j]=U
P_star[j]=P
w_star[j]=w
W_star[j]=W
i_star[j]=i
dL_star[j]=dL
dM_star[j]=dM
dR_star[j]=dR
}

```

 Python code

```

# Load NumPy library
import numpy as np

# Set the number of scenarios (including baseline)
S = 6

# Create arrays to store equilibrium solutions
Y_star = np.zeros(S) # income/output
D_star = np.zeros(S) # (notional) credit-financed aggregate demand
ND_star = np.zeros(S) # income-financed aggregate demand
r_star = np.zeros(S) # lending rate
N_star = np.zeros(S) # employment
U_star = np.zeros(S) # unemployment
P_star = np.zeros(S) # price level
w_star = np.zeros(S) # real wage
W_star = np.zeros(S) # nominal wage
i_star = np.zeros(S) # central bank rate
dL_star = np.zeros(S) # change in loans
dM_star = np.zeros(S) # change in bank deposits
dR_star = np.zeros(S) # change in bank reserves

# Set exogenous variables that will be shifted
c = np.zeros(S) # share of credit demand that is accommodated
d0 = np.zeros(S) # autonomous component of debt-financed aggregate demand
m = np.zeros(S) # mark-up on lending rate
n = np.zeros(S) # mark-up on prices
a = np.zeros(S) # productivity

# Baseline parameterisation
c[:] = 0.8
d0[:] = 5
m[:] = 0.15
n[:] = 0.15
a[:] = 0.8

```

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```

# Construct scenarios
# Scenario 2: increase in credit rationing
c[1] = 0.4

# Scenario 3: increase in autonomous demand
d0[2] = 10

```

6.3.3 Plots

6.1 6.7

```
barplot(Y_star, ylab="Y", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup", "5:rise firm markup", "6:rise pro
```

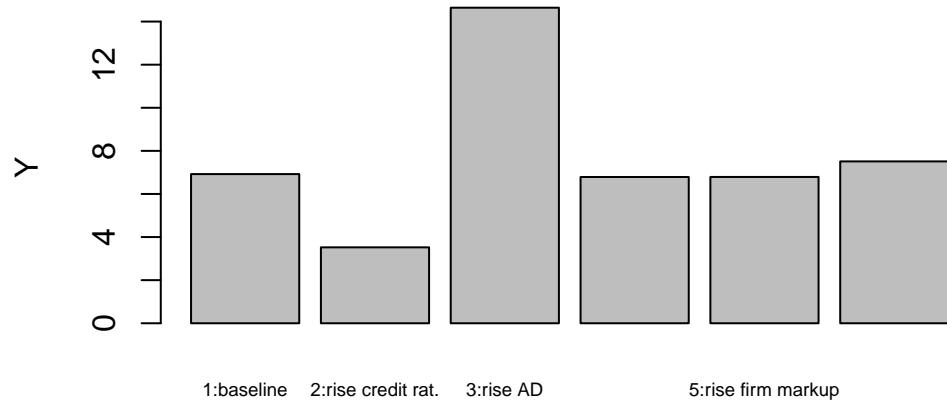


Figure 6.1: Output

```
barplot(P_star, ylab="P", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup", "5:rise firm markup", "6:rise pro
```

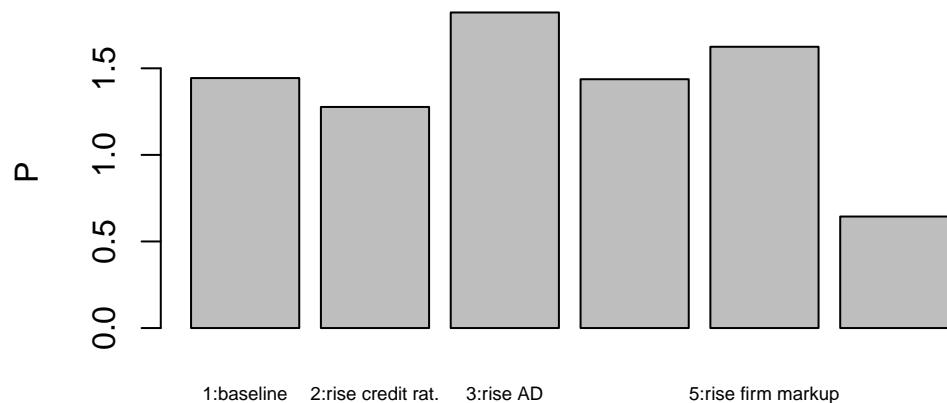


Figure 6.2: Price level

```
barplot(r_star, ylab="r", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup","5:rise firm markup", "6:rise pro
```

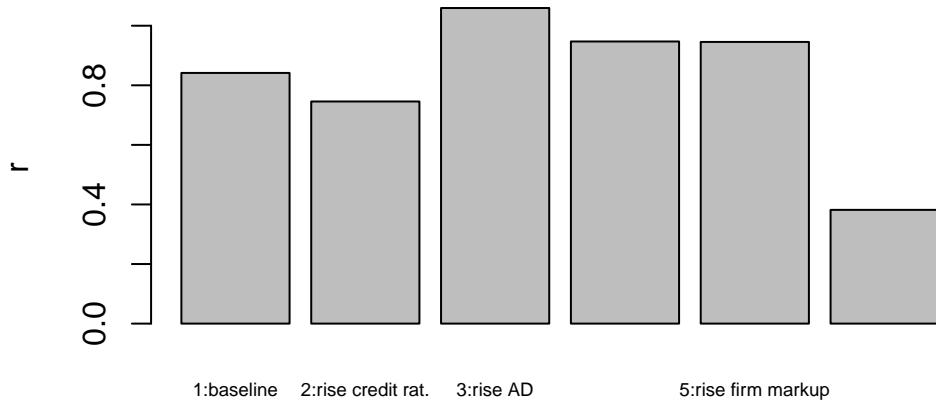


Figure 6.3: Lending rate

```
barplot(dM_star, ylab="dM", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup","5:rise firm markup", "6:rise p
```

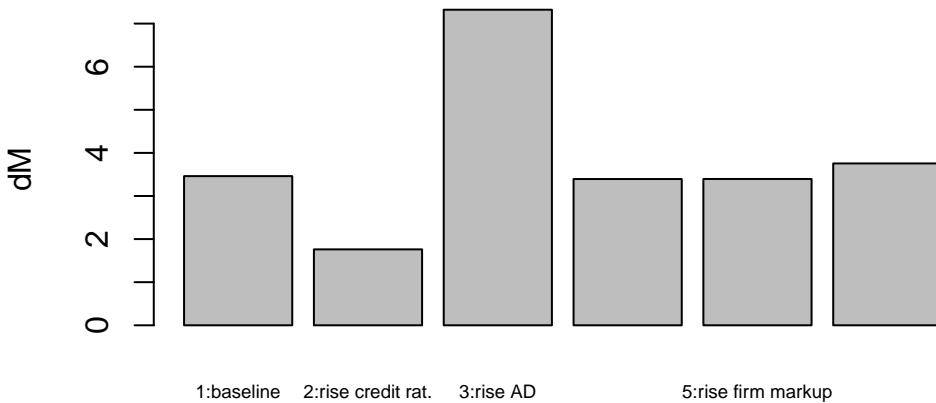


Figure 6.4: Deposit money creation

```
barplot(U_star*100, ylab="U (%)", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                              "4:rise bank markup", "5:rise firm markup", "6:rise prod")
```

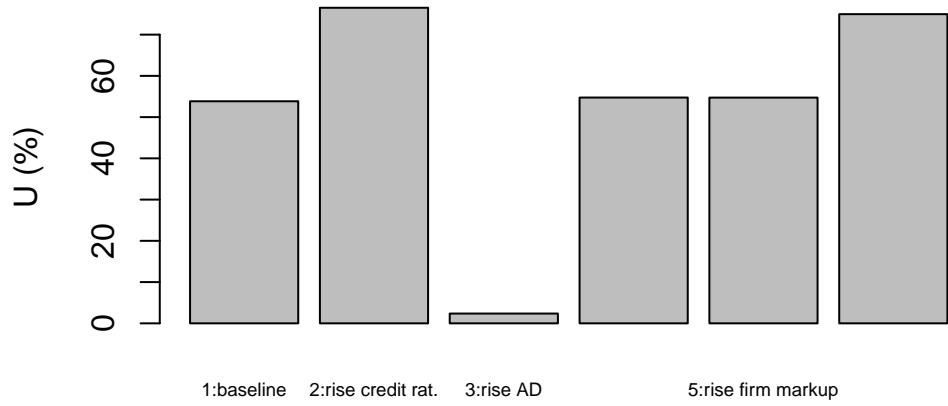


Figure 6.5: Unemployment rate

```
barplot(W_star, ylab="W", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup", "5:rise firm markup", "6:rise prod")
```

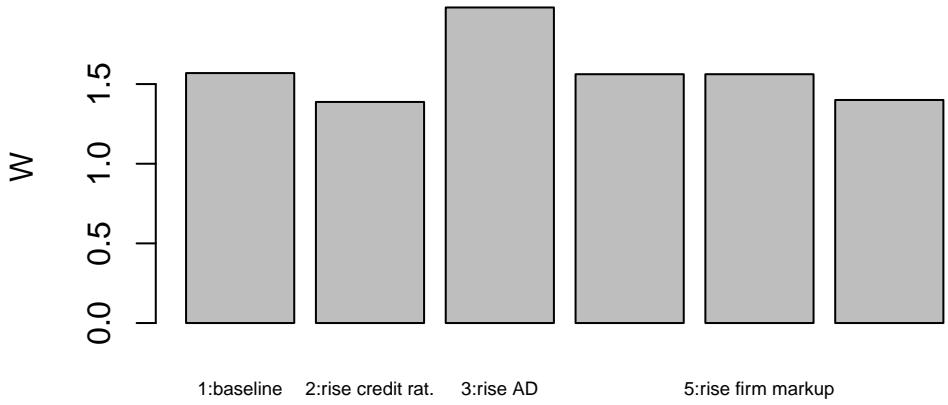


Figure 6.6: Nominal wage

```
barplot(w_star, ylab="w", names.arg=c("1:baseline", "2:rise credit rat.", "3:rise AD",
                                         "4:rise bank markup", "5:rise firm markup", "6:rise pro
```

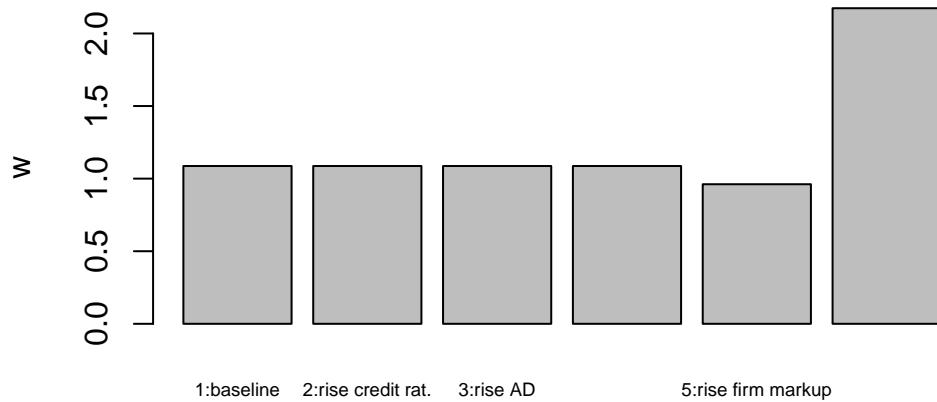


Figure 6.7: Real wage

i Python code

```
# Plot results (here for output only)
import matplotlib.pyplot as plt

scenario_names = ["1:baseline", "2:rise credit rat.", "3:rise AD", "4:rise bank markup", "5:rise firm markup", "6:rise pro"]

# Create a bar plot
plt.bar(scenario_names, Y_star)
plt.ylabel("Y")
plt.xticks(rotation=45, ha="right") # Rotate x-axis labels for better readability
plt.tight_layout() # Ensure the labels fit within the plot area

# Show the plot
plt.show()
```

6.4 Directed graph

```

## Create directed graph
# Construct auxiliary Jacobian matrix for 18 variables:
# r, Y, ND, D, i, P, W, w, N, U, dL, dM, dR, d0, c, m, a, n

M_mat=matrix(c(0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,1,0,0,
              0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,
              0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
              1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,
              0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,1,1,
              0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,
              0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,
              0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
              18, 18, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("r", "Y", "ND", "D", "i", "P", "W", "w", "N", "U", "dL", "dM", "dR", expression

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

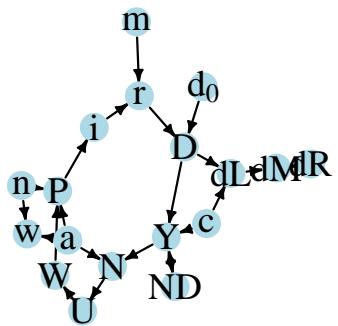


Figure 6.8: Directed graph of post-Keynesian endogenous money model

 Python code

6.8

6.5 Analytical discussion

6.2

6.3

6.1

6.4

6.9

6.10

6.12

6.13

6.5

6.5

6.4

6.10

6.13

6.9

6.5.1 Confirm analytical solutions numerically

```
### Confirm equilibrium solution for Y* (baseline)
# Analytical solution
(c[1]*(d0[1] - d1*(1+m[1])*(i0+i1*(1+n[1])*a[1]*(W0-h))))/(1-b +c[1]*d1*(1+m[1])*i1*(1+n[1])*
```

```
# Numerical solution
Y_star[1]
```

```
### Confirm equilibrium solution for P* (baseline)
# Analytical solution
((1+n[1])*a[1]*((W0-h)*(1-b)+(Nf^-1)*h*a[1]*c[1]*(d0[1]-d1*(1+m[1])*i0[1])))/(1-b +c[1]*d1*
```

```
# Numerical solution
P_star[1]
```

References

7 A Kaldor-Robinson Distribution and Growth Model

7.1 Overview

[1](#)

[2](#)

7.2 The Model

¹See Hein (2014), chap. 4 for a detailed treatment.

²All variables are normalised by the capital stock and thus rendered stationary.

7.1

7.2

7.3
7.3

7.5

7.3 Simulation

7.3.1 Parameterisation

7.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of scenarios (including baselines)
S=3

#Create vector in which equilibrium solutions from different parameterisations will be stored
h_star=vector(length=S) # profit share
g_star=vector(length=S) # growth rate of capital stock
s_star=vector(length=S) # saving rate
c_star=vector(length=S) # consumption rate
r_star=vector(length=S) # profit rate

# Set constant parameter values
v=3      # capital-to-potential output ratio
g1=0.3 # sensitivity of investment with respect to profit rate
un=0.9 # normal rate of capacity utilisation

# Set exogenous variables whose parameterisation changes across regimes
g0=vector(length=S) # animal spirits
sp=vector(length=S) # propensity to save out of profits

### Construct different scenarios

# scenario 1: baseline
g0[] = 0.02
sp[] = 0.6

#scenario 2: increase in animal spirits
g0[2] = 0.04

# scenario 3: increase in propensity to save out of profits
sp[3] = 0.9
```

```

#Check stability condition for all scenarios
for (i in 1:S){
  print(sp[i]>g1)
}

# Initialise endogenous variables at some arbitrary positive value
g = r = s = c = h = 1

#Solve this system numerically through 1000 iterations based on the initialisation
for (i in 1:S){

  for (iterations in 1:1000){

    #(1) Profit rate
    r=(h*un)/v

    #(2) Saving
    s = sp[i]*r

    #(3) Consumption
    c= un/v - s

    #(4) Investment
    g = g0[i]+g1*r

    #(5) Goods market equilibrium profit share
    h=(v/un)*(g0[i]/(sp[i]-g1))

  }

  #Save results for different parameterisations in vector
  h_star[i]=h
  g_star[i]=g
  r_star[i]=r
  s_star[i]=s
  c_star[i]=c
}

```

 Python code

```

import numpy as np

# Clear the environment (not necessary in Python)
# Set number of scenarios (including baselines)
S = 3

# Create arrays to store equilibrium solutions for different parameterizations
h_star = np.empty(S) # profit share
g_star = np.empty(S) # growth rate of capital stock
s_star = np.empty(S) # saving rate
c_star = np.empty(S) # consumption rate
r_star = np.empty(S) # profit rate

# Set constant parameter values
v = 3      # capital-to-potential output ratio
g1 = 0.3   # sensitivity of investment with respect to profit rate
un = 0.9   # normal rate of capacity utilization

# Set exogenous variables whose parameterization changes across regimes
g0 = np.empty(S) # animal spirits
sp = np.empty(S) # propensity to save out of profits

# Construct different scenarios
# Scenario 1: baseline
g0[:] = 0.02
sp[:] = 0.6

# Scenario 2: increase in animal spirits
g0[1] = 0.04

# Scenario 3: increase in propensity to save out of profits
sp[2] = 0.9

# Check stability condition for all scenarios
for i in range(S):
    print(sp[i] > g1)

# Initialize endogenous variables at some arbitrary positive value
g = r = s = c = h = 1

# Solve this system numerically through 1000 iterations based on the initialization
for i in range(S):
    for iterations in range(1000):
        # (1) Profit rate
        r = (h * un) / v

        # (2) Saving
        s = sp[i] * r

        # (3) Consumption
        c = un / v - s

```

7.3.3 Plots

7.1 7.3

```
barplot(h_star, ylab="h", names.arg=c("1: baseline", "2: rise animal spirits", "3:rise saving propensity"))
```

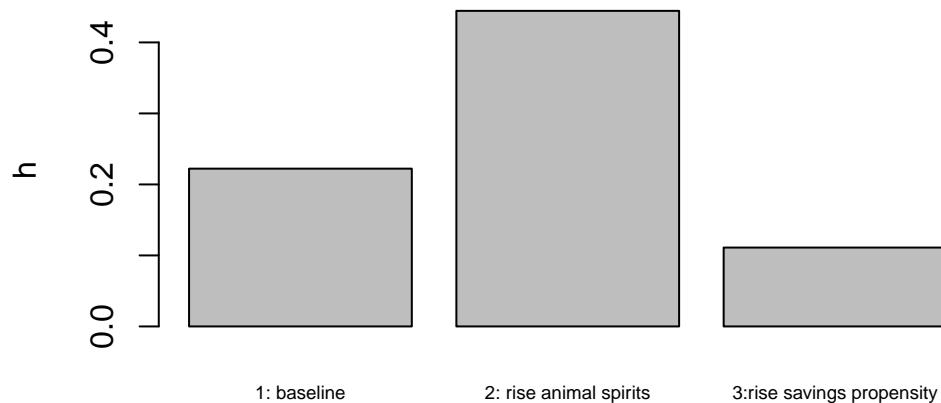


Figure 7.1: Profit share

```
barplot(c_star, ylab="c", names.arg=c("1: baseline", "2: rise animal spirits", "3:rise saving propensity"))
```

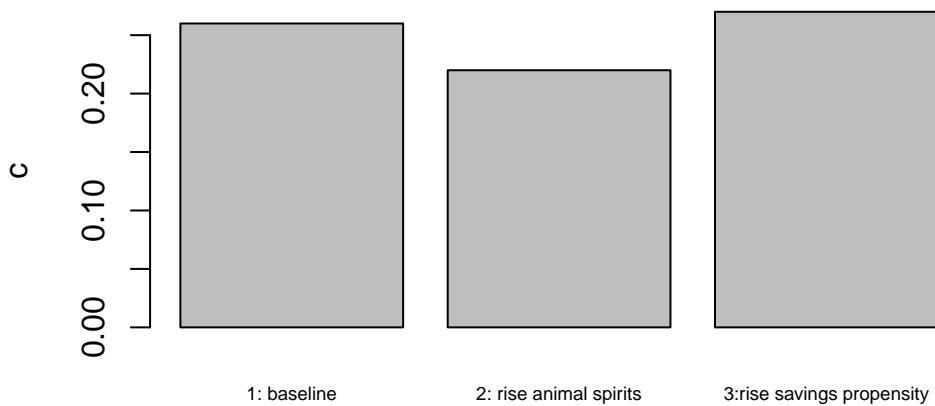


Figure 7.2: Rate of consumption

```
barplot(g_star, ylab="g", names.arg=c("1: baseline", "2: rise animal spirits", "3:rise saving
```

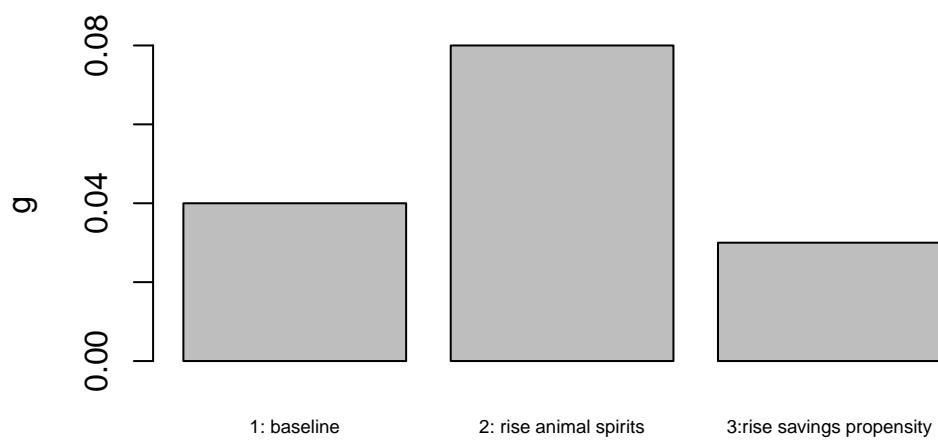


Figure 7.3: Rate of growth

 Python code

```
# Plot results (here only for profit share)
import matplotlib.pyplot as plt

# Scenario labels
scenario_names = ["1: baseline", "2: rise animal spirits", "3: rise savings propensity"]

# Bar plot for h_star
plt.bar(scenario_names, h_star)
plt.ylabel('h')
plt.xticks(scenario_names, rotation=45, fontsize=6)
plt.show()
```

7.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 7 variables:
# r,h,s,g,g0,sp,un
M_mat=matrix(c(0,1,0,0,0, 0, 1,
              0,0,1,1,0, 0, 1,
              1,0,0,0,0, 1, 0,
              1,0,0,0,1, 0, 0,
              0,0,0,0,0, 0, 0,
              0,0,0,0,0, 0, 0,
              0,0,0,0,0, 0, 0),
              7, 7, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
```

```

v(dg)$name=c("r", "h", "s", "g", expression(g[0]), expression(s[Pi]), expression(u[n]))

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

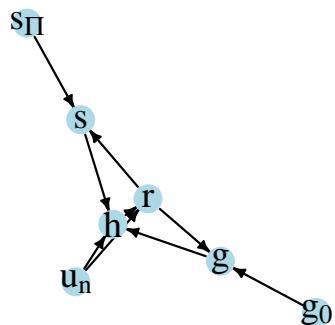


Figure 7.4: Directed graph of Kaldor-Robinson growth model

 Python code

```
# Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the Jacobian matrix
M_mat = np.array([[0, 1, 0, 0, 0, 0, 1],
                  [0, 0, 1, 1, 0, 0, 1],
                  [1, 0, 0, 0, 0, 1, 0],
                  [1, 0, 0, 0, 1, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0]])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "r", 1: "h", 2: "s", 3: "g", 4: r"$g_0$", 5: r"$s_p$", 6: r"$u_n$"}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()
```

7.4

7.5 Analytical discussion

7.4 7.2 7.5 7.1
7.1

7.4

7.5.1 Calculate analytical solutions numerically

```
# Profit rate
for (i in 1:S){
  print((g0[i])/(sp[i]-g1))
}
```

```
# Growth rate
for (i in 1:S){
  print((sp[i]*g0[i])/(sp[i]-g1))
}
```

 Python code

```
# Profit rate
for i in range(S):
    print(g0[i] / (sp[i] - g1))

# Growth rate
for i in range(S):
    print((sp[i] * g0[i]) / (sp[i] - g1))
```

References

8 A Post-Kaleckian Distribution and Growth Model

8.1 Overview

[1](#)

[2](#)

8.2 The Model

¹See Hein (2014), chap. 7 and Lavoie (2014), chap. 6 for detailed treatments.

²All variables are normalised by the capital stock and thus rendered stationary.

8.1

8.2

8.3

8.3

8.5

3

³Bhaduri and Marglin (1990) further discuss the effects on the profit rate.

8.3 Simulation

8.3.1 Parameterisation

8.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of scenarios (including baselines)
S=6

#Create vector in which equilibrium solutions from different parameterisations will be stored
u_star=vector(length=S) # utilisation rate
g_star=vector(length=S) # growth rate of capital stock
s_star=vector(length=S) # saving rate
c_star=vector(length=S) # consumption rate
r_star=vector(length=S) # profit rate

# Set exogenous variables whose parameterisation changes across regimes
g0=vector(length=S) # animal spirits
sw=vector(length=S) # propensity to save out of wages
h=vector(length=S) # profit share
g1=vector(length=S) # sensitivity of investment with respect to utilisation
```

```

#### Construct different scenarios across 3 regimes: (1) WLD/WLG, (2) WLD/PLG, (3) PLD/PLG

# baseline WLD/WLG
g0[1]=0.02
g1[1]=0.1
h[1]=0.2

# increase in profit share in WLD/WLG regime
g0[2]=0.02
g1[2]=0.1
h[2]=0.3

# baseline WLD/PLG
g0[3]=0.02
g1[3]=0.08
h[3]=0.2

# increase in profit share in WLD/PLG regime
g0[4]=0.02
g1[4]=0.08
h[4]=0.3

# baseline PLD/PLG
g0[5]=-0.01
g1[5]=0.1
h[5]=0.2

# increase in profit share in PLD/PLG regime
g0[6]=-0.01
g1[6]=0.1
h[6]=0.3

#Set constant parameter values
v=3      # capital-to-potential output ratio
g2=0.1 # sensitivity of investment with respect to profit share
sp=0.9 # propensity to save out of profits
sw=0.3 # propensity to save out of wages

#Check Keynesian stability condition for all scenarios
for (i in 1:S){
print(((sw+(sp-sw)*h[i])*(1/v) -g1[i])>0)
}

```

```

# Check demand and growth regime for 3 baseline scenarios
for (i in c(1,3,5)){
  print(paste("Parameterisation", i, "yields:"))
  if(g2*(sw/v - g1[i])-g0[i]*(sp-sw)/v<0){
    print("wage-led demand regime")
  } else{
    print("profit-led demand regime")
  }
  if(g1[i]*(g2*(sw/v - g1[i])-g0[i]*(sp-sw)/v)+g2*((sw+(sp-sw)*h[i])*v^(-1)-g1[i])^2<0){
    print("wage-led growth regime")
  } else{
    print("profit-led growth regime")
  }
}

```

```

# Initialise endogenous variables at some arbitrary positive value
g=1
r=1
c=1
u=1
s=1

#Solve this system numerically through 1000 iterations based on the initialisation
for (i in 1:S){

```

```

for (iterations in 1:1000){

  #(1) Profit rate
  r = (h[i]*u)/v

  #(2) Saving
  s = (sw+(sp-sw)*h[i])*(u/v)

  #(3) Consumption
  c= u/v-s

  #(4) Investment
  g = g0[i]+g1[i]*u+g2*h[i]

  #(5) Rate of capacity utilisation
  u = v*(c+g)
}

#Save results for different parameterisations in vector
u_star[i]=u
g_star[i]=g
r_star[i]=r
s_star[i]=s
c_star[i]=c
}

```

 Python code

```

import numpy as np

# Set number of scenarios (including baselines)
S = 6

# Create arrays to store equilibrium solutions for different parameterizations
u_star = np.zeros(S)
g_star = np.zeros(S)
s_star = np.zeros(S)
c_star = np.zeros(S)
r_star = np.zeros(S)

# Set exogenous variables whose parameterization changes across regimes
g0 = np.zeros(S)
sw = np.zeros(S)
h = np.zeros(S)
g1 = np.zeros(S)

# Construct different scenarios across 3 regimes
# Regime 1: WLD/WLG
g0[0] = 0.02
g1[0] = 0.1
h[0] = 0.2

# Regime 2: Increase in profit share in WLD/WLG regime
g0[1] = 0.02
g1[1] = 0.1
h[1] = 0.3

# Regime 3: WLD/PLG
g0[2] = 0.02
g1[2] = 0.08
h[2] = 0.2

# Regime 4: Increase in profit share in WLD/PLG regime

```

8.3.3 Plots

8.1 8.4

⁴

```
barplot(u_star, ylab="u", names.arg=c("1a:baseline WLD/WLG", "1b:rise prof share", "2a:baseline
```

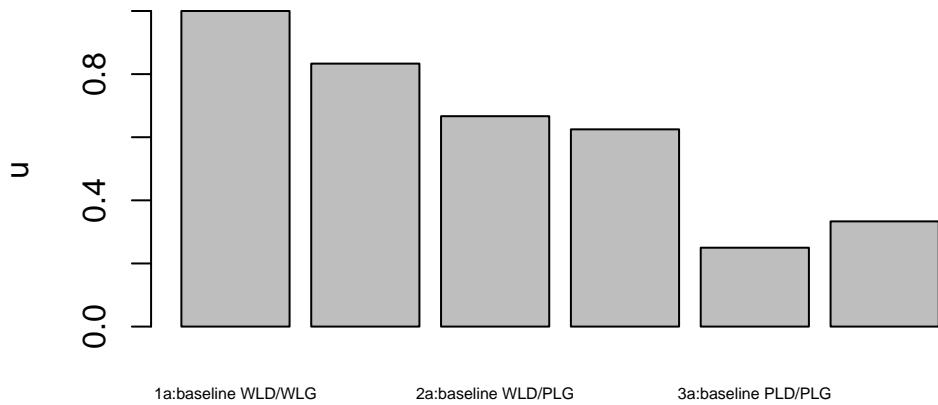


Figure 8.1: Rate of capacity utilisation

```
barplot(g_star, ylab="g", names.arg=c("1:baseline WLD/WLG", "2:rise prof share", "3:baseline
                                         "4:rise prof share",
                                         "5:baseline PLD/PLG", "6: rise prof share"), cex.names
```

⁴If the negative effect on the rate of capacity utilisation was stronger, the profit rate could fall as well. See the analytical discussion for a formal derivation of the condition under which this may happen.

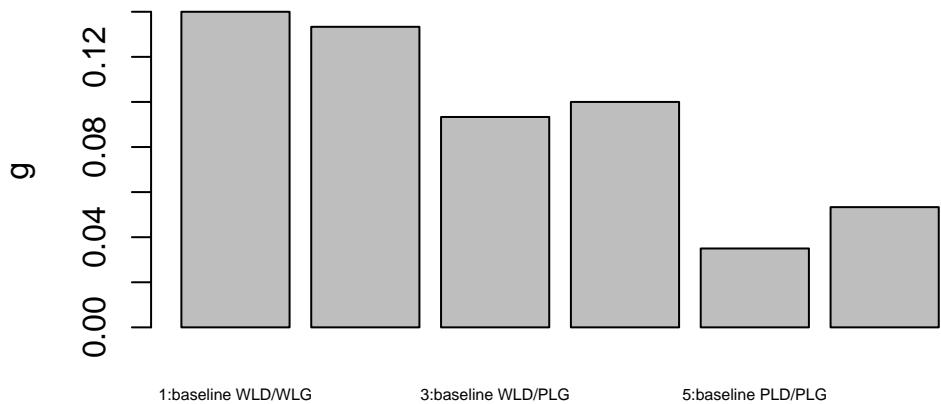


Figure 8.2: Rate of growth

```
barplot(c_star, ylab="c", names.arg=c("1:baseline WLD/WLG", "2:rise prof share", "3:baseline
                                         "4:rise prof share",
                                         "5:baseline PLD/PLG", "6: rise prof share"), cex.names=
```

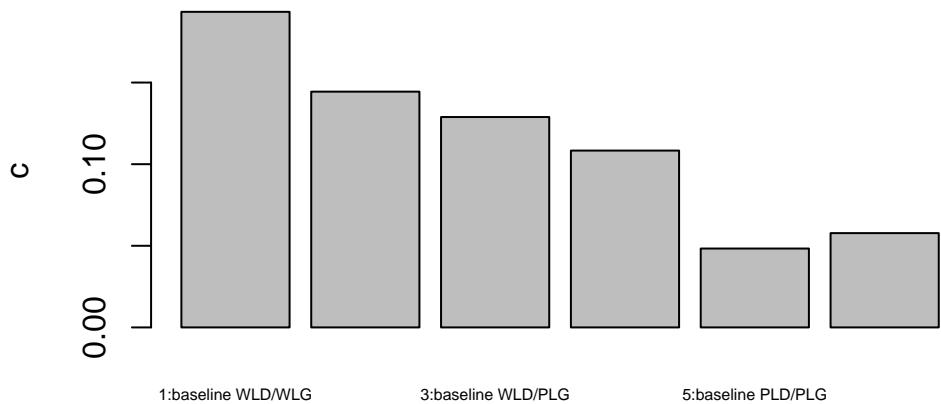


Figure 8.3: Rate of consumption

```
barplot(r_star, ylab="r", names.arg=c("1:baseline WLD/WLG", "2:rise prof share", "3:baseline
                                         "4:rise prof share",
                                         "5:baseline PLD/PLG", "6: rise prof share"), cex.names=
```

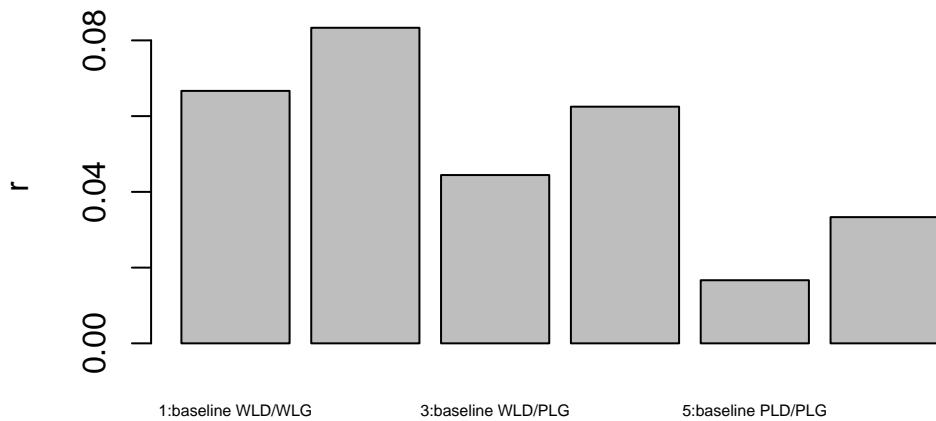


Figure 8.4: Rate of profit

i Python code

```
# Plot results (here only for rate of capacity utilisation)
import matplotlib.pyplot as plt

# Scenario labels
scenario_names = ["1a: baseline WLD/WLG", "1b: rise prof share", "2a: baseline WLD/PLG", "2b: rise prof share"]

# Bar plot for u_star
plt.bar(scenario_names, u_star)
plt.ylabel('u')
plt.xticks(scenario_names, rotation=45, fontsize=6)
plt.show()
```

8.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 6 variables:
# r, h, u, s, c, g

M_mat=matrix(c(0,1,1,0,0,0,
```

```

0,0,0,0,0,0,
0,0,0,0,1,1,
0,1,1,0,0,0,
0,0,1,1,0,0,
0,1,1,0,0,0), 6, 6, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

# Create and plot directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("r", "h", "u", "s", "c", "g")

# Plot directed graph
plot(dg, main="", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

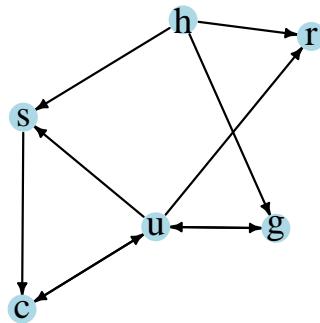


Figure 8.5: Directed graph of post-Kaleckian growth model

 Python code

```
# Load relevant libraries
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the Jacobian matrix
M_mat = np.array([[0,1,1,0,0,0],
                  [0,0,0,0,0,0],
                  [0,0,0,0,1,1],
                  [0,1,1,0,0,0],
                  [0,0,1,1,0,0],
                  [0,1,1,0,0,0],
                  ])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "r", 1: "h", 2: "u", 3: "s", 4: "c", 5: "g"}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()
```

8.5

5

⁵Other important exogenous variables or parameters that may shift but are not depicted here are animal spirits (g_0) or the saving propensities (s_W, s_{Π}). See Hein (2014), chap. 7.2.2, for a detailed discussion of their effects.

8.5 Analytical discussion

8.2 8.4 8.5

8.4

8.1

8.5.1 Calculate analytical solutions numerically

```
# Utilisation rate
for (i in 1:S){
print((g0[i]+g2*h[i])/((sw+(sp-sw)*h[i])/v-g1[i]))}
```

```
# Growth rate
for (i in 1:S){
  print(((g0[i]+g2*h[i])*(sw+(sp-sw)*h[i])/v)/((sw+(sp-sw)*h[i])/v-g1[i]))}
```

```
# Profit rate
for (i in 1:S){
  print((g0[i]+g2*h[i])* (h[i]/v)/((sw+(sp-sw)*h[i])/v-g1[i]))}
```

i Python code

```
# Utilisation rate
for i in range(S):
    print((g0[i]+g2*h[i])/((sw+(sp-sw)*h[i])/v-g1[i]))

# Growth rate
for i in range(S):
    print(((g0[i]+g2*h[i])*(sw+(sp-sw)*h[i])/v)/((sw+(sp-sw)*h[i])/v-g1[i]))

# Profit rate
for i in range(S):
    print((g0[i]+g2*h[i])*(h[i]/v)/((sw+(sp-sw)*h[i])/v-g1[i]))
```

References

Part II

Dynamic Models

9 An Introduction to the Analysis of Dynamic Models

2

9.1 Solution of a single first-order linear difference equation

1

¹We will focus here on difference instead of differential equations, i.e. on dynamics in discrete as opposed to continuous time. Most of the continuous-time counterpart is analogous to the material covered here. Sayama (2015) provides a very accessible and applied introduction to dynamic systems with Python code. An introductory treatment of the underlying mathematics is Chiang and Wainwright (2005), chaps. 15-19. Gandolfo (2009) provides a more advanced treatment of the mathematics as well as many economic examples. A great introduction to linear algebra is Anthony and Harvey (2012).

1.

2.

•

•

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•

9.2 Solution of a linear system of difference equations

[2](#)

²This is because in the product $(PDP^{-1})(PDP^{-1})(PDP^{-1})\dots$, each P cancels a P^{-1} , except for the first P and last P^{-1} .


```

#Clear the environment
rm(list=ls(all=TRUE))

## Find eigenvalues and eigenvectors of matrix
# Define matrix
J=matrix(c(7, -15,
          2, -4), 2, 2, byrow=TRUE)

# Obtain eigenvalues and eigenvectors
ev=eigen(J)
(evals = ev$values

(evecs = ev$vector)

# Normalise eigenvectors by dividing through by the first element
evecs_norm=evecs
for (i in 1:2){
  evecs_norm[,i]=evecs[,i]/evecs[1,i]
}
evecs_norm

```

 Python code

```
import numpy as np

# Define matrix
J = np.array([[7, -15],
              [2, -4]])

# Obtain eigenvalues and eigenvectors
evals, evecs = np.linalg.eig(J)

# Print eigenvalues and eigenvectors
print(evals)
print(evecs)

# Initialize an array to store the normalized eigenvectors
evecs_norm = np.copy(evecs)

# Normalize the eigenvectors
for i in range(2):
    evecs_norm[:, i] = evecs[:, i] / evecs[0, i]

# Print normalized eigenvectors
print(evecs_norm)
```

-
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-

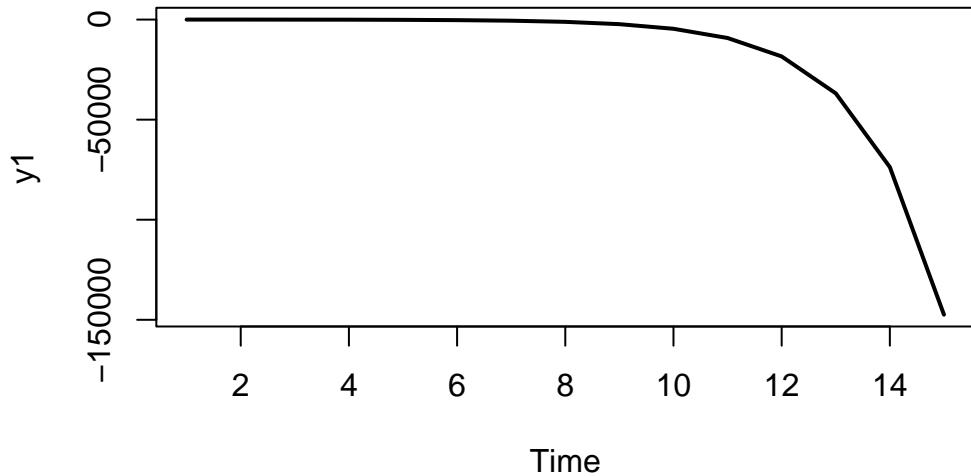
L'Hopital's rule

```
# Set number of periods for which you want to simulate
Q=100

# Construct matrices in which values for different periods will be stored; initialise at 1
y1=matrix(data=1, nrow=1, ncol=Q)
y2=matrix(data=1, nrow=1, ncol=Q)

#Solve this system recursively based on the initialisation
for (t in 2:Q){
  y1[,t] = J[1,1]*y1[, t-1] + J[1,2]*y2[, t-1]
  y2[,t] = J[2,1]*y1[, t-1] + J[2,2]*y2[, t-1]
} # close time loop

# Plot dynamics of y1
plot(y1[1, 1:15], type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="y1")
title(main="", cex=0.8)
```

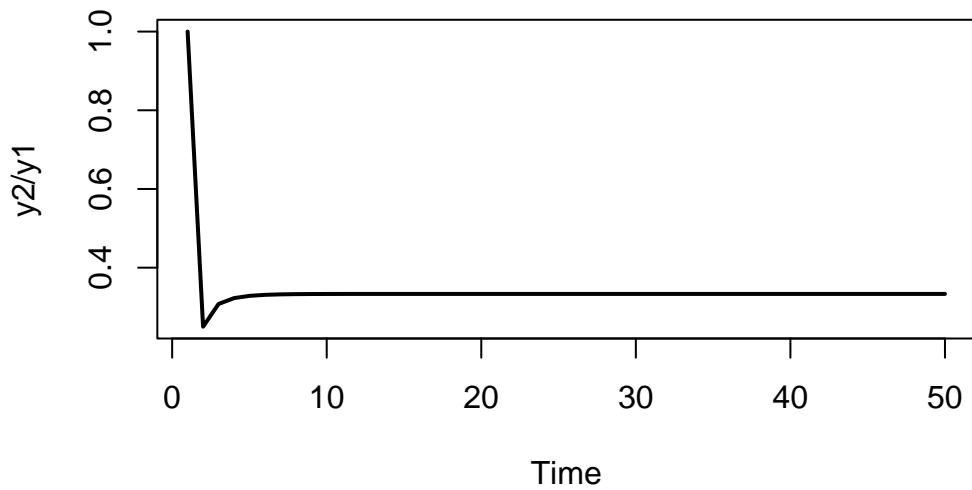


```
# Find arbitrary constants: c=(P^-1)*y0
library(matlib)
y0=c(y1[1,1],y2[1,1]) # create vector with initial conditions y0
c=inv(evecs_norm)%*%y0
c
```

```
## Compute solution manually for y2 at t=10 and compare with simulated solution
t=10
evecs_norm[2,1]*c[1,1]*evals[1]^t + evecs_norm[2,1]*c[2,1]*evals[2]^t # analytical solution
```

```
y2[,t+1] # simulated solution
```

```
# Plot dynamics of y2/y1
y2_y1=y2/y1
plot(y2_y1[, 1:50], type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="y2/y1")
title(main="", cex=0.8)
```



```
# Compare y2/y1 with normalised dominant eigenvector  
y2_y1[,Q]
```

```
evecs_norm[2,1]
```

 Python code

```

import matplotlib.pyplot as plt

# Set the number of periods for simulation
Q = 100

# Initialize arrays to store values for different periods
y1 = np.ones(Q)
y2 = np.ones(Q)

# Solve the system recursively based on the initialization
for t in range(1, Q):
    y1[t] = J[0, 0] * y1[t - 1] + J[0, 1] * y2[t - 1]
    y2[t] = J[1, 0] * y1[t - 1] + J[1, 1] * y2[t - 1]

# Plot dynamics of y1
plt.plot(range(Q), y1, color='b', linewidth=2)
plt.xlabel('Time')
plt.ylabel('y1')
plt.title('Dynamics of y1')
plt.show()

# Define the initial conditions y0
y0 = np.array([y1[0], y2[0]])

# Calculate the arbitrary constants c using the normalized eigenvectors
c = np.linalg.inv(evecs_norm).dot(y0)
c

## Compute solution manually for y2 at t=10 and compare with simulated solution
t = 10 + 1
evecs_norm[1, 1] * c[0] * evals[0] ** t + evecs_norm[1, 1] * c[1] * evals[1] ** t
y2[t-1]

# Calculate the ratio y2/y1
y2_y1 = y2 / y1

# Plot dynamics of y2/y1 for the first 50 periods
plt.plot(y2_y1[:50], color='black', linewidth=2, linestyle='--')
plt.xlabel('Time')
plt.ylabel('y2/y1')
plt.show()

# Compare y2/y1 with normalised dominant eigenvector
y2_y1[Q-1]                               161
evecs_norm[1,0]

```

9.3 Complex eigenvalues and cycles

[2](#)

```

#Clear the environment
rm(list=ls(all=TRUE))

# Set parameter values
c1=0.4
beta=2

# Check if discriminant is negative
(c1*(1+beta))^2-4*c1*beta

```

```

## Find eigenvalues and eigenvectors of matrix
# Define matrix
J=matrix(c(c1, c1,
           beta*(c1-1), beta*c1),
          2, 2, byrow=TRUE)

# Obtain eigenvalues and eigenvectors
ev=eigen(J)
(evals = ev$values)

```

 Python code

```
# Set parameter values
c1 = 0.4
beta = 2

# Check if discriminant is negative
(c1 * (1 + beta))**2 - 4 * c1 * beta

# Define the matrix
J = np.array([[c1, c1],
              [beta * (c1 - 1), beta * c1]])

# Calculate eigenvalues and eigenvectors
evals, evecs = np.linalg.eig(J)

print(evals)
print(evals)
```

```
### Draw Argand diagram
```

```
# Save real and imaginary part of complex eigenvalue
re=Re(evals[1])
im=Im(evals[1])

# Plot complex eigenvalue
par(bty="l")
plot(re,im, type="o", xlim=c(0, 1), ylim=c(0, 1), lwd=2, xlab="h", ylab="m", main="Argand dia

# Plot unit circle
X=seq(0, 1, by=0.001)
Y = sqrt(1 - X^2)
lines(X,Y, type="l", lty="dotted")
```

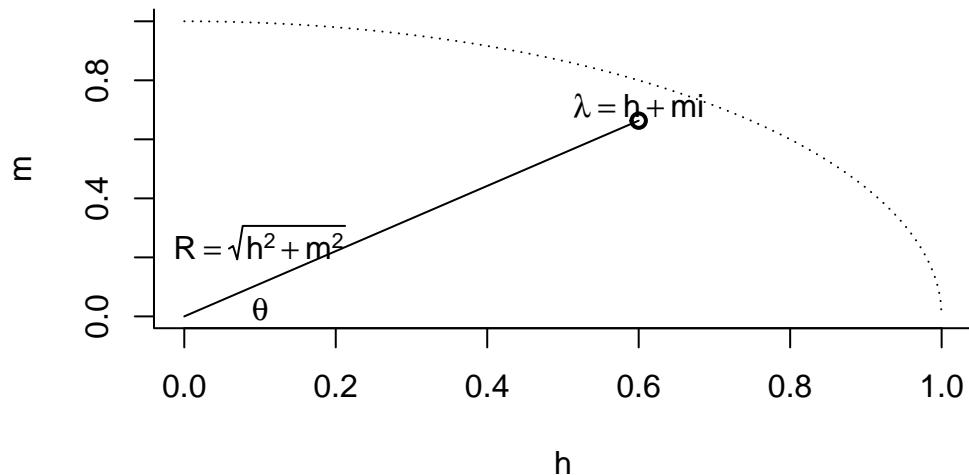
```

# Plot a ray from the origin to eigenvalue
segments(0,0,re,im, lty='solid')

# Add labels
text(0.1, 0.025, expression(theta), cex=1)
text(0.1, 0.25, expression(R==sqrt(h^2+m^2)), cex=1)
text(re, im+0.05, expression(lambda==h+mi), cex=1)

```

Argand diagram of complex eigenvalue



 Python code

```
### Draw Argand diagram

# Save real and imaginary part of complex eigenvalue
re = evals[0].real
im = evals[0].imag

# Create a figure
fig, ax = plt.subplots()
ax.set_xlim(0, 1)
ax.set_ylim(0, 1)
ax.set_xlabel('h')
ax.set_ylabel('m')
ax.set_title('Argand diagram of complex eigenvalue')

# Plot complex eigenvalue
ax.plot(re, im, 'o', markersize=8, color='k')

# Plot unit circle
X = np.linspace(0, 1, 100)
Y= np.sqrt(1-X**2)
ax.plot(X, Y, 'k--')

# Plot a ray from the origin to the eigenvalue
ax.plot([0, re], [0, im], 'k-')

# Add labels
ax.text(0.1, 0.025, r'$\theta$', fontsize=12)
ax.text(0.001, 0.25, r'$R=\sqrt{h^2+m^2}$', fontsize=12)
ax.text(re, im - 0.1, r'$\lambda=h+mi$', fontsize=12)

plt.show()
```

•
•
•
•

```
# Calculate modulus
mod=Mod(evals[1])
mod
```

```
# Calculate cycle length
L=(2*pi)/(acos(re/mod))
L
```

```

# Set number of periods for which you want to simulate
Q=100

# Set number of parameterisations that will be considered
S=1

# Construct matrices in which values for different periods will be stored; initialise at 1
C=matrix(data=1, nrow=S, ncol=Q)
I=matrix(data=1, nrow=S, ncol=Q)

#Construct matrices for exogenous variable
G0=matrix(data=5, nrow=S, ncol=Q)

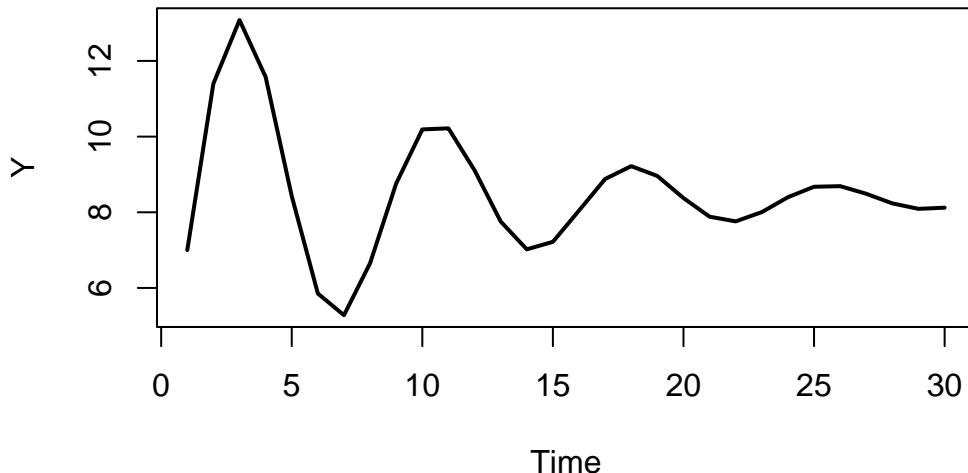
#Solve this system recursively based on the initialisation
for (t in 2:Q){
  C[1,t] = c1*(C[1,t-1] + I[1,t-1] + G0[1,t])
  I[1,t] = beta*(c1*(C[1,t-1] + I[1,t-1] + G0[1,t]) - C[1,t-1])
} # close time loop

# Calculate output
Y=C+G0+I

# Time series chart of output dynamics in Samuelson (1939) model
plot(Y[1, 1:30],type="l", col=1, lwd=2, lty=1, xlab="Time", ylab="Y")
title(main="Output fluctuations in Samuelson model with complex eigenvalues", cex=0.8)

```

Output fluctuations in Samuelson model with complex eigenvalues



 Python code

```
# Calculate modulus
mod = abs(evals[0])
print(mod)

# Calculate cycle length
import math
L = (2 * math.pi) / math.acos(re / mod)
print(L)

# Set the number of periods and parameterizations
Q = 100
S = 1

# Initialize matrices for consumption, investment, and exogenous government spending
C = np.ones((S, Q))
I = np.ones((S, Q))
G0 = np.full((S, Q), 5)

# Solve the system recursively based on the initialization
for t in range(1, Q):
    C[0, t] = c1 * (C[0, t - 1] + I[0, t - 1] + G0[0, t])
    I[0, t] = beta * (c1 * (C[0, t - 1] + I[0, t - 1] + G0[0, t]) - C[0, t - 1])

# Calculate output
Y = C + G0 + I

# Plot the time series chart of output dynamics
plt.plot(Y[0, :30], color='k', linewidth=2, linestyle='--')
plt.xlabel("Time")
plt.ylabel("Y")
plt.title("Output fluctuations in Samuelson model with complex eigenvalues")
plt.show()
```

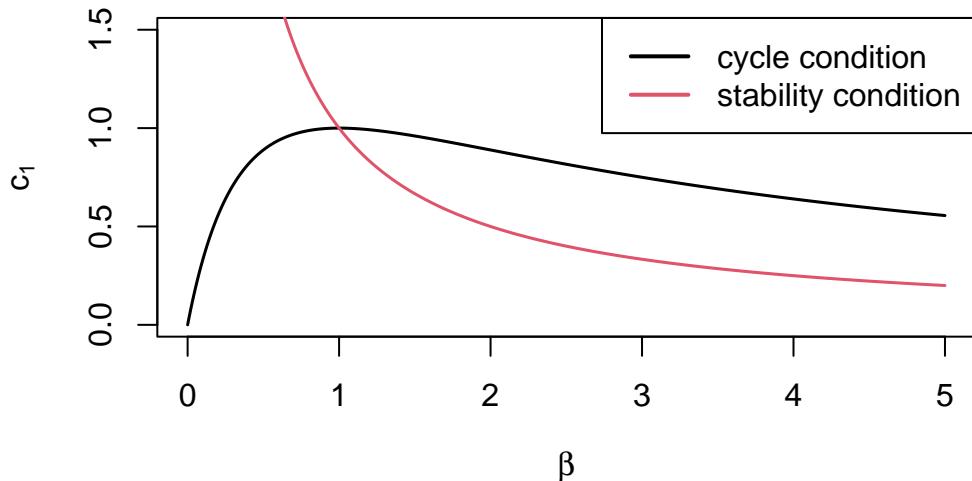
```

# Create function for cycle condition: c1 < (4*beta)/(1+beta)^2
cyc= function (beta) {
  (4*beta)/(1+beta)^2
}

# Create function for stability condition: c1 < 1/beta
stab= function (beta) {
  1/beta
}

# Plot the two functions in (beta, c1)-space
curve(cyc, from = 0, to = 5, col = 1, xlab=expression(beta), ylab=expression(c[1]) , main=""
      lwd=1.5, n=10000, ylim=range(0, 1.5))
curve(stab, from = 0, to = 5, col = 2, lwd=1.5, n=10000, add = TRUE)
legend("topright", legend = c("cycle condition", "stability condition"),
       col = c(1, 2), lwd = 2)

```



 Python code

```
import numpy as np
import matplotlib.pyplot as plt

# Create function for cycle condition using beta as argument
def cyc(beta):
    return (4 * beta) / (1 + beta)**2

# Create function for stability condition using beta as argument
def stab(beta):
    return 1 / beta

# Define the range of beta values
beta = np.linspace(0.001, 5, 10000) # start from 0.001 to avoid division by zero

# Plot the two functions in (beta, c1)-space
plt.plot(beta, cyc(beta), label="cycle condition", color='black', linewidth=1.5)
plt.plot(beta, stab(beta), label="stability condition", color='red', linewidth=1.5)

# Set labels and title
plt.xlabel(r'$\beta$')
plt.ylabel(r'$c_1$')
plt.ylim(0, 2)
plt.legend(loc="upper right")

# Display the plot
plt.show()
```

9.4 Nonlinear systems

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-
-

12

9.5 Key takeaways

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-

9.6 References

10 A New Keynesian 3-Equation Model

10.1 Overview

¹

²

10.2 The Model

¹See Galí (2018) for an overview.

²Note that this is quite different from conventional New Keynesian dynamic general equilibrium models in which the dynamic element stems from agents with rational expectations that react to serially correlated shocks.

10.1

10.2

10.3

10.4

10.5

10.3 Simulation

10.3.1 Parameterisation

10.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
Q=50

# Set number of scenarios
S=3

# Set period in which shock/shift will occur
s=5

# Create (S x Q)-matrices that will contain the simulated data
y=matrix(data=0,nrow=S,ncol=Q) # Income/output
p=matrix(data=0,nrow=S,ncol=Q) # Inflation rate
r=matrix(data=0,nrow=S,ncol=Q) # Real interest rate
rs=matrix(data=0,nrow=S,ncol=Q) # Stabilising interest rate

# Set constant parameter values
a1=0.3 # Sensitivity of inflation with respect to output gap
a2=0.7 # Sensitivity of output with respect to interest rate
b=1 # Sensitivity of central bank to inflation gap
a3=(a1*(1/(b*a2) + a2))^-1

# Set parameter values for different scenarios
A=matrix(data=10,nrow=S,ncol=Q) # autonomous spending
pt=matrix(data=2,nrow=S,ncol=Q) # Inflation target
```

```

ye=matrix(data=5,nrow=S,ncol=Q) # Potential output

A[1,s:Q]=12 # scenario 1: AD boost
pt[2,s:Q]=3 # scenario 2: higher inflation target
ye[3,s:Q]=7 # scenario 3: higher potential output

# Initialise endogenous variables at equilibrium values
y[,1]=ye[,1]
p[,1]=pt[,1]
rs[,1]=(A[,1] - ye[,1])/a1
r[,1]=rs[,1]

# Simulate the model by looping over Q time periods for S different scenarios
for (i in 1:S){

  for (t in 2:Q){

    #(1) IS curve
    y[i,t] = A[i,t] - a1*r[i,t-1]

    #(2) Phillips Curve
    p[i,t] = p[i,t-1] + a2*(y[i,t]-ye[i,t])

    #(3) Stabilising interest rate
    rs[i,t] = (A[i,t] - ye[i,t])/a1

    #(4) Monetary policy rule, solved for r
    r[i,t] = rs[i,t] + a3*(p[i,t]-pt[i,t])

  } # close time loop
} # close scenarios loop

```

 Python code

```

import numpy as np

# Set number of periods
Q = 50

# Set number of scenarios
S = 3

# Set period in which shock/shift will occur
s = 5

# Create (S x Q) arrays to store simulated data
y = np.zeros((S, Q)) # Income/output
p = np.zeros((S, Q)) # Inflation rate
r = np.zeros((S, Q)) # Real interest rate
rs = np.zeros((S, Q)) # Stabilizing interest rate

# Set constant parameter values
a1 = 0.3 # Sensitivity of inflation with respect to output gap
a2 = 0.7 # Sensitivity of output with respect to interest rate
b = 1 # Sensitivity of the central bank to inflation gap
a3 = (a1 * (1 / (b * a2) + a2)) ** (-1)

# Set parameter values for different scenarios
A = np.full((S, Q), 10) # Autonomous spending
pt = np.full((S, Q), 2) # Inflation target
ye = np.full((S, Q), 5) # Potential output

A[0, s:Q] = 12 # Scenario 1: AD boost
pt[1, s:Q] = 3 # Scenario 2: Higher inflation target
ye[2, s:Q] = 7 # Scenario 3: Higher potential output

# Initialize endogenous variables at equilibrium values
y[:, 0] = ye[:, 0]
p[:, 0] = pt[:, 0]
rs[:, 0] = (A[:, 0] - ye[:, 0]) / a1
r[:, 0] = rs[:, 0]

# Simulate the model by looping over Q time periods for S different scenarios
for i in range(S):
    for t in range(1, Q):
        # (1) IS curve
        y[i, t] = A[i, t] - a1 * r[i, t - 1]
        # (2) Phillips Curve
        p[i, t] = p[i, t - 1] + a2 * (y[i, t] - ye[i, t])
        # (3) Stabilizing interest rate
        rs[i, t] = (A[i, t] - ye[i, t]) / a1
        # (4) Monetary policy rule, solved for r
        r[i, t] = rs[i, t] + a3 * (p[i, t] - pt[i, t])

```

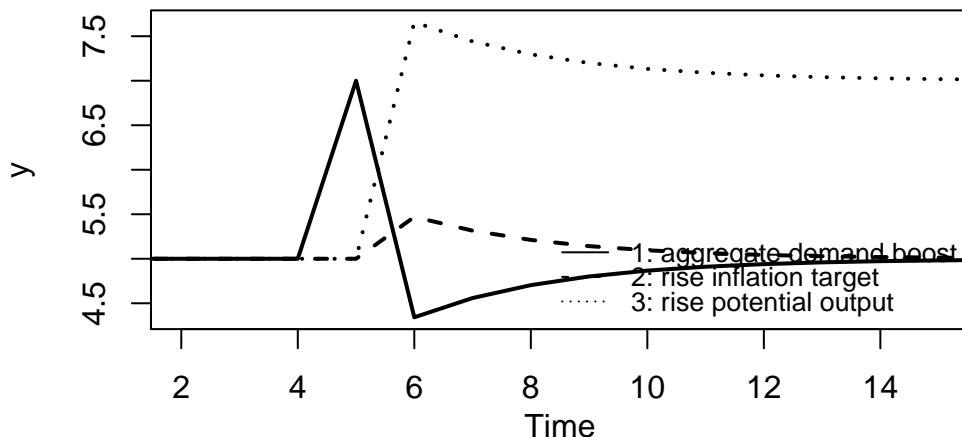
10.3.3 Plots

```
### Plot results

### Plots
# Set maximum period for plots
Tmax=15

# Output under different scenarios
plot(y[1, 1:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlab="", xlim=range(2:(Tmax)), ylab="y"
title(main="Figure 1: Output under different scenarios", xlab = "Time",cex=0.8 ,line=2)
lines(y[2, 1:(Tmax+1)],lty=2, lwd=2)
lines(y[3, 1:(Tmax+1)],lty=3, lwd=2)
legend("bottomright", legend=c("1: aggregate demand boost", "2: rise inflation target", "3: r
```

Figure 1: Output under different scenarios



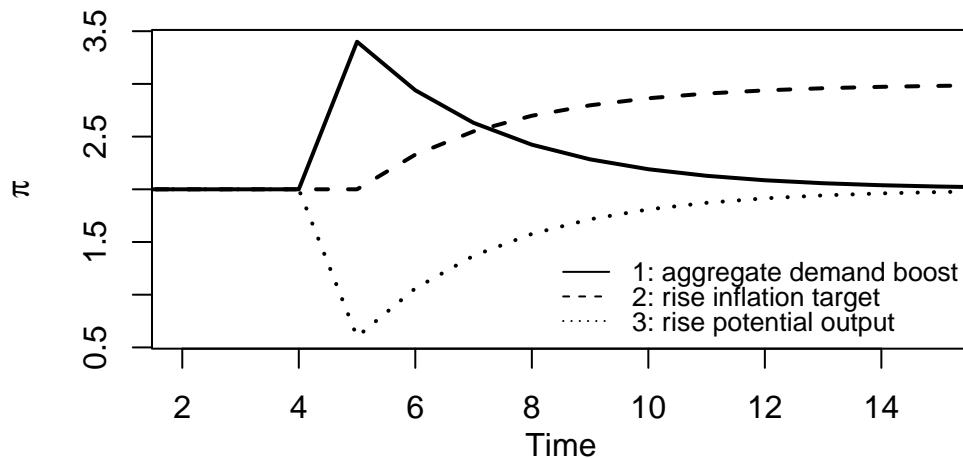
```
# Inflation under different scenarios
plot(p[1, 1:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlab="", xlim=range(2:(Tmax)), ylab=exp
title(main="Figure 2: Inflation under different scenarios", xlab = "Time",cex=0.8 ,line=2)
lines(p[2, 1:(Tmax+1)],lty=2, lwd=2)
```

```

lines(p[3, 1:(Tmax+1)],lty=3, lwd=2)
legend("bottomright", legend=c("1: aggregate demand boost", "2: rise inflation target", "3: r

```

Figure 2: Inflation under different scenarios

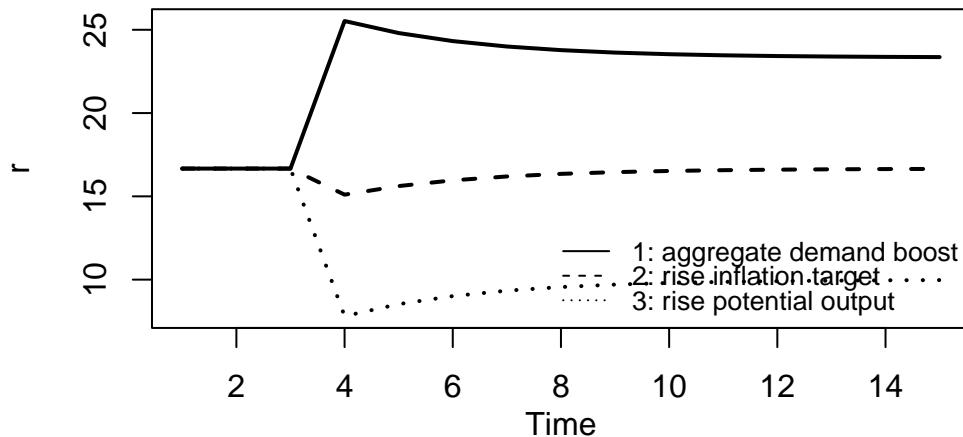


```

# Policy rate under different scenarios
plot(r[1, 2:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlab="", xlim=range(1:(Tmax)), ylab="r"
title(main="Figure 3: Policy rate under different scenarios", xlab = "Time",cex=0.8 ,line=2)
lines(r[2, 2:(Tmax+1)],lty=2, lwd=2)
lines(r[3, 2:(Tmax+1)],lty=3, lwd=2)
legend("bottomright", legend=c("1: aggregate demand boost", "2: rise inflation target", "3: r

```

Figure 3: Policy rate under different scenarios



 Python code

```
import matplotlib.pyplot as plt

# Set maximum period for plots
Tmax = 15

# Plot output under different scenarios
plt.figure(figsize=(8, 6))
plt.plot(y[0, :Tmax + 1], label="Scenario 1: aggregate demand boost",
          color='k', linestyle='solid', linewidth=2)
plt.plot(y[1, :Tmax + 1], label="Scenario 2: Rise inflation target",
          color='k', linestyle='dashed', linewidth=2)
plt.plot(y[2, :Tmax + 1], label="Scenario 3: Rise potential output",
          color='k', linestyle='dotted', linewidth=2)

plt.title("Output under Different Scenarios")
plt.xlabel("Time")
plt.ylabel("y")
plt.xlim(1, Tmax)
plt.ylim(np.min(y), np.max(y))
plt.legend()
plt.show()
```

10.4 Directed graph

```
# Construct auxiliary Jacobian matrix for 7 variables: y, p, r, A, ye, rs, pt
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged
```

```

M_mat=matrix(c(0,0,1,1,0,0,0,
              1,0,0,0,1,0,0,
              0,1,0,0,0,1,1,
              0,0,0,0,0,0,0,
              0,0,0,0,0,0,0,
              0,0,0,1,1,0,0,
              0,0,0,0,0,0,0),7,7, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat=t(M_mat)

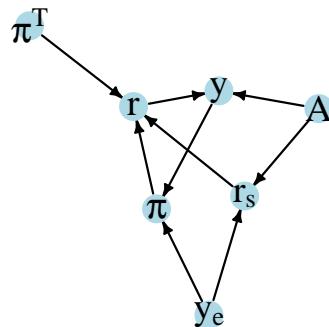
# Create directed graph from adjacency matrix
library(igraph)
dg=graph_from_adjacency_matrix(A_mat, mode="directed", weighted=NULL)

# Define node labels
V(dg)$name=c("y", expression(pi), "r", "A", expression(y[e]), expression(r[s]), expression(pi^T))

# Plot directed graph
plot(dg, main="Figure 4: Directed graph of 3-Equation model", vertex.size=20, vertex.color="NA",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)

```

Figure 4: Directed graph of 3–Equation model



 Python code

```

# Directed graph
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the Jacobian matrix
M_mat = np.array([[0, 0, 1, 1, 0, 0, 0],
                  [1, 0, 0, 0, 1, 0, 0],
                  [0, 1, 0, 0, 0, 1, 1],
                  [0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 1, 1, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0],
                  ])
]

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {
    0: "y",
    1: " ",
    2: "r",
    3: "A",
    4: "y",
    5: "r",
    6: " "
}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()

```

10.5 Analytical discussion

10.5.1 Derivation of core equations

10.5.1.1 IS curve

10.1
3

10.1

10.5.1.2 PC curve

10.2
3

³See chapter 2 of Carlin and Soskice (2014) for details.

10.5
10.6 10.2

10.5.1.3 Monetary policy rule

⁴

10.2

10.2 10.1 10.3
10.4

10.5.2 Equilibrium solutions and stability analysis

10.1 10.2

⁴See chapter 2 of Carlin and Soskice (2014) for details.

10.4

10.1

10.7

10.8

5

```
# Construct Jacobian matrix
J=matrix(c(0,0,-a1,
          0,1,-a1*a2,
          0,a3,-a1*a2*a3), 3, 3, byrow=TRUE)

# Obtain eigenvalues
ev=eigen(J)
(values <- ev$values)
```

⁵As mentioned in footnote 2, this property of the Carlin-Soskice model is very different from conventional New Keynesian models with rational expectations. In these models, variables such as output and inflation are driven by the ‘forward-looking’ behaviour of rational agents, i.e. they depend on expectational terms for their current values rather than lagged values. To ensure what is called ‘determinancy’, these forward-looking variables must adjust fast (or ‘jump’) to bring the economy back onto a path that is consistent with the optimising equilibrium. This requires the number of jump variables to be matched by an equal number of unstable roots (i.e. being outside the unit circle).

```
# Obtain determinant and trace  
det(J)      # determinant
```

```
sum(diag(J)) # trace
```

 Python code

```
import numpy as np  
  
# Construct Jacobian matrix  
J = np.array([[0, 0, -a1],  
             [0, 1, -a1 * a2],  
             [0, a3, -a1 * a2 * a3],])  
  
# Calculate eigenvalues  
eigenvalues = np.linalg.eigvals(J)  
  
# Print the resulting eigenvalues  
print(eigenvalues)  
  
# Calculate the determinant and trace of the Jacobian matrix  
determinant = np.linalg.det(J)  
trace = np.trace(J)  
print(determinant)  
print(trace)
```

10.6 References

11 A Sraffian Supermultiplier Model

11.1 Overview

¹

²

³

¹See chapter 7 in Blecker and Setterfield (2019), Dutt (2018), and chapter 6 in Lavoie (2022) for useful introductions. Note that contrary to what the name may suggest, this is a one-sector model.

²All variables are normalised by the capital stock and thus rendered stationary.

³Section 2.5 explains how continuous time models can be solved numerically.

11.2 The Model

11.1

4

11.2

11.3

11.4

11.5

11.6

11.7

⁴For simplicity, it is assumed that the capital-potential output ratio is equal to unity. This implies that the ratio of actual output to potential output is equal to the ratio of actual output to the capital stock, so that the latter can be taken as a measure of the rate of capacity utilisation.

11.3 Simulation

11.3.1 Parameterisation

11.3.2 Simulation code

```
#Clear the environment
rm(list=ls(all=TRUE))

#Set number of periods
Q = 1000

# Set number of scenarios (including baselines)
S=4

# Set period in which exogenous shift will occur
q=50

#Create (S x Q) matrices in which equilibrium solutions from different parameterisations will
u=matrix(data=0,nrow=S,ncol=Q) # rate of capacity utilisation
g=matrix(data=0,nrow=S,ncol=Q) # growth rate of capital stock
s=matrix(data=0,nrow=S,ncol=Q) # saving rate
c=matrix(data=0,nrow=S,ncol=Q) # consumption rate
r=matrix(data=0,nrow=S,ncol=Q) # profit rate
```

```

g0=matrix(data=0,nrow=S,ncol=Q)# expected growth rate of capital stock
z=matrix(data=0,nrow=S,ncol=Q) # autonomous demand rate

#Set constant parameter values
g1=0.2 # Sensitivity of investment with respect to utilisation
sr=0.8 # propensity to save out of profits
mu=0.08 # adjustment speed of expected growth rate
d=0.1 # time increment

# Set and initialise exogenous variables/parameters that will be shifted
pi=matrix(data=0.35,nrow=S,ncol=Q) # profit share
gz=matrix(data=0.02,nrow=S,ncol=Q) # growth rate of autonomous demand
un=matrix(data=0.75,nrow=S,ncol=Q) # normal rate of capacity utilisation

# Set parameter values for different scenarios
gz[2,q:Q]=0.03 # scenario 2: rise in autonomous demand growth
pi[3,q:Q]=0.4 # scenario 3: rise in profit share
un[4,q:Q]=0.8 # scenario 4: rise in normal rate of utilisation

# Initialise endogenous variables at equilibrium values
u[,1]=un[,1]
g[,1]=gz[,1]
s[,1]=g[,1]
c[,1]=un[,1]-s[,1]
g0[,1]=gz[,1]
z[,1]=sr*pi[,1]*un[,1]-gz[,1]
r[,1]=pi[,1]*un[,1]

# Simulate the model by looping over Q time periods for S different scenarios
for (i in 1:S){

  for (t in 2:Q){

    for (iterations in 1:1000){ # iterate the model 1000-times in each period

      #(1) Profit rate
      r[i,t] =pi[i,t]*u[i,t]

      #(2) Saving
      s[i,t] = -z[i,t] + sr*r[i,t]

      #(3) Consumption
    }
  }
}

```

```

c[i,t] = u[i,t] - s[i,t]

#(4) Investment
g[i,t] = g0[i,t] + g1*(u[i,t] - un[i,t])

#(5) Capacity utilisation
u[i,t] = c[i,t] + g[i,t]

#(6) Dynamic adjustment of expected growth rate of capital stock
g0[i,t] = g0[i,t-1] + mu*(g[i,t-1]-g0[i,t-1])*d

#(7) Dynamic adjustment of autonomous demand
z[i,t] = z[i,t-1] + z[i,t-1]*(gz[i,t-1] - g[i,t-1])*d

} # close iterations loop
} # close time loop
} # close scenarios loop

```

 Python code

```

import numpy as np

# Set number of periods
Q = 1000

# Set number of scenarios (including baselines)
S = 4

# Set period in which exogenous shift will occur
q = 50

# Create (S x Q) matrices for equilibrium solutions
u = np.zeros((S, Q)) # rate of capacity utilization
g = np.zeros((S, Q)) # growth rate of capital stock
s = np.zeros((S, Q)) # saving rate
c = np.zeros((S, Q)) # consumption rate
r = np.zeros((S, Q)) # profit rate
g0 = np.zeros((S, Q)) # expected growth rate of capital stock
z = np.zeros((S, Q)) # autonomous demand rate

# Set constant parameter values
g1 = 0.2 # Sensitivity of investment with respect to utilization
sr = 0.8 # propensity to save out of profits
mu = 0.08 # adjustment speed of expected growth rate
d = 0.1 # time increment

# Set and initialize exogenous variables/parameters that will be shifted
pi = np.full((S, Q), 0.35) # profit share
gz = np.full((S, Q), 0.02) # growth rate of autonomous demand
un = np.full((S, Q), 0.75) # normal rate of capacity utilization

# Set parameter values for different scenarios
gz[1, q:] = 0.03 # scenario 2: rise in autonomous demand growth
pi[2, q:] = 0.4 # scenario 3: rise in profit share
un[3, q:] = 0.8 # scenario 4: rise in normal rate of utilization

# Initialize endogenous variables at equilibrium values
u[:, 0] = un[:, 0]
g[:, 0] = gz[:, 0]
s[:, 0] = g[:, 0]
c[:, 0] = un[:, 0] - s[:, 0]
g0[:, 0] = gz[:, 0]
z[:, 0] = sr * pi[:, 0] * un[:, 0] - gz[:, 0]
r[:, 0] = pi[:, 0] * un[:, 0]

# Simulate the model by looping over 196 time periods for S different scenarios
for i in range(S):
    for t in range(1, Q):
        for iterations in range(1000): # iterate the model 1000 times in each period

            # (1) Profit rate
            r[i, t] = pi[i, t] * u[i, t]

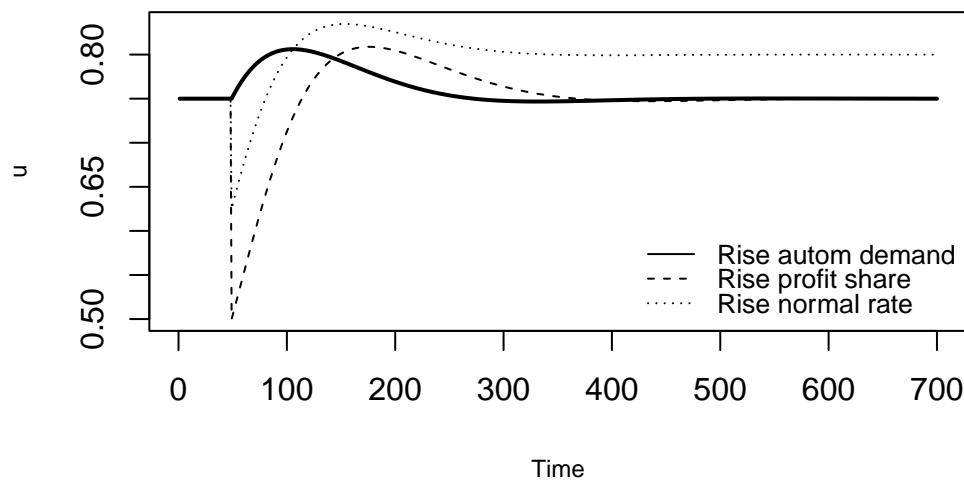
```

11.3.3 Plots

```
# Set maximum period for plots
Tmax=700

# Capacity utilisation
plot(u[2, 2:(Tmax+1)], type="l", col=1, lwd=2, lty=1, font.main=1,cex.main=1,
      ylab = 'u',xlab = 'Time',ylim=range(max(u[, 2:Tmax]),min(u[, 2:Tmax])),cex.axis=1,cex.lab=1
title(main="Figure 1: Rate of capacity utilisation under different scenarios",cex=0.8 ,line=1)
lines(u[3, 2:(Tmax+1)],lty=2)
lines(u[4, 2:(Tmax+1)],lty=3)
legend("bottomright", legend=c("Rise autom demand", "Rise profit share", "Rise normal rate"),
       lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 1: Rate of capacity utilisation under different scenarios

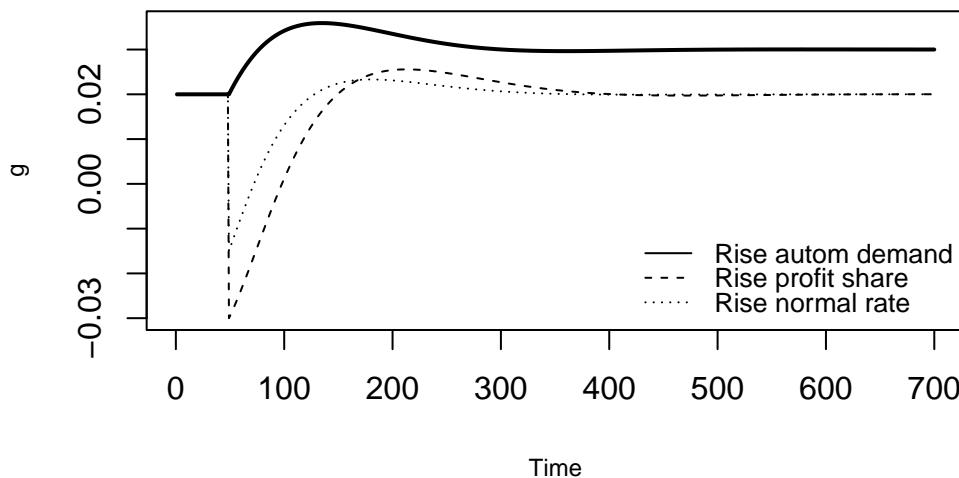


```

# Growth
plot(g[2, 2:(Tmax+1)], type="l", col=1, lwd=2, lty=1, font.main=1,cex.main=1,
      ylab = 'g',xlab = 'Time',ylim=range(max(g[, 2:Tmax]),min(g[, 2:Tmax])),cex.axis=1,cex.la
title(main="Figure 2: Growth rate under different scenarios",cex=0.8 ,line=2)
lines(g[3, 2:(Tmax+1)],lty=2)
lines(g[4, 2:(Tmax+1)],lty=3)
legend("bottomright", legend=c("Rise autom demand", "Rise profit share", "Rise normal rate")
      lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)

```

Figure 2: Growth rate under different scenarios

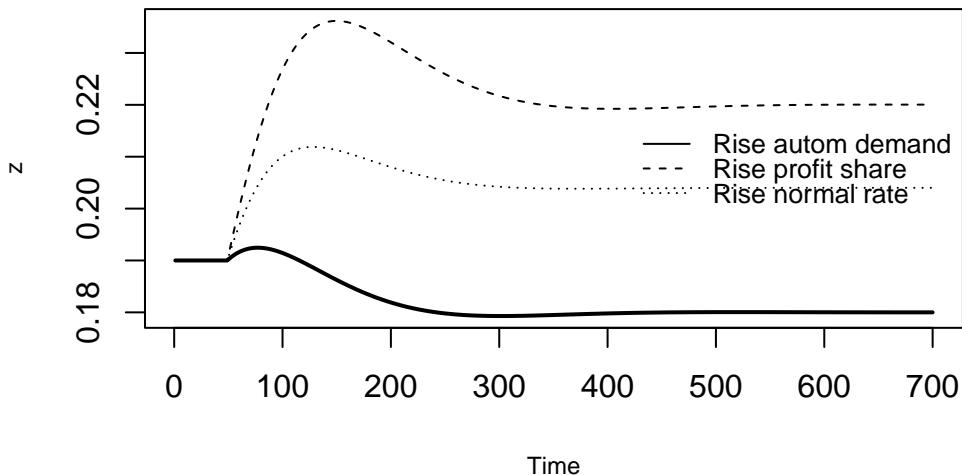


```

# Autonomous demand rate
plot(z[2, 2:(Tmax+1)], type="l", col=1, lwd=2, lty=1, font.main=1,cex.main=1,
      ylab = 'z',xlab = 'Time',ylim=range(max(z[, 2:Tmax]),min(z[, 2:Tmax])),cex.axis=1,cex.la
title(main="Figure 3: Rate of autonomous demand under different scenarios",cex=0.8 ,line=2)
lines(z[3, 2:(Tmax+1)],lty=2)
lines(z[4, 2:(Tmax+1)],lty=3)
legend("right", legend=c("Rise autom demand", "Rise profit share", "Rise normal rate"),
      lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)

```

Figure 3: Rate of autonomous demand under different scenarios



i Python code

```
## Plots (here for capacity utilisation only)

import matplotlib.pyplot as plt

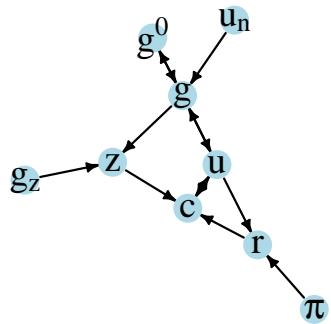
# Set maximum period for plots
Tmax = 700

# Plot capacity utilization
plt.plot(u[1, 1:Tmax], label='Rise autom demand', linestyle='-', linewidth=2, color='k')
plt.plot(u[2, 1:Tmax], label='Rise profit share', linestyle='--', linewidth=2, color='k')
plt.plot(u[3, 1:Tmax], label='Rise normal rate', linestyle='-.', linewidth=2, color='k')
plt.title('Rate of Capacity Utilization under Different Scenarios')
plt.xlabel('Time')
plt.ylabel('u')
plt.legend(loc='lower right')
plt.show()
```

11.4 Directed graph

```
# Construct auxiliary Jacobian matrix for 9 variables:  
# r, c, g, u, g0, z, pi, gz, un  
  
M_mat=matrix(c(0,0,0,1,0,0,1,0,0,  
              1,0,0,1,0,1,0,0,0,  
              0,0,0,1,1,0,0,0,1,  
              0,1,1,0,0,0,0,0,0,  
              0,0,1,0,0,0,0,0,0,  
              0,0,1,0,0,0,0,1,0,  
              0,0,0,0,0,0,0,0,0,  
              0,0,0,0,0,0,0,0,0,  
              0,0,0,0,0,0,0,0,0), 9, 9, byrow=TRUE)  
  
# Create adjacency matrix from transpose of auxiliary Jacobian and add column names  
A_mat=t(M_mat)  
  
# Create directed graph from adjacency matrix  
library(igraph)  
dg=graph_from_adjacency_matrix(A_mat, mode="directed", weighted=NULL)  
  
# Define node labels  
V(dg)$name=c("r", "c", "g", "u", expression(g^0), "z", expression(pi), expression(g[z]), exp  
  
# Plot directed graph  
plot(dg, main="Figure 4: Directed graph of Sraffian Supermultiplier Model", vertex.size=20,  
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,  
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,  
      vertex.frame.color="NA", margin=-0.08)
```

Figure 4: Directed graph of Sraffian Supermultiplier Model



 Python code

```

# Directed graph
import networkx as nx
import matplotlib.pyplot as plt
import numpy as np

# Define the Jacobian matrix
M_mat = np.array([[0, 0, 0, 1, 0, 0, 1, 0, 0],
                  [1, 0, 0, 1, 0, 1, 0, 0, 0],
                  [0, 0, 0, 1, 1, 0, 0, 0, 1],
                  [0, 1, 1, 0, 0, 0, 0, 0, 0],
                  [0, 0, 1, 0, 0, 0, 0, 0, 0],
                  [0, 0, 1, 0, 0, 0, 0, 1, 0],
                  [0, 0, 0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 0, 0, 0, 0]])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "r",
            1: "c",
            2: "g",
            3: "u",
            4: r"$g^0$",
            5: "z",
            6: r"$\pi$",
            7: r"$g_z$",
            8: r"$u_n$"}

# Plot the directed graph
pos = nx.spring_layout(G, seed=43)
nx.draw(G, pos, with_labels=True, labels=nodelabs, node_size=300, node_color='lightblue',
        font_size=10)
edge_labels = {(u, v): '' for u, v in G.edges}
nx.draw_networkx_edge_labels(G, pos, edge_labels=edge_labels, font_color='black')
plt.axis('off')
plt.show()

```

11.5 Analytical discussion

11.4

11.5

11.1

11.7

11.6

11.7

```

# Construct Jacobian matrix at the equilibrium

J=matrix(c((mu*g1)/(sr*pi[1,Q]-g1), (mu*g1)/(sr*pi[1,Q]-g1),
           -z[1,Q]*(sr*pi[1,Q]/(sr*pi[1,Q]-g1)), -z[1,Q]*(g1/(sr*pi[1,Q]-g1))), 2, 2, byrow=T)

```



```

# Obtain eigenvalues
ev=eigen(J)
(values <- ev$values)

```



```

# Obtain determinant and trace
det(J) # determinant

```



```

sum(diag(J)) # trace

```



```

# Check stability conditions for all scenarios
for (i in 1:S){
  print(paste0("Scenario ", i, ":"))
  print(sr*pi[i,1]>g1) # Keynesian stability condition
  print(mu<sr*un[i,1]*pi[i,1]-gz[i,1])
}

```

 Python code

```
# Construct Jacobian matrix
J = np.array([
    [(mu * g1) / (sr * pi[0, Q-1] - g1), (mu * g1) / (sr * pi[0, Q-1] - g1)],
    [-z[0, Q-1] * (sr * pi[0, Q-1] / (sr * pi[0, Q-1] - g1)), -z[0, Q-1] * (g1 / (sr * pi[0, Q-1] - g1))],
])
print(J)

# Obtain eigenvalues, determinant, and trace
eigenvalues, eigenvectors = np.linalg.eig(J)
print(eigenvalues)

determinant_J = np.linalg.det(J)
print(determinant_J)

trace_J = np.trace(J)
print(trace_J)

# Check stability conditions for all scenarios
for i in range(1, S + 1):
    print(f"Scenario {i}:")
    print(sr * pi[i - 1, 0] > g1) # Keynesian stability condition
    print(mu < sr * un[i - 1, 0] * pi[i - 1, 0] - gz[i - 1, 0])
```

11.6 References

12 A Malthusian Model

12.1 Overview

An Essay on the Principle of Population
¹

Karl Whelan's lecture notes

12.2 The Model

12.1

12.3

12.4

12.2

¹See chapter 2 of Foley (2006) for an excellent introduction.

12.3 Simulation

12.3.1 Parameterisation

12.3.2 Simulation code

```
# Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
T=100

# Set number of scenarios (including baseline)
S=4

# Set period in which shock/shift will occur
s=5

# Create (S x T)-matrices that will contain the simulated data
N=matrix(data=0,nrow=S,ncol=T) # population
Y=matrix(data=0,nrow=S,ncol=T) # real income
B=matrix(data=0,nrow=S,ncol=T) # births
```

```

D=matrix(data=0,nrow=S,ncol=T) # deaths
N_eq=vector(length=S)           # equilibrium population
Y_eq=vector(length=S)           # equilibrium real income
B_eq=vector(length=S)           # equilibrium births
D_eq=vector(length=S)           # equilibrium deaths

# Set baseline parameter values
b0=matrix(data=0.5,nrow=S,ncol=T) # Exogenous birth rate
b1=0.5 # Sensitivity of births with respect to real income
d0=2.5 # Exogenous death rate
d1=0.5 # Sensitivity of deaths with respect to real income
a0=matrix(data=2.5,nrow=S,ncol=T) # Exogenous component of real income
a1=matrix(data=0.05,nrow=S,ncol=T) #Sensitivity of the real income with respect to population

# Set parameter values for different scenarios
b0[2,s:T]=0.4 # scenario 2: reduction in birth rate
a1[3,s:T]=0.07 # scenario 3: increase in sensitivity of real income with respect to population
a0[4,s:T]=2.6 # scenario 4: improvement in productivity

# Initialise
N[,1]=1
Y[,1]=1
B[,1]=1
D[,1]=1

# Simulate the model by looping over T time periods for S different scenarios
for (i in 1:S){

  for (t in 2:T){

    for (iterations in 1:1000){ # run the model 1000-times in each period

      # (1) Population dynamics
      N[i,t] = N[i,t-1] + B[i,t-1] - D[i,t-1]

      # (2) Births
      B[i,t] = (b0[i,t] + b1*Y[i,t])*N[i,t]

      # (3) Deaths
      D[i,t] = (d0 - d1*Y[i,t])*N[i,t]

      # (4) Real income
    }
  }
}

```

```
Y[i,t] = a0[i,t] - a1[i,t]*N[i,t]

} # close iterations loop
} # close time loop
} # close scenario loop
```

 Python code

```

# Load relevant libraries
import numpy as np

# Set number of periods
T = 100

# Set number of scenarios (including baseline)
S = 4

# Set period in which shock/shift will occur
s = 5

# Create (S x T)-matrices that will contain the simulated data
N = np.zeros((S, T)) # population
Y = np.zeros((S, T)) # real income
B = np.zeros((S, T)) # births
D = np.zeros((S, T)) # deaths
N_eq = np.zeros((S)) # equilibrium population
Y_eq = np.zeros((S)) # equilibrium real income
B_eq = np.zeros((S)) # equilibrium births
D_eq = np.zeros((S)) # equilibrium deaths

# Set baseline parameter values
b0 = np.zeros((S, T)) + 0.5 # Exogenous birth rate
b1 = 0.5 # Sensitivity of births with respect to real income
d0 = 2.5 # Exogenous death rate
d1 = 0.5 # Sensitivity of deaths with respect to real income
a0 = np.zeros((S, T)) + 2.5 # Exogenous component of real income
a1 = np.zeros((S, T)) + 0.05 # Sensitivity of the real income with respect to population

# Set parameter values for different scenarios
b0[1, s:T] = 0.4 # scenario 2: reduction in birth rate
a1[2, s:T] = 0.07 # scenario 3: increase in sensitivity of real income with respect to population
a0[3, s:T] = 2.6 # scenario 4: improvement in productivity

# Initialise
N[:,0] = 1
Y[:,0] = Y_eq[0]
B[:,0] = B_eq[0]
D[:,0] = D_eq[0]

# Simulate the model by looping over T time periods for S different scenarios
for i in range(S):
    for t in range(1, T):
        for iterations in range(1000): # run the model 1000-times in each period (to make sure
            # (1) Population dynamics      212
            N[i,t] = N[i,t-1] + B[i,t-1] - D[i,t-1]
            # (2) Births
            B[i,t] = (b0[i,t] + b1*Y[i,t])*N[i,t]
            # (3) Deaths
            D[i,t] = (d0 - d1*Y[i,t])*N[i,t]
            # (4) Real income
            Y[i,t] = a0[i,t] + a1[i,t]*N[i,t]

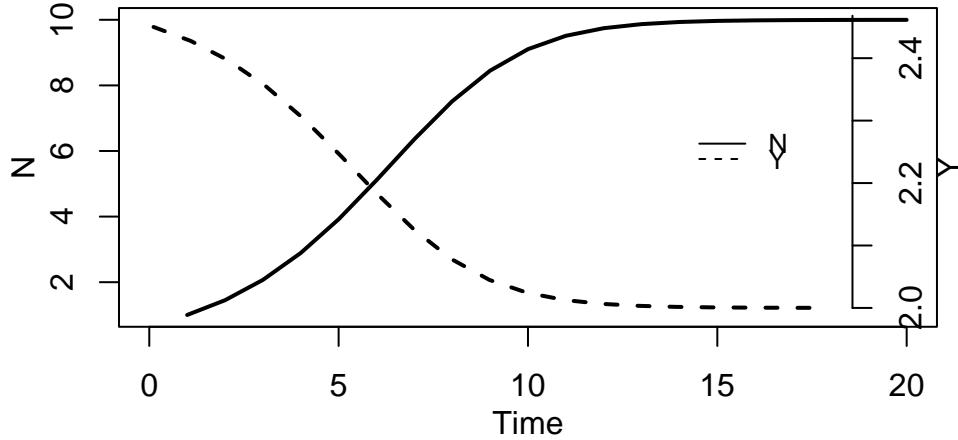
```

12.3.3 Plots

```
# Set maximum period for plots
Tmax=20

## Baseline
#Population and real income
plot(N[1, 2:(Tmax+1)],type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylab = '', xlab = '')
title(main="Figure 1: Population and real income, baseline",ylab = 'N', xlab = 'Time',cex=0.8)
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(Y[1, 2:Tmax],type="l", col=1, lwd=2, lty=2, font.main=1,cex.main=1,ylab = '', axes=FALSE,
      xlab = '',ylim = range(Y[1, 2:20]),cex=0.8)
axis(side = 4, at = pretty(range(Y[1, 2:Tmax])))
mtext("Y", side = 4, line = 2)
legend(15, 2.3, legend=c("N", "Y"),
       lty=1:2, cex=0.8, bty = "n", y.intersp=0.5)
```

Figure 1: Population and real income, baseline



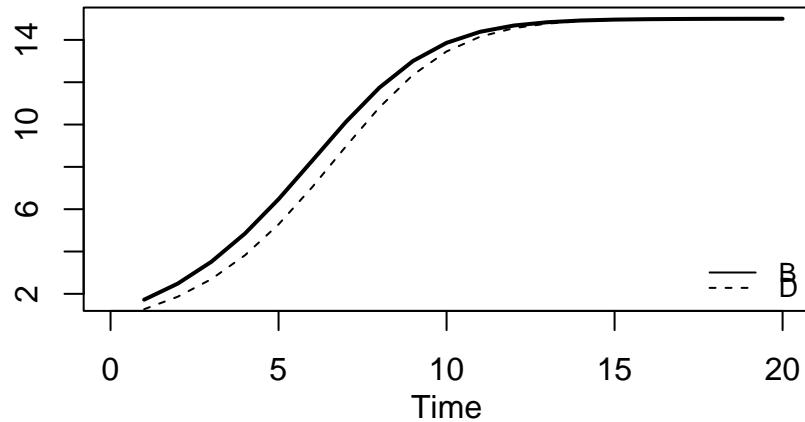
```
# Births and deaths
plot(B[1, 2:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab="")
```

```

title(main="Figure 2: Births and deaths, baseline", xlab = 'Time', cex=0.8, line=2)
lines(D[1, 2:Tmax], lty=2)
legend("bottomright", legend=c("B", "D"),
      lty=1:2, cex=0.8, bty = "n", y.intersp=0.5)

```

Figure 2: Births and deaths, baseline

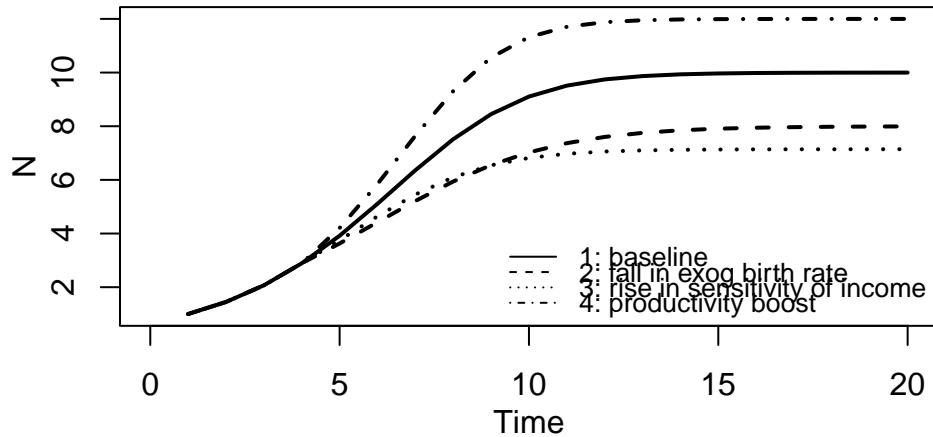


```

## Population dynamics under different scenarios
plot(N[1, 2:(Tmax+1)], type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylim=range(N[4, 2:Tmax]))
title(main="Figure 3: Population dynamics under different scenarios", ylab = 'N', xlab = 'Time')
lines(N[2, 2:(Tmax+1)], lty=2, lwd=2)
lines(N[3, 2:(Tmax+1)], lty=3, lwd=2)
lines(N[4, 2:(Tmax+1)], lty=4, lwd=2)
legend("bottomright", legend=c("1: baseline", "2: fall in exog birth rate", "3: rise in sensi",
      "4: productivity boost"), lty=1:4, cex=0.8, bty = "n", y.intersp=0.5)

```

Figure 3: Population dynamics under different scenarios



i Python code

```
### Plots (here for population and real income only)

import matplotlib.pyplot as plt

# Set maximum period for plots
Tmax = 20

## Baseline
# Population and real income
fig, ax1 = plt.subplots()
ax1.plot(N[0, 2:(Tmax+1)], linestyle='solid', label='N', linewidth=0.8, color="black")
ax1.set_xlabel('Time')
ax1.set_ylabel('N', rotation=0)
ax2 = ax1.twinx()
ax2.plot(Y[0, 2:Tmax], linestyle='dashed', label='Y', linewidth=0.8, color="black")
ax2.set_ylabel('Y', rotation=0)
lines, labels = ax1.get_legend_handles_labels() #collect legend in one box
lines2, labels2 = ax2.get_legend_handles_labels()
ax2.legend(lines + lines2, labels + labels2, loc=5)
plt.show()
```

12.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 6 variables: N, B, D, Y, b0, a0,
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged

M_mat=matrix(c(0,1,1,0,0,0,
              1,0,0,1,1,0,
              1,0,0,1,0,0,
              1,0,0,0,0,1,
              0,0,0,0,0,0,
              0,0,0,0,0,0), 6, 6, byrow=TRUE)

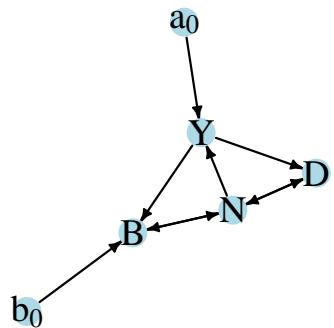
# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg=graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("N", "B", "D", "Y", expression(b[0]), expression(a[0]))

# Plot directed graph matrix
plot(dg, main="Figure 4: Directed graph of Malthusian model", vertex.size=20, vertex.color="black",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)
```

Figure 4: Directed graph of Malthusian model



 Python code

```
import networkx as nx

#Construct auxiliary Jacobian matrix for 6 variables: N, B, D, Y, b0, a0
M_mat = np.array([[0,1,1,0,0,0],
                  [1,0,0,1,1,0],
                  [1,0,0,1,0,0],
                  [1,0,0,0,0,1],
                  [0,0,0,0,0,0],
                  [0,0,0,0,0,0]])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "N", 1: "B", 2: "D", 3: "Y", 4: "$b_0$", 5: "$a_0$"}

# Plot the graph
pos = nx.spring_layout(G)
nx.draw_networkx(G, pos, node_size=500, node_color="lightblue",
                 edge_color="black", width=1.2, arrowsize=10,
                 arrowstyle='->', font_size=12, font_color="black",
                 with_labels=True, labels=nodelabs)
plt.axis("off")
plt.title("Figure 4: Directed graph of Malthusian model")
plt.show()
```

12.5 Analytical discussion

12.1 12.2 12.4

2

12.4

12.5

²A trivial steady state is at $N^* = 0$.

```

# Calculate analytical equilibrium solutions
for (i in 1:S){
  N_eq[i]=(b0[i,T]-d0+a0[i,T]*(b1+d1))/(a1[i,T]*(b1+d1))
  Y_eq[i]=(d0-b0[i,T])/(b1+d1)
  B_eq[i]=(b0[i,T] + b1*Y_eq[i])*N_eq[i]
  D_eq[i]=(d0 - d1*Y_eq[i])*N_eq[i]
}

# Compare with numerical solutions (here for the example of Y, scenario1)
Y_eq[1]

```

Y[1,T]

```

# Check stability condition for all scenarios
for (i in 1:S){
  print(paste0("Scenario ", i, ":"))
  print(abs(1-b0[i,T]+d0-a0[i,T]*(b1+d1)) < 1)
}

```

 Python code

```
# Calculate analytical equilibrium solutions
for i in range(S):
    N_eq[i] = (b0[i, T-1] - d0 + a0[i, T-1] * (b1 + d1)) / (a1[i, T-1] * (b1 + d1))
    Y_eq[i] = (d0 - b0[i, T-1]) / (b1 + d1)
    B_eq[i] = (b0[i, T-1] + b1 * Y_eq[i]) * N_eq[i]
    D_eq[i] = (d0 - d1 * Y_eq[i]) * N_eq[i]

# Compare with numerical solutions (here for the example of Y, scenario1)
print(Y_eq[0])
print(Y[0,T-1])

# Check stability condition for all scenarios
for i in range(S):
    print(f"Scenario {i + 1}:")
    print(abs(1 - b0[i, T-1] + d0 - a0[i, T-1] * (b1 + d1)) < 1)
```

12.6 References

13 A Ricardian One-Sector Model

13.1 Overview

On the Principles of Political Economy and Taxation

¹

²

13.2 The Model

¹See chapter 2 of Foley (2006) for an excellent introduction.

²See Chapter 14 for a two-sector extension of the model.

$$\begin{array}{ccccccc}
 & 13.1 & & 13.2 & & 13.3 & \\
 & & ^3 & & & & \\
 & & & 13.2 & & & \\
 & & & & 13.3 & & 13.5 \\
 & & & & & & \\
 & & ^4 & & & & \\
 & & 13.6 & & & & 13.7 \\
 & & & & 13.8 & &
 \end{array}$$

13.3 Simulation

13.3.1 Parameterisation

³Pasinetti (1960) specifies a generic function $f(N_t)$ with $f(0) \geq 0$, $f'(0) > w^*$, and $f''(N_t) < 0$. Equation 13.1 satisfies these conditions.

⁴Equation 13.5 is based on the definition of total rent as the sum of the net gains of the non-marginal landowners. See Pasinetti (1960) for a formal derivation.

13.3.2 Simulation code

```
# Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
Q=500

# Set number of scenarios (including baseline)
S=4

# Set period in which shock/shift will occur
s=20

# Create (S x Q)-matrices that will contain the simulated data
Y=matrix(data=1,nrow=S,ncol=Q) # Income/output
R=matrix(data=1,nrow=S,ncol=Q) # Rent
P=matrix(data=1,nrow=S,ncol=Q) # Profits
N=matrix(data=1,nrow=S,ncol=Q) # employment
w=matrix(data=1,nrow=S,ncol=Q) # real wage
K=matrix(data=1,nrow=S,ncol=Q) # capital stock
MPL=matrix(data=1,nrow=S,ncol=Q) # marginal product of labour
W=matrix(data=1,nrow=S,ncol=Q) # wage bill
N_eq=vector(length=S)          # equilibrium population
K_eq=vector(length=S)          # equilibrium capital

# Set baseline parameter values
A=matrix(data=2,nrow=S,ncol=Q) # productivity
a=matrix(data=0.7,nrow=S,ncol=Q) # labour elasticity of output
beta=1 # Sensitivity of investment with respect to profits
```

```

gamma=5 # adjustment speed of population
wS=matrix(data=0.5,nrow=S,ncol=Q) # subsistence wage rate

# Set parameter values for different scenarios
A[2,s:Q]=3 # scenario 2: productivity boost I
a[3,s:Q]=0.75 # scenario 3: productivity boost II
wS[4,s:Q]=0.6 # scenario 4: increase in subsistence wage

# Initialise variables such that employment and the capital stock are below the equilibrium
N[,1]=1
K[,1]=1
Y[,1]=A[,1]*N[,1]^(a[,1])
MPL[,1]=a[,1]*A[,1]*(N[,1]^(a[,1]-1))
w[,1]=wS[,1]

# Simulate the model by looping over Q time periods for S different scenarios
for (i in 1:S){

  for (t in 2:Q){

    for (iterations in 1:1000){ # run the model 1000-times in each period

      #Model equations

      #(1) Output
      Y[i,t] = A[i,t]*N[i,t]^(a[i,t])

      #(2) Wage bill
      W[i,t] = K[i,t]

      #(3) Real wage rate
      w[i,t] = W[i,t]/N[i,t]

      #(4) Marginal product of labour
      MPL[i,t] = a[i,t]*A[i,t]*(N[i,t]^(a[i,t]-1))

      #(5) Rents
      R[i,t] = Y[i,t] - N[i,t]*MPL[i,t]

      #(6) Profits
      P[i,t] = Y[i,t] - R[i,t] - N[i,t]*w[i,t]
    }
  }
}

```

```
# (7) Capital accumulation
K[i,t] = K[i,t-1] + beta*P[i,t-1]

#(8) Employment/population dynamics
N[i,t] = N[i,t-1] + gamma*(w[i,t-1] - wS[i,t-1])

} # close iterations loop
} # close time loop
} # close scenario loop
```

 Python code

```

import numpy as np

# Set number of periods
Q = 500

# Set number of scenarios (including baseline)
S = 4

# Set period in which shock/shift will occur
s = 20

# Create (S x Q)-matrices that will contain the simulated data
Y = np.ones((S, Q)) # Income/output
R = np.ones((S, Q)) # Rent
P = np.ones((S, Q)) # Profits
N = np.ones((S, Q)) # employment
w = np.ones((S, Q)) # real wage
K = np.ones((S, Q)) # capital stock
MPL = np.ones((S, Q)) # marginal product of labour
W = np.ones((S, Q)) # wage bill

# Set baseline parameter values
A = np.ones((S, Q)) * 2 # productivity
a = np.ones((S, Q)) * 0.7 # labour elasticity of output
beta = 1 # Sensitivity of investment with respect to profits
gamma = 5 # adjustment speed of population
wS = np.ones((S, Q)) * 0.5 # subsistence wage rate

# Set parameter values for different scenarios
A[1, s:Q] = 3 # scenario 2: productivity boost I
a[2, s:Q] = 0.75 # scenario 3: productivity boost II
wS[3, s:Q] = 0.6 # scenario 4: increase in subsistence wage

# Initialise variables such that employment and the capital stock are below the equilibrium
N[:, 0] = 1
K[:, 0] = 1
Y[:, 0] = A[:, 0] * N[:, 0]**(a[:, 0])
MPL[:, 0] = a[:, 0] * A[:, 0] * (N[:, 0]**(a[:, 0] - 1))
w[:, 0] = wS[:, 0]

# Simulate the model by looping over Q time periods for S different scenarios
for i in range(S):
    for t in range(1, Q):
        for iterations in range(1000): # run the model 1000 times in each period
            # Model equations
            # (1) Output
            Y[i, t] = A[i, t] * N[i, t]**(a[i, t])
            # (2) Wage bill
            W[i, t] = K[i, t]
            # (3) Real wage rate
            w[i, t] = W[i, t] / N[i, t]
            # (4) Marginal product of labour
            MPL[i, t] = a[i, t] * A[i, t] * (N[i, t]**(a[i, t] - 1))

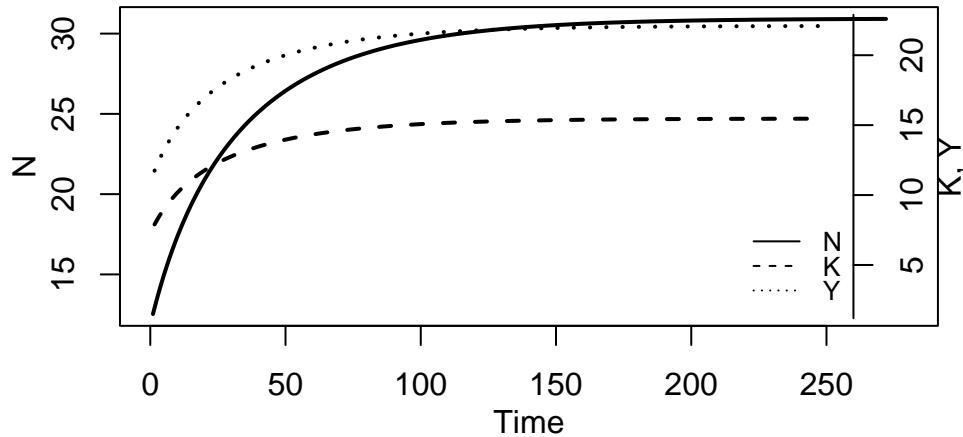
```

13.3.3 Plots

```
# Set start and end periods for plots
Tmax=280
Tmin =10

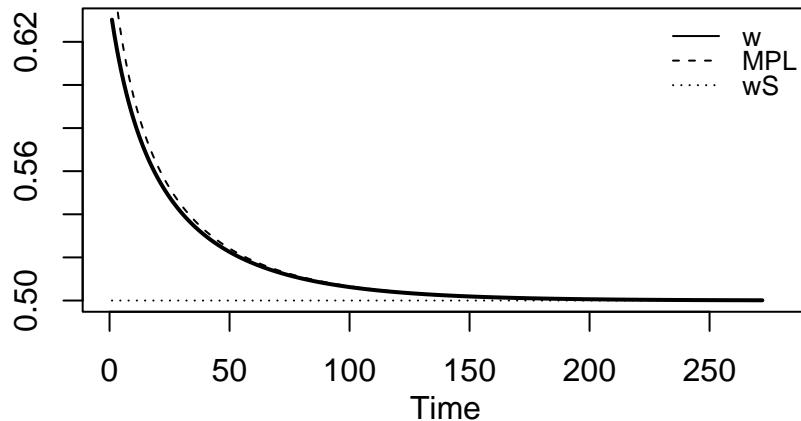
## Baseline
#Employment, capital accumulation, and income
plot(N[1, Tmin:(Tmax+1)],type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylab = '', xlab = '')
title(main="Figure 1: Employment, capital accumulation, and income",ylab = 'N', xlab = 'Time')
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(K[1, Tmin:Tmax],type="l", col=1, lwd=2, lty=2, font.main=1,cex.main=1,ylab = '', axes=F,
      xlab = '',ylim = range(Y[1, 2:(Tmax+1)]),cex.axis=1,cex.lab=0.75)
lines(Y[1, Tmin:(Tmax+1)],lty=3, lwd=2)
axis(side = 4, at = pretty(range(Y[1, 2:(Tmax+1)])))
mtext("K, Y", side = 4, line = 2)
legend("bottomright", legend=c("N", "K", "Y"),
       lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 1: Employment, capital accumulation, and income



```
# Real wage, subsistence wage, and MPL
plot(w[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab="")
title(main="Figure 2: Real wage, marginal product of labour, and subsistence wage", xlab = 'Time')
lines(MPL[1, Tmin:Tmax], lty=2)
lines(wS[1, Tmin:Tmax], lty=3)
legend("topright", legend=c("w", "MPL", "wS"),
       lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 2: Real wage, marginal product of labour, and subsistence



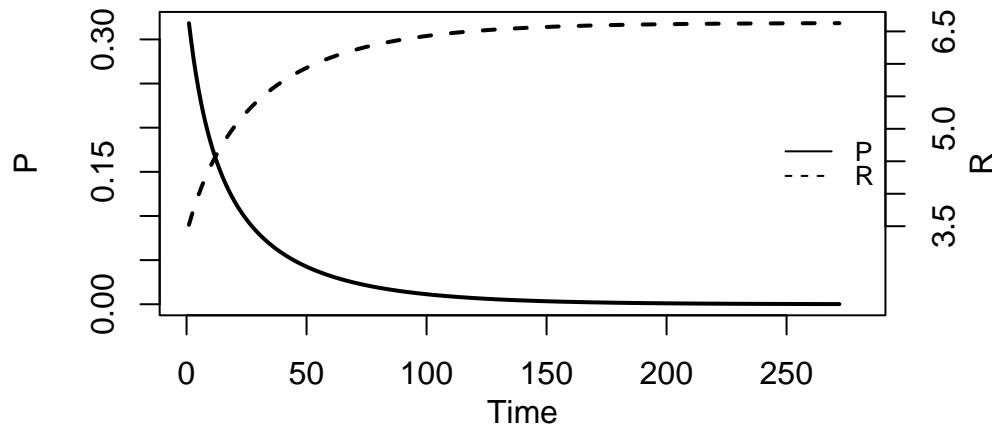
```
# Profits and Rents
plot(P[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab="")
title(main="Figure 3: Profits and rents", xlab = 'Time',cex=0.8,line=2)
```

```

par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(R[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=2, xlim=range(0:(Tmax)), xlab="", ylab=
    ylim=range(R[1, 3:Tmax]), axes=FALSE)
axis(side = 4, at = pretty(range(R[1, Tmin:(Tmax+1)])))
mtext("R", side = 4, line = 2)
legend("right", legend=c("P", "R"), lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)

```

Figure 3: Profits and rents

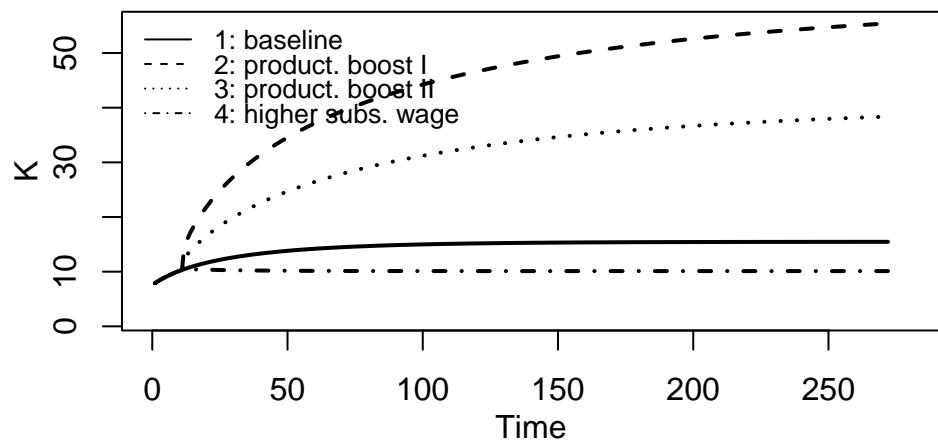


```

## Different scenarios
# Capital accumulation
plot(K[1, Tmin:(Tmax+1)], type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylim=range(K[1, 2:Tmax])
title(main="Figure 4: Capital accumulation under different scenarios", ylab = 'K', xlab = 'Time')
lines(K[2, Tmin:(Tmax+1)], lty=2, lwd=2)
lines(K[3, Tmin:(Tmax+1)], lty=3, lwd=2)
lines(K[4, Tmin:(Tmax+1)], lty=4, lwd=2)
legend("topleft", legend=c("1: baseline", "2: product. boost I", "3: product. boost II", "4: I"))

```

Figure 4: Capital accumulation under different scenarios



Python code

```
## Plots (here for employment, capital accumulation, and income only)

import matplotlib.pyplot as plt

# Set start and end periods for plots
Tmax = 280
Tmin = 10

# Baseline
# Employment, capital accumulation, and income
fig, ax1 = plt.subplots()
ax1.plot(N[0, 2:(Tmax+1)], linestyle='solid', label='N', linewidth=0.8, color="black")

ax1.set_xlabel('Time')
ax1.set_ylabel('N', rotation=0)
ax2 = ax1.twinx()
ax2.plot(K[0, 2:Tmax], linestyle='dashed', label='K', linewidth=0.8, color="black")
ax2.plot(Y[0, 2:Tmax], linestyle='dotted', label='Y', linewidth=0.8, color="black")
ax2.set_ylabel('Y, K', rotation=0)
lines, labels = ax1.get_legend_handles_labels() #collect legend in one box
lines2, labels2 = ax2.get_legend_handles_labels()
ax2.legend(lines + lines2, labels + labels2, loc=5)
plt.title("Figure 1: Employment, capital accumulation, and income")
plt.show()
```

13.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 10 variables: Y W w MPL R P K N A wS,
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged
M_mat=matrix(c(0,0,0,0,0,0,0,1,1,0,
              0,0,0,0,0,0,1,0,0,0,
              0,1,0,0,1,0,0,1,0,0,
```

```

0,0,0,0,0,0,0,1,1,0,
1,0,0,1,0,0,0,1,0,0,
1,0,1,0,1,0,0,1,0,0,
0,0,0,0,0,1,0,0,0,0,
0,0,1,0,0,0,0,0,0,1,
0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0),
A_mat=t(M_mat)

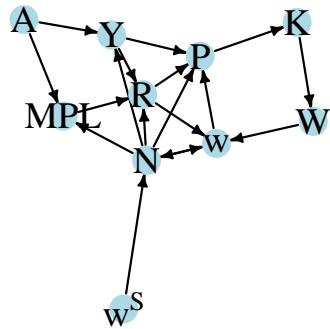
# Create and plot directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y", "W", "w", "MPL", "R", "P", "K", "N", "A", expression(w^S))

# Plot directed graph
plot(dg, main="Figure 5: Directed graph of Ricardian One-Sector Model", vertex.size=20, vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2, edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2, vertex.frame.color="NA", margin=-0.08)

```

Figure 5: Directed graph of Ricardian One-Sector Mode



 Python code

```
# Create directed graph

import networkx as nx

# Construct auxiliary Jacobian matrix for 10 variables: Y W w MPL R P K N A wS,
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged
M_mat = np.array([
    [0, 0, 0, 0, 0, 0, 0, 1, 1, 0],
    [0, 0, 0, 0, 0, 0, 1, 0, 0, 0],
    [0, 1, 0, 0, 1, 0, 0, 1, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 1, 1, 0],
    [1, 0, 0, 1, 0, 0, 0, 1, 0, 0],
    [1, 0, 1, 0, 1, 0, 0, 1, 0, 0],
    [0, 0, 0, 0, 0, 1, 0, 0, 0, 0],
    [0, 0, 1, 0, 0, 0, 0, 0, 0, 1],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0],
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
])

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: 'Y', 1: 'W', 2: 'w', 3: 'MPL', 4: 'R', 5: 'P', 6: 'K', 7: 'N', 8: 'A', 9: 'wS'}

# Plot the graph
pos = nx.spring_layout(G)
nx.draw_networkx(G, pos, node_size=500, node_color="lightblue",
                 edge_color="black", width=1.2, arrowsize=10,
                 arrowstyle='->', font_size=12, font_color="black",
                 with_labels=True, labels=nodelabs)

plt.axis("off")
plt.title("Figure 5: Directed graph of Ricardian One-Sector Model")
plt.show()
```

13.5 Analytical discussion

13.7 13.2 13.1 13.3 13.6 13.8

13.7 13.8

13.5 13.6

```

# Calculate equilibrium solutions
for (i in 1:S){
  N_eq[i]=(wS[i,Q]/(a[i,Q]*A[i,Q]))^(-1/(1-a[i,Q]))
  K_eq[i]=a[i,Q]*A[i,Q]*(wS[i,Q]/(a[i,Q]*A[i,Q]))^(-a[i,Q]/(1-a[i,Q]))
}

# Compare with numerical solutions (here only for baseline)
N_eq[1]

```

N[1,Q]

```
K_eq[1]
```

```
K[1,Q]
```

```
### Examine model properties (here for the baseline scenario only)
# Construct Jacobian matrix at the equilibrium
J=matrix(c(1-beta, beta*a[1,Q]*wS[1,Q],
           beta*(wS[1,Q]/(a[1,Q]*A[1,Q]))^(1/(1-a[1,Q])),
           1-gamma*a[1,Q]*A[1,Q]*(wS[1,Q]/(a[1,Q]*A[1,Q]))^((2-a[1,Q])/(1-a[1,Q])), 2, 2, by
```

```
# Obtain eigenvalues
ev=eigen(J)
(values = ev$values)
```

```
# Obtain determinant and trace
det=det(J)      # determinant
tr=sum(diag(J)) # trace

#Check general stability conditions
print(1+tr+det>0)
```

```
print(1-tr+det>0)
```

```
print(1-det>0)
```

```
# Check specific stability condition for the case beta=1
for (i in 1:S){
  print(paste0("Scenario ", i, ":"))
  print(2-gamma*a[i,Q]*(A[i,Q]*(wS[i,Q]/(a[i,Q]*A[i,Q]))^((2-a[i,Q])/(1-a[i,Q]))
    + wS[i,Q]*(wS[i,Q]/(a[i,Q]*A[i,Q]))^(1/(1-a[i,Q])))>0)
}
```

 Python code

```

# Initialize arrays for equilibrium solutions
N_eq = np.zeros(S)
K_eq = np.zeros(S)

# Calculate equilibrium solutions
for i in range(S):
    N_eq[i] = (wS[i, Q-1] / (a[i, Q-1] * A[i, Q-1])) ** (-1 / (1 - a[i, Q-1]))
    K_eq[i] = a[i, Q-1] * A[i, Q-1] * (wS[i, Q-1] / (a[i, Q-1] * A[i, Q-1])) ** (-a[i, Q-1])

# Compare with numerical solutions (here only for baseline)
N_eq[0]
N[0,Q-1]

# Construct Jacobian matrix at the equilibrium
J = np.array([
    [1 - beta, beta * a[0, Q-1] * wS[0, Q-1]],
    [beta * (wS[0, Q-1] / (a[0, Q-1] * A[0, Q-1])) ** (1 / (1 - a[0, Q-1])),
     1 - gamma * a[0, Q-1] * A[0, Q-1] * (wS[0, Q-1] / (a[0, Q-1] * A[0, Q-1])) ** ((2 - a[0, Q-1]) / (1 - a[0, Q-1]))]
])

# Obtain eigenvalues
eigenvalues, eigenvectors = np.linalg.eig(J)
print(eigenvalues)

# Obtain determinant and trace
det = np.linalg.det(J)
tr = np.trace(J)

# Check general stability conditions
print(1+tr+det>0)
print(1-tr+det>0)
print(1-det>0)

# Check specific stability condition for the case beta=1
for i in range(S):
    print(f"Scenario {i + 1}:")
    print(2 - gamma * a[i, Q-1] * (
        A[i, Q-1] * (wS[i, Q-1] / (a[i, Q-1] * A[i, Q-1])) ** ((2 - a[i, Q-1]) / (1 - a[i, Q-1])) -
        wS[i, Q-1] * (wS[i, Q-1] / (a[i, Q-1] * A[i, Q-1])) ** (1 / (1 - a[i, Q-1])))
    ) > 0)

```

13.6 References

14 A Ricardian Two-Sector Model

On the Principles of Political Economy and Taxation

1

2

14.1 The Model

¹See chapter 2 of Foley (2006) for an excellent introduction.

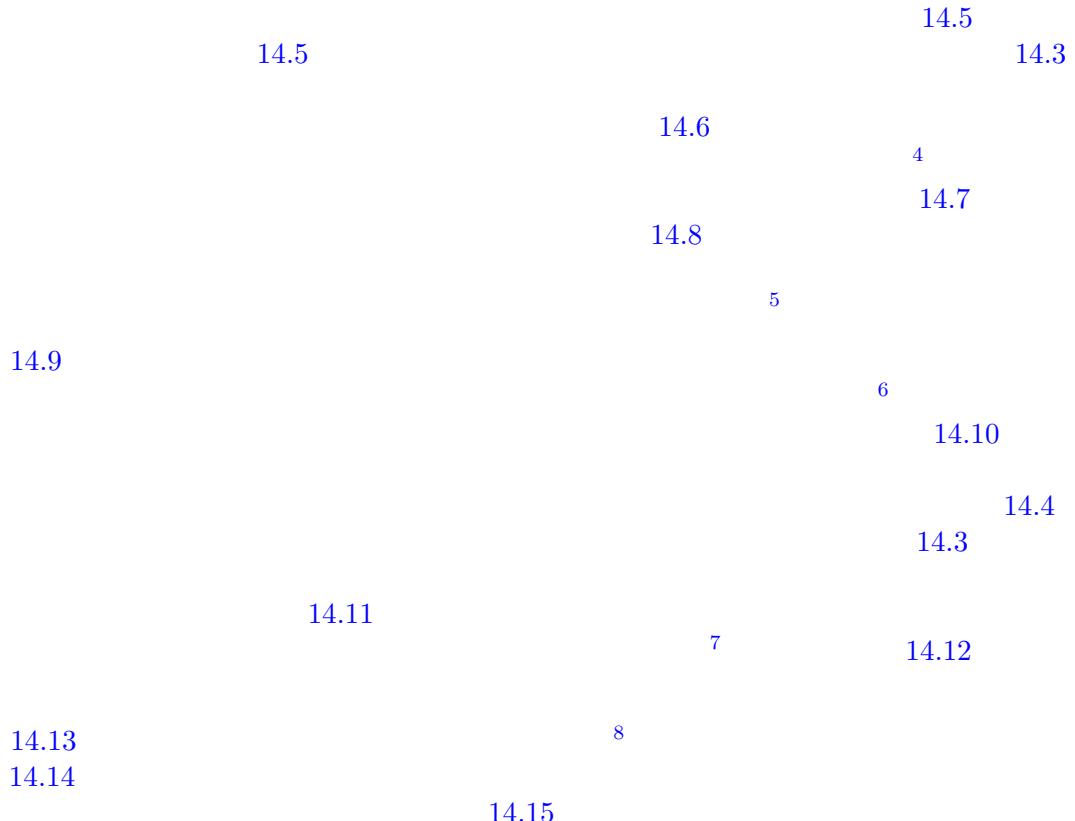
²See Chapter 13 for a simpler one-sector version of the model,

[14.1](#)

[3](#)

[14.4](#)

³Pasinetti (1960) specifies a generic function $f(N_t)$ with $f(0) \geq 0$, $f'(0) > w^*$, and $f''(N_t) < 0$. Equation [14.1](#) satisfies these conditions.



14.2 Simulation

14.2.1 Parameterisation

⁴Equation 14.6 is based on the definition of total rent as the sum of the net gains of the non-marginal landowners. See Pasinetti (1960) for a formal derivation. Note that by using Equation 14.2, Equation 14.6 can also be written as $R_t = Y_{1t}(1 - a_1)$.

⁵To see this, notice that equation Equation 14.8 can be derived from $p_{t1}Y_{t1} - p_{t1}R_t = N_{t1}$ if combined with equation Equation 14.6.

⁶Output in equation Equation 14.9 is expressed in real terms and can be derived from $p_2Y_{2t} = p_{1t}R_t$.

⁷The luxury good may therefore serve as Ricardo's 'invariable standard of value' in terms of which the value of all commodities could be expressed.

⁸Note that by combining Equation 14.13 with Equation 14.9, total profits can also be written as $P_t = p_{1t}(Y_{1t} - W_t)$. In other words, total profits are independent of output in sector 2.

14.2.2 Simulation code

```
# Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
Q=600

# Set number of scenarios (including baseline)
S=5

# Set period in which shock/shift will occur
s=15

# Create (S x Q)-matrices that will contain the simulated data
Y1=matrix(data=1,nrow=S,ncol=Q) # Output in sector 1
Y2=matrix(data=1,nrow=S,ncol=Q) # Output in sector 2
R=matrix(data=1,nrow=S,ncol=Q) # Rent
P=matrix(data=1,nrow=S,ncol=Q) # Qotal profits
P1=matrix(data=1,nrow=S,ncol=Q) # Profits in sector 1
P2=matrix(data=1,nrow=S,ncol=Q) # Profits in sector 2
N=matrix(data=1,nrow=S,ncol=Q) # total employment
N1=matrix(data=1,nrow=S,ncol=Q) # employment in sector 1
N2=matrix(data=1,nrow=S,ncol=Q) # employment in sector 2
w=matrix(data=1,nrow=S,ncol=Q) # real wage
wn=matrix(data=1,nrow=S,ncol=Q) # nominal wage
```

```

K=matrix(data=1,nrow=S,ncol=Q) # capital stock
MPL=matrix(data=1,nrow=S,ncol=Q) # marginal product of labour (in sector 1)
r=matrix(data=1,nrow=S,ncol=Q) # profit rate
p1=matrix(data=1,nrow=S,ncol=Q) # price of good from sector 1
p2=matrix(data=1,nrow=S,ncol=Q) # price of good from sector 2
N_eq=vector(length=S)           # equilibrium population
K_eq=vector(length=S)           # equilibrium capital

test=matrix(data=1,nrow=S,ncol=Q) # price of good from sector 2

# Set baseline parameter values
A=matrix(data=2,nrow=S,ncol=Q) # productivity
a1=matrix(data=0.7,nrow=S,ncol=Q) # labour elasticity of output, sector 1
a2=matrix(data=0.5,nrow=S,ncol=Q) # labour coefficient, sector 2
gamma=5 # adjustment speed of population
beta=1 # Sensitivity of investment with respect to profits
wS=matrix(data=0.5,nrow=S,ncol=Q) # natural wage rate

# Set parameter values for different scenarios
A[2,s:Q]=3      # scenario 2: productivity boost I
a1[3,s:Q]=0.75 # scenario 3: productivity boost II
a2[4,s:Q]=0.55 # scenario 4: productivity boost III
wS[5,s:Q]=0.6  # scenario 5: higher subsistence wage

# Initialise variables such that employment and the capital stock are below the equilibrium
N1[,1]=1
N2[,1]=1
N[,1]=N1[,1]+N2[,1]
K[,1]=1
w[,1]=wS[,1]
Y1[,1]=A[,1]*N1[,1]^(a1[,1])
MPL[,1]=a1[,1]*A[,1]*(N1[,1]^(a1[,1]-1))

# Simulate the model by looping over Q time periods for S different scenarios
for (i in 1:S){

  for (t in 2:Q){

    for (iterations in 1:1000){ # run the model 1000-times in each period

      #Model equations

```

```

#(2) Wage bill (omitted for simplicity)
#W[i,t]=K[i,t]

#(3) Output sector 1
Y1[i,t] = A[i,t]*(N1[i,t]^a1[i,t])

#(4) Employment sector 1
N1[i,t] = N[i,t] - N2[i,t]

#(5) Marginal product of labour (sector 1)
MPL[i,t]=a1[i,t]*A[i,t]*(N1[i,t]^(a1[i,t]-1))

#(6) Rent (simplified equation)
R[i,t]= Y1[i,t]*(1-a1[i,t])

#(7) Profits sector 1
P1[i,t] = Y1[i,t] - R[i,t] - N1[i,t]*w[i,t]

#(8) Prices sector 1
p1[i,t] = 1/(MPL[i,t])

#(9) Output sector 2
Y2[i,t]=(p1[i,t]/p2[i,t])*R[i,t]

#(3) Real wage rate
w[i,t] = K[i,t]/N[i,t]

#(10) Employment sector 2
N2[i,t]= Y2[i,t]/a2[i,t]

#(11) Prices
p2[i,t] = 1/a2[i,t]

#(12) Profits sector 2
P2[i,t] = Y2[i,t] - (p1[i,t]/p2[i,t])*N2[i,t]*w[i,t]

#(13) Total profits
P[i,t]=p1[i,t]*Y1[i,t] + p2[i,t]*Y2[i,t] - p1[i,t]*R[i,t] - p1[i,t]*K[i,t]

#(14) Capital accumulation
K[i,t]= K[i,t-1] + beta*(P[i,t-1]/p1[i,t-1])

```

```
#(8) Employment/population dynamics  
N[i,t] = N[i,t-1] + gamma*(w[i,t-1] - wS[i,t-1])  
  
} # close iterations loop  
} # close time loop  
} # close scenarios loop
```

 Python code

```

import numpy as np

# Set number of periods
Q = 600

# Set number of scenarios (including baseline)
S = 5

# Set period in which shock/shift will occur
s = 15

# Create (S x Q)-matrices that will contain the simulated data
Y1 = np.ones((S, Q))
Y2 = np.ones((S, Q))
R = np.ones((S, Q))
P = np.ones((S, Q))
P1 = np.ones((S, Q))
P2 = np.ones((S, Q))
N = np.ones((S, Q))
N1 = np.ones((S, Q))
N2 = np.ones((S, Q))
w = np.ones((S, Q))
wn = np.ones((S, Q))
K = np.ones((S, Q))
MPL = np.ones((S, Q))
r = np.ones((S, Q))
p1 = np.ones((S, Q))
p2 = np.ones((S, Q))
N_eq = np.zeros(S)
K_eq = np.zeros(S)
test = np.ones((S, Q))

# Set baseline parameter values
gamma = 5
beta = 1
A = np.full((S, Q), 2.0)
a1 = np.full((S, Q), 0.7)
a2 = np.full((S, Q), 0.5)
wS = np.full((S, Q), 0.5)

# Set parameter values for different scenarios
A[1, s:] = 3      # scenario 2: productivity boost I
a1[2, s:] = 0.75 # scenario 3: productivity boost II
a2[3, s:] = 0.55 # scenario 4: productivity boost III
wS[4, s:] = 0.6  # scenario 5: higher subsistence wage

```

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```

# Initialize variables
N1[:, 0] = 1
N2[:, 0] = 1
N[:, 0] = N1[:, 0] + N2[:, 0]
K[:, 0] = 1
w[:, 0] = wS[:, 0]
v1[:, 0] = A[:, 0] * N1[:, 0] ** (a1[:, 0])

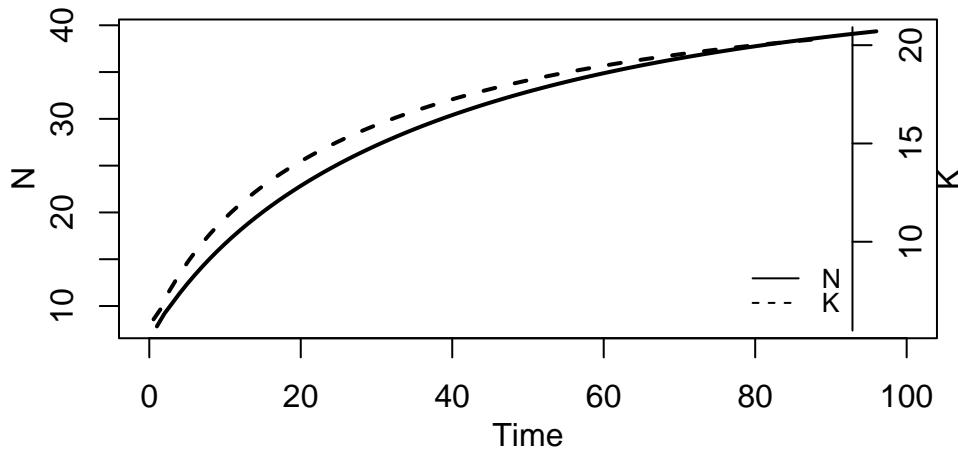
```

14.2.3 Plots

```
# Set start and end periods for plots
Tmax=100
Tmin=6

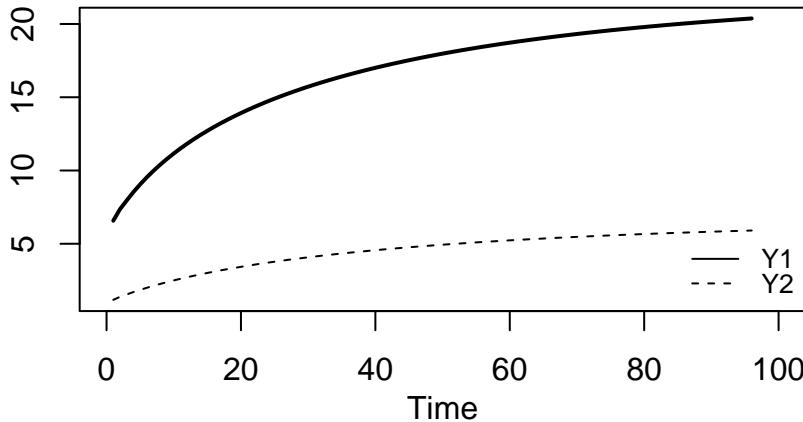
## Baseline
#Employment and capital accumulation
plot(N[1, Tmin:(Tmax+1)], type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylab = '', xlab = '')
title(main="Figure 1: Employment and capital accumulation", ylab = 'N', xlab = 'Time', cex=0.8)
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(K[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=2, font.main=1, cex.main=1, ylab = '', axis=2,
     xlab = '', ylim = range(K[1, Tmin:(Tmax+1)]), cex=0.8)
axis(side = 4, at = pretty(range(K[1, 2:(Tmax+1)])))
mtext("K", side = 4, line = 2)
legend("bottomright", legend=c("N", "K"),
       lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 1: Employment and capital accumulation



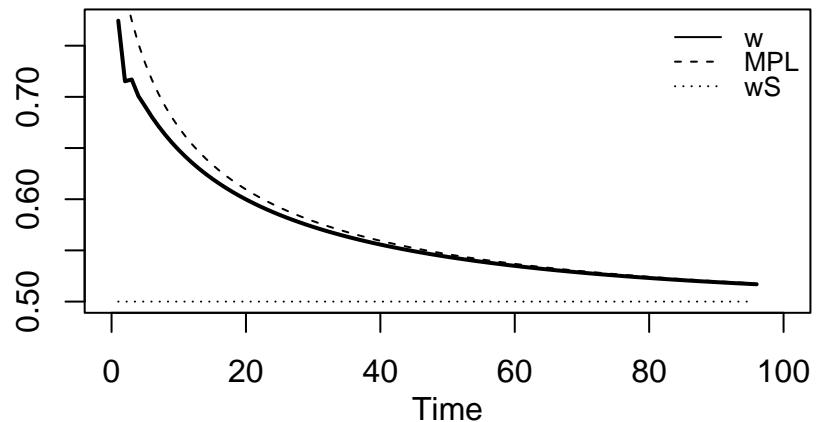
```
#Output in the two sectors
plot(Y1[1, Tmin:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab=
title(main="Figure 2: Output in agriculture and luxuries", xlab = 'Time',cex=0.8 ,line=2)
lines(Y2[1, Tmin:(Tmax+1)],lty=2)
legend("bottomright", legend=c("Y1", "Y2"),
lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 2: Output in agriculture and luxuries



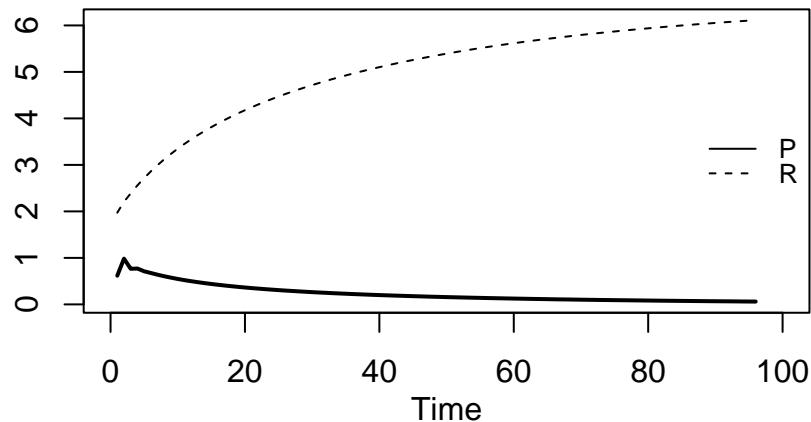
```
# Real wage, MPL, and subsistence wage
plot(w[1, Tmin:(Tmax+1)],type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab=
title(main="Figure 3: Real wage, marginal product of labour, and subsistence wage", xlab = 'T
lines(MPL[1, Tmin:Tmax],lty=2)
lines(wS[1, Tmin:Tmax],lty=3)
legend("topright", legend=c("w", "MPL", "wS"),
lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

3: Real wage, marginal product of labour, and subsistence



```
# Total Profits and Rents
plot(P[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=1, xlim=range(0:(Tmax)), xlab="", ylab=
title(main="Figure 4: Total profits and rents", xlab = 'Time', cex=0.8, line=2)
lines(R[1, Tmin:(Tmax+1)], lty=2)
legend("right", legend=c("P", "R"),
      lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Figure 4: Total profits and rents

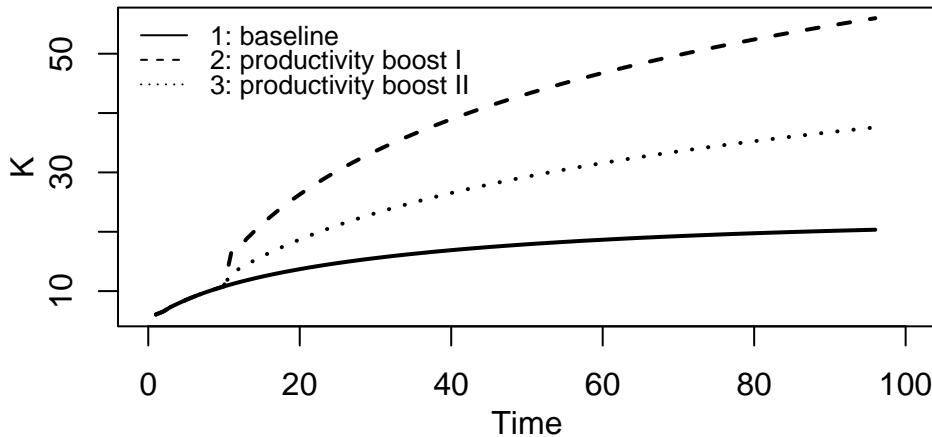


```

## Scenarios
# Capital accumulation under scenarios 1-3
plot(K[1, Tmin:(Tmax+1)], type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylim=range(K[1, Tmin:(Tmax+1)]))
title(main="Figure 5: Capital accumulation under different scenarios (pt 1)", ylab = 'K', xlab = 'Time')
lines(K[2, Tmin:(Tmax+1)], lty=2, lwd=2)
lines(K[3, Tmin:(Tmax+1)], lty=3, lwd=2)
legend("topleft", legend=c("1: baseline", "2: productivity boost I", "3: productivity boost II"))

```

Figure 5: Capital accumulation under different scenarios (pt 1)



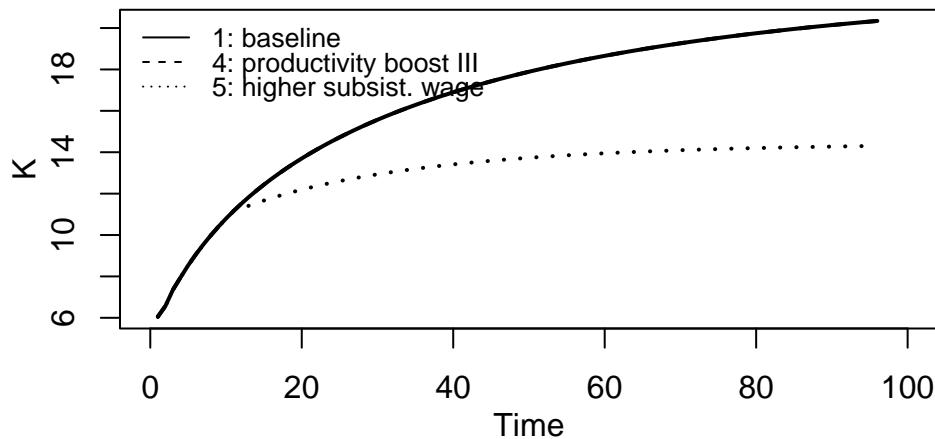
```

# Capital accumulation under scenarios 1, 4+5
plot(K[1, Tmin:(Tmax+1)], type="l", lwd=2, lty=1, xlim=range(0:(Tmax)), ylim=range(K[1, Tmin:(Tmax+1)]))
title(main="Figure 6: Capital accumulation under different scenarios (pt 2)", ylab = 'K', xlab = 'Time')
lines(K[4, Tmin:(Tmax+1)], lty=2, lwd=2)
lines(K[5, Tmin:(Tmax+1)], lty=3, lwd=2)
legend("topleft", legend=c("1: baseline", "4: productivity boost III", "5: higher subsist. wage"))

```

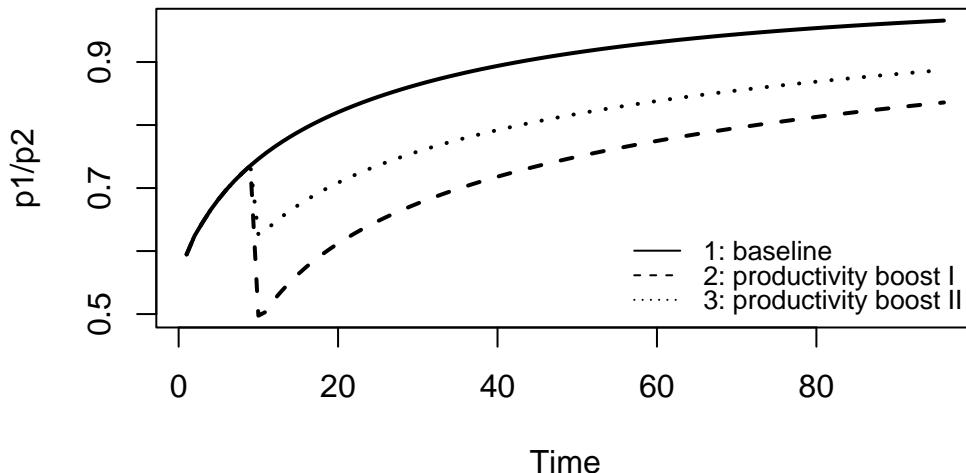
⁹The increase in a_2 does raise real output and profits in sector 2 but it leaves total profits unchanged.

Figure 6: Capital accumulation under different scenarios (p



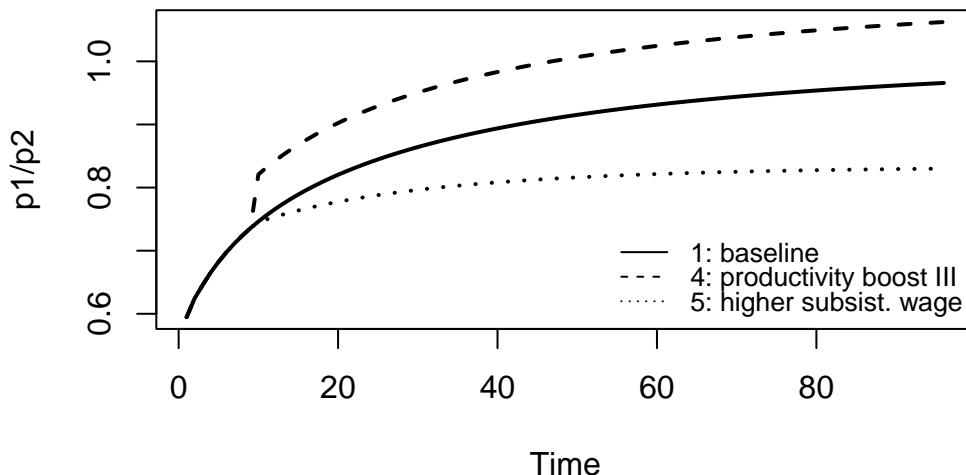
```
# Relative prices under scenarios 1 - 3
relpr=p1/p2
plot(relpr[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=1, font.main=1, cex.main=1,
     main="Figure 7: Relative prices under different scenarios (pt 1)", ylab = 'p1/p2', xlab =
lines(relpr[2, Tmin:(Tmax+1)], lty=2, lwd=2)
lines(relpr[3, Tmin:(Tmax+1)], lty=3, lwd=2)
legend("bottomright", legend=c("1: baseline", "2: productivity boost I", "3: productivity bo
```

Figure 7: Relative prices under different scenarios (pt 1)



```
# Relative prices under scenarios 1, 4-5
plot(relpr[1, Tmin:(Tmax+1)], type="l", col=1, lwd=2, lty=1, font.main=1, cex.main=1,
      main="Figure 8: Relative prices under different scenarios (pt 2)", ylab = 'p1/p2', xlab =
lines(relpr[4, Tmin:(Tmax+1)], lty=2, lwd=2)
lines(relpr[5, Tmin:(Tmax+1)], lty=3, lwd=2)
legend("bottomright", legend=c("1: baseline", "4: productivity boost III", "5: higher subsist.
```

Figure 8: Relative prices under different scenarios (pt 2)



 Python code

```
# Plots (here for employment and capital accumulation only)

import matplotlib.pyplot as plt

# Set start and end periods for plots
Tmax = 100
Tmin = 6

# Baseline
# Employment and capital accumulation
fig, ax1 = plt.subplots()
ax1.plot(N[0, 2:(Tmax+1)], linestyle='solid', label='N', linewidth=0.8, color="black")

ax1.set_xlabel('Time')
ax1.set_ylabel('N', rotation=0)
ax2 = ax1.twinx()
ax2.plot(K[0, 2:Tmax], linestyle='dashed', label='K', linewidth=0.8, color="black")
ax2.set_ylabel('K', rotation=0)
lines, labels = ax1.get_legend_handles_labels() #collect legend in one box
lines2, labels2 = ax2.get_legend_handles_labels()
ax2.legend(lines + lines2, labels + labels2, loc=5)
plt.title("Figure 1: Employment and capital accumulation")
plt.show()
```

14.3 Directed graph

10

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 18 variables:
#(1)Y1 (2)N1 (3)MPL (4)R (5)P1 (6)p1 (7)Y2 (8)w (9)N2 (10)p2 (11)P2
#(12)P (13)K (14)N (15)A (16)a1 (17)a2 (18)wS,
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged
```

¹⁰Valuation effects from changes in relative prices were omitted for simplicity.

```

#          1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
M_mat=matrix(c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0, #1
              0,0,0,0,0,0,0,0,0,1,0,0,0,0,1,0,0,0,0,0, #2
              0,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0, #3
              1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #4
              1,1,0,1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0, #5
              0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #6
              0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #7
              0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0, #8
              0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,1,0,0, #9
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0, #10
              0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,0,0, #11
              0,0,0,0,1,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0, #12
              0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0, #13
              0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,1,0, #14
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #15
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #16
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #17
              0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, #18
              ), 18,18, byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

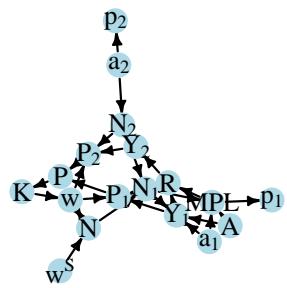
# Create and plot directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c(expression(Y[1]), expression(N[1]), "MPL", "R", expression(P[1]),
              expression(p[1]), expression(Y[2]), "w", expression(N[2]),
              expression(p[2]), expression(P[2]), "P", "K", "N", "A",
              expression(a[1]), expression(a[2]), expression(w^S))

# Plot directed graph
# Plot directed graph
plot(dg, main="Figure 9: Directed graph", vertex.size=20, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=0.8,
      vertex.frame.color="NA", margin=0.08)

```

Figure 9: Directed graph



 Python code

```

# Create directed graph

import networkx as nx

# Construct auxiliary Jacobian matrix for 18 variables:
#(1)Y1 (2)N1 (3)MPL (4)R (5)P1 (6)p1 (7)Y2 (8)w (9)N2 (10)p2 (11)P2
#(12)P (13)K (14)N (15)A (16)a1 (17)a2 (18)wS,
# where non-zero elements in regular Jacobian are set to 1 and zero elements are unchanged

#          1  2   3   4   5   6   7   8   9   10  11  12  13  14  15  16  17  18
M_mat = np.array([
    [0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0], #1
    [0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0], #2
    [0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0], #3
    [1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #4
    [1, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #5
    [0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #6
    [0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #7
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0], #8
    [0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1], #9
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1], #10
    [0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0], #11
    [0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0], #12
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0], #13
    [0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1], #14
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #15
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #16
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0], #17
    [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]]])#18

# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat = M_mat.transpose()

# Create the graph from the adjacency matrix
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {
    0: r'$Y_1$', 1: r'$N_1$', 2: 'MPL', 3: 'R', 4: r'$P_1$',
    5: r'$p_1$', 6: r'$Y_2$', 7: 'w', 8: r'$N_2$', 9: r'$p_2$',
    10: r'$P_2$', 11: 'P', 12: 'K', 13: 'N', 14: 'A',
    15: r'$a_1$', 16: r'$a_2$', 17: r'$w^S$'
}

# Plot the graph
pos = nx.spring_layout(G, k=0.9)
nx.draw_networkx(G, pos, node_size=200, node_color="lightblue",
                 edge_color="black", width=1.2, arrowsize=10,
                 arrowstyle='->', font_size=8, font_color="black",
                 with_labels=True, labels=nodelabs)

plt.axis("off")
plt.title("Figure: Directed graph of Ricardian Two-Sector Model")
plt.show()

```

14.4 Analytical discussion

14.14

14.4

14.1

14.5

14.13

14.15

14.14

14.15

14.6

14.13

```

# Calculate equilibrium solutions
for (i in 1:S){
  N_eq[i]=(wS[i,Q]/((a1[i,Q]^a1[i,Q])*A[i,Q]))^(-1/(1-a1[i,Q]))
  K_eq[i]=(a1[i,Q]^a1[i,Q])*A[i,Q]*(wS[i,Q]/((a1[i,Q]^a1[i,Q])*A[i,Q]))^(-a1[i,Q]/(1-a1[i,Q]))
}

# Compare with numerical solutions (here for the example of Y, baseline)
N_eq[1]

```

```
N[1,Q]
```

```
K_eq[1]
```

```
K[1,Q]
```

```
### Examine model properties (here for the baseline scenario only)
# Construct Jacobian matrix at the equilibrium
J=matrix(c(1-beta,
           beta*a1[1,Q]*wS[1,Q],
           gamma*(wS[1,Q]/((a1[i,Q]^a1[i,Q])*A[1,Q]))^(1/(1-a1[1,Q])),
           1-gamma*(a1[i,Q]^a1[i,Q])*A[1,Q]*(wS[1,Q]/((a1[i,Q]^a1[i,Q])*A[1,Q]))^((2-a1[1,Q]/
           # Obtain eigenvalues
ev=eigen(J)
(values = ev$values)

# Obtain determinant and trace
det=det(J)      # determinant
tr=sum(diag(J)) # trace

#Check stability conditions
print(1+tr+det>0)

print(1-tr-det>0)
```

```
print(1-det>0)
```

```
# Check specific stability condition for the case beta=1
for (i in 1:S){
  print(paste0("Scenario ", i, ":"))
  print(2-gamma*((a1[i,Q]^a1[i,Q])*A[i,Q]*(wS[i,Q]/(((a1[i,Q]^a1[i,Q])*A[i,Q])))^((2-a1[i,Q])/
```

 Python code

```

# Initialize arrays for equilibrium solutions
N_eq = np.zeros(S)
K_eq = np.zeros(S)

# Calculate equilibrium solutions
for i in range(S):
    N_eq[i] = (wS[i, Q-1] / ((a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1])) ** (-1 / (1 - a1[i, Q-1]))
    K_eq[i] = (a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1] * (wS[i, Q-1] / ((a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1])) ** (1 / (1 - a1[i, Q-1]))

# Compare with numerical solutions (example for N, baseline)
N_eq[0]
N[0,Q-1]

# Construct Jacobian matrix at the equilibrium
J = np.array([
    [1 - beta, beta * a1[0, Q-1] * wS[0, Q-1]],
    [gamma * (wS[0, Q-1] / ((a1[0, Q-1] ** a1[0, Q-1]) * A[0, Q-1])) ** (1 / (1 - a1[0, Q-1])),
     1 - gamma * (a1[0, Q-1] ** a1[0, Q-1]) * A[0, Q-1] * (wS[0, Q-1] / ((a1[0, Q-1] ** a1[0, Q-1]) * A[0, Q-1])) ** (1 / (1 - a1[0, Q-1]))]
])

# Obtain eigenvalues
eigenvalues, eigenvectors = np.linalg.eig(J)
print(eigenvalues)

# Obtain determinant and trace
det = np.linalg.det(J)
tr = np.trace(J)

# Check general stability conditions
print(1+tr+det>0)
print(1-tr+det>0)
print(1-det>0)

# Check specific stability condition for the case beta=1
for i in range(S):
    print(f"Scenario {i + 1}:")
    print(2 - gamma * (
        (a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1] *
        (wS[i, Q-1] / ((a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1])) ** ((2 - a1[i, Q-1]) / (1 - a1[i, Q-1]) * wS[i, Q-1] * (wS[i, Q-1] / ((a1[i, Q-1] ** a1[i, Q-1]) * A[i, Q-1]))) **
        ) > 0)

```

14.5 References

15 A Lewis Model of Economic Development

15.1 Overview

15.2 The Model

15.1

15.2

15.3

15.4

15.5

15.6

15.7

15.7

15.8

15.9

15.3 Simulation

15.3.1 Parameterisation

15.3.2 Simulation code

```
# Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
Q=250

# Set number of scenarios (including baseline)
S=3

# Set period in which shock/shift will occur
s=1

# Create (S x Q)-matrices that will contain the simulated data
Y1=matrix(data=1,nrow=S,ncol=Q) # Output in sector 1 (traditional)
Y2=matrix(data=1,nrow=S,ncol=Q) # Output in sector 2 (modern)
L1=matrix(data=1,nrow=S,ncol=Q) # employment in sector 1
L2=matrix(data=1,nrow=S,ncol=Q) # employment in sector 2
w2=matrix(data=1,nrow=S,ncol=Q) # real wage sector 2
MPL2 = matrix(data=1, nrow=S, ncol=Q) # marginal product of labour in sector 2
K=matrix(data=1,nrow=S,ncol=Q) # capital stock (only in sector 2)
P2=matrix(data=1,nrow=S,ncol=Q) # profits in sector 2

# Set fixed parameter values
```

```

alpha=0.9 # labour elasticity of output, sector 1
rho=1      # wage premium
L=20       # total labour supply (exogenous)
lambda=10 # employment at which MPL in sector 1 becomes zero
beta=0.7  # labour elasticity of output, sector 2
delta = 0.5 # sensitivity of employment in sector 2 to deviation of MPL2 from w2

# Set baseline parameter values
w1=matrix(data=0.4,nrow=S,ncol=Q) # subsistence real wage sector 1
gamma=matrix(data=0.12, nrow=S, ncol=Q) # labour supply coefficient, sector 2

# Set parameter values for different scenarios
w1[2,s:Q]=0.3          # scenario 2: fall in subsistence wage
gamma[3,s:Q]=0.17        # scenario 3: rise in labour supply elasticity

# Create vectors that will record when the turning point occurs and when the simulation ends
tp = rep(NA, S)
end = rep(NA, S)

# Initialise such that there is surplus labour (L1 > lambda)
L1[,1]= 0.9*L
L2[,1]= L - L1[,1]

# Simulate the model by looping over T time periods for S different scenarios
for (i in 1:S){

  # Create flag that will be set to TRUE when the turning point has been reached
  cond = FALSE

  # Inititalise time index
  t = 2

  # Run the model as long as the number of periods Q hasn't been reached yet and employment :
  while (t <= Q && L1[i, t-1] > 0) {

    for (iterations in 1:1000){

      ## Model equations
      # Output sector1 and wages sector 2
      if (!cond && L1[i, t-1] > lambda) {
        Y1[i,t] = lambda^alpha
        w2[i,t]= w1[i,t]*(1 + rho)
      }
    }
  }
}

```

```

    }

else{
Y1[i,t] = (L1[i,t]^alpha)
w2[i,t]= gamma[i,t]*L2[i,t]
cond = TRUE # set the flag to TRUE once the condition is violated
            #(this prevents the iterations loop from getting trapped between the two cond)
}

# Employment sector 1
L1[i,t] = L - L2[i,t]

# Output sector 2
Y2[i,t]=(L2[i,t]^beta)*(K[i,t]^(1-beta))

# MPL sector 2
MPL2[i,t] = beta* (Y2[i, t]/L2[i, t])

# Employment sector 2
L2[i,t] =L2[i, t-1] + delta*(MPL2[i,t-1] - w2[i,t-1])

# Profits sector 2
P2[i,t]=Y2[i,t] - w2[i,t]*L2[i,t]

# Capital accumulation sector 2
K[i,t]= K[i,t-1] + P2[i,t-1]

} # close iterations loop

if (L1[i, t] > lambda) {
  tp[i] = t # record when turning point occurs
}

if (L1[i, t] <= 0) {
  end[i] = t # record when L1 becomes non-positive, which terminates the simulation
}

# Update time index
t = t + 1

} # close time loop
} # close scenarios loop

```

```
# Calculate profits in S1
P1=Y1 - w1*L1

#Calculate aggregate profit share
PS=(P1 + P2)/(Y1 + Y2)

# Calculate sectoral profit shares
PS1=(P1)/(Y1)
PS2=(P2)/(Y2)
```

 Python code

```

import numpy as np

# Set number of periods
Q = 250

# Set number of scenarios (including baseline)
S = 3

# Set period in which shock/shift will occur
s = 1

# Create (S x Q)-matrices that will contain the simulated data
Y1 = np.ones((S, Q)) # Output in sector 1 (traditional)
Y2 = np.ones((S, Q)) # Output in sector 2 (modern)
L1 = np.ones((S, Q)) # Employment in sector 1
L2 = np.ones((S, Q)) # Employment in sector 2
w2 = np.ones((S, Q)) # Real wage sector 2
MPL2 = np.ones((S, Q)) # Marginal product of labour in sector 2
K = np.ones((S, Q)) # Capital stock (only in sector 2)
P2 = np.ones((S, Q)) # Profits in sector 2

# Set fixed parameter values
alpha = 0.9 # Labour elasticity of output, sector 1
rho = 1 # Wage premium
L = 20 # Total labour supply (exogenous)
lambda_ = 10 # Employment at which MPL in sector 1 becomes zero
beta = 0.7 # Labour elasticity of output, sector 2
delta = 0.5 # Sensitivity of employment in sector 2 to deviation of MPL2 from w2

# Set baseline parameter values      277
w1 = np.full((S, Q), 0.4) # Subsistence real wage sector 1
gamma = np.full((S, Q), 0.12) # Labour supply coefficient, sector 2

# Set parameter values for different scenarios
w1[1, s:Q] = 0.3 # Scenario 2: fall in subsistence wage
gamma[2, s:Q] = 0.17 # Scenario 3: rise in labour supply elasticity

```

15.3.3 Plots

15.1 15.3

```
# Set start and end periods for plots
Tmax=end[1]-2
Tmin=2

#Output in the two sectors, baseline
plot(Y1[1, Tmin:Tmax],type="l", col=1, lwd=2, lty=1, xlab="", ylab="Y", ylim=range(Y1[1, Tmin:Tmax]), title(main="Output in traditional (Y1) and modern (Y2) sector", xlab = 'Time', cex=0.8 ,line=2)
lines(Y2[1, Tmin:Tmax],lty=2)
abline(v = tp[1], col = "darkred")
legend("topleft", legend=c("Y1", "Y2"),
       lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Output in traditional (Y1) and modern (Y2) sector

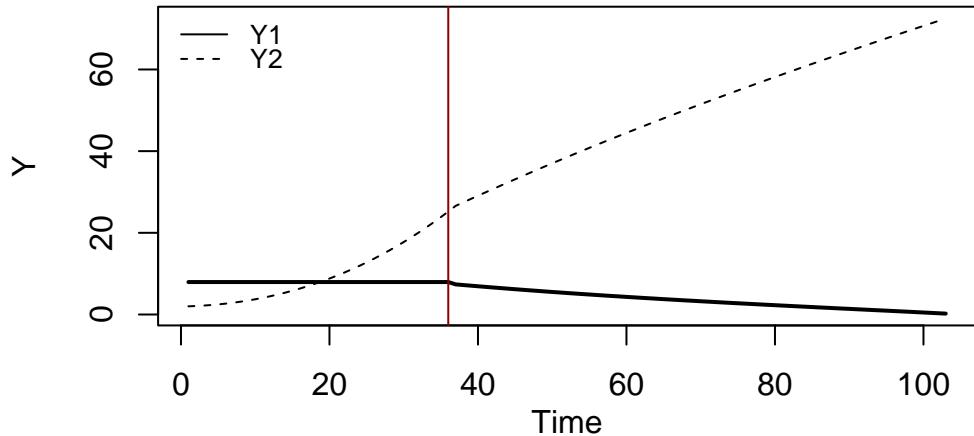


Figure 15.1: Output in traditional (Y1) and modern (Y2) sector

```
#Employment in the two sectors, baseline
plot(L1[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=1, xlab="", ylab="L", ylim=range(L1[1, Tmin:Tmax]))
title(main="Employment in traditional (L1) and modern (L2) sector", xlab = 'Time', cex=0.8, lineheight=1.2)
lines(L2[1, Tmin:Tmax], lty=2)
abline(v = tp[1], col = "darkred")
legend("right", legend=c("L1", "L2"),
       lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Employment in traditional (L1) and modern (L2) sector

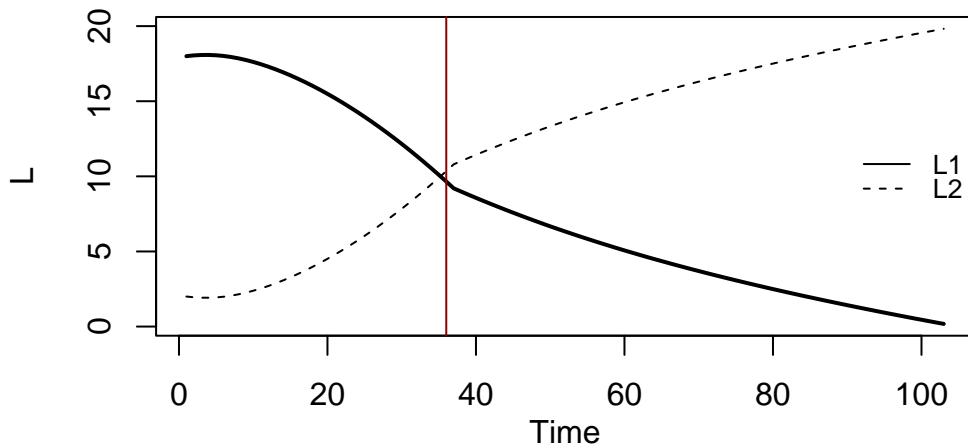


Figure 15.2: Employment in traditional (L1) and modern (L2) sector

```
#Profits and capital accumulation in manufacturing, baseline
plot(P2[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=1, xlab="", ylab="P", ylim=range(P2[1, Tmin:Tmax]))
title(main="Capital accumulation and profits in modern sector", ylab = 'P', xlab = 'Time', cex=0.8, lineheight=1.2)
abline(v = tp[1], col = "darkred")
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(K[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=2, font.main=1, cex.main=1, ylab = 'K', axes=F)
xlab = 'K', ylab = range(K[1, Tmin:Tmax]), cex.axis=1, cex.lab=0.75)
axis(side = 4, at = pretty(range(K[1, Tmin:Tmax])))
mtext("K", side = 4, line = 2)
legend("bottomright", legend=c("P", "K"),
       lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

Capital accumulation and profits in modern sector

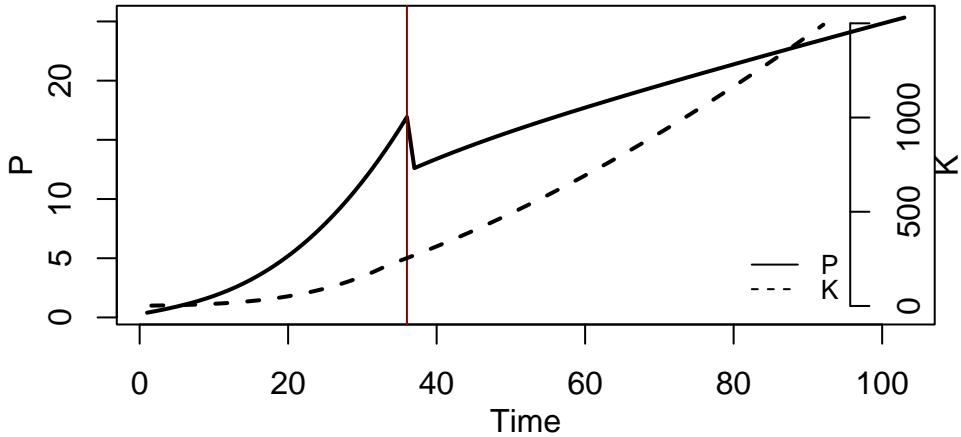


Figure 15.3: Capital accumulation and profits in modern sector

15.4

15.5

1

```
# Real wage and profit share in manufacturing
plot(PS2[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=1, xlab="", ylab="", xlim=range(Tmin:Tmax),
      title(main="Profit share and real wage in modern sector", ylab = 'pshare2', xlab = 'Time', cex=1),
      abline(v = tp[1], col = "darkred")
par(mar = c(5, 4, 4, 4) + 0.3)
par(new = TRUE)
plot(w2[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=2, font.main=1, cex.main=1, ylab = '',
      axes=TRUE,
      xlab = '', ylim = range(w2[1, Tmin:Tmax]), cex.axis=1, cex.lab=0.75)
axis(side = 4, at = pretty(range(w2[1, Tmin:Tmax])))
mtext("w2", side = 4, line = 2)
legend("topleft", legend=c("pshare2", "w2"),
      lty=1:2, cex=0.8, bty = "n", y.intersp=0.8)
```

¹In equilibrium, where $L_{2t} - L_{2t-1} = 0$, the real wage w_2 will be equal to the MPL in sector 2. The profit share is then constant and given by $\frac{P_2}{Y_2} = 1 - \beta$.

Profit share and real wage in modern sector

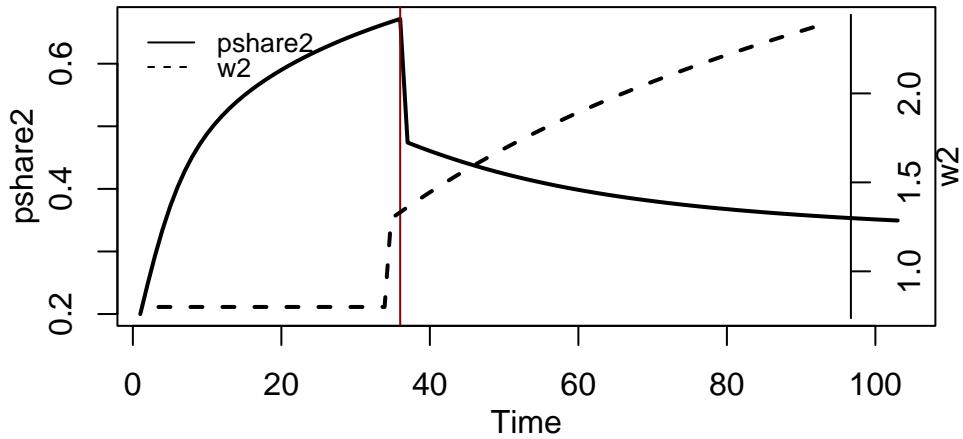


Figure 15.4: Real wage and profit share in modern sector

```
# Aggregate profit share
plot(PS[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=1, xlab="", ylab="",
      xlim=range(Tmin:Tmax)
      title(main="Aggregate profit share", ylab = '', xlab = 'Time', cex=0.8, line=2)
      abline(v = tp[1], col = "darkred")
```

Aggregate profit share

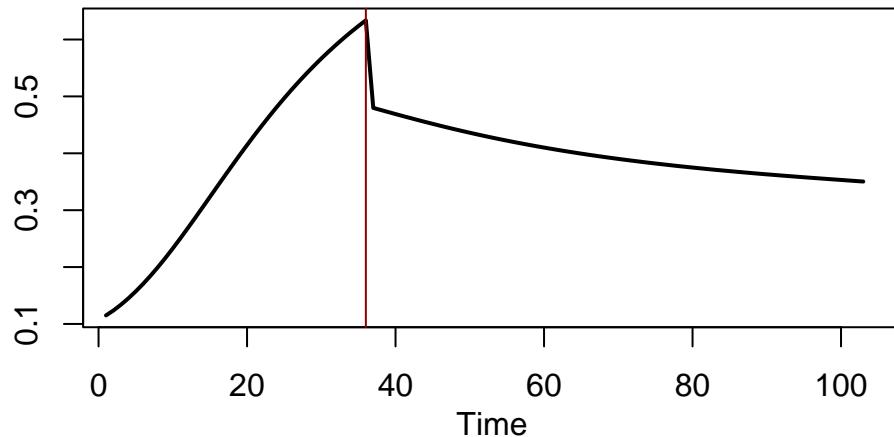


Figure 15.5: Aggregate profit share

16.2

```

Tmax=end[2]-2
plot(Y2[1, Tmin:Tmax], type="l", col=1, lwd=2, lty=1, xlim=range(Tmin:Tmax), xlab="", ylab="Y2")
title(main="Output in modern sector", xlab = 'Time', cex=0.8, line=2)
lines(Y2[2, Tmin:Tmax], lty=2)
lines(Y2[3, Tmin:Tmax], lty=3)
abline(v = tp[1], col = "darkred")
abline(v = tp[2], col = "red")
legend("bottomright", legend=c("1: baseline", "2: lower subsistence wage", "3: higher labour
    lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)

```

Output in modern sector

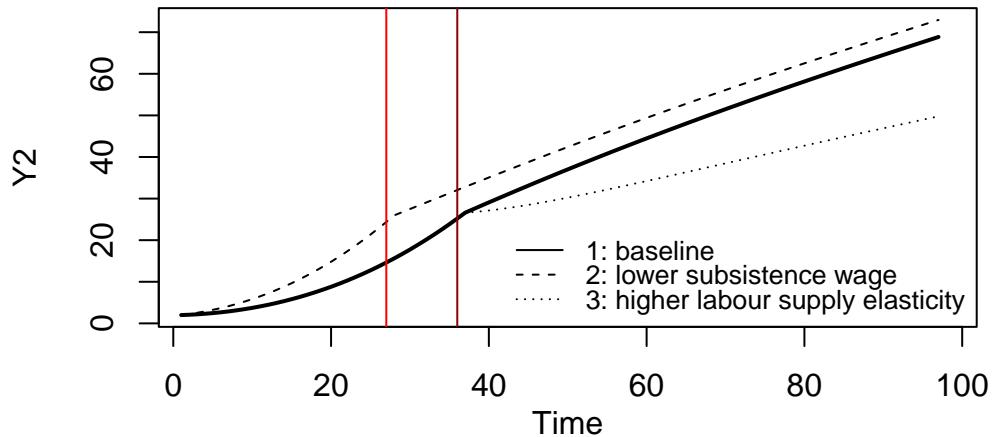


Figure 15.6: Output in modern sector under different scenarios

 Python code

```
### Plots (here only for output)
import matplotlib.pyplot as plt

# Set start and end periods for plots (set as integers)
Tmax = int(end[0] - 2)
Tmin = int(2)

# Output in the two sectors, baseline
plt.plot(range(Tmin, Tmax + 1), Y1[0, Tmin:Tmax + 1], 'k-', linewidth=2, label='Y1')
plt.plot(range(Tmin, Tmax + 1), Y2[0, Tmin:Tmax + 1], 'k--', linewidth=2, label='Y2')

# Highlight Lewis turning point
plt.axvline(x=tp[0], color='darkred', linestyle='--')

# Set plot labels and title
plt.title('Output in traditional (Y1) and modern (Y2) sector')
plt.xlabel('Time')
plt.ylabel('Y')
plt.ylim(min(Y1[0, Tmin:Tmax]), max(Y2[0, Tmin:Tmax]))

# Add legend
plt.legend(loc='upper left')

# Show the plot
plt.show()
```

15.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 9 variables:

#           Y1,Y2,L1,L2,w1,w2,P2,K, MPL2
M_mat=matrix(c(0, 0, 1, 0, 0, 0, 0, 0,
```

```

0, 0, 0, 1, 0, 0, 0, 1, 0,
0, 0, 0, 1, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 1, 0, 0, 1,
0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 1, 0, 0, 0, 0,
0, 1, 0, 1, 0, 1, 0, 0, 0,
0, 0, 0, 0, 0, 1, 0, 0, 0,
0, 1, 0, 1, 0, 0, 0, 0, 0),
byrow=TRUE)

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat=t(M_mat)

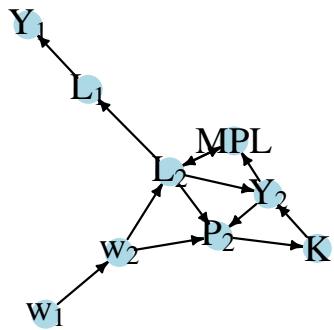
# Create directed graph from adjacency matrix
library(igraph)
dg= graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c(expression(Y[1]), expression(Y[2]), expression(L[1]), expression(L[2]),
expression(w[1]), expression(w[2]), expression(P[2]), "K", "MPL")

# Plot directed graph
plot(dg, main="Directed Graph of Lewis Model", vertex.size=20, vertex.color="lightblue",
vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
vertex.frame.color="NA", margin=-0.08)

```

Directed Graph of Lewis Model



 Python code

```
# Create directed graph
import networkx as nx

# Create the adjacency matrix (M_mat in R)
M_mat = np.array([[0, 0, 1, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 1, 0, 0, 0, 1, 0],
                  [0, 0, 0, 1, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 0, 1, 0, 0, 1],
                  [0, 0, 0, 0, 0, 0, 0, 0, 0],
                  [0, 0, 0, 0, 1, 0, 0, 0, 0],
                  [0, 1, 0, 1, 0, 1, 0, 0, 0],
                  [0, 0, 0, 0, 0, 1, 0, 0, 0],
                  [0, 1, 0, 1, 0, 0, 0, 0, 0]])

# Transpose the matrix to get A_mat
A_mat = M_mat.transpose()

# Create a directed graph from the adjacency matrix using networkx
G = nx.DiGraph(A_mat)

# Define the node labels as expressions for plotting
nodelabs = {0: r'$Y_1$', 1: r'$Y_2$', 2: r'$L_1$', 3: r'$L_2$',
            4: r'$w_1$', 5: r'$w_2$', 6: r'$P_2$', 7: 'K', 8: 'MPL'}

# Plot the graph
pos = nx.spring_layout(G, k=0.4)
nx.draw_networkx(G, pos, node_size=200, node_color="lightblue",
                  edge_color="black", width=1.2, arrowsize=10,
                  arrowstyle='->', font_size=8, font_color="black",
                  with_labels=True, labels=nodelabs)
plt.axis("off")
plt.title("Directed Graph of Lewis Model")
plt.show()
```

15.5 Analytical discussion

15.7 15.6
15.9 15.8
15.7

```

### Examine stability before the turning point (here for the baseline scenario only)

# Construct Jacobian matrix before the turning point
J=matrix(c(1 + delta*beta*(beta-1)*(L2[1,tp[1]-1]^(beta-2))*(K[1,tp[1]-1]^(1-beta)),
          delta*beta*(1-beta)*(L2[1,tp[1]-1]^(beta-1))*(K[1,tp[1]-1]^(-beta)),
          beta*(L2[1,tp[1]-1]^(beta-1))*(K[1,tp[1]-1]^(1-beta)) - w2[1,tp[1]-1],
          1 + (1-beta)*(L2[1,tp[1]-1]^(beta))*(K[1,tp[1]-1]^(-beta))),
          2, 2, byrow=TRUE)

# Obtain eigenvalues
ev=eigen(J)
(values = ev$values)

# Obtain determinant and trace
(det=det(J))      # determinant

(tr=sum(diag(J))) # trace

#Check stability conditions
print(1+tr+det>0)

print(1-tr+det>0)

print(1-det>0)

```

```
# Check simplified stability condition
print(w2[1,(tp[1]-1)] - Y2[1,(tp[1]-1)]/L2[1,(tp[1]-1)] >0)
```

i Python code

```
### Examine stability before the turning point (here for the baseline scenario only)

# Set turning point as integer
tp = tp.astype(int)

# Construct Jacobian matrix before the turning point
J = np.array([
    [1 + delta * beta * (beta - 1) * (L2[0, tp[0]-1] ** (beta - 2)) * (K[0, tp[0]-1] ** (1 - beta) * (1 - beta) * (L2[0, tp[0]-1] ** (beta - 1)) * (K[0, tp[0]-1] ** (-beta)) * (beta * (L2[0, tp[0]-1] ** (beta - 1)) * (K[0, tp[0]-1] ** (1 - beta)) - w2[0, tp[0]-1] * (1 + (1 - beta) * (L2[0, tp[0]-1] ** beta) * (K[0, tp[0]-1] ** (-beta)))])
])

# Obtain eigenvalues
eigenvalues, eigenvectors = np.linalg.eig(J)
print(eigenvalues)

# Obtain determinant and trace
det = np.linalg.det(J)
tr = np.trace(J)

# Check general stability conditions
print(1+tr+det>0)
print(1-tr+det>0)
print(1-det>0)

# Check simplified stability condition
print(w2[0, tp[0]-1] - Y2[0, tp[0]-1] / L2[0, tp[0]-1] > 0)
```

15.6 References

16 A Hicksian Business Cycle Model with Floors and Ceilings

16.1 Overview

2

9

1

16.2 The Model

¹Following Hommes (1995), we consider a stationary version of the model that abstracts from the growth path assumed in J. R. Hicks (1950).

16.1

16.2

16.3

²

16.3 Simulation

16.3.1 Parameterisation

16.3.2 Simulation code

```
# Clear the environment
rm(list=ls(all=TRUE))

# Set number of periods
Q=200

# Set number of scenarios (including baseline)
S=4
```

²This differs from Samuelson (1939), who assumed that investment reacts to changes in consumption, see Chapter 2.

```

# Set period in which shock/shift will occur
s=50

# Create (S x Q)-matrices that will contain the simulated data
Y=matrix(data=1,nrow=S,ncol=Q) # Income/output
C=matrix(data=1,nrow=S,ncol=Q) # Consumption
I=matrix(data=1,nrow=S,ncol=Q) # Investment

# Set fixed parameter values
c0=0
c1=0.75
I0=10

# Set baseline parameter values
Yc=matrix(data=80,nrow=S,ncol=Q)      # output ceiling
D=matrix(data=10,nrow=S,ncol=Q)        # investment floor (depreciation)
beta=matrix(data=1.25,nrow=S,ncol=Q)    # accelerator coefficient

# Set parameter values for different scenarios
Yc[2,s:Q]=100 # scenario 2: increase in output ceiling
D[3,s:Q]=1     # scenario 3: increase in investment floor
beta[4,s:Q]=0.8 # scenario 4: reduction in accelerator coefficient

# Simulate the model by looping over Q time periods for S different scenarios
for (i in 1:S){

  for (t in 2:Q){

    for (iterations in 1:500){ # run the model 500-times in each period

      #Model equations

      #(1) Output
      Y[i,t] = min(C[i,t]+I[i,t], Yc[i,t])

      #(2) Consumption
      C[i,t] = c0 + c1*Y[i,t-1]

      #(3) Investment
      I[i,t] = I0 + max(beta[i,t]*(Y[i,t-1] - Y[i,t-2]), -D[i,t])

    } # close iterations loop
  }
}

```

```
    }    # close time loop  
}    # close scenario loop
```

 Python code

```

import numpy as np

# Set number of periods
Q = 200

# Set number of scenarios (including baseline)
S = 4

# Set period in which shock/shift will occur
s = 50

# Create (S x Q)-arrays that will contain the simulated data
Y = np.ones((S, Q)) # Income/output
C = np.ones((S, Q)) # Consumption
I = np.ones((S, Q)) # Investment

# Set fixed parameter values
c0 = 0
c1 = 0.75
I0 = 10

# Set baseline parameter values
Yc = np.full((S, Q), 80)      # output ceiling
D = np.full((S, Q), 10)        # investment floor (depreciation)
beta = np.full((S, Q), 1.25)   # accelerator coefficient

# Set parameter values for different scenarios
Yc[1, s:Q] = 100      # scenario 2: increase in output ceiling
D[2, s:Q] = 1          # scenario 3: increase in investment floor
beta[3, s:Q] = 0.8     # scenario 4: reduction in accelerator coefficient

# Simulate the model by looping over Q time periods for S different scenarios
for i in range(S):

    for t in range(1, Q):

        for iterations in range(500): # run the model 500-times in each period

            # Model equations

            # (1) Output
            Y[i, t] = min(C[i, t] + I[i, t], Yc[i, t])

            # (2) Consumption
            C[i, t] = c0 + c1 * Y[i, t - 1]
                        294
            # (3) Investment
            I[i, t] = I0 + max(beta[i, t] * (Y[i, t - 1] - Y[i, t - 2]), -D[i, t])

            # Close iterations loop
        # Close time loop
    # Close scenario loop

```

16.3.3 Plots

16.1

```
# Set start and end periods for plots
Tmax=100
Tmin =10

#Income, consumption, and investment
plot(Y[1, Tmin:(Tmax)],type="l", col=1, lwd=2, lty=1, xlab="", ylab="Y, C, I", ylim=range(I[1:Tmax])
title(main="Income, consumption, and investment (baseline)", xlab = 'Time',cex=0.8,line=2)
lines(C[1, Tmin:Tmax],lty=2)
lines(I[1, Tmin:Tmax],lty=3)
legend("topleft", legend=c("Y", "C", "I"),
      lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Income, consumption, and investment (baseline)

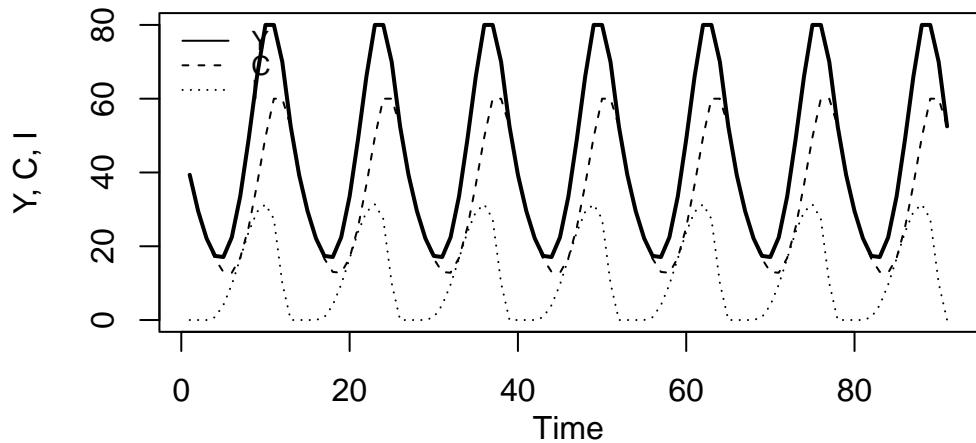


Figure 16.1: Income, consumption, and investment (baseline)

16.2

```
# Scenario 2: increase in ceiling
plot(Y[2, Tmin:(Tmax)], type="l", col=1, lwd=2, lty=1, xlab="", ylab="Y, C, I", ylim=range(I[2,])
title(main="Scenario 2: Increase in output ceiling", xlab = 'Time', cex=0.8, line=2)
lines(C[2, Tmin:Tmax], lty=2)
lines(I[2, Tmin:Tmax], lty=3)
legend("topright", legend=c("Y", "C", "I"),
      lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Scenario 2: Increase in output ceiling

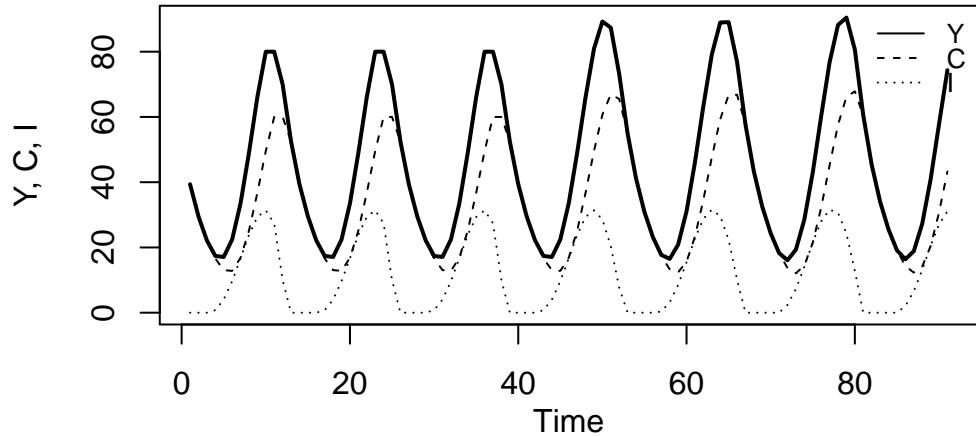


Figure 16.2: Increase in output ceiling

16.3

```
# Scenario 3: increase in investment floor
plot(Y[3, Tmin:(Tmax)],type="l", col=1, lwd=2, lty=1, xlab="", ylab="Y, C, I", ylim=range(I[3, Tmin:(Tmax)]))
title(main="Scenario 3: Increase in investment floor", xlab = 'Time',cex=0.8,line=2)
lines(C[3, Tmin:Tmax],lty=2)
lines(I[3, Tmin:Tmax],lty=3)
legend("topright", legend=c("Y", "C", "I"),
       lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Scenario 3: Increase in investment floor

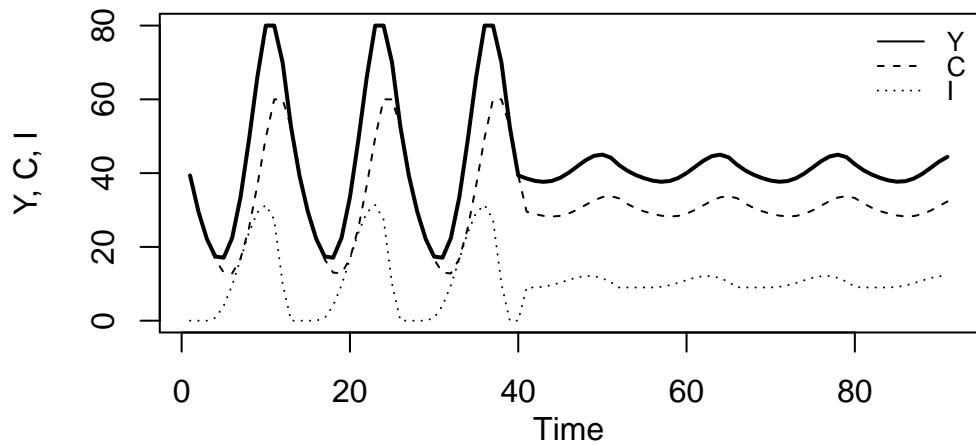


Figure 16.3: Increase in investment floor

16.4

```
# Scenario 4: Reduction in accelerator coefficient
plot(Y[4, Tmin:(Tmax)],type="l", col=1, lwd=2, lty=1, xlab="", ylab="Y, C, I", ylim=range(I[4, Tmin:(Tmax)]))
title(main="Scenario 4: Reduction in accelerator coefficient", xlab = 'Time',cex=0.8,line=2)
lines(C[4, Tmin:Tmax],lty=2)
lines(I[4, Tmin:Tmax],lty=3)
legend("topright", legend=c("Y", "C", "I"),
       lty=1:3, cex=0.8, bty = "n", y.intersp=0.8)
```

Scenario 4: Reduction in accelerator coefficient

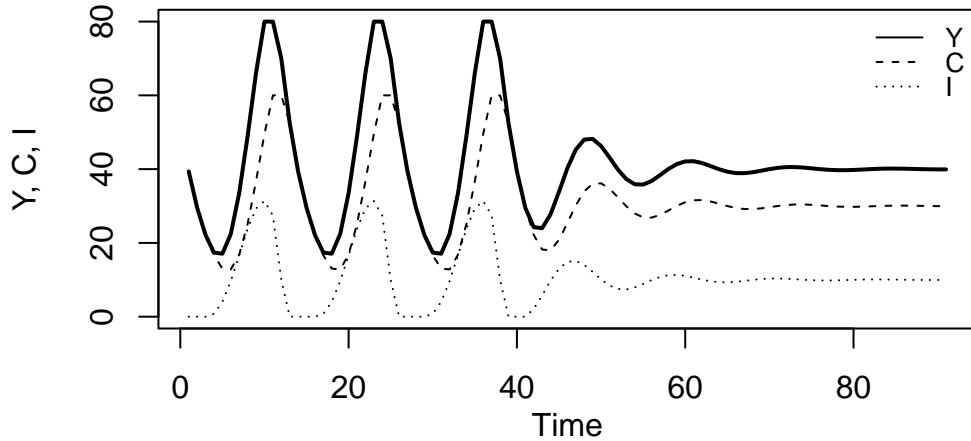


Figure 16.4: Reduction in accelerator coefficient

Python code

```
### Plots (here only for baseline)
import matplotlib.pyplot as plt

# Set start and end periods for plots
Tmax = 100
Tmin = 10

# Plot income (Y), consumption (C), and investment (I)
plt.plot(range(Tmin, Tmax), Y[0, Tmin:Tmax], label='Y', color='black', linewidth=2, linestyle='solid')
plt.title("Income, consumption, and investment (baseline)", fontsize=10)
plt.xlabel('Time')
plt.ylabel('Y, C, I')
plt.plot(range(Tmin, Tmax), C[0, Tmin:Tmax], label='C', linestyle='--', color='black')
plt.plot(range(Tmin, Tmax), I[0, Tmin:Tmax], label='I', linestyle=':', color='black')

# Add a legend to the top-left corner
plt.legend(loc='upper left', fontsize=8, frameon=False)

# Show the plot
plt.show()
```

16.4 Directed graph

```
## Create directed graph
# Construct auxiliary Jacobian matrix for 5 variables:
# endogenous: (1) Y, (2) C, (3) I
# exogenous: (4) IO-D, (5) Yc

          #Y C I IO-D Yc
M_mat=matrix(c(0,1,1, 0,  1, # Y
              1,0,0, 0,  0, # C
              1,0,0, 1,  0, # I
              0,0,0, 0,  0, # IO-D
              0,0,0, 0,  0),# Yc
              5, 5, byrow=TRUE)

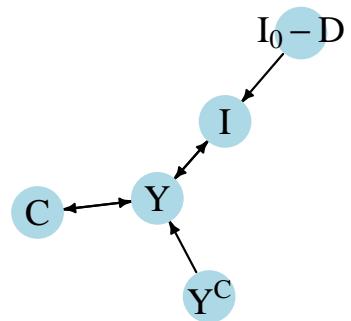
# Create adjacency matrix from transpose of auxiliary Jacobian and add column names
A_mat=t(M_mat)

# Create directed graph from adjacency matrix
library(igraph)
dg=graph_from_adjacency_matrix(A_mat, mode="directed", weighted= NULL)

# Define node labels
V(dg)$name=c("Y", "C", "I", expression(I[0]-D), expression(Y^C))

# Plot directed graph matrix
plot(dg, main="Directed graph of Hicks model", vertex.size=40, vertex.color="lightblue",
      vertex.label.color="black", edge.arrow.size=0.3, edge.width=1.1, edge.size=1.2,
      edge.arrow.width=1.2, edge.color="black", vertex.label.cex=1.2,
      vertex.frame.color="NA", margin=-0.08)
```

Directed graph of Hicks model



 Python code

```
### Directed graph
import networkx as nx

# Construct auxiliary Jacobian matrix for 5 variables:
# endogenous: (1) Y, (2) C, (3) I
# exogenous: (4) IO-D, (5) Yc

# Create the matrix M_mat
M_mat = np.array([[0, 1, 1, 0, 1], # Y
                  [1, 0, 0, 0, 0], # C
                  [1, 0, 0, 1, 0], # I
                  [0, 0, 0, 0, 0], # IO-D
                  [0, 0, 0, 0, 0]]) # Yc

# Create adjacency matrix from transpose of auxiliary Jacobian
A_mat = M_mat.T

# Create directed graph from adjacency matrix using networkx
G = nx.DiGraph(A_mat)

# Define node labels
nodelabs = {0: "Y", 1: "C", 2: "I", 3: "$I_0 - D$",
            4: "$Y^C$"}

# Plot directed graph
pos = nx.spring_layout(G, k=0.08)
nx.draw_networkx(G, pos, node_size=200, node_color="lightblue",
                  edge_color="black", width=1.2, arrowsize=10,
                  arrowstyle='->', font_size=8, font_color="black",
                  with_labels=True, labels=nodelabs)
plt.axis("off")
plt.title("Directed Graph of Lewis Model")
plt.show()
```

16.5 Analytical discussion

9

16.5

16.4

16.7

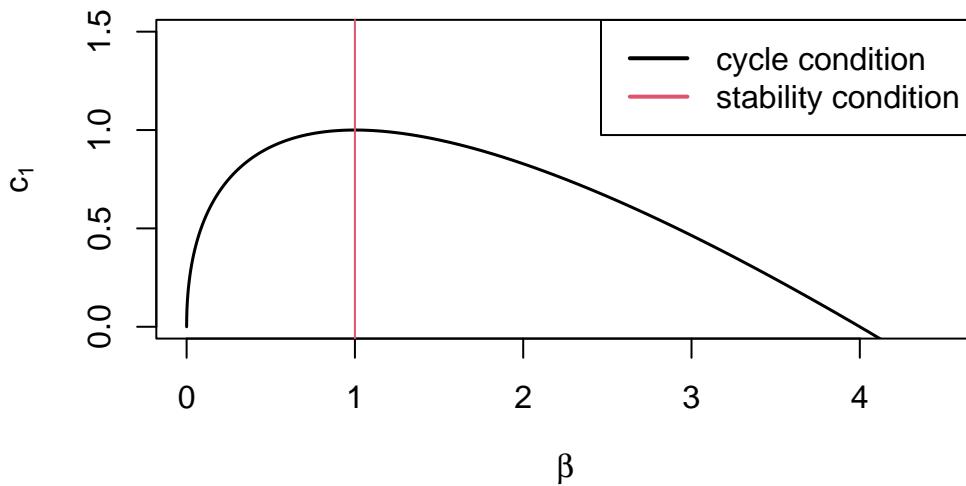
16.6

16.7

16.8

```
# Create function for cycle condition using beta as argument
cyc= function (beta) {
  2*sqrt(beta)-beta
}

# Plot the two conditions in (beta, c1)-space
curve(cyc, from = 0, to = 4.5, col = 1, xlab=expression(beta), ylab=expression(c[1]) , main=
      lwd=1.5, n=10000, ylim=range(0,1.5))
abline(v=1, col=2)
legend("topright", legend = c("cycle condition", "stability condition"),
       col = c(1, 2), lwd = 2)
```



³To create the function for the cycle condition, we set $\left(\frac{c_1+\beta}{2}\right)^2 = \beta$ and solve for c_1 , where we only consider positive values for c_1 and β .

 Python code

```
# Create function for cycle condition using beta as an argument
def cyc(beta):
    return 2 * np.sqrt(beta) - beta

# Define the range for beta
beta_values = np.linspace(0, 4.5, 10000)

# Compute the corresponding c1 values using the cyc function
c1_values = cyc(beta_values)

# Plot the cycle condition in (beta, c1)-space
plt.plot(beta_values, c1_values, color='black', linewidth=1.5, label='cycle condition')

# Plot the stability condition as a vertical line at beta = 1
plt.axvline(x=1, color='red', linewidth=2, label='stability condition')

# Set labels and title
plt.xlabel(r'$\beta$', fontsize=12)
plt.ylabel(r'$c_1$', fontsize=12)
plt.title('')

# Set y-axis limit
plt.ylim(0, 1.5)

# Add legend
plt.legend(loc='upper right')

# Show the plot
plt.show()
```

```
### Stability analysis
## Baseline

# Construct Jacobian matrix
J_base=matrix(c(c1, 1,
                 beta[1,1]*(c1-1), beta[1,1]),
```

```
2, 2, byrow=TRUE)
```

```
# Obtain eigenvalues
```

```
ev_base=eigen(J_base)
```

```
(evals_base = ev_base$values)
```

```
# Obtain determinant and trace
```

```
(det=det(J_base))      # determinant
```

```
tr=sum(diag(J_base)) # trace
```

```
# Calculate modulus
```

```
(mod_base=Mod(evals_base[1]))
```

```
#Check general stability conditions
```

```
print(1+tr+det>0)
```

```
print(1-tr+det>0)
```

```
print(1-det>0)
```

```
# Check analytical stability condition
```

```
beta[1,1] < 1
```

```
## Compare with scenario 4
J_scen4=matrix(c(c1, 1,
                  beta[4,s]*(c1-1), beta[4,s]),
                2, 2, byrow=TRUE)

# Obtain eigenvalues
ev_scen4=eigen(J_scen4)
(evals_scen4 = ev_scen4$values)
```

```
# Obtain determinant and trace
(det=det(J_scen4))      # determinant
```

```
tr=sum(diag(J_scen4)) # trace

# Calculate modulus
(mod_scen4=Mod(evals_scen4[1]))
```

```
#Check general stability conditions
print(1+tr+det>0)
```

```
print(1-tr+det>0)
```

```
print(1-det>0)
```

```

# Check analytical stability condition
beta[4,s] < 1

#### Check cycle condition and compute cycle length (baseline)

# Check analytical cycle condition
(c1+beta[1,1])^2 - 4*beta[1,1] < 0

# Save real and imaginary part of complex eigenvalue
re=Re(evals_base[1])
im=Im(evals_base[1])

# Calculate cycle length
L=(2*pi)/(acos(re/mod_base))
L

```

 Python code

```

### Stability Analysis - Baseline
# Construct the Jacobian matrix for the baseline scenario
J_base = np.array([[c1, 1],
                  [beta[0, 0] * (c1 - 1), beta[0, 0]]])

# Obtain eigenvalues
evals_base, _ = np.linalg.eig(J_base)
print("Eigenvalues (Baseline):", evals_base)

# Obtain determinant and trace
det_base = np.linalg.det(J_base) # determinant
tr_base = np.trace(J_base) # trace

# Calculate modulus of the first eigenvalue
mod_base = np.abs(evals_base[0])
print("Modulus (Baseline):", mod_base)

# Check general stability conditions
print("Stability conditions (Baseline):")
print(1 + tr_base + det_base > 0)
print(1 - tr_base + det_base > 0)
print(1 - det_base > 0)

# Check analytical stability condition
print("Analytical stability condition (Baseline):", beta[0, 0] < 1)

### Compare with Scenario 4
# Construct the Jacobian matrix for scenario 4
J_scen4 = np.array([[c1, 1],
                    [beta[3, s] * (c1 - 1), beta[3, s]]])

# Obtain eigenvalues
evals_scen4, _ = np.linalg.eig(J_scen4)

# Print eigenvalues
print("Eigenvalues (Scenario 4):", evals_scen4)

# Obtain determinant and trace
det_scen4 = np.linalg.det(J_scen4) # determinant
tr_scen4 = np.trace(J_scen4) # trace

# Calculate modulus of the first eigenvalue
mod_scen4 = np.abs(evals_scen4[0])
print("Modulus (Scenario 4):", mod_scen4)
310

# Check general stability conditions
print("Stability conditions (Scenario 4):")
print(1 + tr_scen4 + det_scen4 > 0)
print(1 - tr_scen4 + det_scen4 > 0)
print(1 - det_scen4 > 0)

# Check analytical stability condition

```

16.6 References

Additional Online Resources

Economic Modelling in General

- [Sayama \(2015\)](#)
- [QuantEcon](#)

Stock-Flow Consistent Modelling

- Marco Veronese Passarella's website [Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth](#)
- SFC Models

Agent-Based Modelling

- Alessandro Caiani's website [Economics with Heterogeneous Interacting Agents: A Practical Guide to Agent-Based Modeling](#)

Coding

- [Coding for Economists](#)

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