Elder Mauricio Silva

AGENT-BASED MACROECONOMICS:
Applied to Monetary Policy Experiments

Tese submetida ao Programa de Pós-Graduação em Economia da Universidade Federal de Santa Catarina para a obtenção do Grau de Doutor em Economia.

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RESUMO

Neste trabalho utilizamos um modelo baseado em agentes para realizar experimentos com políticas monetárias. Nossa inovação consiste em incluir um sistema interbancário em uma macroeconomia constituída por agentes com capital e crédito e uma autoridade monetária. Realizamos experimentos de política monetária convencional e não-convencional (à la *quantitative easing*). A flexibilidade do modelo nos permite simular diferentes reações da autoridade monetária perante situações parecidas com a emergência de crises. Nosso principal resultado é poder comparar a eficácia da autoridade monetária em mitigar o impacto das reduções no emprego e produto. Em geral, as regras utilizadas em períodos mais recentes pelas autoridades monetárias apresentam melhores resultados em termos suavização de crises. No total, testamos quatro conjuntos de políticas monetárias convencionais e quatro não convencionais, sendo que estes últimos proporcionaram melhores resultados.

Palavras-chave: Crises financeiras. Macroeconomia baseada em agentes. Política monetária.

ABSTRACT

Here we present a macroeconomic agent-based model with credit and capital where we consider an interbank market and a monetary authority. Our innovation is the possibility to assess monetary policies conducted by the monetary authority. We show eight monetary experiments in total, four representing conventional monetary policies, and another four being non-conventional monetary responses (quantitative easing policies). In general, we observe that non-conventional policies present better results in terms of reducing the fluctuations in output and employment. One of the four non-conventional policies is even capable to suppress the emergence of crisis in our simulations.

Keywords: Financial crisis. Agent-based macroeconomic model. Monetary policy.

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1 INTRODUCTION

This work presents an Agent-Based Macroeconomic Model with an interbank market and a central bank. The objective is to use this framework to test monetary policies. We implement experiments that simulate monetary authorities' responses in two ways, using a conventional approach and a non-conventional way to deal with the fluctuations in real GDP and unemployment. In total, eight experiments are tested, four using the conventional framework and four with the non-conventional monetary response by the monetary authority. In general, the non-conventional behavior of the monetary authority shows better results in terms of reducing the fluctuations in real GDP and of reducing the impact of crisis on the unemployment rate.

The model is an agent-based macroeconomic model that uses as a framework an agent-based macroeconomic model with capital and credit (ABMM-CC) in which we consider an interbank market and a central bank. Assenza et al. (2015) present an agent-base macroeconomic model with a stylized supply chain, capital goods firms (K-firms) and consumer goods firms (C-firms), where firms resort to bank loans to satisfy their financial needs. The model has two-way feedbacks between firms and markets, which lead to an emerging property at the macro level, where credit suffers sizable slumps followed by a long recovery. The novelty of our model is to include an interbank market and a monetary authority (central bank). After we consider the interbank market and the monetary authority, the same dynamics that appears in Assenza et al. (2015) is replicated, where periods of crisis emerge endogenously.

The importance of considering the interbank market in such a model can be appreciated in Gertler et al. (2016), who observe that the debate about which is the best approach to model financial crisis has come back in full since the 2008 financial crisis. The debate is not new, actually. Bernanke and Gertler (1989) and Kyotaki and Moore (1997), for example, already indicated the importance of the interbank market as a source of financial friction and later potential effect of the financial crisis on real output. The balance sheets of the financial sector tend to be procyclical, that is, when the economy is growing the supply of credit is also expanding, and when the economy slows down, the supply of credit moves also in the same direction, in movements that tend to amplify each other through a positive feedback loop. Moreover, Gertler et al. (2016) argue that during the financial crisis wholesale banks play a major role. A wholesale bank is a bank that is highly leveraged, usually in short-term debts. It relies on debts with other financial institutions rather than borrowing money from households. The work of borrowing money from households is made by retail banks. A retail bank collects deposits from the households and offer loans to firms as well as for the interbank market. Therefore, it is necessary an interbank market for one to have a good model of the transmission of the financial crisis to the real economy.

To be able to implement monetary experiments with the model we need to endogenize the free interest rate because in our ABMM-CC framework the free interest rate is exogenous. To do that we include a central bank that will choose the free interest rate according to Taylor's rule (Taylor, 1993). The free interest rate chosen by the central bank is used by the banks to calculate the loans to the firms. It is also used to decide the intrabank interest rate. Taylor's rule is widely considered for modeling the stylized behavior of a monetary authority because it reflects the tradeoff between output/unemployment and inflation. When using such a rule, the monetary authority needs to decide how much attention to give for the fluctuations in either real output or inflation. When output deviation is large, the ongoing interest rate tends to be reduced; however, when inflation rises, the interest rate tends to increase. Nevertheless, using this framework creates: which set of parameters to use. In Clarida et al. (2000) there is a valuable discussion about this point. These authors estimated a monetary reaction function for each Fed president in postwar American economy. They found that the set of parameters that Taylor considers in his original work (Taylor, 1993) was a particular one, that is, it works well for the period considered by Taylor, but not for preceding periods as well as for the post-1993 period. For example, in the Volcker-Greenspan period, the function reaction they estimated for the US monetary authority is much more sensitive to changes in inflation than that in the pre-Volcker period. Therefore, the response of the monetary authority changes over the time. We spot here an opportunity, and we use these different responses found by Clarida et al. (2000) as an input for our own monetary experiments. However, Clarida et al.'s study consider data until the late 90s only. During the last few years, the behavior of the monetary authority changed once again. Kim and Pruitt (2017) study the response of the monetary authority in the United States for the past years and use data for the post-2008 financial crisis, a period known as the zero lower bound (ZLB), because central banks shrunk their interest rates across the world to near zero, usually below 25 basis points. They found that the Fed's inflation response has significantly decreased. Thus, in our experiments, we use the three sets of parameters proposed by Clarida et al. (2000) and also consider a scenario with the set of parameters as in Kim and Pruitt (2017).

At the same time, central banks around the world lost their power to influence the economy through the interest rate, once rates approach zero. Then, the central banks started to test new ways to prevent reductions in real output. They started to buy assets directly from the market, trying to stop the falling prices of these assets. These purchase programs were used by the Federal Reserve, the Bank of England, the European Central Bank and the Bank of Japan. Fawley and Neely (2013) evaluate the success of these programs, known as quantitative easing. The programs were implemented to attempt to alleviate financial market distress, but soon broadened to achieve inflation goals. As crises impact these economies differently, and each economy has its own particularities, the way each central bank managed its quantitative easing varied. However, the core of such programs was the same: acquiring private assets for a temporary period of time. Also, the extent of quantitative easing varied as a proportion of real GDP. Japan presented the highest level (37.5% of GDP) and Europe the lowest (3.5% of GDP). At its highest point the Federal Reserve held the equivalent of 22.1% of GDP, and the Bank of England, 26.3% of GDP. As the power of conventional monetary policy faded, alternative policies grew in importance. Thus, we use our model to simulate both types of policy, conventional and alternative. When we compare the results of the policies, for example in terms reduction real GDP fluctuation, the alternative policies perform better than in the experiments where only conventional monetary policies are considered.

In the next chapter of this work, our model is presented and the robustness of the results from policy experiments are evaluated. To present our model, we use the ODD protocol (Grimm et al. 2010) to describe it. The ODD, which stands by Overview, Design concepts and Details, is a document that supports itself. The primary objectives of the ODD are to make the model description more understandable and complete, making it less subject to the criticism of being irreproducible. However, it can be sometimes lengthy, so we decided to place the complete ODD document in Appendix B.

The robustness check of the model also uses the protocol TRACE ("TRAnsparent and Comprehensive model Evaluation") based on Schmolke et al. (2010) and Grimm et al. (2014). This framework provides a checklist that leads to a constant check for robustness throughout the construction of the model. Each time a new submodel is included in the code, or every time it is possible to test the results under a new set of parameters, we did so, and registered the results using the TRACE protocol. The TRACE is also a document that is self-contained. It is available in Appendix A. In Chapter 3 we summarize the results for the robustness, looking at some statistical properties that emerge from the model, as well as we check for some stylized facts.

In Chapter 4 we detail our experiments. As observed, we run eight experiments, four related to conventional policy experiments and four related to non-conventional policies. Finally, Chapter 5 shows the main results, compare them across the experiments, and discusses them.

1.1 RELATED LITERATURE

The agent-based model's literature is vast in both science and economics. Yet, as pointed out by Haldane and Turrel (2017), there are important differences between the agent-based model in science and in economics. In economics, the agent level behavior is not known at the degree of accuracy as it is described in, for example, biology or the physics of particles. When studying the behavior of economic agents, one need to have in mind that the agents' behavior may change over the time as a response to the environment. Therefore, the assumptions in economics need to be rigorously tested and varied. Haldane and Turrel also notice that due to the inherent uncertainty the agent behavior in economics can fit the data in a probabilistic way only, but moments stylized facts can be reproduced. Thus, the use of an agent-based model posits a tradeoff between bias and variance. Using an agent-based model brings a lower bias, but at the cost of higher variance. This situation offers advantages and downsides. For instance, statistical models such as DSGEs say little about heterogeneous agents, while agent-based models offer more room to heterogeneity than the DSGEs models. As for forecasting, there is a restriction to the use of an agent-based model because there are models better suited to tackle the problem, such as dynamic factor models or machine learning (Stock and Watson, 2011; Chakraborty and Joseph, 2017). The agent-based model is better suited when the problem studied is a particular policy. Haldane and Turrel cite as an example of good places to apply the agent-based model in epidemiology (Degli Atti et al., 2008), where the model can be used to identify risk factors of virus outbreak in a region and its spreading through other regions, but at the same time the model would be incapable of predicting a single state of outbreak in a specific period. When comparing the DSGE model with the agent-based models, Haldane and Turrel (2017) point out that the DSGE models come bundled with a set of assumptions that includes rational expectations. In contrast, agent-based models do not offer a core model. Rather, they are a more flexible tool that can be used to solve complex problems involving heterogeneous agents, where agents can optionally use rational expectations or not. This flexibility explains the crescent use of agent-based models in economics. The downside of this additional flexibility is the loss of analytical certainty, which needs be replaced by numerical convergence. Also, it is necessary to see the agent-based models from a different perspective when looking at results. Agent-based models have to be viewed as a machine used to generate many alternative results possible in the world. Because of this, it is useful to make many experiments, that is, many realizations of a single model. Due to the inherent complexity of the interaction in agent-based models, these consider the outcomes of the model as ones accruing from real data within confidence intervals. Haldane and Turrel argue that the bottom line whether an agent-based model is good or bad depends on its assumptions, and how it is used, and how its results are interpreted.

The agent-based macroeconomic models fit this interpretation. They allow for more flexibility to create models with more complexity, which means more heterogeneity. A sample of models of this family is found in the EURACE framework (Cincotti et al., 2010; Deissenberg et al., 2008; Dawid et al., 2012). In these models, firms produce final goods and use capital as an input, and the capital used by those firms is produced by another set of firms that produces capital goods. Both firms need workers, and they hire and fire employees at will. Workers receive wages and consume the goods produced by the firms. The capital sector has an inherent technological advantage through stochastic innovation processes.

The model we present here brings similarity to those in Gatti et al. (2011) and Assenza et al. (2015). In Gatti et al. (2011) the agent-based model has a capital market, a goods market, and a labor market. Capital goods and labor are not differentiable, and firms engage in the research process. Assenza et al. (2015) build an agent-based macroeconomic model with capital and credit that incorporates capital and investment. Firms need heterogeneous capital to produce goods and heterogeneous labor to produce either goods or capital. There are four categories of agents: households, firms producing consumption goods, firms producing capital goods, and banks. The series of GDP they compute fluctuates around a long-run mean, but it endogenously creates a crisis. GDP falls in large scale in a few periods that take longer to be back to the normal level. Unemployment rate can overshoot a 15% level, a situation that characterizes a crisis. The model recreates the dynamics of crisis propagation, when the credit available to the firms is restricted in an adverse scenario that causes investment to shrink, production of capital to be reduced, consumption to decrease, and GDP and employment to fall.

When one decides to insert a monetary authority in such a model, one needs to face the question of how to model the behavior of this new agent. In the literature, the work of Taylor (1993) offers a solution to this kind of problem. The monetary authority has a tradeoff between output and inflation, which also means the authority is concerned with both inflation and employment. Orphanides (2003) presents a Taylor-rule framework study to describe the policy debate and the evolution of monetary policy in the US since the 1920s. Orphanides finds a "surprising consistency" with Taylor's rule. The economic activity, normal or potential, was influenced by the monetary authority's actions, sometimes excessive, as in the Great Inflation and the Great Depression. In the last two decades of his study, the behavior of the monetary authority was broadly consistent with variants of Taylor rule which exhibit less activism. Thus, Taylor-rule framework probes to be useful for interpreting past policy decision and also the mistakes made by monetary authorities. Orphanides claims that even the behavior of the authorities during the 1920s appears to be broadly consistent with Taylor's rule.

While Orphanides (2003) makes a point for the usefulness of Taylor's rule to a long run study of the America economy, Clarida et al. (2000) focus on estimating the parameters of a Taylor's rule over time. They estimated a monetary policy reaction function for the postwar economy. The results they found point to a substantial difference in the estimated rule across periods. The Volcker-Greenspan period appears to be much more sensitive to changes in inflation than the previous period. Their estimations show a significant difference in the way that monetary policy was conducted before and after 1979. Before 1979 (the pre-Volcker era), the monetary authority typically raised the nominal rates by less than the increase in inflation. Such a behavior led to a short-term interest rate decline as anticipated inflation rose. However, in the post-1979 years, the monetary authority raised nominal and real interest rates in response to higher inflation. Their results support the view that the Federal Reserve's response to inflation was stronger in the past two decades before their study. Due to the 2008 financial crisis, the scenario changed and the behavior of the monetary authority changed accordingly.

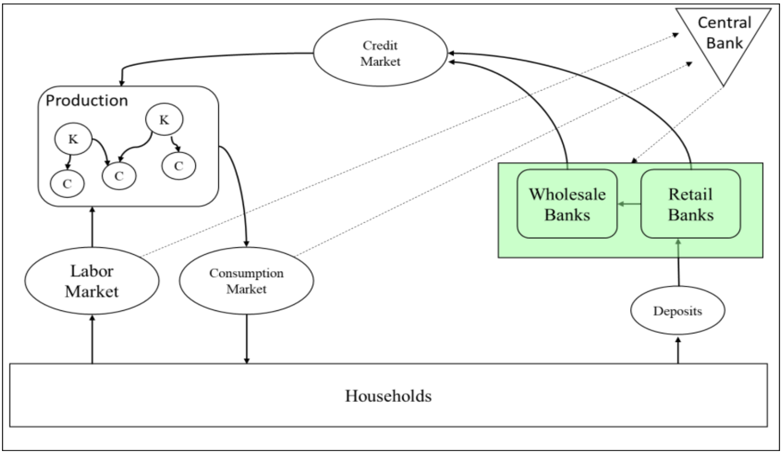
Kim and Pruitt (2017) study the response of the monetary authority after the 2008 crisis under a Taylor-rule perspective. They use a professional forecast to estimate the Federal Reserve's policy response to inflation and output. Kim and Pruitt compare the results obtained with historical data. They found a qualitative agreement with their estimates, which supports the idea that forecasts and historical data show similar policy response functions. When they used the historical data to estimate the coefficient during the ZLB (zero lower bound), they found a virtual coefficient of zero. Yet, when they used the forecast data during the ZLB, they found coefficients that were statistically significant to the policy response coefficients. Furthermore, they found evidence that the inflation response had diminished, while the unemployment response elevated. In short, the Fed’s inflation response significantly dropped after the 2008 crisis while in the meantime the Fed’s response to unemployment remained strong.

2 THE MODEL

The model shown here is an agent-based macroeconomic model with capital and credit (ABMM-CC). The core of the model is similar to Assenza et al.’s (2015). The major novelty our model presents is the possibility of simulating monetary policies. It is a medium size agent-based model, with 3,250 households (divided between workers and capitalists), 250 firms (divided between capital-goods firms and consumer-goods firms), two commercial banks (a retail bank and a wholesale bank), and a central bank. A full description is available in an ODD (Overview Design and Concepts, Grimm et al. 2010) format, which is in Appendix B. The model is programmed in R-NetLogo, and the code is available in both Appendix C and the NetLogo library at http://modelingcommons.org/browse/one_model/5070#model_tabs_bowse_info. Next, we present a succinct description of the model that places emphasis on the changes implemented.

The model is composed of a consumer market, a capital market, a labor market, and a credit market. The central bank receives input from the labor and consumption market, and its decisions impact the financial sector. A summary of this structure is shown in Figure 1.

Figure 1. Agents and markets. Production sector with firms that produce capital goods (K) and consumption goods (C). The central bank perceives the unemployment from the labor market, the inflation from the consumer market, and then dictates the rules for the financial system



Source: the author (2019).

2.1 ENTITIES, STATE VARIABLES, AND SCALES

Agents: We use agents to represent the minimal unit of behavior of the members of this economy; they represent the participants of the productive, consumption, and financial sector of the economy.

Spatial units: The patches of a grid are occupied by only one firm per patch. There are as many patches as a number of firms. The NetLogo software is programmed to have 250 patches.

Environment: The households can move through the patches freely. The position of the firms is constant during all the experiments, that is, they do not change their address. All the patches have the same characteristics. Each period represents a quarter, and the simulations run for an arbitrary number of periods.

Collectives: The agents are of three types: 1) firms that are responsible for production in this economy; 2) households composed of workers and owners of the firms; and 3) a financial sector, encompassing a retail bank, a wholesale bank, and a central bank.

2.2 PROCESS OVERVIEW AND SCHEDULING

Time is a discrete variable where each period represents a quarter. A firm decides in each period how much to produce and which price to charge. A household decides how much to consume and save their remaining money as a deposit in the commercial bank. Such a decision follows a rule of thumb, as in Assenza et al. (2015).

Job market: Unemployed workers approach a restrict number of firms trying to find a job position. Wages are homogeneous, so a worker accepts the first job offer she receives. Productivity is homogeneous among the workers, and firms contract the first worker to apply for a vacancy position.

Consumption market: Households have a certain amount of money they spend each period. They approach a restrict number of firms and try to buy their goods at the lowest price. Whenever a firm with the best price does not have enough quantity of the good, a household approaches the next firm. Whenever there are not enough goods in all firms approached, the household saves the money.

Capital market: Consumption firms combine labor and capital to produce goods. Capital and labor are perfect complements, that is, it is assumed a Leontief production function. A consumption firm approaches capital goods firms and try to buy at the lowest price, similar to the behavior of households in the consumer market.

Credit market: Sometimes the firms need to access the credit market. In such a situation, a firm asks a bank for a loan. The bank evaluates if it has available money enough to lend; if it has, then the bank decides which interest rate to charge for this financial transaction. To determine the interest rate, the bank also considers the free interest rate set by the central bank.

2.3 THE NOVELTIES

To allow our model to simulate monetary policies we first endogenize the risk free interest rate:

$$r_t = \pi_t + r^* + \alpha_\pi \, (\pi_t - \pi^*) + \alpha_Y \, (Y_t - \bar{Y}), \tag{1}$$

where r_t is the current free interest rate; r^* is the natural interest rate, $r^* \in (0,1) \subset$ R; α_π is a parameter, $\alpha_\pi \in [0, 2.5] \subset \mathbb{R}$; α_Y is a parameter, $\alpha_Y \in [0, 1.3] \subset \mathbb{R}$; Y_t is current GDP.

As for the non-conventional monetary policies, the central bank is restrained by rule:

$$A_t^{C.B.} = \begin{cases} 0 \, , if \; the \; {H_t^U}/{H_t^E} < \psi \; ; \\ \max \chi Y, \; if \; {H_t^U}/{H_t^E} \geq \psi \, , \end{cases} \tag{2}$$

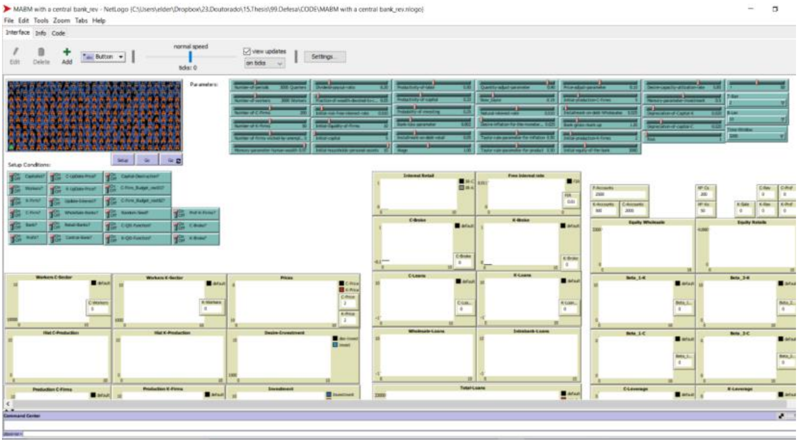
where $A_t^{C.B.}$ is the total of private assets held by the central bank in period *t*; $H_t^{E.}$ is the total of workers with a job position in period *t*; $H_t^{U.}$ is the total of workers without a job position in period *t*; $\psi \in (0,1) \subset$ R is the threshold after which the central is allowed to buy assets; χ is a parameter, $\chi \in (0,1) \subset$ R.

The discussion about the values assumed by these parameters is given in Chapter 4.

2.4 INITIALIZATION

There is a total of 200 consumption goods firms and 50 capital goods firms, and each occupies one slot in the grid. Banks and the central bank occupies arbitrary slots, and their addresses coincide with those of the firms. So, the grid has 250 patches. There are 250 capitalists, each of them linked with a unique firm. The total of workers is 3,000.

Figure 2. The interface guide of NetLogo with the initial parameters of the model set



Source: http://modelingcommons.org/browse/one_model/5070#model_tabs_bowse_info

3 CHECKING FOR ROBUSTNESS

This chapter explores the statistical properties of the model and compares them with the properties of observed series. The checking for robustness is done in two major ways: 1) looking for the statistical properties from the series, and 2) checking whether the simulated time series are capable of reproducing some stylized facts about the interbank structure reported in the literature. The robustness check document in full is provided in Appendix A, where is also contemplated the implementation of submodels and subroutines of the model.

3.1 STATISTICAL PROPERTIES

The observed economic time series we are interested in are: GDP, investment, consumption, and unemployment. We consider these four because they are the series employed in related works to check for agent-based macroeconomic model's robustness. These series are collected from the FRED database under the respective codes: GDPC1; LRUN64TTUSQ156N; DPCERO1Q156NBEA; B006RO1Q156NBEA. For each series, we apply the HPfilter to detrend the series. The results in Table 1 are for the cyclical component of such observed time series.

As can be seen, all the series present a high first autocorrelation, a property absent from the simulated times series at the beginning of the modeling process (Table 2). However, for the model completed with all the process included it is possible to see that the simulated times series also show a high first lag autocorrelation and the standard deviations are also close to the observed series, as shown in Table 3 and Table 4. One important point we are interested in is the capacity of the model to endogenously create crises. We define a crisis as a period where the unemployment rate overshoots 15 percent. In an initial stage, the series extracted from the model do not show emergence of crises. But after the insertion of the interest rate routines (Table 2, line 3), it is possible to observe crises. The last step of the modeling process is the introduction of the interbank market; after that, crises still emerge.

While Table 2 summarizes the data only for real GDP, the next two tables show the results for all simulated times series; they also show similarities with the observed series. The initial test is for the core of the model, before the implementation of the routines that make the model capable to simulate monetary policies. In Table 3, we see the results for the simulated time series after the inclusion of the first experiment routine (conventional monetary policy). That experiment is run for four different sets of parameters to study the implications of a conventional monetary policy. All of them pass the robustness check.

Table 1. Standard deviation and first lag autocorrelation of the cyclical component of the observed time series. The data have been downloaded from FRED, quarterly data range from 1955 to 2015

Observed series	Standard deviation	1st lag ACF
GDP	2.22	0.798
Investment	11.32	0.738
Consumption	1.68	0.747
Unemployment	16.81	0.842

Source: FRED.

Table 2. Summary of robustness check for a few submodels

Submodel inclusion	Crisis?	1st lag ACF (GDP)
Price decision	No	0.259
Retail bank	No	0.350
Interest rate update	Yes	0.634
Interbank market	Yes	0.613

Source: the author (2019).

Table 3. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series for conventional monetary policy. Both the autocorrelation and the standard deviation are the average over 10 runs. From 2,500 run periods, only the last 2,000 are considered to compute statistics.

Experiment	GDP		Investment		Consumption		Unemployment	
	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF
Pre-Volcker	1.57	0.58	29.0	0.37	1.04	0.08	34.4	0.35
V.-Greenspan	1.58	0.56	22.6	0.24	1.00	0.12	35.5	0.36
Post 1982	1.72	0.58	21.3	0.33	0.99	0.10	35.8	0.31
Post ZLB	1.51	0.57	25.2	0.37	0.99	0.15	34.8	0.35

Source: the author (2019).

The second set of parameters is run to simulate a non-conventional monetary policy. They are shown in Table 4. Again, we check the first lag autocorrelation and the standard deviation of the series for the four sets of parameters. The results can be compared with the values in Table 1.

Table 4. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series for non-conventional monetary policy experiments. Both the autocorrelation and the standard deviation are the average over 10 runs. From the 2,500 run periods, only the last 2,000 are considered to compute statistics.

Experiment	GDP		Investment		Consumption		Unemployment	
	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF
1st Policy	2.61	0.66	12.5	0.50	1.20	0.35	19.2	0.40
2nd Policy	2.76	0.64	14.5	0.46	1.21	0.36	22.1	0.37
3rd Policy	2.97	0.65	15.3	0.49	1.15	0.37	23.0	0.36
4th Policy	2.39	0.64	11.7	0.42	1.17	0.39	22.3	0.42

Source: the author (2019).

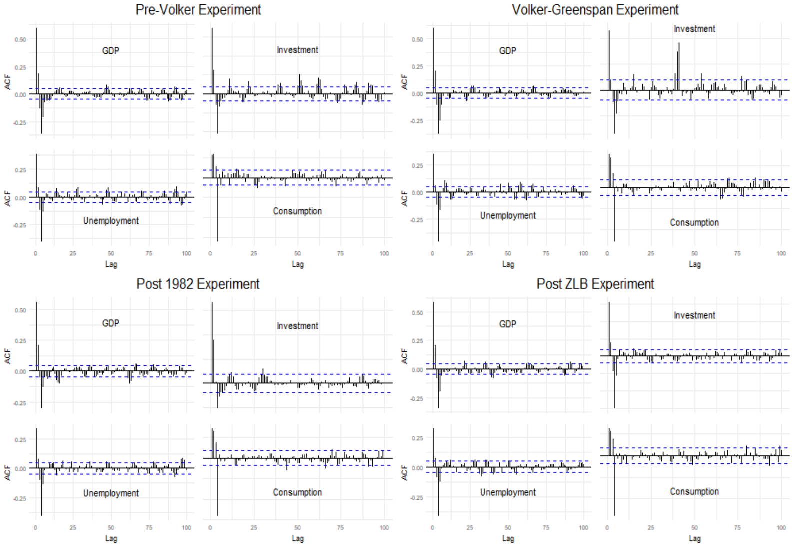
To visualize the dispersion of the autocorrelation of our series, we plot the first 100 lags for a sample of each set of parameters. Figure 3 shows the autocorrelations of the model for the experiments of a conventional monetary policy. Apart from investment series, all the other series do not show high significant autocorrelation. For at least two samples of the experimental data, the investment series presents significant autocorrelation for higher than 30 periods.

For the samples of the autocorrelations employed to explore the second set of parameters (Figure 4) which simulates non-conventional monetary police, the results continue to be the same, with the series of investment showing the largest significant autocorrelation values.

3.2 INTERBANK MARKET PROPERTIES

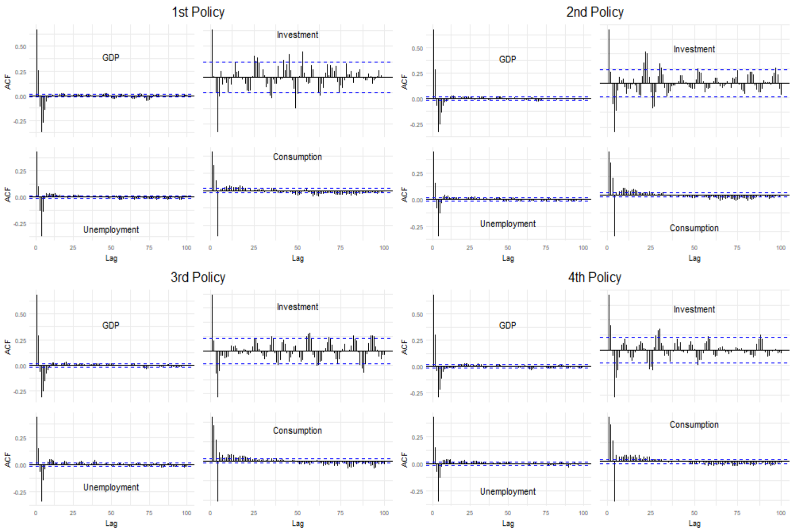
One more property of the model is of vital interest: the interbank market dynamics. That is because in the last world financial crisis there was credit restriction between the banks, leading many banks to incur in insolvency processes. According to Gertler at al. (2016), the culprits are wholesale banks that built up reserves of short-term contracts and provided loans of long-term returns. As for the retail banks, these just offered short-term credit after receiving deposits from households. The retail banks' demand for long-term loans was supplied by the wholesale banks, which did not cash in deposits from households. Wholesale banks offered credit to firms in the credit market and only received money from retail banks from whom they built their liabilities.

Figure 3. Sample of autocorrelation functions for a conventional monetary policy experiment. Results are picked from a single random simulation



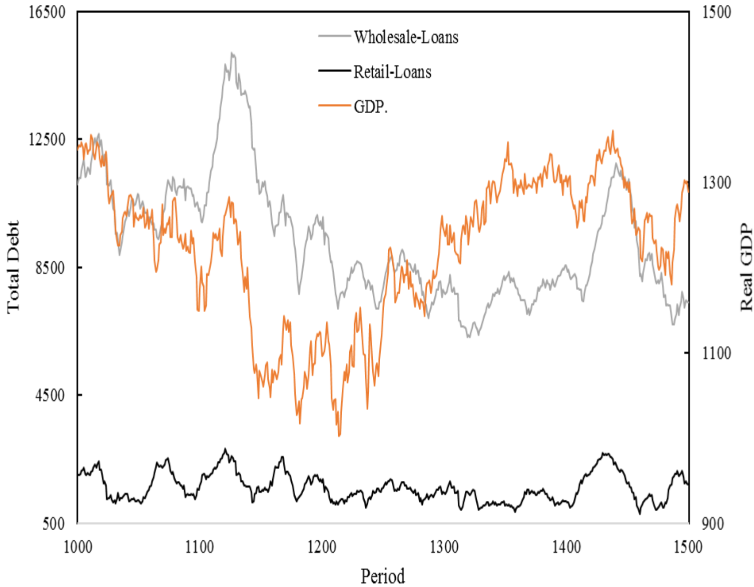
Source: the author (2019).

Figure 4. Sample of autocorrelation functions for a non-conventional policy experiment. Results are picked from a single random simulation



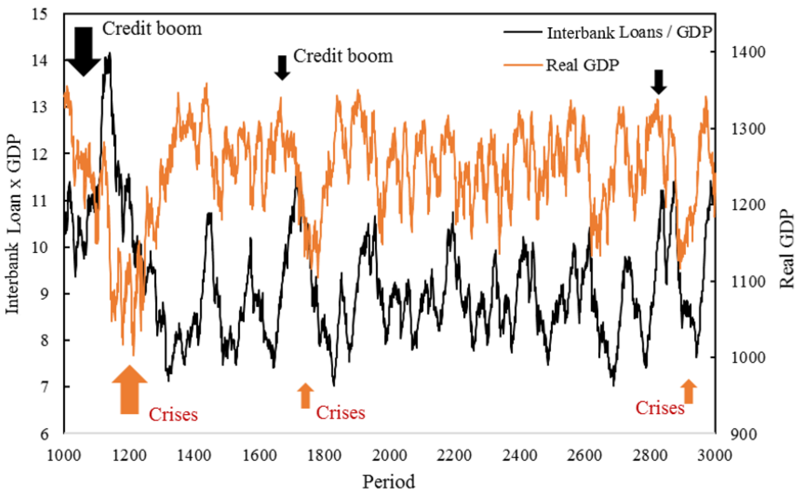
Source: the author (2019).

Figure 5. Total debt, retail and wholesale loans, and real GDP, from a single simulation



Source: the author (2019).

Figure 6. Interbank loan and GDP. The crisis' period is preceded by a boom in credit. This is a sample from a single simulation



Source: the author (2019).

In a boom, wholesale banks are assured the inflow of money is enough to repay their debts. The installments received and the interests received are satisfactory. However, when friction is added into this process, the problem begins. If some of the firms do not honor their debts with the wholesale banks, these cannot afford to repay their short-term debts to retail banks. Retail banks retaliate and cut new credit for the wholesale banks. That is when the liquidity plummets. This affects the interbank spread, and then the real side of the economy (Curdia et al., 2010).

Figure 5 shows the total of credit supplied by the banks to the firms in the model. Wholesale banks have the lowest installment debt rates, firms prefer to borrow from them. Wholesale banks' loans have the highest impact on simulations, by causing booms and crashes. The dynamics of credit availability to firms from wholesale banks emerges as a result of the liquidity of interbank credit, as those need the retail banks' money to supply the system. Consumer goods production firms (C-firms) need credit to invest. They have a probability to invest each period, and if they invest in a determined period, quantity invested should be enough to satisfy their needs for the next periods. Often firms do not have available money enough to make the desired investment and resort to the credit market for loans. If the C-firms do not have access to credit, their investments are most likely to be reduced due to the money shortage. This affects the capital goods firms (K-firms) because their demands are reduced. Both sectors fire workers during this process. Once there is capital shortage from the C-firms, total production is reduced and workers are fired. Moreover, the K-firms face lower demand and now need fewer workers.

Figure 6 shows the behavior of the interbank credit and real GDP. As related to the literature there is a shrunk of interbank credit preceding the fall of real GDP. That is, the financial crisis in the model is in accordance to the related mechanism in a real-world financial crisis, where a financial liquidity shortage precedes the impact on the real economy. Our model provides a narrative for why this occurs.

4 POLICY EXPERIMENTS

We consider two major experiments. The first one examines the influence of the parameters of Taylor's rule on the outputs of the simulated economy. This situation corresponds to a conventional tool being used by the monetary authority. The other one, related to non-conventional tools, examines the situation where bad assets are purchased during crisis times, and the central bank intervenes to buy assets from wholesale banks when it finds this appropriate.

4.1 CONVENTIONAL MONETARY POLICY EXPERIMENT

In this experiment the risk free interest rate is endogenous, that is, the central bank uses Taylor's rule to choose the risk free interest rate. Which parameters should we consider in this experiment?

The original Taylor experiment is quite difficult to be extended to others periods than that set in Taylor (1993). As pointed out by Clarida et al. (2000) and Orphanides (2003), the original work replicates well the moves from 1987 to 1992, but not before. Moreover, later periods should also be considered. Clarida et al. (2000) replicate the experiment for later periods and for periods that preceded 1987. They realize that the monetary authority had been changing their balance between monetary stability and output. As the original experiment, they consider data from the US and measure the response of the US monetary authority over time. They analyze data from the end of the World War II to the late 90's. Whoever was the FED's chairman is considered to define the periods of study. The first estimated period is dubbed Pre-Volcker. Volcker assumed the FED in 1979 and needed to deal with the high inflation of the post-oil shock period. For the pre-Volcker period, estimation of the parameters used in Taylor's rule is below one for both inflation and output. To the post-1979 Volcker-Greenspan era, attention to inflation raised and the parameter for inflation is above one, while the parameter for output remains below one. For the post-1982 period, the parameter which tracks output shrinks to almost zero, while the inflation parameter increases to above two.

After the 2008 crisis, policymakers' direction changed. The attention to output increased, while the preoccupation with inflation decreased. Kim and Seth (2017) examine the behavior of the monetary authority after that period, named the zero lower bound (ZLB). They compute data from 2009 to 2014, when the Fed kept the rate interest between zero and 25 basis points. Because conventional data could not be used in such a situation, the authors used alternative data from professional forecasters to evaluate what a possible monetary policy could be running during the ZLB period. Their results indicate that, in the opinion of forecasters, the response of the Federal Reserve to inflation had decreased and the response to unemployment (and output) had increased.

Although the aforementioned studies use different methods to estimate their parameters for monetary policies, we still believe they are useful to employ as an input in our model to test the parameters' impact on the simulated economy. These sets of parameters are shown in Table 5. For each of the four sets of parameters, the model is run 10 times. Each simulation has 2,500 periods, and the data is collected at the end of each simulation. One period is called "in crisis" if in that period the unemployment rate overshoots 15 percent. Figure 9 to Figure 12 show samples of a single simulation for each of the experiments.

Table 5. Summary of the experiments and parameters used in the simulations for the conventional monetary policy experiment

Experiment label	α_π	α_y
Pre-Volcker*	0.86	0.39
Volcker-Greenspan*	1.72	0.34
Post-1982*	2.55	0.00
Post-ZLB**	0.00	1.30

* Parameters from Clarida et al. (2000); ** Parameters from Kim and Seth (2017).
Source: the author (2019).

The unemployment rate for the entire simulation is shown on top of Figure 9. The gray area represents a 400-period window selected to be scrutinized in detail (periods from 900 to 1,300). Below the first plot there are four others, showing real GDP, investment, consumption and also unemployment for the window chosen. In this random example from the pre-Volcker's experiment, we have several cases where the unemployment rate grows above 15 percent, thus characterizing crises. One major crisis occurs around period 600, and another around period 1,250. The second is the one which is highlighted in Figure 9. GDP plot shows that real GDP falls to the minimum point just after 20 periods following the outset of the initial crisis; this is fast contraction. The same is seen in the consumption series. The investment decreases to stay near zero during the crisis times. While the fall is fast, recover is sluggish. GDP only reaches the pre-crisis level after 100 periods. The impact on unemployment is similar, which means many more periods are needed to recovery than those that destroyed jobs. The other three figures show similar patterns.

Figure 7 and Table 6 show the total number of crises per simulation throughout the conventional monetary policy experiment. The pre-Volcker experiment, which has both inflation and output parameters below one, shows an average of 52 periods in crisis per simulation. The Volcker-Greenspan experiment has a similar value for the output parameter, but a higher value for the inflation parameter, $\alpha_i = 1.72$. Despite that, such an experiment shows a lower number of crises, with an average of 30 crises per simulation. The post-1982 experiment is the one with the poorest performance in terms of total number of crises: the average is 86 periods in crisis per simulation. The post-1982 experiment is set with zero attention to output and 2.55 to inflation. Besides that, the model still runs without exploding, and its set of parameters passes the robustness check of the previous chapter. With 10 crises per simulation as average, the post-ZLB experiment is the one with better performance among the four. Remember that the post-ZLB has $\alpha_\pi = 0$ and $\alpha_y = 1.3$.

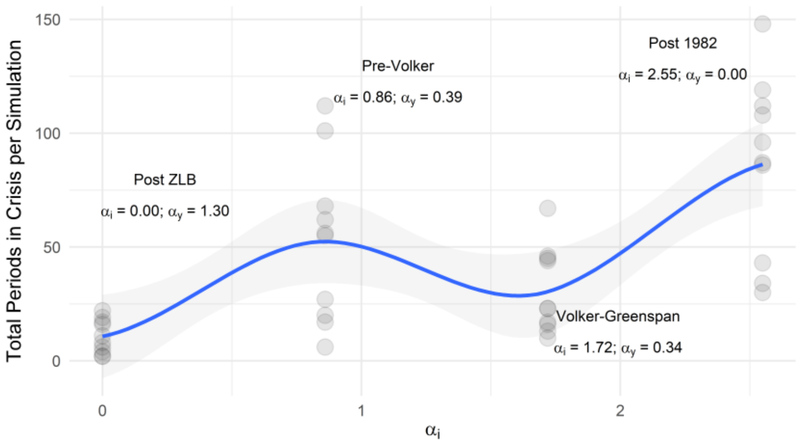
Table 6. Summary of the total number of crises for the conventional monetary policy experiment

Experiment label	α_π	α_y	Total number of crises per simulation
Pre-Volcker	0.86	0.39	52 (±29)
Volcker-Greenspan	1.72	0.34	30 (±11)
Post-1982	2.55	0.00	86 (±37)
Post-ZLB	0.00	1.30	10 (±6)
Average			44

Source: the author (2019).

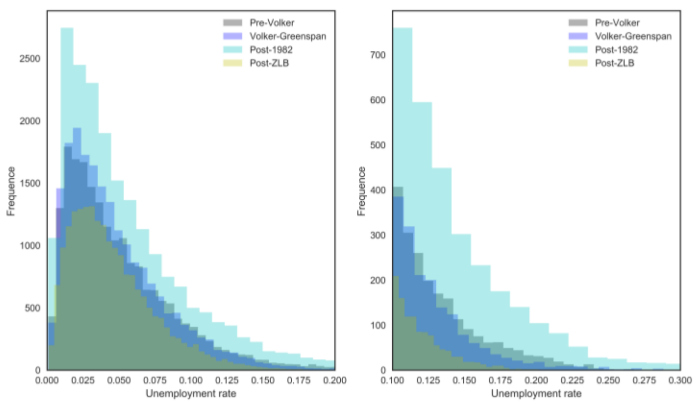
Figure 7 plots the total number of crises per experiment. The parameter for inflation (α_π) is in *x*-axis. The policy with the minimum value for α_π is shown at the extreme left (post-ZLB) and the policy with the highest value, at the extreme right (post-1982). These two experiments also have, respectively, the lowest and the highest number of crises per period. However, the relation between the total number of crises and α_π cannot be considered linear. The interaction between the two alphas does not lead to a linear fit across the experiments.

Figure 7. Crises across the conventional monetary policy experiments. Each simulation runs for 2,500 periods and the last 2,000 are used to compute statistics. We consider a total of 10 simulations per experiment.



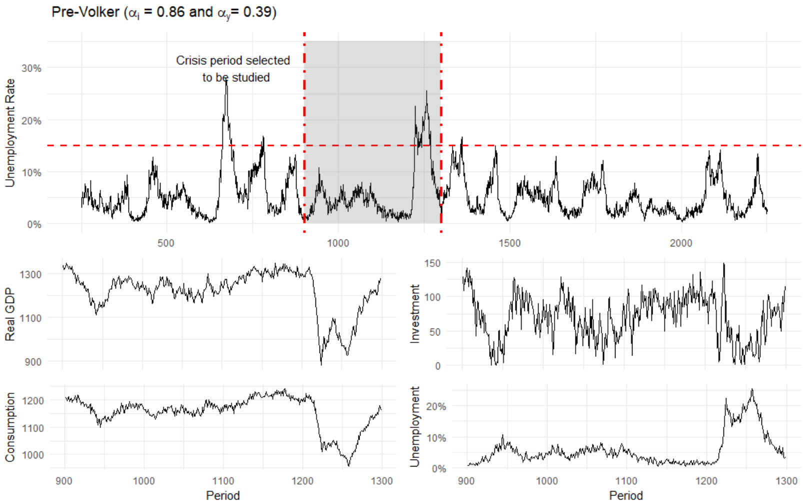
Source: the author (2019).

Figure 8. Histogram of the unemployment rate across the conventional monetary policies experiments. We consider a total of 20,000 periods per experiment (10 runs with 2,000 periods each). On the left, the histogram for total unemployment uses bins = 50. On the right, the final tail, it uses bins = 25



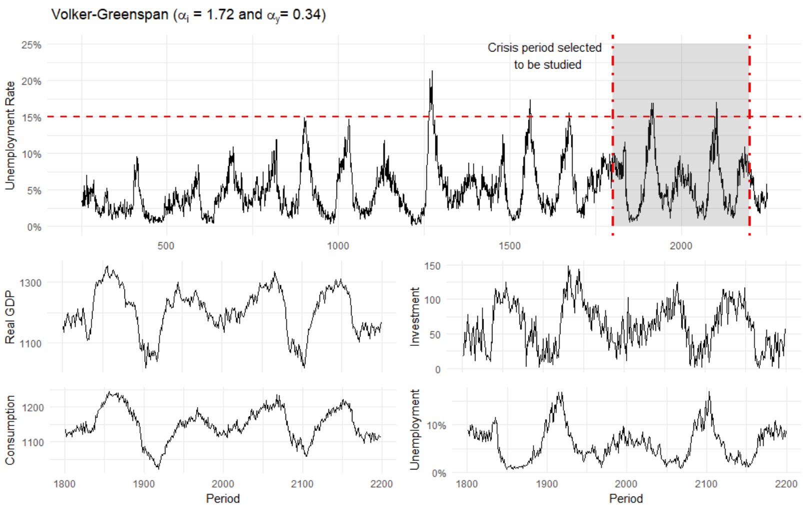
Source: the author (2019).

Figure 9. Highlight of a crisis period from a sample in the pre-Volcker experiment



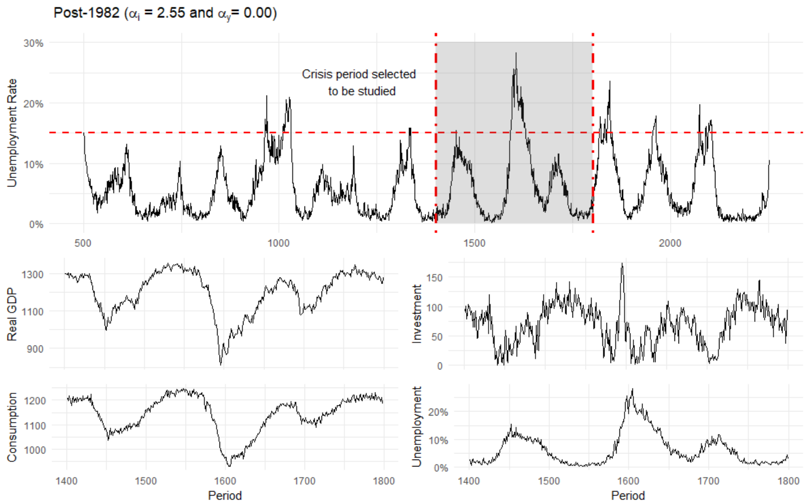
Source: the author (2019).

Figure 10. Highlight of a crisis period from a sample in the Volcker-Greenspan experiment



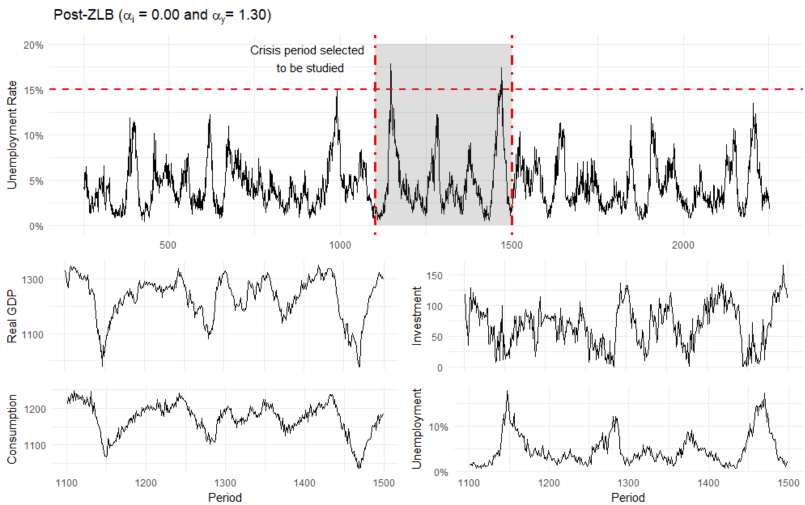
Source: the author (2019).

Figure 11. Highlight of a crisis period from a sample in the post-1982 experiment



Source: the author (2019).

Figure 12. Highlight of a crisis period from a sample in the post-ZLB experiment



Source: the author (2019).

4.2 NON-CONVENTIONAL MONETARY POLICY EXPERIMENT

Now we deal with a non-conventional set of monetary policies. First, we search in the literature to find a way to perform the experiments. Non-conventional policies were widely used across the world in the post-2008 crisis. Each central bank applied these policies their own way, but the most common method was intervention in financial markets through purchase of private assets directly from the banks (Fawley and Neely, 2013). Central banks differed in the intensity of use of such a method. The Central Bank of Japan (BoJ) bought assets till 37.5 percent of GDP. The Bank of England (BoE) accumulated a total of assets equivalent to 26.3 percent of GDP. This nearly matched the number of the Fed (22.1 percent). However, the European Central Bank (ECB) did much less and stayed in 3.5 percent of GDP. To set our experiments we choose to use 20 percent of GDP as a limit for the central bank to hold private assets, a figure only 2.3 percent lower than the average practiced by the real-world central banks.

Table 7. Total of private assets held by central banks as a result of purchase programs as a percent of GDP

Central bank	Percent of GDP
FED	22.1
BoE	26.3
ECB	3.5
BoJ	37.5
Mean	22.3

Source: Fawley and Neely (2013).

The central banks did not use non-conventional policies in a row. They only resorted to them when the circumstances were bad (this meaning high unemployment) and the conventional policies had already shown signs that they were not working. The same attitude is adopted here in our experiments. We choose four start points for the central bank to be authorized to initiate a non-conventional monetary policy. These points are triggered by the unemployment rate. Starting with a minimum of 8 percent of unemployment, and then increasing this threshold by 2 percent. In the last non-conventional policy, the central bank is only allowed to buy private assets after 14 percent of unemployment, as summarized in Table 8.

Table 8. Summary of the experiments and parameters used in the simulations for the asset purchase experiment

Experiment	ψ $(policy\ starts)$*	χ $(limit\ purchase)$**
1st Policy	8%	20%
2nd Policy	10%	20%
3rd Policy	12%	20%
4th Policy	14%	20%

* Unemployment rate; ** Percentage of real GDP.
Source: the author (2019).

For each of the non-conventional policies parameters, the model is run 10 times. Each simulation has 2,500 periods, and data is collected at the end of each simulation. Again, a period is called “in crisis” if in that period the unemployment rate is above 15 percent. Figure 15 to Figure 18 show the samples of a single simulation for each of the experiments.

The entire series of unemployment for a selected random simulation is shown on top of Figure 15. This plot displays the results of a simulation using the first policy where the threshold for the central bank to start purchasing private assets is 8 percent. Although unemployment goes above 10 percent several times, it never reaches 15 percent. The gray shaded area in Figure 15 highlight 400 periods selected. The four others plots show the series of GDP, consumption, investment, and unemployment for the same 400 periods. Contrasting with the conventional policy experiment, now GDP does not plummet. It starts to fall but short spikes allow it to avoid a quick decline as in the conventional policy experiment. The investment series also reaches low values during turbulences times, but it does not stay for too long near zero, as is the conventional policy experiment. We examine other series for this first policy only to realize these patterns remain. This policy was the only one capable to avoid the emergence of crises.

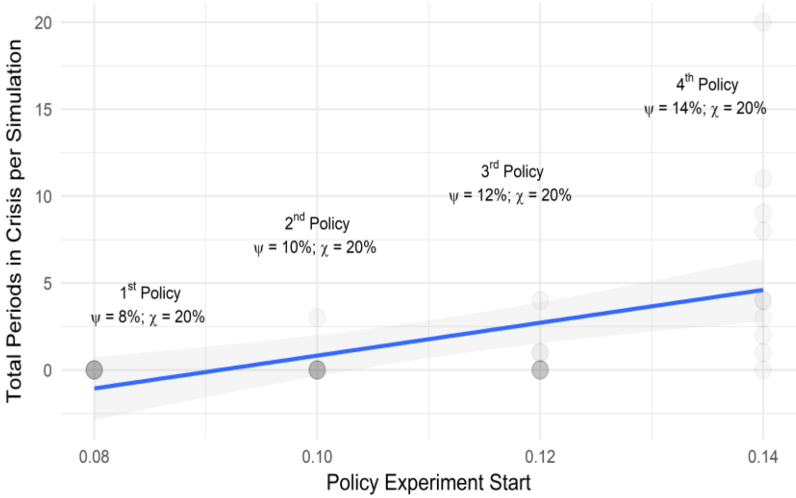
This non-conventional policy loses effectiveness as we move the starting point forwards. Indeed, the last fourth policy is the least effective. Figure 18 shows an example of this experiment. The unemployment rate (top of Figure 18) reaches 15 percent and for several periods stays there. The four plots below show GDP, consumption, and investment. Despite the presence of crises, the behavior in the GDP fall is different. The slope of the fall is quite similar to the slope of the recovery period. The last three non-conventional policies are not capable of avoiding crises, however they dampen the crises, as consumption and GDP fall slower than in conventional policy experiments.

Table 9. Summary of the total number of crises for the non-conventional monetary policy experiments. Each simulation considers 2,500 periods with the last 2,000 used to compute the statistics. We run ten simulations for each experiment

Experiment label	ψ	χ	Total number of crises per simulation
1st Policy	8%	20%	0 (-)
2nd Policy	10%	20%	1 (±1)
3rd Policy	12%	20%	2 (±2)
4th Policy	14%	20%	7 (±3)
Average			4.75

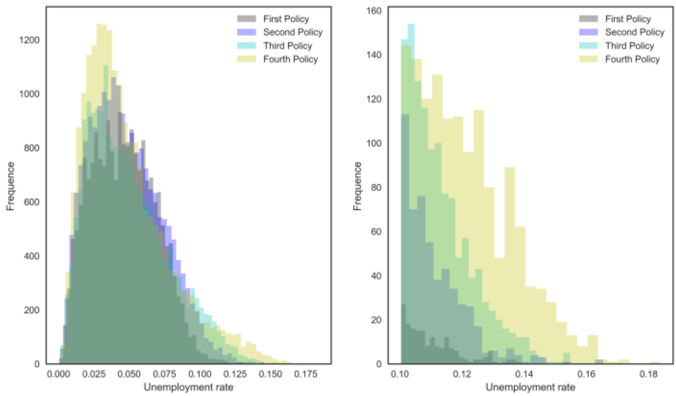
Source: the author (2019).

Figure 13. Crises in the private asset purchases experiments. The unemployment rate as a percentage of GDP is used as a start point. Each simulation has 2,500 periods and the last 2,000 are used to compute the statistics. We consider a total of 10 simulations per experiment



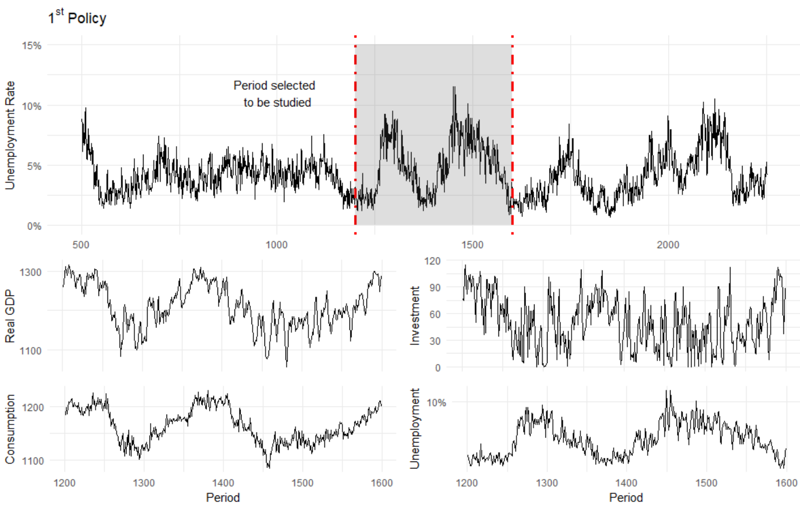
Source: the author (2019).

Figure 14. Histogram of the unemployment rate across the non-conventional monetary policy experiments. We consider a total of 20,000 periods per experiment (10 runs with 2,000 periods each). On the left, the histogram for unemployment considers bins = 50. On the right, the final tail, it considers bins = 25



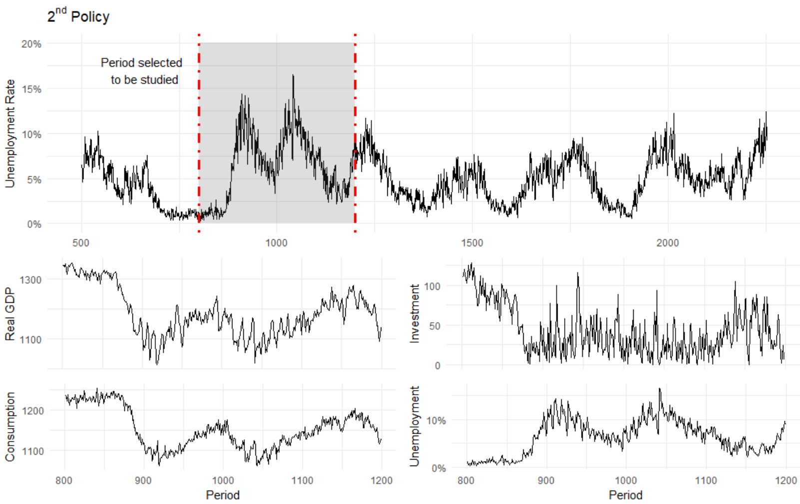
Source: the author (2019).

Figure 15. Highlight of a sample in a non-conventional monetary policy experiment ($\Psi = 8\%$; $\chi = 20\%$)



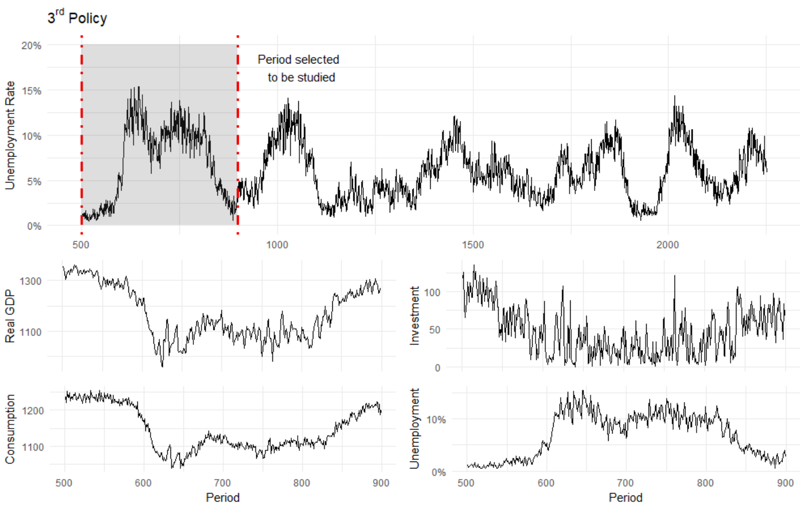
Source: the author (2019).

Figure 16. Highlight of a sample in a non-conventional monetary policy experiment ($\Psi = 10\%$; $\chi = 20\%$)



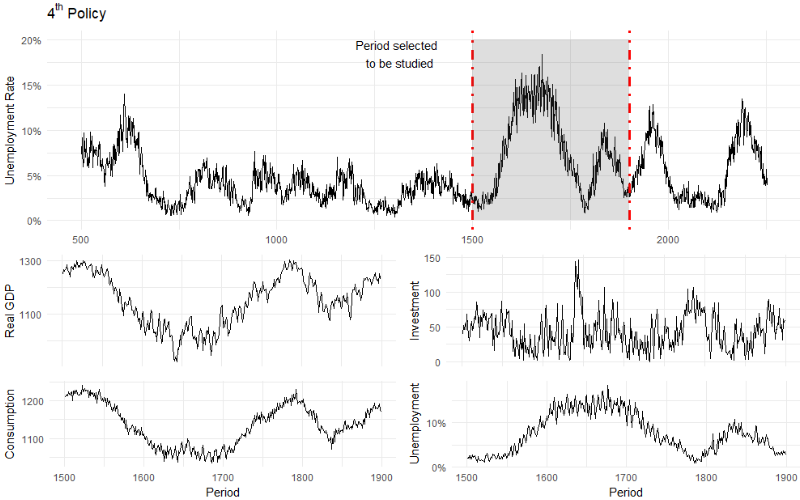
Source: the author (2019).

Figure 17. Highlight of a sample in a non-conventional monetary policy experiment ($\Psi = 12\%$; $\chi = 20\%$)



Source: the author (2019).

Figure 18. Highlight of a sample in a non-conventional monetary policy experiment ($\Psi = 14\%$; $\chi = 20\%$)



Source: the author (2019).

5 FINAL CONSIDERATIONS

The purpose of this work is to examine monetary policies in the presence of crises. A total of eight policies are simulated using our agent-based macroeconomic model with credit and capital. One of these policies is capable of suppressing the emergence of crises altogether (Table 9). The eight policies are divided into two groups, conventional monetary policy and non-conventional monetary policy. In general, the set of non-conventional policies shows a better performance in minimizing crises relative to the conventional ones.

Table 10. Summary of the experiments. The risk free interest rate management uses as a parameter the attention to inflation α_π and output α_Y. The private assets purchase experiments consider the unemployment rate as a triggering point to launch the alternatives policies

	Experiment label	Periods in Crisis per simulation	Capable of suppressing crisis?
Conventional policy	Pre-Volcker	52 (±29)	No
	Volcker-Greenspan	30 (±11)	No
	Post-1982	86 (±37)	No
	Post-ZLB	10 (±6)	No
Non-conventional policy	1st Policy	0 (-)	Yes
	2nd Policy	1 (±1)	No
	3rd Policy	2 (±2)	No
	4th Policy	7 (±3)	No

Source: the author (2019).

A closer look reveals that the differences between the policy performances in terms of unemployment is low. The average unemployment for the conventional policies is 4.975 percent, while that for the non-conventional policies is 4.75 percent, a difference lower than 25 basis points. What made the difference between being successful or not, in terms of preventing crises, is the standard deviation. While the top policy (first policy) has a standard deviation of 0.022, the worst performance (post-1982) has a standard deviation of 0.047. The maximum unemployment observed for the post-1982 experiment is 43.9 percent, while for the first policy is 13.9 percent.

Table 11. Mean, standard deviation, and quartiles values for the unemployment rate series across the experiments

Experiment Label	Total Period	Mean	Std. deviation	Max	25%	50%	75%
Pre-Volcker	20,000	0.050	0.038	0.274	0.022	0.040	0.069
Volcker-Greenspan	20,000	0.048	0.035	0.288	0.021	0.039	0.065
Post-1982	20,000	0.056	0.047	0.439	0.022	0.042	0.075
Post-ZLB	20,000	0.045	0.029	0.201	0.023	0.039	0.061
1st Policy	20,000	0.046	0.022	0.139	0.028	0.045	0.063
2nd Policy	20,000	0.047	0.025	0.165	0.028	0.044	0.065
3rd Policy	20,000	0.049	0.028	0.154	0.026	0.043	0.066
4th Policy	20,000	0.048	0.029	0.183	0.026	0.041	0.063

Source: the author (2019).

As a take-home message, our model shows a potential for agent-based macroeconomic models to examine monetary policies. A same agent-based macroeconomic model is capable of considering both conventional monetary policies (as those currently practiced by central banks) and non-conventional monetary policies. A same framework can be used to compare the impact of monetary policies on the macroeconomic variables.

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APPENDIX A - TRACE document

TRACE document

This is a TRACE (TRAnsparent and Comprehensive model Evaluation) document that provides supporting evidence that our model is thoughtfully designed, correctly implemented, thoroughly tested, well understood, and appropriately used for its intended purpose (Grimm et al., 2014).

The rationale of this document follows and uses the updated standard terminology and document structure in Schmolke et al. (2010) and Grimm et al. (2014).

1. INTRODUCTION

The TRACE document we use is based on Grimm et al. (2014). The objective of this document is to show the steps we make to achieve the final version of our model, the results of the robustness test we implement, and the results collected for analysis of the model. The complete description of the model can be found as a supplementary material, which is written following the ODD protocol (Grimm et al., 2010).

To help the reader, we consider the strategy of separating the description in one file and the operation construction in another. One may be interested only to know which are the hypothesis of the model, or which are the equations that rule the behavior of agents. Here, the ODD can fulfill expectations. The ODD can also be enough to reproduce the model. If someone wishes to rewrite the code, the ODD description must be sufficient. However, for those who want to see whether the model is correctly implemented, and the robustness of the result is believable, then this TRACE document is the place.

We will avoid reproducing here the details of the ODD document. Yet, a full understanding will still need the reading of the ODD description of the model.

First, we quickly review the model and present its basic goals. Secondly, we present actual data to point where the model should go. Then, we present the implementation and verification, that is, we show the tests of submodels, which errors appear and how these had been fixed. The output inspection is shown in a separate section. All these sections were written during the process of coding, that is, whenever it is possible to run a robustness analysis or the check the step of some submodel, that is done and registered in here.

2. MODEL DESCRIPTION

The aim is to build an agent-based macroeconomic model with capital and credit (ABMM-CC) that considers an interbank market, where credit is split between a retail bank and a wholesale bank. There is a consumption market, a job market and a capital goods market. The model must be able to reproduce some stylized facts, such as the series of GDP, unemployment, consumption, and investment.

The initial conditions and values of the parameters are shown in Table 2.1. The full description of the model can be found in Appendix B.

Table 2.1. Initial conditions and parameters

Parameters	Description	Value
T	Number of periods	2500
H	Number of workers	3000
F_c	Number of consumptions firms	200
F_k	Number of capital goods firms	50
B_r	Number of retail banks	1
B_w	Number of wholesale banks	1
Z_e	Number of firms approached by unemployed workers	5
Z_c	Number of consumption firms approached by consumers	2
Z_k	Number of capital goods firms approached by a C-firm	2
ε	Memory parameter or human wealth	0.96
τ	Dividend-payout ratio	0.20
χ	Fraction of wealth allocated to consumption	0.05
r	Initial risk free interest rate	0.01
ρ	Quantity adjustment parameter	0.90
η	Price adjustment parameter (random variable)	U(0,0.1)
μ	Bank gross markup	1.20
α	Productivity of labor	0.50
κ	Productivity of capital	0.33

Parameters	Description	Value
γ	Probability of investing	0.25
ζ	Banks' loss parameter	0.002
θ^r	Installment of the retail bank	0.05
θ^w	Installment on debt of the wholesale bank	0.025
δ	Depreciation of capital	0.02
ν	Memory parameter of investment	0.50
$\overline{\omega}$	Desired capacity utilization rate	0.85
w	Wage	1.00
D_1^f	Initial liquidity of all firms	10
K_1	Initial capital	10
Y_1^c	Initial production of consumption goods firms	5
Y_1^k	Initial production of capital goods firms	2
E_1^b	Initial equity of all banks	3000
E_1^h	Initial households' personal assets	2
r^*	Natural interest rate	0.01
α_π	Taylor' rule parameter for inflation	[0.0, 2.5]
α_Y	Taylor' rule parameter for output	[0.0, 1.3]
Ψ	Threshold for starting the private asset purchase policy	(0.08, 0.14)
χ	**Private asset purchase parameter of the central bank**	**0.20**

Source: the author (2019).

3. OBSERVED SERIES OF ACTUAL DATA

As observed, it is expected that the model can reproduce some stylized facts. The series of GDP, unemployment, personal consumption, and investment are available on the site of the Fed of St. Louis. We used the following code series for each of this series of data: GDPC1; LRUN64TTUSQ156N; DPCERO1Q156NBEA; B006RO1Q156NBEA. The frequency of these series is quarterly. We examine the standard deviation and the first autocorrelation of the cyclical component of such series.

The series of actual data have 140 events, from the first quarter of 1955 to the last quarter of 2015. The HP filter was applied to the series to isolate the cyclical components. The same procedure will be applied to the simulated series. The results from the actual data analysis are shown in Table 3.1.

Table 3.1. Standard deviation the first lag autocorrelation of the cyclical component of the observed time series, quarterly data range from 1955 to 2015

Observed series	Standard deviation	First lag autocorrelation
GDP	2.22	0.798
Investment	11.32	0.738
Consumption	1.68	0.747
Unemployment	16.81	0.842

Source: FRED.

4. SUBMODELS IMPLEMENTED AND VERIFICATION

This section shows the construction of the submodels, the sequences they have been implemented, the tests run to assure us they are running well and make us confident the model is well built.

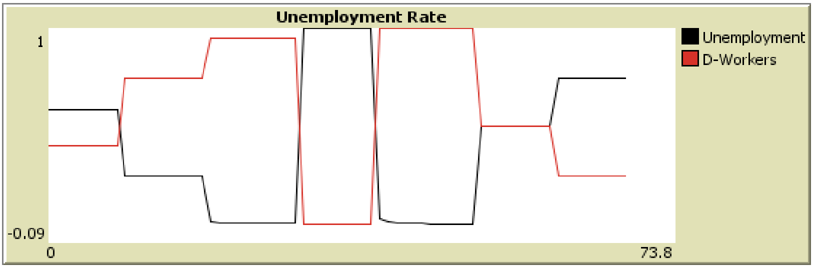
4.1 The Job Market

To check this submodel, we create 3,000 workers and 250 firms. In each period a firm demands some amount of labor. Initially, the demand for labor is set exogenously. Figure 4.1 shows the resulting unemployment for each of level of demand set.

Each worker can approach five firms per period when trying to find a vacancy position. If they find a job, their status changes for hired and their income becomes equal to their current wage. Labor is homogeneous as is the wage, then a worker accepts the first firms' offer she receives; and the firm contracts the first worker who applies for a vacancy position.

The search mechanism in this submodel is tested using an exogenous demand for labor. When this is zero, none of the workers is hired. When the demand for labor overshoots some high threshold value, the unemployment rate shrinks to zero. The mechanism for dismissing workers is also evaluated. Figure 4.1 show all these scenarios. As can be seen, the unemployment rate rises when the demand for labor decreases, and vice-versa.

Figure 4.1. The unemployment rate and the workers desired by firms. When desired workers are maximum, there is no unemployed worker, and when there is no desire for labor any worker can be hired



Source: the author (2019).

Table 4.1 Results for the unemployment rate and total income for simulations with 3,000 periods for just one kind of firm and the demand for labor set exogenously. Results show the state of the agents in the last period simulated

Demand for labor	Unemployment	Total income received by workers (10^3)	Expected income (10^3)	Appropriate?
0.00	1.00	0.00	0.00	Yes
0.10	0.83	0.17	0.17	Yes
0.20	0.75	0.25	0.25	Yes
0.30	0.67	0.33	0.33	Yes
0.40	0.58	0.42	0.42	Yes
0.50	0.50	0.50	0.50	Yes
0.60	0.33	0.67	0.67	Yes
0.70	0.25	0.75	0.75	Yes
0.80	0.17	0.83	0.83	Yes
0.90	0.08	0.92	0.92	Yes
1.00	0.00	1.00	1.00	Yes

Source: the author (2019).

Another important thing to notice is whether the income of workers is updated accordingly. Here, the total income of workers can be compared to the unemployment rate. Source: the author (2019).

Table 4.1 displays the simulation results of the demand for labor varying from zero to one. At the end of each simulation, we find the results for unemployment and total income appropriate.

We report there was an error in the code in our first attempt. Vacancies were not updated after a firm hired a worker and, a result, there was no unemployment. And, apart from the null demand, all the other values for the demand of labor created full employment and thus maximum incomes. The results shown in Source: the author (2019).

Table 4.1 present the corrected version of the submodel, with this problem fixed.

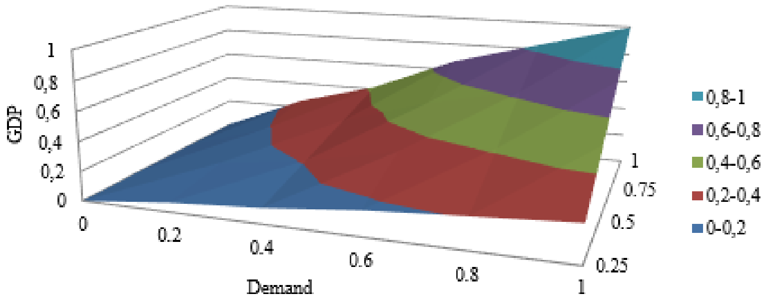
4.2 Production of C-Firms

Next, we intend to test the situation where the firms produced goods using only labor. While in the previous section firms could contract workers, now they can use this labor force to produce goods. The function is linear, labor is homogenous, and the productivity of labor is also homogeneous and constant over time. For this first exercise, we use an exogenous demand for goods. To sastify demand, firms have to employ the correct amount of labor force, and this makes the demand for labor endogenous.

Next, GDP enters the model for the first time. After the firms had produced according to their will, output is aggregated, and thus GDP measured. Here, we also need to check whether this procedure works correctly. Initially, only consumption goods firms (C-firms) using only labor as an input are considered. Capital goods firms are considered later.

Figure 4.2 shows the results for 240 simulations with different combinations of demand and productivity of labor for each of the 3,000 periods. The results are the average of ten simulations for a set of parameters. It was tested the response of GDP to variations of labor productivity, which started at 0.25 and increased until 1. GDP reacted well, thus confirming firms’ function of production was properly set. For demand, values from 0 to 1, the results for GDP were consistent as well.

Figure 4.2. GDP, demand and productivity of labor. GDP responds well in that it reacts to increases of both exogenously set demand and productivity of labor. Each simulation has 3,000 periods and values are the averages of ten simulations for each set of parameters



Source: the author (2019).

Table 4.2. Firms produce goods for an exogenous demand. Results for the ending of 3,000 periods with the productivity of labor constant at 0.50. The submodel is consistent, that is, unemployment rate, current income of workers, and production responded to the variations of demand

Demand	Production	Inventories	Current Income (10^3)	Unemployment (%)
0.0	0	0	0.00	1.00
0.2	375	375	0.75	0.75
0.4	625	650	1.26	0.58
0.6	1000	1000	2.00	0.33
0.8	1250	1250	2.49	0.17
1.0	1500	1500	3.00	0.00

Source: the author (2019).

So far there is no consumption of goods. Households supply labor but do not demand goods. So, the inventories of firms are equal to their production in Table 4.2. This changes if consumption is endogenous, as done later.

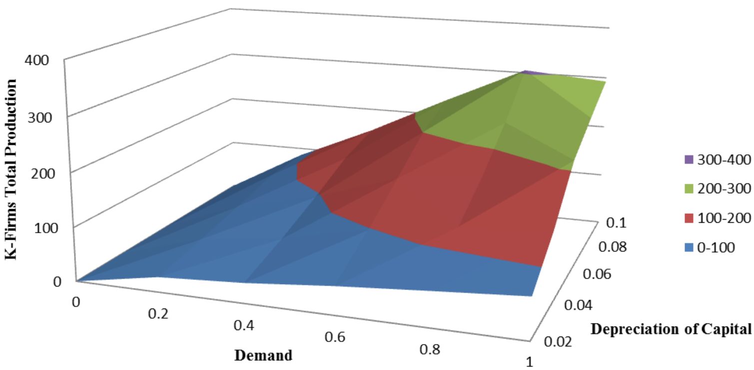
4.3 Production of K-Firms

Using the configuration of the previous exercise, now we include the capital goods firms. Firms now need to combine capital and labor to produce goods. If capital is abundant, a C-firm can produce whatever it wishes. In the presence of a restriction that calls for extra capital, a firm cannot produce the desired quantity.

The productivity of labor is taken as the same in both. The K-firm demands labor by using the same routine we tested before. Workers have no preference between the two groups of firms.

C-firms carry inventories from one period to another but this is not true for the K-firms. K-firms can store their unsold output to try to sell it the next periods. There is no price making and thus price is the same across firms. C-firms decide randomly from which K-firm to buy, because capital goods are homogenous.

Figure 4.3. Test of whether the production of K-firms respond to variation of the depreciation of capital and demand. The demand for consumption goods is set exogenously. To respond to this demand, the C-firms need to increase production and demand more capital goods



Source: the author (2019).

The capital employed by C-firms also depreciates. Thus, we should test whether the capital depreciation function works properly. To do this, we simulate different values of the depreciation of capital by considering the same demands. We expected this variation to increase the production in the K-firms, and was confirmed (Figure 4.3)

Table 4.3. Results for the test of the employment of workers by the K-firms, where the demand for consumption goods is exogeneous and the C-firms demand capital goods from the K-firms. Results show the means of the last period from 10 simulations with 3,000 periods each

Demand	GDP	Percentage of Workers in K-Firms	Percentage of Workers In C-firms	Unemployment
0.0	0.00	0.00	0.00	1.00
0.2	0.26	0.04	0.22	0.74
0.4	0.43	0.07	0.36	0.57
0.6	0.68	0.11	0.58	0.32
0.8	0.85	0.13	0.72	0.15
1.0	1.00	0.14	0.86	0.00

Source: the author (2019).

We also tested the interconnection of the functions to evaluate whether there are any misreading values between these interactions. For example, after the first round of simulations, the total investment realized by the C-firms was higher than the total production of all K-firms combined. That occurred because the function of search utilized by the C-firm did not update the value of investment correctly after a C-firm approached its suppliers. The C-firm has its need for capital and approaches two K-firms to try to buy capital goods. If there are no inventories in those two firms, they are not able to fully invest. Table 4.4 shows the results after this problem is fixed. With a depreciation of capital at 0.02 and the total capital stocks of the C-firms at 5,340, for example, the desired investment is higher than 100 per period. Variations occur from period to period, but the total investment is now always equal to the total sales of K-firms at the period.

Table 4 displays an example of a regular period.

Table 4.4. Checking whether the interconnected functions are running well. To keep their stock of capital, the C-firms need to invest, that is, they buy more capital. Results display an example of an ordinary period, where the total investment is equal to the sales of K-firms, and total sales are lower than the production of the K-firms.

GDP	Total investment	Production of the K-firms	Sales of the K-firms	Total capital stock of the C-firms
1500	85.39	86.88	85.39	5340

Source: the author (2019).

4.4 Revenues, Expenditures and Profits

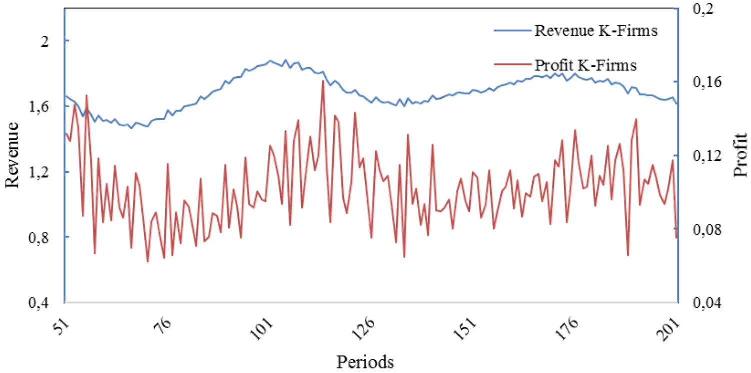
The objective of this section it to check the cash flows of the firms. We evaluate whether have updated their expenditures – wages and investment – and their revenues from sales. So far the model has only workers. Capitalists will be considered next. They will receive part of the profits of the firms; they can also use these profits when the firms need to be recapitalized. For while, we are interested in checking whether the mechanism of profit measurement is working well.

Table 4.5. Checking whether the functions of cash flows are running well. Firms update their revenues each period along with their expenses with employees and then compute the profit. Results display the means of each sector after 3,000 periods simulated

	C-firms	K-firms	Correct?
Revenue	2610.72	198.14	-
Payroll	2463.30	186.57	-
Expected profit (Revenue – Payroll)	147.42	11.57	-
Profit	147.42	11.57	Yes

Source: the author (2019).

Figure 4.4. Sum of revenues and profits from the K-firms. Profit is revenue less payroll



Source: the author (2019).

Each firm is scrutinized individually to check whether their functions are appropriate. Profit is defined as the revenue from sales less the expenses with wages. For the C-firms, demand is set exogenously. Whenever all the production of consumption goods was demanded (full employment), revenues of the C-firms matched production all production was sold. The aggregate situation is shown in Table 4.5. As can be seen, mean profit equals the expected value for them.

For the K-firms, demand is endogenous. Some fluctuations in their sales occur, thus changing their revenues. Figure 4.4 shows this, that is, swings in the total revenues received by the K-firms along with high variations of computed profit.

4.5 Household's Consumption

So far, households did not consume any goods. The demand for consumption goods was set exogenously. Now it is made endogenous. Households are assumed to have a consumption desire, which is based on their current income and is as a function of their human wealth. This hypothesis is based on the human life cycle hypothesis and has as a consequence the fact that a household can consume even when it has no current income.

For the first time, now we can compare some model's results with the stylized facts we propose at the beginning of this TRACE document; this comparative work is the objective of the next chapter of the document.

Each household approaches two C-firm in a given period. They evaluate the prices charged by those firms and then try to buy their desired quantities with the firm that has the better price. If the first firm does not have stocks available, a household attempts to buy at the second firm. If the total number of goods of both firms does not fulfill the desired quantity the household wishes, it ends up saving money (by consuming less than it planned), and this money can be used for it to consume in the future.

Table 4.6. Checking whether the consumption of households is equal to the sales of the C-firms. Results are collected in the end of the simulations, which have 3,000 periods each

Simulation number	Total consumption of the households	Total sales of the C-firms	Total production of the C-firms	Appropriate?
1	1364.42	1364.42	1371.42	Yes
2	1363.78	1363.78	1370.80	Yes
3	1364.07	1364.07	1371.09	Yes
4	1365.64	1365.64	1372.66	Yes
5	1362.16	1362.16	1369.18	Yes

Source: the author (2019).

The K-firms must employ part of the workers to produce capital. Therefore, they employ 3,000 workers, the productivity of labor is 0.50 and the maximal production of consumption goods is 1,500. Table 4.6 shows the results of a couple of simulations. In all of them, the total production of the C-firms is lower than 1,400, and total sales are always equal to consumption of the households.

Table 4.7. Checking the function for an ordinary household. We take some arbitrary periods from a single simulation to evaluate whether a bank deposit had been updated accordingly. We expect bank deposits to increase with current income and to decrease with the expenditures of consumption

Period	Income (A)	Consumption expenditures (B)	Bank Deposits (C)	Expected value (C + A – B)	Correct?
1001	1.0	0.47356	54.77939	54.77939	-
1002	1.0	0.47344	55.30596	55.30596	Yes
1003	1.0	0.47341	55.83255	55.83255	Yes
1004	1.0	0.47379	56.35876	56.35876	Yes
1005	1.0	0.47360	56.88516	56.88516	Yes

Source: the author (2019).

The price of goods is set at one. So far, firms do not have a function to update their prices. At this price, there is a higher demand for goods than the firms can produce. The households try to buy some quantity of goods, but fail. Therefore, their bank deposits increase, because they are forced to save money. Table 4.7 shows this situation, where an ordinary household is selected and its functions are observed for all the periods throughout the simulation. Table 4.7 shows five arbitrary periods of that exercise. The objective is to check whether its bank deposits are properly updated.

Table 4.8. Checking the cash flow between the households and the C-firms. We expect total expenditures of the households to match total revenues of the C-firms. Results are for the last period of a simulation with 3,000 periods each

Simulation Number	Total expenditures of the households (A)	Total Revenues of the C-firms (B)	Correct? (A = B?)
1	1414.91	1414.91	Yes
2	1417.94	1417.94	Yes
3	1420.96	1420.96	Yes
4	1420.25	1420.25	Yes
5	1418.23	1418.23	Yes

Source: the author (2019).

An extra exercise was to check whether firm revenues match household expenditures. We run the model for 3,000 periods and then pick the data in the end of the simulations. Results are compiled in Table 4.8. As can be seen, households and consumption firms are in tune.

4.6 Enter the Capitalists

There exists only one capitalist in each firm and thus 250 in total. Their income comes from the profit of the firms. Although we have already checked for profits, now we assess how the firms distribute part of their profits to owners.

As for consumption, there is no difference between capitalists and workers. Therefore, a capitalist approaches two consumption goods firms each period and try to buy at the lowest price.

To check the function relating the flow of profits from firms to capitalists we perform two exercises. First, we look at the aggregate values in the end of a period to check whether the sum of profits distributed matches the sum of incomes of the capitalists. Whenever a firm experiences negative profit, it distributes no dividend. Secondly, we consider one individual firm and its respective owner to check whether they communicate with each other properly.

Table 4.9. Checking whether total dividends match incomes. Results are for the last period of different simulations with 3,000 periods each

Simulation	Total profits	Total dividends	Total incomes	Match?
1	62.09	12.42	12.42	Yes
2	33.51	6.70	6.70	Yes
3	24.28	4.86	4.86	Yes
4	56.00	11.20	11.20	Yes
5	37.30	7.46	7.46	Yes

Source: the author (2019).

Table 4.10. Exercise for one firm and its owner to check whether cash flows between them are working well. Results show the last period of a simulation, and one firm is picked randomly in each simulation

Period	Firm’s profit	Firm’s Dividend	Capitalist’s income	Match?
1001	0.33	0.07	0.07	Yes

1002	0.49	0.10	0.10	Yes
1003	0.42	0.08	0.08	Yes
1004	0.30	0.06	0.06	Yes
1005	0.60	0.12	0.12	Yes

Source: the author (2019).

Both tests bring goods results. Tables 4.9 and 4.10 display the results for simulations considering both aggregate and single results. The profit share distribution is set at 20 percent. Every firm distribute to owners this percentage each period. The first result in Table 4.9 informs that total transfers run smoothly. The second result in Table 4.10 allows one to realize the functions work well.

4.7 Setting Prices

So far we considered that firms produce and sell their goods without concerns about the price. Price is set at the beginning and remains constant throughout the simulations. Now price is made endogenous to check the consistency of price making. Here, we consider that a firm looks at two signals when deciding to update its current price. The firm increases its current price when 1) its forecast error is negative, that is, actual demand is higher than expected demand; and 2) when its price is equal or lower than the aggregate price level. Thus, the firm checks its forecast error and its relative price.

Table 4.11. Experiment for the function of price updating from a firm. The first condition checks whether inventories change in a period. The second condition checks relative price. Results show a typical firm for 20 periods taken randomly

Period	Inventories	Relative Price	Increase Price?	Cut Price?	Current Price	Correct?
1	Up	expensive	No	Yes	1.2757	-
2	Down	expensive	No	No	1.2757	-
3	Down	expensive	No	No	1.2757	-
4	Down	cheap	Yes	No	1.3330	Yes
5	Down	expensive	No	No	1.3330	-
6	Up	expensive	No	Yes	1.2666	Yes
7	Down	expensive	No	No	1.2666	-
8	Up	cheap	No	No	1.2666	-
9	Down	cheap	Yes	No	1.3022	Yes
10	Up	expensive	No	Yes	1.1998	Yes
11	Down	cheap	Yes	No	1.2155	Yes
12	Up	cheap	No	No	1.2155	-
13	Up	cheap	No	No	1.2155	-
14	Down	cheap	Yes	No	1.3219	Yes
15	Up	expensive	No	Yes	1.2064	Yes
16	Up	cheap	No	No	1.2064	-
17	Down	cheap	Yes	No	1.3011	Yes
18	Down	expensive	No	No	1.3011	-
19	Up	expensive	No	Yes	1.2623	Yes
20	Down	cheap	Yes	No	1.2978	Yes

Source: the author (2019).

Table 4.11 shows a piece of the experiment for changes in inventories and relative price. After an experiment, the data is tested to try to find any errors in the price update process.

4.8 Available Money

With no banks, total money keeps constant over time. At the beginning of a simulation each agent has an initial endowment of money. This can flow between the agents as if transactions are made directly, with no bank credit available. Thus, it is possible negative amount of money for an agent is a given time period. Later, we will call this situation a bankruptcy. For now, we are only interested in checking whether the total amount of available money remains constant. If some agent has a negative position that must be compensated by a positive position from another agent.

Table 4.12 shows a piece of the experiment where agents start with 9,000 units of money. Though money flows across periods, in any given period the total amount of money remains constant.

Table 4.12. Experiment to check the total amount of money for an initial condition with 9,000 units of money and a random set of periods. The simulations are run for 3,000 periods and repeated 10 times. In all the cases, results are consistent

Period	Workers	Capitalists	Total Households	C-Firms	K-Firms	Total Firms	Total
	(A)	(B)	(C = A+B)	(D)	(E)	(F = D+E)	(C+F)
0	6000.0	500.0	6500.0	2000.0	500.0	2500.0	9000
1000	8337.1	820.1	9157.2	11574	-11732.0	-157.2	9000
1001	8096.6	794.6	8891.3	11912	-11803.9	108.7	9000
1002	7920.8	759.5	8680.3	12225	-11906.1	319.6	9000
1003	7696.4	745.5	8441.9	12516	-11958.5	558.0	9000
1004	7561.2	715.5	8276.8	12787	-12063.9	723.1	9000

Source: the author (2019).

4.9 Considering the Retail Bank

In our full-blown model, we end up with two banks. One receives deposits from households and firms and then lends to other households and firms. This is the retail bank. The other receives money from the first bank and make loans to firms. This is the wholesale bank. Our first task is to incorporate the retail bank into the model.

All agents have an account with the retail bank. Their deposits do not receive interest and the bank do not charge their clients. The revenue of the retail bank comes from the loans it makes.

The first exercise consists of checking this primary function of the retail bank: receiving deposits. Here, we just need to check the total amount of money deposit the bank holds and compare it with the credit hold by each agent. As there is no credit yet, such total amount should be constant.

Table 4.13. Piece of the experiment that checks the retail bank's function of deposit for the other agents

Period	Worker's money	Bank account for workers	Capitalists' money	Bank account for capitali st	Correct?
0	6000	6000	500	500	Yes
301	4970	4970	352	352	Yes
302	4979	4979	359	359	Yes
303	4979	4979	359	359	Yes
304	4979	4979	356	356	Yes
Period	C-Firms' money	Bank account for C-Firms	K-Firms' money	Bank accoun t for K-Firms	Correct?
0	2000	2000	500	500	Yes
301	14737	14737	-11060	-11060	Yes
302	14694	14694	-11031	-11031	Yes
303	14669	14669	-11007	-11007	Yes
304	14633	14633	-10968	-10968	Yes

Source: the author (2019).

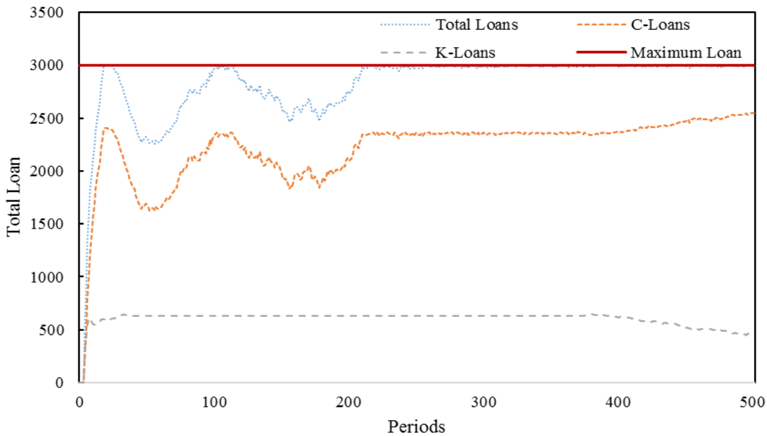
4.9.1 Retail Bank's Loans

The next experiment is set to test the loan function of the retail bank. Initially, the bank lends the money it has as its own capital. Then, leverage is allowed.

Firms check their financial position and measure their necessity of money for the next period. A firm may need money for it desired investment, for example, a C-firm may need to buy more capital goods. Both types of firm need money to pay their employees. After checking its current amount of money available in its bank's account, a firm may realize that is not enough. When this happens, the firm asks for a loan at the bank. Let us begin considering the retail bank, and later the wholesale bank is included.

In this first exercise, the bank charges the minimal interest rate for a loan. All firms then face the same lowest risk possible. In the follow up, this is updated to consider individualized interest rates compatible with the appropriate evaluation of risk of each firm.

Figure 4.5. Testing the retail bank's loan function. The bank can loan a maximum of 3,000 units of money in this exercise. The results from one of the simulations with 500 periods are shown. C-loans represent the total loans taken by C-firms, and K-loans are the total loans contracted by K-firms



Source: the author (2019).

The flow of payments between the firms can now be tested. We evaluate the function that connects the payment of loans made with the loans taken. We also check the interest rate payment. Table 4.14 shows the results of an experiment for 3,000 periods, where such a function is checked after each period. The idea is look whether the interest and the installment on debt are properly updated by both firms and the bank. Results show the function works well for all the firms in all time periods.

The next task is to check the update of the interest rate. Now, each firm has its own interest rate. The bank charges a specific interest rate for each new loan by considering the leverage rate of a firm. The bank uses a logistic regression to estimate the life span of the firm. Firms with high probability of going bankrupt have a shorter time to repay their debts, and the interest rate is higher. The bank is informed of the debts of firms. This exercise also applies to the wholesale bank.

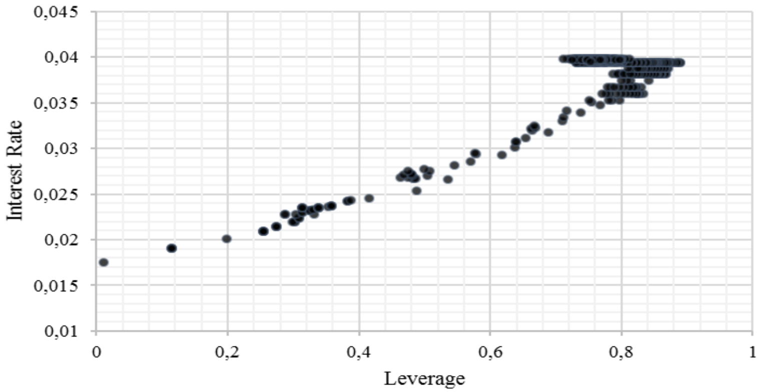
Table 4.14. Testing the updating function of the retail bank and firms. Five randomly extracted periods are shown

Period	Interest Paid by Firms (A)	Installment Paid by Firms (B)	Interest Received (C)	Installment Received (D)	Correct? (A = C and B = D)
100	25.44	127.18	25.44	127.18	Yes
101	25.40	127.00	25.40	127.00	Yes
102	25.05	125.27	25.05	125.27	Yes
103	24.72	123.62	24.72	123.62	Yes
104	24.62	123.09	24.62	123.09	Yes

Source: the author (2019).

To focus on this situation, we plot a series of interest rate for a single firm and its leverage rate in Figure 4.6.

Figure 4.6. Evolution of the interest rate for a single firm. As its leverage rate increases, the interest rate charged also increases. The current interest rate is an average of the previous rates weighted by the volume of each loan. A drop in the leverage rate takes time to be reflected in the updated interest rate



Source: the author (2019).

5. OUTPUT

In this section, we check the modelling consistency of output. We consider the behavior of the autocorrelation and standard deviation of the GDP, unemployment, consumption, and investment series, for the principal features of the model. We begin with the price making decision. We check how the model works after the inclusion of this submodel. There is no unemployment yet, but it is possible to check the others series. After inserting the retail bank into the model, we end up with all the series working properly. However, results are not yet that good when we consider actual series. Nevertheless, the inclusion of the interest rate submodel into model makes the simulated series to fit well with actual series.

5.1 Price Making Decision

This submodel is included with an exogenous demand. Because of this, there is no unemployment yet. Results for standard deviation and autocorrelations are shown in Table 5.1. Standard deviation of the investment series is high with no first lag autocorrelation.

Table 5.1. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. The simulation considers 3,000 periods, but only the last 2,000 are used to compute the statistics

Simulated time series	Standard deviation	First lag autocorrelation
GDP	0.577	0.259
Investment	20.52	-0.198
Consumption	0.997	0.022
Unemployment	-	-

Source: the author (2019).

5.2 Enter the Retail Bank

Considering the inclusion of the retail bank, now a firm can make loans to boost its investment level. The model is already full-blown, but there is no rule for the update of the interest rate paid by the firms. Every firm still pays the minimal interest rate. Also, the bank does not yet assess the risk of an individual firm, which means there is no restriction of credit. Results show an economy that does not present the same time series of the real world.

Table 5.2. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average over 10 runs. The simulation occurs for 3,000 periods, but only the last 2,000 are used to compute the statistics

Simulated time series	Standard deviation	First lag autocorrelation
GDP	1.587	0.350
Investment	21.94	0.180
Consumption	0.985	0.087
Unemployment	32.11	0.273

Source: the author (2019).

5.3 Interest Rate Update

The bank uses logistic regression to measure the risk of each firm. It employs a moving window to collect information about the past of firms – either C-firms or K-firms – and updates the interest rate charge for a firm according to its level of leverage. After introducing this dynamics, our model becomes capable of reproducing more accurately the real world series. Now, first lag autocorrelations become positive for all series, as can be seen in Table 5.3.

Table 5.3. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. The simulation spans for 3,000 periods, but only the last 2,000 are used to compute the relevant statistics

Simulated time series	Standard deviation	First lag autocorrelation
GDP	2.177	0.674
Investment	14.205	0.661
Consumption	1.199	0.635
Unemployment	20.009	0.601

Source: the author (2019).

5.4 Interbank market

The wholesale bank borrows money only from the retail bank. It lends money to a firm for a period longer period than that of the retail bank, so firms give preference to the wholesale bank if it has money to spare. The update mechanism of the interest rate is the same as before. As the volume of credit increases, a firm has more leverage, thus trigering more consequential crises (compare Table 5.4 with previous Table 5.3).

Table 5.4. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. The simulation runs for 3,000 periods, but only the last 2000 are used to compute the desired statistics

Simulated time series	Standard deviation	First lag autocorrelation
GDP	2.472	0.613
Investment	18.404	0.554
Consumption	1.201	0.630
Unemployment	24.230	0.577

Source: the author (2019).

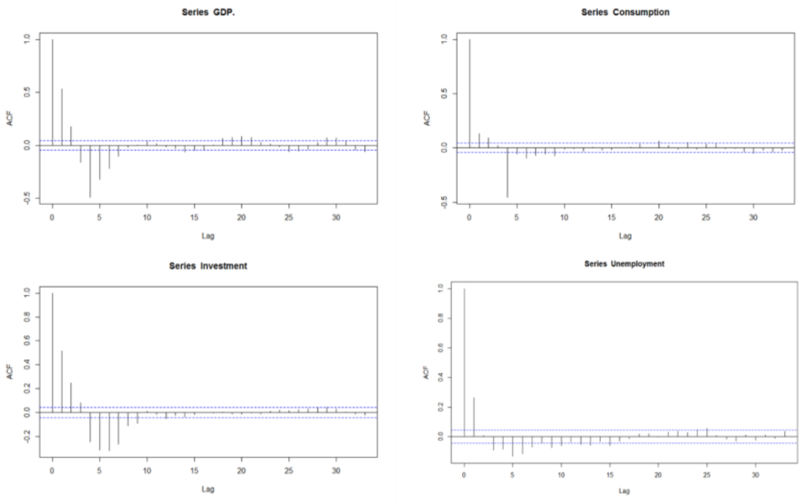
6. MODEL ANALYSIS

This section is designed to explore in depth the results of the model. The main objective of the model is to assess the effects of a crisis in real GDP on the financial sector, paying special attention to interbank moves during the crisis.

The full-blown model (after the inclusion of the wholesale bank) shows series of GDP, consumption, investment, and unemployment with high first lag autocorrelation. Figure 6.1 displays the autocorrelation of one the series extracted from the model. As in the actual series, the first lag autocorrelation is positive and, after a few lags, it turns to negative.

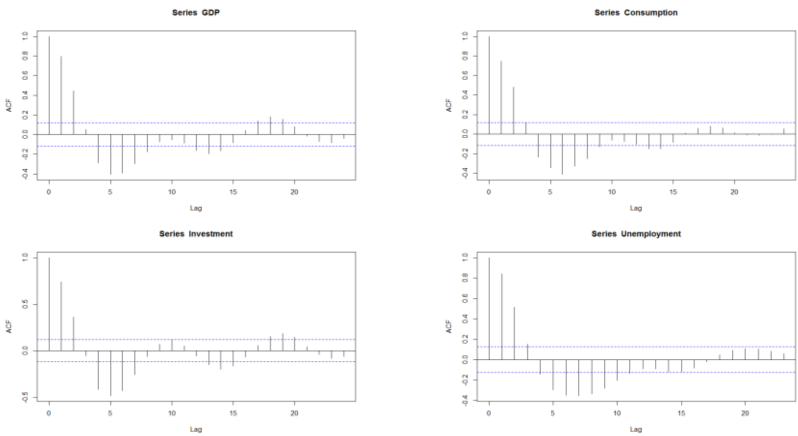
We run simulations with different random seeds to generate our artificial times series. For a specific random seed, we study in detail the results of booms and slumps that emerge. Tables 5.3 and 5.4 compare the results for an average of 10 different random seeds, while Figures 6.1 and 6.2 compare the results for a single random seed and the actual times series.

Figure 6.1. Autocorrelations of the artificial time series from a specific random seed



Source: the author (2019).

Figure 6.2. Autocorrelation of observed real world time series



Source: the author (2019).

6.1 The emergence of crises

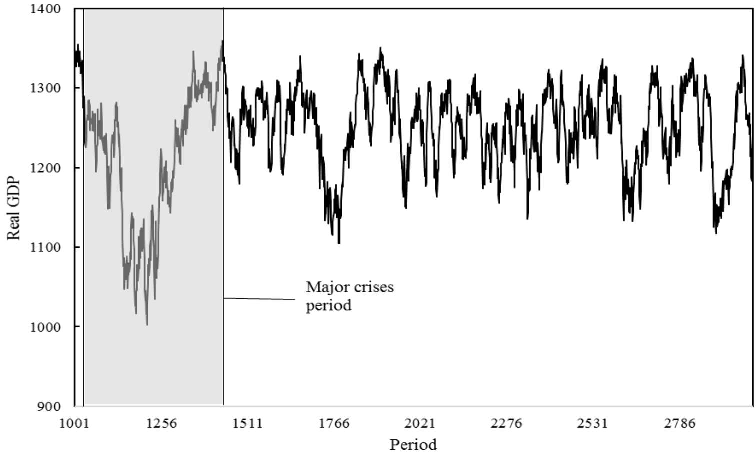
Now we turn to the crises that emerge in our model.

We pick one random seed and run a couple of simulations. Figure 6.3 highlights one period of crisis. Near period 1200, real GDP falls to close to 1,000. Figure 6.4 shows the unemployment rate for the same simulation; it reaches 18 percent in period 1,200. In our economy, consumption goods firms need capital to produce goods. To be able to invest, they sometimes make loans in the financial sector. Since the installment on debt charged by the wholesale bank is lower than that of the retail bank, firms try first to borrow from the wholesale bank. The capital goods firms also need cash in times when their revenue is not enough to pay for their expenditures. As unemployment increases, consumption shrinks, and crisis sets in (Figure 6.5). What we look from now on is how this movement of loans from the bank to firms impacts crisis scenarios.

As in Assenza et al. (2015), in periods of crisis the capital goods price index plummets. Investments of consumption goods firms reduce as a result of the credit crunch. The capital goods price index reflects it and falls as a consequence. Figure 6.6 shows the behavior of the capital goods price index. It starts to fall around period 1,050 and continues to decay until period 1,200, when it reaches its minimum value, which is almost 40 percent lower than the average capital goods price index before the crisis. As GDP growth resumes, the index also responds and returns to its previous level.

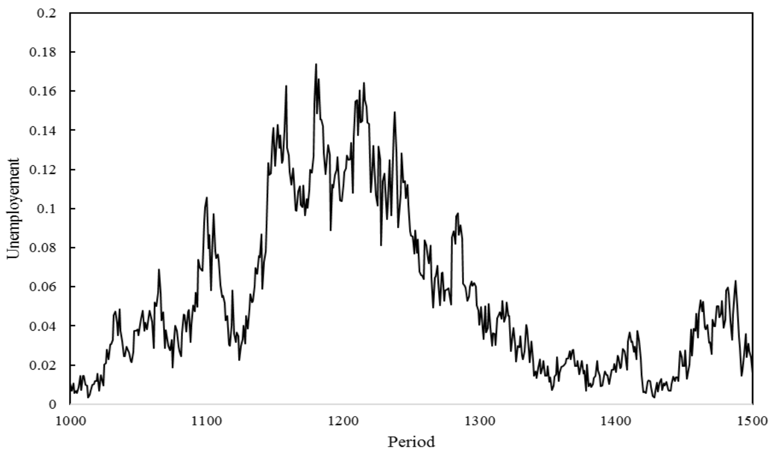
To understand what happened to GDP, and what triggered the crisis, one needs to look at the credit market. First, the behavior of loans from the retail bank and wholesale bank. As observed, in our model firms prefer to borrow from the wholesale bank, because it charges the same interest rate as that of the retail bank but provides a longer time for the loan repayment. Thus, more credit comes from the wholesale bank to the firms. Figure 6.7 shows the total amount of credit supplied by the wholesale bank and retail bank. Although, both banks present fluctuations throughout the simulation, total loans from the wholesale bank are higher in absolute value. Zooming in the period of crisis as defined early, Figure 6.8 shows loans reach a peak just after period 1,100 that precedes the crisis.

Figure 6.3. Real GDP series in a sample simulation and highlight of a crisis period



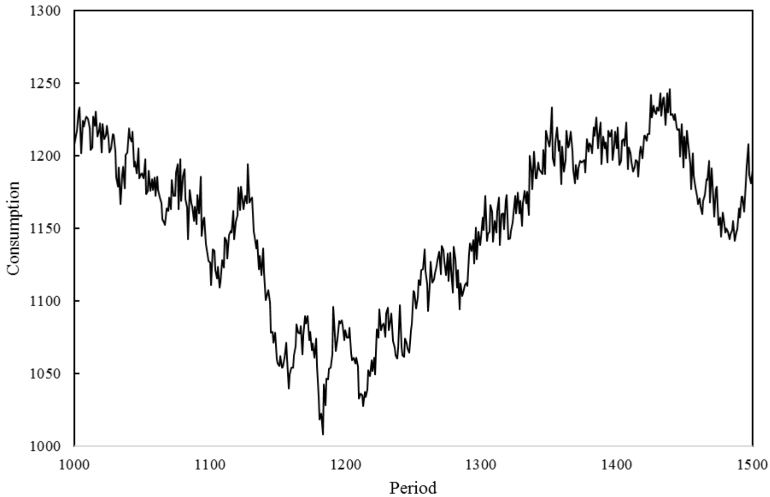
Source: the author (2019).

Figure 6.4. Crisis period in an unemployment rate series from the sample simulation



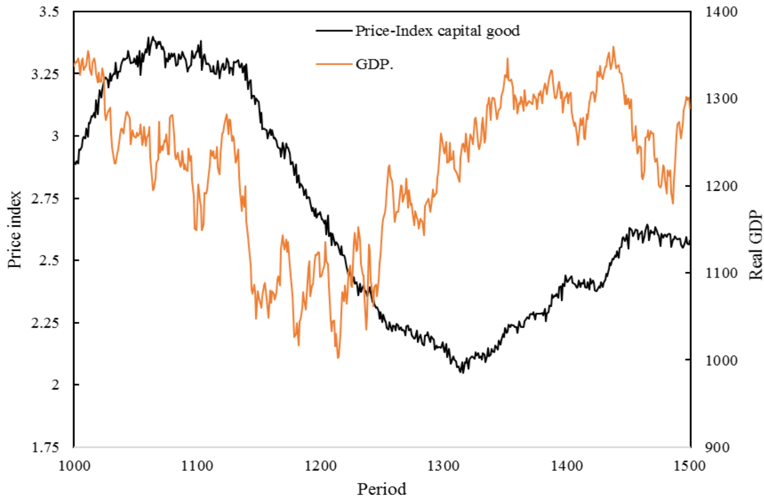
Source: the author (2019).

Figure 6.5. Movements of real consumption from the simulation in a crisis period



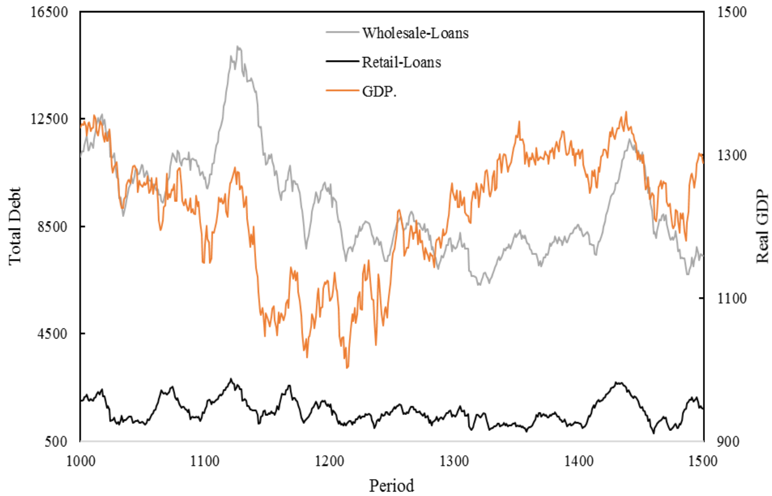
Source: the author (2019).

Figure 6.6. Capital goods price index and real GDP from the simulation in a crisis period



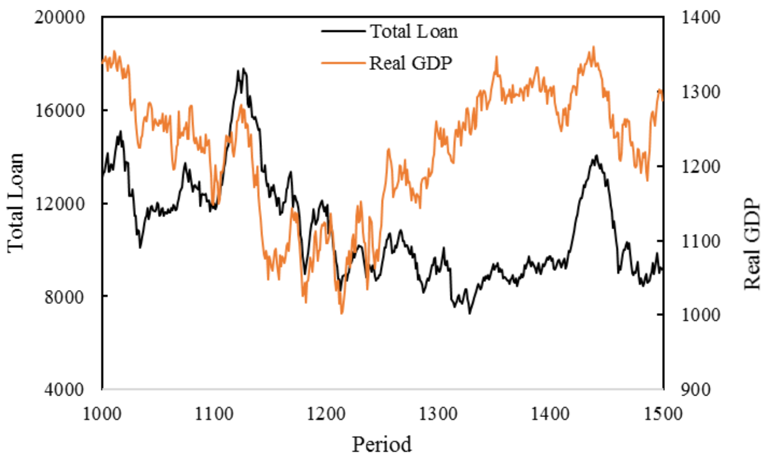
Source: the author (2019).

Figure 6.7. Total debt, retail and wholesale loans, and real GDP from the simulation in a crisis period



Source: the author (2019).

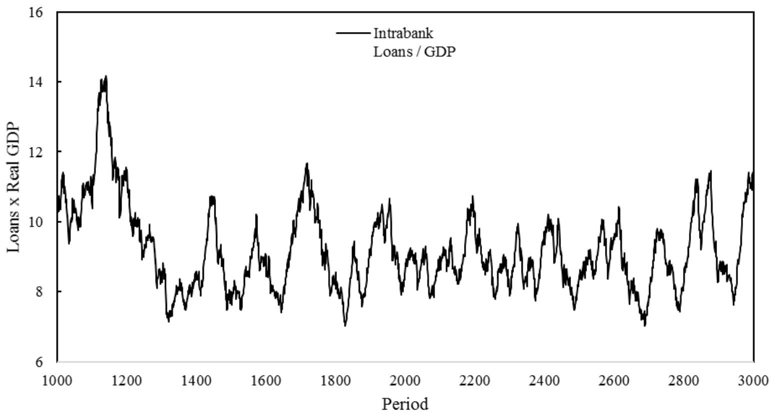
Figure 6.8. Total loans and real GDP from the simulation in a crisis period



Source: the author (2019).

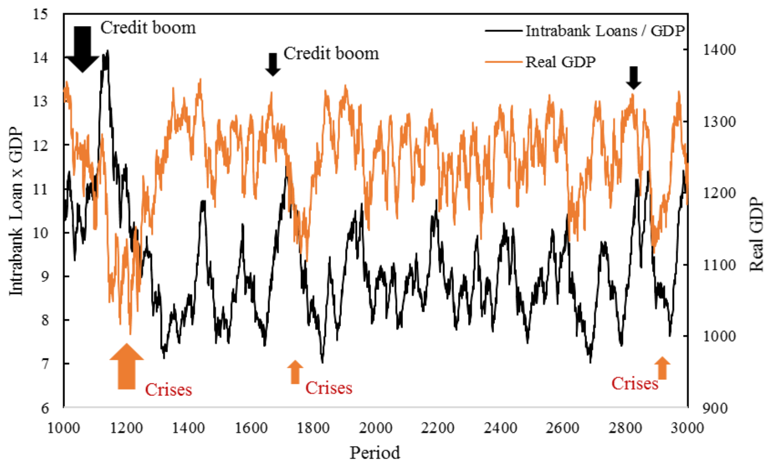
When we look at the interbank credit behavior, money that flows from the retail bank to the wholesale bank also fluctuates (Figure 6.9). However, it gets more interesting when we look at this fluctuation together with that of real GDP (Figure 6.10).

Figure 6.9. Total loans divided by real GDP



Source: the author (2019).

Figure 6.10. Interbank loans and real GDP: The crisis period is preceded by a boom of credit



Source: the author (2019).

As can be seen, the burst of interbank credit precedes the period of crisis. Interbank credit crunches a few periods before the crisis reaches real GDP. As previously happens to the retail bank, the wholesale bank starts to face some bad credits, too, and it begins to have problems in paying the installments to the retail bank. The situation only comes back on track when the economy starts to grow again. In sum, our model is capable of reproducing real world facts after we insert the interest rate submodel (Table 6.1).

Next section evaluates the results of the policy experiments.

Table 6.1. Summary of results after a submodel inclusion

Submodel inclusion	Crisis	GDP Autocorrelation
Price Decision	**x**	0.259
Retail Bank	**x**	0.350
Interest Rate Update	✓	0.634
Interbank Market	✓	0.613

Source: the author (2019).

7. POLICY EXPERIMENTS

We check two major experiments. First, the influence of the parameters of Taylor's rule on output in the simulated economy. This situation represents a conventional tool being applied by the monetary authority. The other one refers to a non-conventional tool. A situation where bad assets are purchased during crisis times and the central bank intervenes by buying assets from the wholesale bank whenever it thinks this policy is appropriate.

7.1 Taylor rule experiment

As pointed by Orphanides (2003), Taylor's rule captures the monetary policy dilemma between inflation and economic growth. Orphanides (2003) discusses the intertemporal behavior of the Fed through the lens of Taylor's rule. Prior to 1930, its behavior seemed to be consistent with Taylor's rule. However, its focus changed in the subsequent years, and a dual objective – price stability and maximum growth – occupied center stage as a result of the 1946 Employment Act. In 1977 the motto was "maximum employment, stable prices, and moderate long-term interest rates." By 2000 it formed "the FOMC's consensus about the balance risks to the attainment of its long-run goals of price stability and sustainable economic growth." While it is possible to identify the use of Taylor's rule through the 20th century, it is not possible to apply Taylor's original results to the period preceding 1987 (Orphanides, 2003).

So we have the problem of identifying the proper parameters to be used in our conventional policy experiment. Clarida et al. (2000) agree with Orphanides that the original work of Taylor replicated well the movements for 1987 through 1992, but not before. Clarida et al. (2000) replicated the experiment for more recent years as well as for the periods that preceded 1987 and found that the monetary authority had been changing their balance between monetary stability and output growth. They considered data since the end of World War II until the late nineties. A Fed's chairman was considered to defined the periods of study. The first period was named as Pre-Volcker. Volcker assumed the Fed in 1979 and needed to deal with the high inflation of the post-oil shock period. For the Pre-Volcker period, their estimation of the parameters used in Taylor's rule was below one for both, inflation and output. To the post-1979 Volcker-Greenspan era, attention to inflation heightened, and the parameter for inflation was above one, while the parameter for output remained below one. For the next period named Post-1982, the parameter of attention to output approached zero, while the inflation parameter increased even more and stayed above two.

Table 7.1. Summary of the experiments and parameters used in the simulations for the Taylor's rule experiment

Experiment	α_π	α_y
Pre-Volcker*	0.86	0.39
Volcker-Greenspan*	1.72	0.34
Post-1982*	2.55	0.00
Post-ZLB**	0.00	1.30

* Parameters from Clarida et al. (2000); ** Parameters from Kim and Seth (2017).
Source: the author (2019).

After the 2008 crisis, monetary policy changed as compared with the previous years. Attention to output was heightened while concerns with inflation faded. Kim and Seth (2017) studied the behavior of the monetary authority after that period, known as the zero lower bound

(ZLB). They computed data from 2009 through 2014, where the Fed kept interest rates between zero and 25 basis points. This tiny nominal interest rate cannot provide any useful conventional data. Thus, they resorted to an alternative data – from professional forecasters – to evaluate what kind of monetary policy could be implemented during the ZLB period. In the opinion of the forecasters the response of the Fed to inflation decreased while its response to unemployment and output increased.

We consider Kim and Seth's (2017) results as an input in our own model.

Our model is then calibrated with those four sets of parameter in Table 7.1. The first step is to check for the robustness of the model, that is, standard deviations and autocorrelation functions from the simulated series. Then, the crisis periods are scrutinized for each of these sets of parameters.

7.2 Robustness check for the experimental Taylor's rule series

Table 7.2 shows the results for the standard deviation and first lag of the autocorrelation function (ACF) for the series. Each result is an average of 50 experiments. At the end of a simulation, one series is collected, the HP-filter is applied to it, as done earlier (Table 3.1) for the observed series.

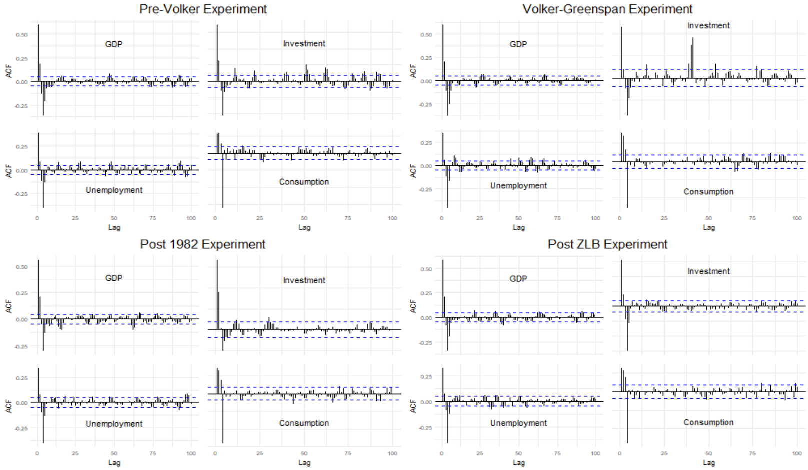
Table 7.2. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. Simulations involve 2,500 periods, but only the last 2,000 are used to compute the statistics

Experiment	GDP		Invest.		Cons.		Unemployment	
	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF
Pre-Volcker	1.57	0.58	29.0	0.37	1.04	0.08	34.4	0.35
V.-Greenspan	1.58	0.56	22.6	0.24	1.00	0.12	35.5	0.36
Post-1982	1.72	0.58	21.3	0.33	0.99	0.10	35.8	0.31
Post-ZLB	1.51	0.57	25.2	0.37	0.99	0.15	34.8	0.35

Source: the author (2019).

Figure 7.1 displays the results of the ACF for a single simulation. For each experiment, a random run generates the plots of the autocorrelation functions.

Figure 7.1. Sample of the ACF for the Taylor's rule experiment



Source: the author (2019).

7.3 Crisis period analysis for the Taylor's rule experiments

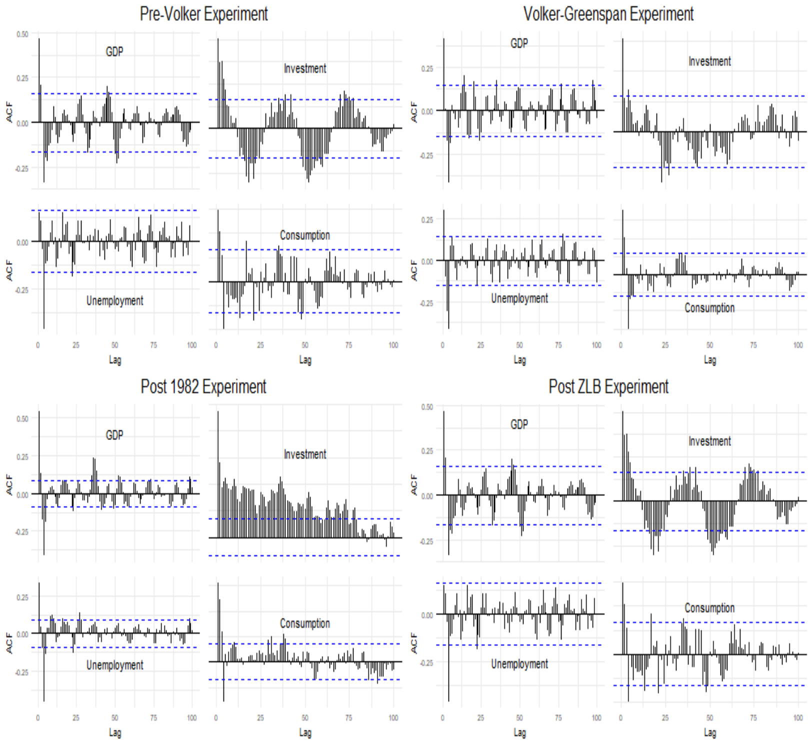
Now we focus on the picture of the crisis periods, when the unemployment rate hits 15 percent or higher. We compute the standard deviation and autocorrelation of the series during this period to later compare with a situation where monetary policies are introduced.

Table 7.2. Crisis periods selected only for standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. Simulations run for 2,500 periods, but only the last 2,000 are used

Experiment	GDP		Invest.		Cons.		Unemployment	
	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF
Pre-Volcker	2.52	0.52	17.85	0.41	1.19	0.33	7.73	0.34
V.-Greenspan	2.61	0.42	21.80	0.39	1.43	0.39	6.64	0.30
Post-1982	3.11	0.54	26.01	0.59	1.31	0.39	7.80	0.34
Post-ZLB	2.15	0.47	18.21	0.50	1.46	0.37	8.29	0.15

Source: the author (2019).

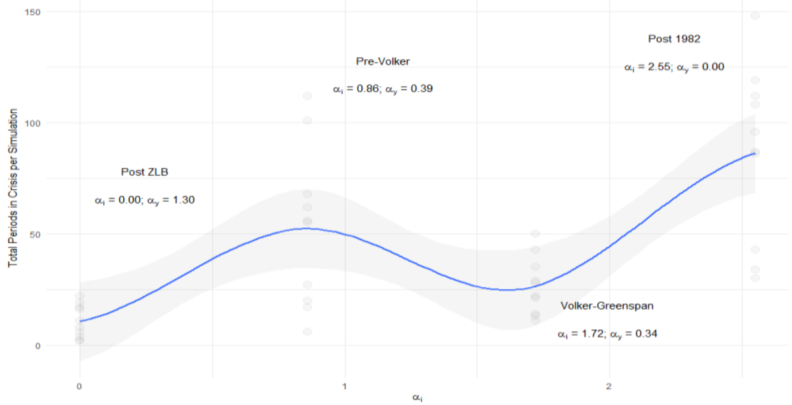
Figure 7.2. Sample of ACF for the Taylor's rule experiment for crisis periods only



Source: the author (2019).

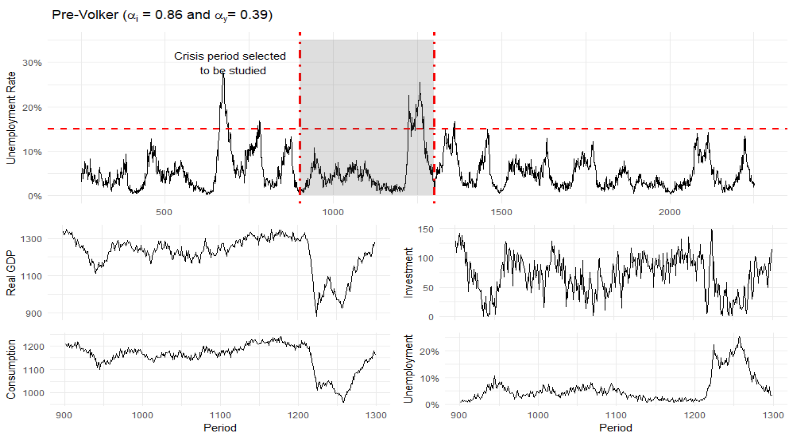
After introduction of a monetary authority that control the risk free interest rate, crises still emerge in our simulations. Figure 7.2 shows the dispersion of the total of crisis periods per simulation for each set of parameters of the Taylor's rule experiment. Any sets of parameters are incapable of suppressing a crisis. Even the Post-ZLB policy failed, and, worst, it is the most volatile with a huge dispersion of the crisis periods across the simulations.

Figure 7.3. Crisis dispersion across the Taylor's rule experiments



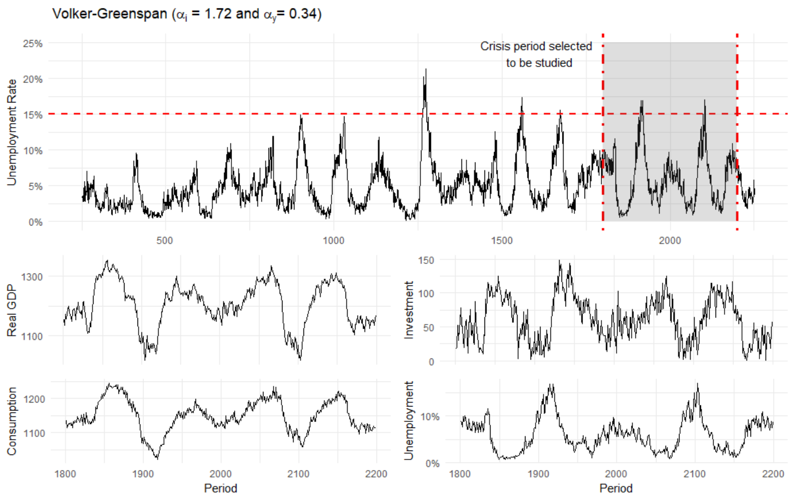
Source: the author (2019).

Figure 7.4. Highlight of a crisis period from a sample in the Pre-Volcker experiment



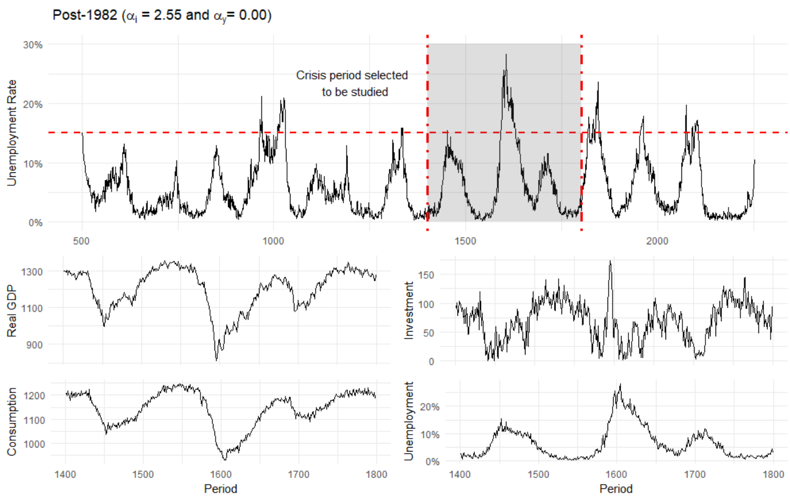
Source: the author (2019).

Figure 7.5. Highlight of a crisis period from a sample in the Volcker-Greenspan experiment



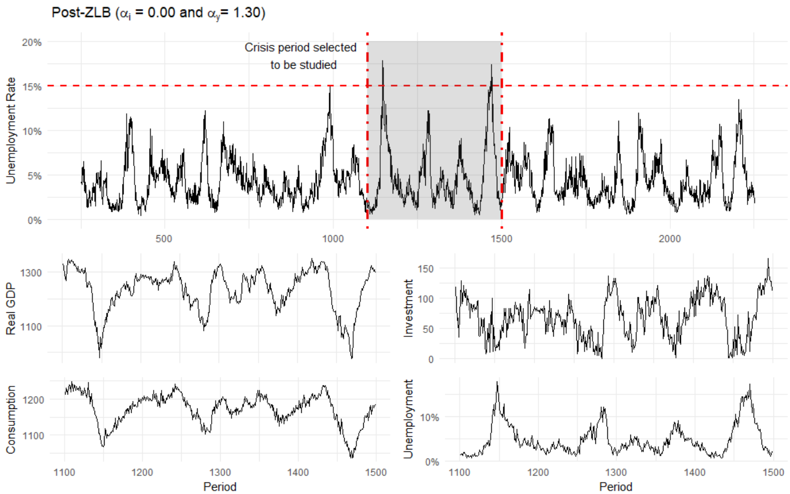
Source: the author (2019).

Figure 7.6. Highlight of a crisis period from a sample in Post-1982 experiment



Source: the author (2019).

Figure 7.7. Highlight of a crisis period from a sample in the Post-ZLB experiment



Source: the author (2019).

7.4 Private assets purchase experiments

In this experiment, the central bank is allowed to buy assets from the wholesale bank for a short period of time after a threshold of unemployment rate is reached. The dynamics are as follows. The wholesale bank is the first one to face problems in a crisis, because it holds riskier loans. The central bank is allowed to buy some of such bad debt. The bail out allows the wholesale bank to honor its obligations with the retail bank. Thus, the wholesale bank creates new credit for the firms in trouble. This exercise tests alternative thresholds for the central bank to act and then evaluates the effects of such actions. The parameter used to trigger the private assets purchase is the unemployment rate, as observed.

As in the Taylor rule's experiment, the series that show indistinguishable differences is that of real GDP. However, real GDP drops as the threshold decreases. The same is true of the consumption series. Consumption can be boosted if the central bank starts its assets purchases earlier. For thresholds are tested: the first one is 8 percent unemployment rate and the last one, 14 percent. Remember that a crisis period is defined for an unemployment rate above 15 percent. We count how many crisis periods occurs until the maximum of 2,000 (which is the total period analyzed).

By assumption, the central bank intervenes until the limit of purchases of 20 percent of real GDP. This choice of limit mimics the real one adopted by the central banks after the 2008 financial crisis. Fawley and Neely (2013) collected data from four central banks – Fed (USA), BoE (England), ECB (European Community), and BoJ (Japan) – and sorted the non-conventional policies adopted by such banks in two categories: 1) a central bank intervenes by buying assets from the financial system; and 2) a central bank eases credit to galvanize the economy. According to their data, central banks around the rich world reached purchases as a percent of real GDP between 2009 and 2012 as in Table 7.3.

Table 7.3. Private assets purchase as a percent of real GDP

Central Bank	Percent of Real GDP
FED	22.1
BoE	26.3
ECB	3.5
BoJ	37.5
Mean	22.3

Source: Fawley and Neely (2013).

Table 7.4. Summary of the experiments and parameters used in the simulations for the private assets purchases experiment

Experiment	ψ $(policy\ starts)$*	χ $(limit\ purchase)$**
1st Policy	8%	20%
2nd Policy	10%	20%
3rd Policy	12%	20%
4th Policy	14%	20%

* Unemployment rate; ** Percentage of real GDP.
Source: the author (2019).

7.5 Robustness check for the asset purchases experiment

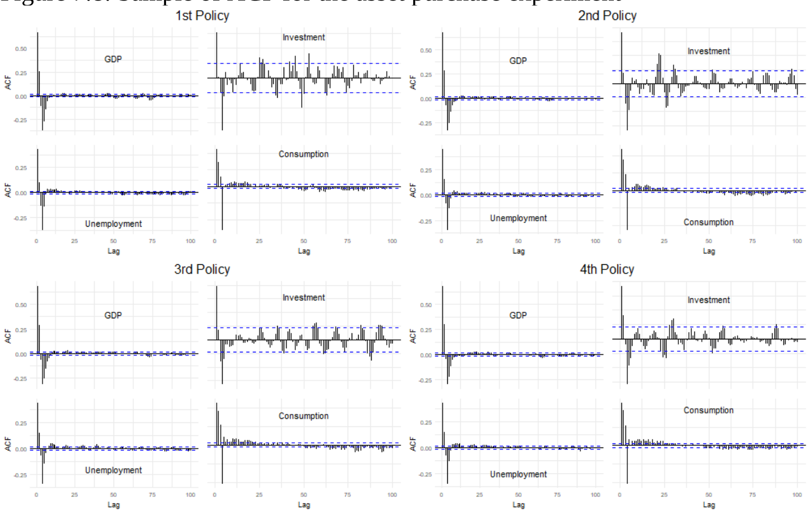
Table 7.5 shows standard deviations and first lag autocorrelations of the series after applying the HP-filter. Similar to the Taylor's rule experiment, introduction of this new experiment does not affect the robustness of the model.

Table 7.5. Standard deviation and first lag autocorrelation of the cyclical component of the simulated time series. Both the autocorrelation and standard deviation are the average of 10 runs. Simulations run for 2,500 periods, but only the last 2,000 are used to compute the statistics

Experiment	GDP		Invest.		Cons.		Unemployment	
	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF	S.D.	1st lag ACF
1st Policy	2.61	0.66	12.5	0.50	1.20	0.35	19.2	0.40
2nd Policy	2.76	0.64	14.5	0.46	1.21	0.36	22.1	0.37
3rd Policy	2.97	0.65	15.3	0.49	1.15	0.37	23.0	0.36
4th Policy	2.39	0.64	11.7	0.42	1.17	0.39	22.3	0.42

Source: the author (2019).

Figure 7.8. Sample of ACF for the asset purchase experiment



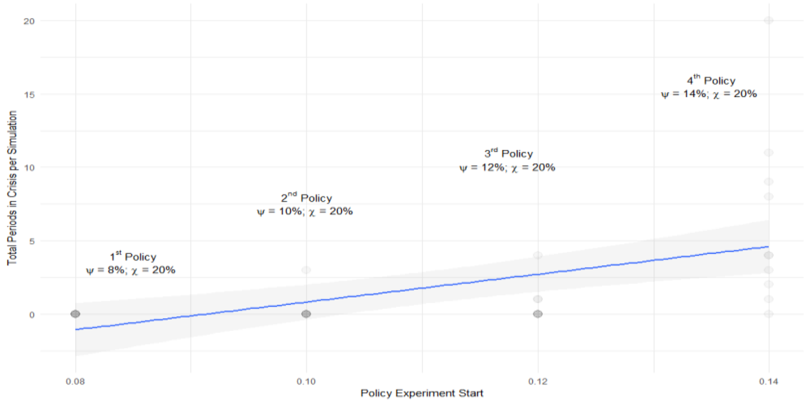
Source: the author (2019).

7.6 Crisis period analysis for the asset purchase experiments

For the first time, we experience series without a crisis period. Figure 7.9 shows the summary of the crisis periods in four experiments. The 1st Policy parameters is capable of preventing the emergence of crisis, and the number of crisis periods increases as the threshold is reduced. The 4th Policy is one with the highest number of crisis periods.

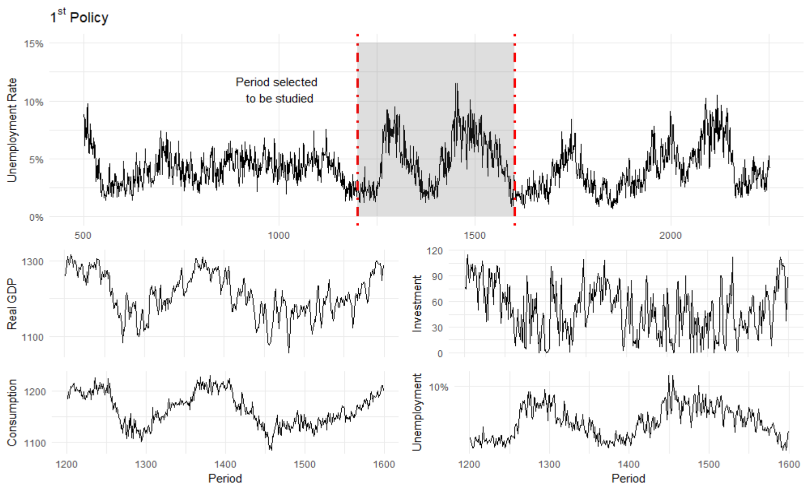
Figures 7.10 to 7.14 are samples of the experiments for selected periods. Series of real GDP, unemployment, investment, and consumption are shown.

Figure 7.9. Crisis dispersion across asset purchase experiments. Unemployment rate is used as policy trigger and purchases are limited to 20 percent of real GDP



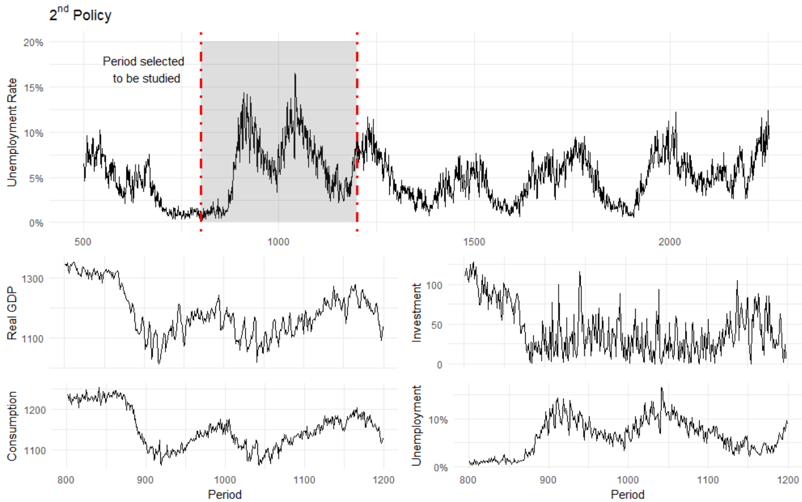
Source: the author (2019).

Figure 7.10. Highlight of a crisis period from a sample in the asset purchase experiment. (Experiment starts at 8% of unemployment; Purchase limit = 20% of GDP)



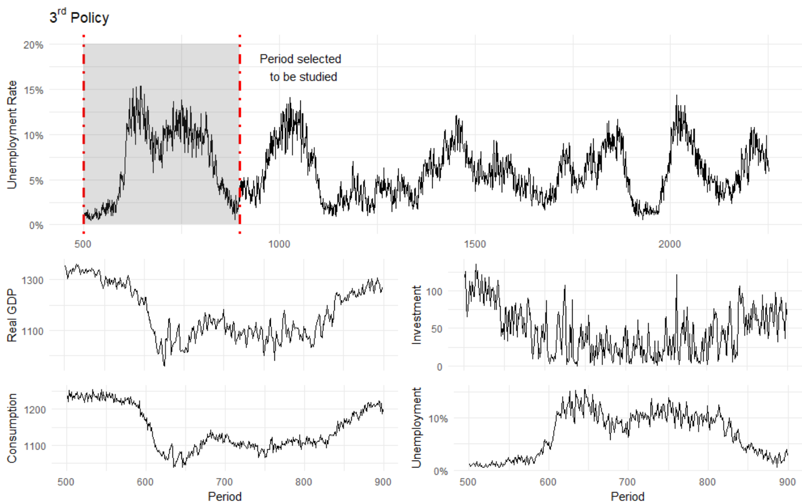
Source: the author (2019).

Figure 7.11. Highlight of a crisis period from a sample in the asset purchase experiment. (Experiment start = 10%; Purchase limit = 20%)



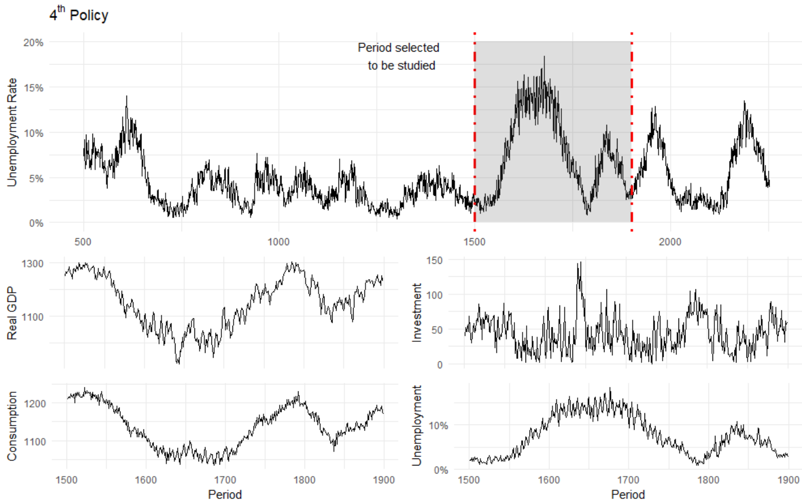
Source: the author (2019).

Figure 7.12. Highlight of a crisis period from a sample in the asset purchase experiment. (Experiment start = 12%; Purchase limit = 20%)



Source: the author (2019).

Figure 7.14. Highlight of a crisis period from a sample in the asset purchase experiment. (Experiment start = 14%; Purchase limit = 20%)



Source: the author (2019).

7.7 Summary

Experiments are considered to test if a crisis could be prevented. Each experiment runs for a total of 80,000 periods, divided into 40 simulations with 2,000 periods each. The first experiment tries to manage the economy through a risk free interest rate. Using a Taylor's rule, different sets of parameters are tested to verify their effects on output. The alternatives modify the parameter which weighs the impact of output and the parameter that gauges inflation. The combinations described in Clarida et al. (2000) and Kim and Seth (2017) are considered as inputs. In no situation crises can be prevented using only the risk free interest rate management.

This prompts us to the next experiments that are built on non-conventional policies. This time, there emerges a set of parameters for which crises are prevented to occur. This scenario refers to central bank's temporary purchases of bad assets from the wholesale bank. Whenever the unemployment rate reaches some threshold, the central bank starts to buy bad debts that are in the wholesale bank's portfolio until a limited percentage of real GDP. In what we name the 1st Policy, the triggering point of 8 percent of unemployment is capable of avoiding a crisis.

However, the other non-conventional monetary policies continue to be ineffective.

Table 7.15. Summary of the experiments. The risk free interest rate management uses as a parameter the attention to inflation α_i and to output α_Y. The purchase experiment uses the unemployment rate as a triggering point to start the alternatives policies

Experiment	Parameters	Crisis periods per simulation	Capable of preventing a crisis?
Taylor rule Experiment	Pre-Volcker	52 (±29)	No
	Volcker-Greenspan	30 (±11)	No
	Post-1982	86 (±37)	No
	Post-ZLB	10 (±6)	No
Purchase asset experiment	1st Policy	0 (-)	Yes
	2nd Policy	1 (±1)	No
	3rd Policy	2 (±2)	No
	4th Policy	7 (±3)	No

Source: the author (2019).

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APPENDIX B - ODD

ODD

1. Introduction

ODD Template

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2010).

Purpose

To use an agent-based macroeconomic model with credit and capital to simulate monetary policies, both standard and alternative.

2. Entities, state variables, and scales

- *Agents*. We consider agents to represent the minimal unit of behavior of the participants in this economy; they will represent individuals in the production, consumption, and financial sectors of the economy.
- *Spatial units*. The patches of the grid are occupied by only one firm per patch. There are as many patches as a number of firms.
- *Environment*. Households can transit across the patches freely. The position of the firms is constant throughout in the experiments, which means they do not change address. All the patches have the same characteristics. Each period represents a quarter and the simulations can run for an arbitrary number of periods.
- *Collectives*. There are three types of agents: (i) firms, which are responsible for production; (ii) householders, composed of workers and owners of the firms; (iii) financial sector, which includes commercial banks and a monetary authority, who manages the basic interest rate.

AGENTS

Production sector

There are two groups of firms: (i) producers of consumption goods; and (ii) producers of capital goods. Households buy the consumption goods and firms that produce consumption goods buy capital goods.

Financial sector

A retail bank receives deposits from households and firms. A wholesale bank contracts debt with the retail bank and credit with the firms. The central bank does not interact with either the productive sector or the households; it only controls the interest rate and the level of minimum reserves.

Households

There are two types of households: workers and capitalists. Workers sell their workforce in the job market to the firms, receive wages, and use the wages to buy goods in the consumption market. Capitalists are the owners of firms and banks. Each firm has only one owner, who has the same share in a bank.

Information

Available information is limited but any agent can have access to complete information. A firm that produces consumption goods knows the price level of their sector as well as the quantities demanded from clients. A firm that produces capital goods knows the price level of their sector as well as the quantities demanded from clients. Such information is available during the decision process of the firms.

A household can approach a restrict number of firms per period. It has information of the prices charged by the firms and the quantities supplied by them. The household use such information when deciding how much and from whom to buy.

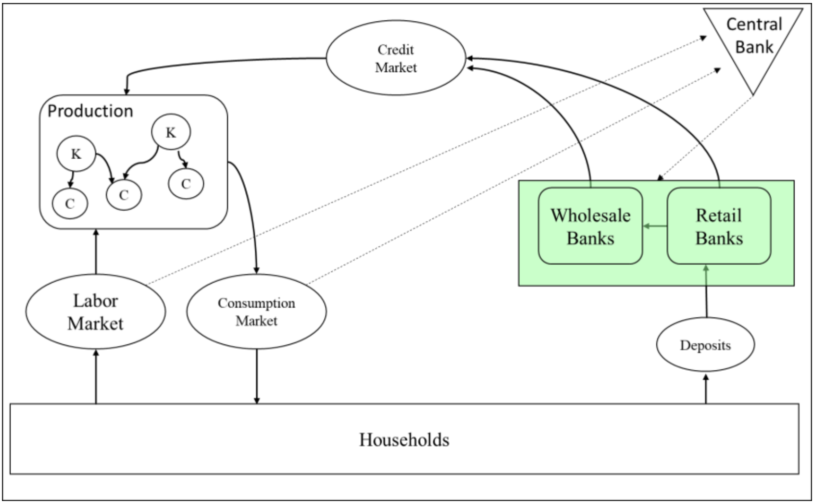
A bank decides whether to offer or not a loan and which rate to charge in each transaction. For that, the bank gauges the financial health of a firm, which means to find out how much leveraged the firm is. The bank knows how much money the firm has in deposits as well as how much credit the firm has taken before. Such information is available for each firm individually and thus the bank can evaluate risk for the entire market.

The central bank cares about the production of the economy as well as the price level movements, that is, inflation. Then, it decides what to do with the free interest rate based on observation of these two variables.

3. Process overview and scheduling

Time is a discrete variable, where each period represents a quarter. In each period, a firm decides how much to produce and which price to charge. A household decides how much to consume and then saves the remaining money, which is deposited in a bank.

Figure 1. Agents and markets; production sector with firms that produces capital goods (K) and consumption goods (C). The central bank checks the unemployment from the labor market, the inflation from the consumption market; and dictates the rules for the financial system



Source: the author (2019).

Job market

Unemployed workers approach a restrict number of firms to try to find a job. Wages are homogeneous, so a worker accepts the first job she is offered. Productivity is homogeneous across workers, so firms employ the first worker to apply for a vacancy position.

Consumption market

Households have a certain amount of money they should spend each period. They visit a restrict number of firms and try to buy their goods at the lowest price. If a firm with the best price does not have enough quantity to supply, a household approaches the next firm. If there are not enough goods in all firms approached, the household has no choice but saving money.

Capital market

The consumption firms combine labor and capital to produce goods. Capital and labor are perfect complements (Leontief production function). A consumption goods firm approaches a capital goods firm and try to buy for the lowest price, similar to the behavior of households in the consumption market.

Credit market

From time to time firms need to access the credit market, when they apply form a bank loan. A bank gauges whether it has enough available money to spare with a firm which is applying for a loan, and then the bank decides which interest rate to change. To set the charged interest rate the bank also considers the free interest rate determined by the central bank.

3.1 Design concepts

Basic principles. The macroeconomy we simulate here emerges as a result of the behavior of individuals who strive to keep constant their consumption level over time. Thus, we assume the permanent income hypothesis, which posits that an individual consumes not only as a function of her current income but also as a function of the expectation of her entire life wealth. Firms some monopolistic power, so that some can experience extraordinary profits while others can go bankrupt. The limitation of information is a key factor for such distinct firm performance. As the economy is not always in full employment, there is room for monetary policy to tackle crises.

Emergency. Errors in forecasting can drive some firms into trouble in difficult times, and this can be transmitted to the others firms through the credit market. As a result of positive feedback, investment projects can cease. This occurs because banks consider market risk to decide whether or not to provide credit. So, even if one particular firm is in good shape, its credit can be halted. The series of GDP and employment that emerge at the aggregate level are also affected by these circumstances and thus can show abrupt changes.

Adaptation. Households use an adaptation rule to decide how much to consume each period. A household gauges the wealth of its entire life, not only its current income, when choosing how much to consume. Each period the household updates its permanent income (the amount deposited in a bank plus current income). Firms then adapt their price and quantity supplied, accordingly. They thus increase or decrease their production with consequences to the labor market, that is, they can hire or fire workers.

Objectives. The central bank aims to keep the unemployment level low, but at the same time, it aims to prevent big swings in the price level. Households use a rule of thumb to decide how much to consume each period. Profit-maximizing firms try to sell their products, update prices, and adjust labor demand.

Learning. Not applied. The rules are assumed to be the same across all experiments.

Prediction. When behaving like consumers, households assume the near future is a continuation of recent past, and thus their rule of thumb for consuming does not change over time. For example, if an individual is employed, she assumes she will be employed next period too, a prediction that may end up incorrect.

Sensing. Households observe price and quantity supplied by the firms they approach. Consumption goods firms observe price and quantity available to the firms they approach when trying to buy capital goods.

Interaction. When approaching firms, households interact with them opportunistically. There is no such thing as loyalty. Firms interact indirectly with each other in the own sector. They compete in price and quantity. Because households lack loyalty, firms find it difficult to formulate their forecasts, and thus competition takes place under the information of the previous period. Banks interact with firms directly by demanding and supplying financial services.

Stochasticity. Firms update their prices upward or downward stochastically. A firm picks a value from a uniform distribution every time it sets a new price and then it charges such a price with a small stochastic variation.

Collectives. Banks consider both consumption goods firms and capital goods firms to gauge market risk, and this risk increases with the number of firms in financial woes in each of these sectors.

Observation. The series of GDP, price, and unemployment rate can be exported and analyzed. Credit market behavior can also be exported, via the total of loans granted or not. The connection of the credit market with GDP is a key to understand a crisis. Such data are collected in the end of the simulations.

3.2. Initialization

We start with 200 consumption firms and 50 capital firms; where each occupies one position in the grid. Banks and the central bank occupy arbitrary positions, and their addresses coincide with one of a firm. So, the grid has 250 patches. Thus, there are 250 capitalists, who are uniquely associated with a single firm. There are 3,000 workers.

Initial conditions and parameters are displayed in Table 1. Parameters are set using actual FRED's data from the Federal Reserve for the years 1955 to 2013. Taylor's parameters are the same as in Taylor (1993). Further details can be found in Assenza at al. (2015).

Table 1. Initial conditions and parameters

Parameters	Description	Value
T	Number of periods	2,500
H	Number of workers	3,000
F_c	Number of consumption goods firms	200
F_k	Number of capital goods firms	50
B_R	Number of retail banks	1
B_W	Number of wholesale banks	1
Z_e	Number of firms approached by unemployed workers	5
Z_c	Number of consumption firms approached by consumers	2
Z_k	Number of capital goods firms approached by C-firms	2
ε	Human wealth (memory)	0.96
τ	Dividend payout ratio	0.20
χ	Fraction of wealth destined to consumption	0.05
r	Initial risk free interest rate	0.01
ρ	Quantity adjustment	0.90
η	Price adjustment (random)	U(0,0.1)
μ	Bank gross markup	1.20
α	Productivity of labor	0.50
κ	Productivity of capital	1/3
γ	Probability of investing	0.25
ζ	Banks' loss parameter	0.002
θ	Installment on debt	0.05
δ	Depreciation of capital	0.02
ν	Investment (memory)	0.50
$\overline{\omega}$	Capacity utilization rate desired	0.85
w	Wage	1.00
D_1^f	Initial liquidity of all firms	10
K_1	Initial capital	10
Y_1^c	Initial production of consumption goods firms	5
Y_1^k	Initial production of capital goods firms	2
E_1^b	Initial equity of a bank	3,000
E_1^h	Initial personal assets of a household	2
r^*	Natural interest rate	0.01
α_π	Taylor's rule parameter for inflation	[0.0, 2.5]
α_Y	Taylor's rule parameter for output	[0.0, 1.3]
Ψ	Threshold for triggering the central bank's private asset purchase	(0.08, 0.14)
χ	Central bank's asset purchase parameter	0.20

Source: the author (2019).

3.3 Submodels

Workers and capitalists behave the same way in the consumption goods market. Their sources of income are:

$$Y_{c,t} = \begin{cases} w\,,\ if\ it\ is\ a\ worker\ with\ a\ job\ contract, \\ \tau\pi_{f,t-1},\ if\ it\ is\ a\ capitalist\ receiving\ dividends. \end{cases} \quad . \tag{1}$$

$Y_{c,t}$ *is current income*, $Y_{c,t} \in (0, \infty) \subset \mathbb{R}$;
w *is wage*, $\omega \in (0, \infty) \subset \mathbb{R}$;
τ *is the dividend ratio*, $\tau \in (0, 1) \subset \mathbb{R}$;
π *is profit of the period*, $\pi \subset \mathbb{R}$.

Households have bounded rationality. They use a rule of thumb to decide how much to consume. First, a household estimates its own lifetime wealth, $\bar{Y}_{c,t}$, as a proxy for its own future income, which means it expects future wealth similar to current wealth. Thus, it uses this adaptive rule:

$$\bar{Y}_{c,t} = \varepsilon\bar{Y}_{c,t-1} + (1-\varepsilon)Y_{c,t}, \tag{2}$$

$\bar{Y}_{c,t}$ *is lifetime wealth estimate*, $\bar{Y}_{c,t} \in (0, \infty) \subset \mathbb{R}$;
ε *is a memory parameter*, $\varepsilon \in (0,1) \subset \mathbb{R}$.

If the household has no income in a period, it still consumes by reducing its savings. Savings also drop whenever current consumption is bigger than current income:

$$D_{c,t} = D_{c,t-1} + Y_{c,t} - C_{c,t}, \tag{3}$$

$D_{c,t}$ *is savings*, $D_{c,t} \in (0, \infty) \subset \mathbb{R}$;
$C_{c,t}$ *is current consumption*, $C_{c,t} \in (0, \infty) \subset \mathbb{R}$.

Each household approaches a number Z_c of firms by period. It tries to consume goods for the lowest price. To produce consumption goods, firms employ labor and capital. At the beginning of a period, a firm checks its own position $(P_{i,t}, Y_{i,t})$, that is, its prices and quantities of the previous period. $P_{i,t}$ represents the last price set. The firm also knows quantity it actually sold $Q_{i,t}$. As sales take place after the firm has set its production level, a queue of clients unsatisfied may occur or an undesirable inventory in the end of a period. Goods of the consumption market are assumed to be perishables, so that goods not sold are wasted, that is, they are not available for sale in the next period. So, the firm strives to find the correct level of production by using two pieces of information: current sector price level and its forecast error, that is, the difference between expectation of sales and actual sales:

$$\Delta_{(i,t)} = Q^e_{i,t} - Q^d_{i,t}, \tag{4}$$

$\Delta_{i,t}$ *is forecast error*, $\Delta_{(i,t)} \subset \mathbb{Z}$;
$Q^e_{i,t}$ *is current production* , $Q^e_{i,t} \subset \mathbb{N}$;
$Q^d_{i,t}$ *is quantity demanded*, $Q^d_{i,t} \subset \mathbb{N}$.

$$P^c_t = \frac{1}{Q} \sum_{i=1}^{N} Q^d_{i,t} \, P^c_{i,t}, \tag{5}$$

P^c_t *is consumption sector price level price*, $P^c_t \in (0, \infty) \subset \mathbb{R}$;
$P^c_{i,t}$ *is price of* i^{th} *firm*, $P^c_{i,t} \in (0, \infty) \subset \mathbb{R}$;
$Q^d_{i,t}$ *is quantity sold by* i^{th} *firm*, $Q^c_{i,t} \subset \mathbb{N}$;
Q *is total quantity sold*, $Q \subset \mathbb{N}$.

$$Q^e_{i,t+1} = Q^d_{i,t} - \rho \, \Delta_{i,t} \;\; if \;\; \{\Delta_{i,t} \leq 0 \; and \; P^c_{i,t} \geq P^c_t\} \; or \; \{\Delta_{i,t} > 0 \; and \; P^c_{i,t} < P^c_t\}, \tag{6}$$

ρ *is quantity adjustment parameter*, $\rho \in (0,1) \subset \mathbb{R}$.

$$P^c_{i,t} = P^c_{i,t}(1 + \eta_{i,t+1}) \;\; if \;\; \{\Delta_{i,t} \leq 0 \; and \; P^c_{i,t} < P^c_t\} \; and \; \{\Delta_{i,t} > 0 \; and \; P^c_{i,t} \geq P^c_t\}, \tag{7}$$

η *is price adjustment parameter*, $\eta \in U(0{,}0.1) \subset \mathbb{R}$.

The firm produces employing available labor and capital:

$$\hat{Y}_{i,t} = \min\{\alpha N_{i,t}, \; \kappa K_{i,t}\}, \tag{8}$$

$\hat{Y}_{i,t}$ *is current production of* i^{th} *firm*;
$K_{i,t}$ *is current capital of* i^{th} *firm*, $K_{i,t} \in (0, \infty) \subset \mathbb{R}$;
$N_{i,t}$ *is the number used by* i^{th} *firm*, $N_{i,t} \subset \mathbb{N}$;
α *is productivity of labor*, $\alpha \in (0,1) \subset \mathbb{R}$;
κ *is productivity of capital*, $\kappa \in (0,1) \subset \mathbb{R}$.

Capital in use by the firm depreciates, so the firm have to invest, that is, to buy new capital goods, to keep its production level constant:

$$K_{i,t+1} = \left(1 - \delta\omega_{i,t}\right)K_{i,t} + I_{i,t}\ , \tag{9}$$

δ *is depreciation of capital*, $\delta \in (0,1) \subset \mathbb{R}$;
$w_{i,t}$ *is capacity utilization by* i^{th} *firm*, $w_{i,t} \in (0,1) \subset \mathbb{R}$;
$I_{i,t}$ *is investment made by* i^{th} *firm*, $I_{i,t} \in (0, \infty) \subset \mathbb{R}$.

A firm's demand fluctuates, so the firm is not always in full employment. That means the firm envisages the long run when targeting its desired amount of capital, that is,

$$\bar{K}_{i,t-1} = \nu\bar{K}_{i,t-2} + (1-\nu)\omega_{i,t-1}K_{i,t-1}, \tag{10}$$

$\bar{K}_{i,t}$ *is long run desired capital by* i^{th} *firm*, $\bar{K}_{i,t} \in (0, \infty) \subset \mathbb{R}$;
ν *is memory of the investment parameter*, $\nu \in (0,1) \subset \mathbb{R}$.

When the firm learns its long run desired capital, it is able to calculate its investment level:

$$I_{i,t}^{r} = \frac{\delta}{\gamma}\ \bar{K}_{i,t-1}, \tag{11}$$

γ *is probability to invest*, $\gamma \in (0,1) \subset \mathbb{R}$.

We can rewrite the law of capital as:

$$K_{i,t+1} = \left(\frac{1}{\bar{\omega}} + \frac{\delta}{\gamma}\right)\bar{K}_{i,t-1} - \delta\omega_{i,t}K_{i,t}, \tag{12}$$

$\bar{\omega}$ *is long run desired capacity utilization*, $\bar{\omega} \in (0,1) \subset \mathbb{R}$.

Then the quantity of labor can be found, as a result. The firm does not know a priori whether it has all that necessary labor, and then it opens some vacancies at the job market in the hope that some available worker will apply:

$$K^*_{i,t+1} = \omega^*_{i,t+1} K_{i,t+1} \tag{13}$$

$$\omega^*_{i,t+1}\ is\ desired\ capacity\ to\ be\ used\ by\ i^{th} firm,$$

$$N^*_{i,t+1} = \min\left\{ K^*_{i,t+1}\frac{\kappa}{\gamma}\ ,\ K_{i,t+1}\frac{\kappa}{\gamma}\right\}. \tag{14}$$

Equation (14) shows quantity of labor needed. When the capital available is restricted, $K_{i,t+1}\frac{\kappa}{\gamma}$, the quantity of labor varies in response to that. If there is capital to spare, the firm employs only a portion of it, and the quantity of labor also varies accordingly.

So far, we are talking about the decision process of the firms that produce goods for the consumption market. A firm that produces capital goods has a different task. It does not use a combination of labor and capital, but only labor. Also, as its output is a capital good, it can store unsold production. It thus chooses quantity by the rule:

$$Q^k_{j,t+1} = \left(Q^k_{j,t} + \Delta^k_{j,t}\right)(1 - \delta^\kappa) \tag{15}$$

$\Delta^k_{j,t}$ *is variation of inventory of* j^{th} *firm,* $\Delta^k_{j,t} \subset \mathbb{R}$;
δ^k *is depreciation of capital in stock,* $\delta^k \in (0,1) \subset \mathbb{R}$.

Its rule for price is similar to that of a firm in the consumption goods market:

$$P^K_{j,t} = P^K_{i,t}\left(1 + \eta_{j,t+1}\right)\ if\ \left\{\Delta^k_{j,t} \leq 0\ and\ P^K_{j,t} < P^k_t\right\}$$

$$and\left\{\Delta^k_{j,t} > 0\ and\ P^K_{j,t} \geq P^k_t\right\} \tag{16}$$

Finally, an adaptive rule considering both the forecast error and current stock guide its production decision:

$$Q_{j,t}^{*} = Q_{j,t}^{K} - \rho\, \Delta_{j,t}^{k} \quad if \quad \{\Delta_{j,t}^{k} \leq 0 \; and \; P_{j,t}^{K} \geq P_{t}^{K}\} \; or \; \{\Delta_{j,t}^{k} > 0 \; and \; P_{j,t}^{K} < P_{t}^{K}\}, \tag{17}$$

$$Q_{j,t}^{K} = \alpha N_{j,t}. \tag{18}$$

As can be seen in Equation (18), production in the capital goods sector depends only on the level of labor. Labor productivity is the same in both sectors and it time independent. If a firm needs more workers or dismissing some, it checks its desired production, $Q_{j,t+1}^{*}$, and the productivity of labor, α:

$$N_{j,t+1}^{*} = \frac{Q_{j,t+1}^{*}}{\alpha}. \tag{19}$$

Whenever an expectation is not fulfilled, a firm can be in trouble to honor its bills, that is, to pay wages and for investments. Its assets are deposited at a bank and this bank may or may not help the firm in times liquidity constraint. We define the need for financial help as the gap between current expenditure and revenues. Equation (20) captures that for a firm that produces consumption goods. A firm that produces capital goods is different because it does not need to invest (Equation (21)):

$$F_{i,t}^{C} = \max\{wN_{i,t} + P_{t-1}^{K} I_{i,t} - D_{i,t-1},\; 0\}, \tag{20}$$

$F_{i,t}$ *is the financial gap of* i^{th} *firm*, $F_{i,t} \subset \mathbb{R}$;
$D_{i,t}$ *are assets of* i^{th} *firm*, $D_{i,t} \subset \mathbb{R}$.

$$F_{j,t}^{K} = \max\{\,\omega N_{j,t} - D_{j,t-1}\,,\; 0\}, \tag{21}$$

Because the bank possesses this information, it updates the firm's risk. Then, the bank checks the leverage ratio of the firm that reveal the size of its financial problem. When the firm is in perfect financial health, its leverage ratio tends to zero, that is, the firm is run with its own money. In contrast, when the firm has few assets, its leverage ratio tends to one:

$$\lambda_{f,t} = \frac{L_{f,t-1} + F_{f,t}}{E_{f,t-1} + L_{f,t-1} + F_{f,t}}, \tag{22}$$

λ *is leverage ratio*, $\lambda \in (0,1) \subset \mathbb{R}$;

$L\ is\ accumulated\ debt, \quad L \in (0,\infty) \subset \mathbb{R};$
$E\ are\ assets, \quad E \in (0,\infty) \subset \mathbb{R}.$

If a firm had no doubt about the return of a loan, its bank would target the minimal gross rate:

$$R = \left(1 + \frac{r}{\theta}\right), \tag{23}$$

$R\ is\ gross\ rate, \quad R \in (0,1) \subset \mathbb{R};$
$r\ is\ free\ interest\ rate, \quad r \in (0,1) \subset \mathbb{R};$
$\theta\ is\ installment\ on\ debt, \quad \theta \in (0,1) \subset \mathbb{R}.$

Because such an ideal situation is unlikely to hold, the bank keeps evaluating the risk of loans. The bank calculates such a risk for each firm individually by considering the leverage ratio of the market to build a logistic regression ($\phi_{f,t}$) and the leverage ratio of the firm to measure its life expectancy, $T_{f,t}$. When a firm has a low leverage ratio its life expectancy tends to infinity and its situation converges to the ideal situation described above:

$$T_{f,t} = \frac{1}{\phi_{f,t}\lambda_{f,t}}, \tag{24}$$

$\phi_{f,t}\ is\ a\ logistc\ regression\ for\ measuring\ market\ risk\ ,$
$\phi_{f,t} \subset \mathbb{R}^{+};$
$T\ is\ expected\ survival\ time, \quad T \subset \mathbb{R}^{+}.$

The gross rate charged to a particular firm thus depends on that set of information: life expectancy of the firm, which also depends on market risk, the free interest rate of the monetary authority, and the installment on debt:

$$R_{f,t} = \left(\theta + r_{f,t}\right)\frac{1-(1-\theta)^{T_{f,t+1}}}{\theta}, \tag{25}$$

Rewriting the above equation by setting $\Xi = 1 - (1 - \theta)^{T_{f,t+1}}/\theta$, we have:

$$r_{f,t} = \mu\left(\frac{1+\frac{r}{\theta}}{\Xi} - \theta\right), \tag{26}$$

μ *is bank markup*, $\mu \in (1, \infty) \subset \mathbb{R}$.

The bank applies a markup to find the interest rate to charge the firm in Equation (26). The bank then has to decide how much credit is available for the firm. It knows current loans ($L_{f,t-1}$) and the firm's need for loans. The bank has a limit of acceptable loss, ζE_t^b, and it only offers new credit if this loss limit is not exceeded:

$$\phi_f\left(\Delta L_{f,t} + L_{f,t-1} \right) \leq \zeta E_t^b, \tag{27}$$

ζ *is the bank's loss parameter*, $\zeta \in (0,1) \subset \mathbb{R}$.

The monetary authority uses a simple Taylor's rule to set the free interest rate. It needs to know the natural rate of the gross domestic product of this economy. As labor productivity is known and constant, its task is feasible:

$$\bar{Y} = \alpha H, \tag{28}$$

$\bar{Y}$ *is potential GDP*;
α *is productivity of labor*, $\alpha \in (0,1) \subset \mathbb{R}$;
H *is the total of workers*, $H \subset \mathbb{N}$.

The current inflation level is described as the difference between the current and the previous price level:

$$\pi_t = \frac{P_t - P_{t-1}}{P_{t-1}}, \tag{29}$$

π_t *is current inflation*.

Thus, the monetary authority has the tools to apply Taylor's rule:

$$r_t = \pi_t + r^* + \alpha_\pi \left(\pi_t - \pi^* \right) + \alpha_Y \left(Y_t - \bar{Y} \right), \tag{30}$$

r_t *is current free interest rate*;
r^* *is natural interest rate*, $r^* \in (0,1) \subset \mathbb{R}$;
α_π *is a parameter*, $\alpha_\pi \in [0, 2.3] \subset \mathbb{R}$;
α_Y *is a parameter*, α_Y *in* $[0, 1.3] \subset \mathbb{R}$;
Y_t *is current gross domestic product*.

The other way the monetary authority has to manage this economy is buying assets directly from the wholesale bank. This is an emergency mechanism that central bank resorts only under certain critical conditions. Moreover, there is an upper bound in the number of assets the central bank can hold:

$$A_t^{C.B.} = \begin{cases} 0\ , if\ the\ {H_t^U}\Big/{H_t^E} < \psi\ ; \\ \max \chi Y,\ if\ {H_t^U}\Big/{H_t^E} \geq \psi \end{cases} \tag{31}$$

$A_t^{C.B.}$ $is\ total\ private\ assets\ held\ by\ the\ central\ bank\ in\ period\ t$;
$H_t^{E.}$ $is\ the\ total\ of\ workers\ with\ a\ job\ position\ in\ period\ t$;
$H_t^{U.}$ $is\ the\ total\ of\ workers\ without\ a\ job\ position\ in\ period\ t$;
ψ $is\ the\ threshold\ after\ which\ the\ central\ is\ allowed\ to\ buy\ assets$ $\in (0,1) \subset \mathbb{R}$;
$\chi\ is\ a\ parameter,\quad \chi \in (0,1) \subset \mathbb{R}$.

This terminates the description.

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