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Knightian Uncertainty in Banking Crises

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Good times for a change
see, the luck I've had
can make a good man turn bad.
So please, please, please
let me, let me, let me,
let me get what I want
this time.

-The Smiths-

Abstract

This essay is about Knightian uncertainty in the banking system and its effects on the productive sector and on the rest of the economy. A real business cycle model that explicitly models the banking sector is considered to describe the main macroeconomic variables. Unlike other papers, here no particular assumption on bank capital requirements or market frictions are made. It turns out that uncertainty about the likelihood of future events hitting the banks' capital is sufficient to produce a consistent credit crunch and a consequent depression of economic activity. Moreover, in this setting standard expansionary fiscal policies are insufficient to restore the pre-shock situation.

Contents

1. Introduction

Until recently, the role of financial intermediation has been neglected in the study of macroeconomic fluctuations. The recent crisis urged economists to explicitly investigate how shocks propagates through the financial sector to affect macroeconomic variables. The subprime crisis, in fact, made it evident that financial intermediation itself is a channel for the propagation of shocks, especially for those originating in the credit market.

Roughly speaking the current literature on this topic can be divided between two lines of research. The first one focuses its attention on imperfections in the credit market. Asymmetric information, collateral requirements and imperfect competition in the banking sector constitute the main sources of propagation of shocks. The second one focuses on the study of bank capital requirements. Shocks in the credit market can directly or indirectly reduce the capital of banks. If banks are forced by law, or by market forces, to keep some minimum amount of capital as a fraction of their assets, shocks hitting their capital induce banks to either recapitalize or deleverage. In either case the result is a tightening of the credit supply which causes a reduction of investments and GDP.

My goal in this essay is to propose a third mechanism through which the banking sector could have contributed to the recession following the subprime crisis.

In the years preceding the crisis deregulation in the financial sector and financial innovation spurred enthusiasm in financial markets, but made also the system much more fragile. When the subprime crisis struck the economy, it became clear that all the knowledge about financial innovations was indeed a pretense of knowledge. Beside the direct losses that many institutions incurred, the unfolding of the crisis contributed to a significant rise of uncertainty, in the sense of Knight (1921), in the system. The default of many triple-A rated securities, the complex way in which many of them where interconnected and the pervasiveness of their diffusion, forced financial institutions to reconsider the validity of their pricing models[1]. The idea that Knightian uncertainty affects the economy in the presence of innovation is not new and not limited to the financial market. In an article on the Financial Times, Phelps argues that it is indeed an important characteristic of capitalism:

> From the outset [of capitalism], the biggest downside was that creative ventures caused uncertainty not only for the entrepreneurs themselves but also for everyone else in the global economy. Swings in venture activity created a fluctuating economic environment. Frank Knight, observing US capitalism in his 1921 book, said that a company, in all of its decisions aside from the handful of routine ones, faces what is now called "Knightian uncertainty". In an innovative economy there are not enough precedents to be able to estimate the probability of this or that outcome. John Maynard Keynes in 1936 insisted on the "precariousness" of much of the "knowledge" used to value an investment - thus the "flimsiness" of investors' beliefs.

In this essay I argue that an ambiguity shock, a sudden increase of uncertainty, in the banking sector produces a consistent tightening of credit supply with a subsequent reduction of investments and GDP. To do so, I develop a simple general equilibrium model with three agents, a worker, an

[1] See "model uncertainty" in Routledge and Zin (2009).

entrepreneur and a banker, based on Kollmann et al. (2011). The original model shows that a shock in the credit market produces a rise in the interest rate spread and a credit crunch. The results they obtain are critically dependent on an exogenous capital requirement (they do not specify whether the requirement is imposed by law or by market forces). When a shock reduces the bank's capital, the bank raises the credit spread and the amount of loans falls. Dropping the assumption about this capital requirement, the model predicts nearly no changes in the amount of loans from and deposits at the bank. The peculiarity of ambiguity shocks are that they require no particular assumption about capital or collateral requirements and other market imperfections[2] to generate a significant credit crunch. My model is indeed able to predict a much larger crunch than the one predicted by the original model. The latter in its full specification predicts a drop in the stock of loans of about 3%. This is in line with the data, but this prediction does not take into account the nature of the loans. In fact, in reality the outstanding stock of loans is composed by new loans and old long-maturity loans, while in the model all the loans mature in one period. This implies that the model describes indeed the dynamics of new short term loans, which during the crisis dropped by more than 40% (Ivashina and Scharfstein, 2010). In other words, if we focus of new emissions, ambiguity shocks can better explain the drop in the emission of new bank loans than the original model. In the end, I will also evaluate the effectiveness of a direct support to the banking system against an increase in public purchases as a means to respond to an ambiguity shock.

The next section is a short review of some literature regarding the banking system as a source of shock transmission and amplification mechanisms. Section 3 briefly defines Knightian uncertainty presenting some literature that is relevant for the following discussion. Section 4 describes the model, while section 5 shows the graphical output and the results of the policy ex-

[2]All market imperfection will be proxied by a "redistribution shock". See below.

periments. Finally, section 6 concludes.

2. Banks in Macroeconomics

Since the importance of financial intermediation in the determination of the business cycle was recognized by academics, a great effort has been made to understand the functioning of the banking sector in the macroeconomic context. Both researchers and regulators have put a lot of attention on the role of bank capital and banks' balance sheets as they are deemed to be among the most relevant variables to consider when studying financial stability.

Two are the main theories regarding the role of bank capital as a requirement for the well-functioning of the credit market. The first states that bank capital is fundamental to solve the moral hazard problem incurring between banks and creditors. The idea is that if banks do not have enough own resources involved in their investments, they may take investment decisions that, while optimal for shareholders, may be suboptimal from the society as a whole. For instance, they may have an incentive to undertake riskier projects to maximize the return on equity at the expenses of bondholders or deposit insurance funds. The second theory sees bank capital as a safety net for deposits. Since in the presence of losses bank capital must fall to zero before any loss can pass on depositors, equity constitutes a cushion against losses for depositors. In both cases, the lack of an adequate amount of equity may make it hard for a bank to raise enough loanable funds to exploit all the profitable investment opportunities.

Despite the unquestionable importance of the banking sector as an intermediary between savings and investments, the numerous banking crises occurred in the last decades have shown that the banking system itself constitutes a source of financial and economic instability. In fact, the banking sector provides both a transmission channel for the propagation of shocks originating outside it and a source of shocks that are passed on to the whole economy.

Many macroeconomic models that aim to the study of credit markets include some version of what is called the financial accelerator. The financial accelerator is a mechanisms that explains how shock to asset values can give birth to a vicious circle depressing the economy. A very influential paper on this topic is due to Kiyotaki and Moore (1995). The key assumption in their model is that creditors (households) cannot force borrowers (firms) to repay their debt, unless it is secured. This means that there is a moral hazard problem between creditors and borrowers that is solved assuming that only collateralized loans are issued. In other words borrowers face a credit constraint, namely they cannot borrow more than the market value of the capital they own. Since capital is the only factor used in production, its market value depends positively on its productivity. Thus, when a negative productivity shock hits the economy its value drops. This in turn reduces the capacity of borrowers to roll over their debt, forcing them to deleverage and reduce their demand for capital, which further depresses the price of capital. Moreover the credit constraint implies that firms have lower resources to undertake otherwise profitable investments. This produces a further reduction of future output. Thus, the financial accelerator highlights the importance of the borrowers' net worth in the unfolding of the business cycle. While the original formulations did not involve a banking sector, recent studies have reformulated the financial accelerator theory to fit a credit market where banks play a central role. Von Peter (2004) develops an overlapping-generations model designed for asset prices to play a similar central role. Most importantly, he shows how a fall in asset prices affects the banks' activities even when these assets are not held directly by them. Moreover, he shows that the presence of a binding capital constraint produces a feedback from the banking system to asset prices. As in Kiyotaki and Moore (1995), a negative shock in productivity causes a drop in asset prices. This in turn may lead borrowers to default. Banks absorb the related losses reducing their profit but, if the shock is big enough, they suffer losses on equity. In the latter scenario an exogenously imposed capital requirement (a fixed capital asset ratio in the model) forces the bank to deleverage, reducing the supply of credit. As in the standard formulation of the financial accelerator, the result is a further drop in asset prices and another wave of defaults.

The explicit inclusion of financial intermediation in macroeconomic models gives the opportunity to study other transmission mechanisms. Needless to say, bank capital plays a central role. Meh and Moran (2010) develop a model in which bank capital emerges endogenously to solve an asymmetric information model between banks and their creditors. The assumption is that investors are not willing to invest directly into productive activities since they are not able to monitor directly how their resources are spent. Thus they need banks to intermediate and monitor on their behalf. Yet monitoring is costly, which means banks will do as little monitoring as they can. In this setting bank capital is needed to ensure that some level of monitoring occurs. In the extreme case where bank capital is zero, the bank would have problems attracting loanable funds because, since all the risk is borne by investors, banks have no incentive to monitor and investors would not be willing to provide funds to them. Bank capital mitigates this problem because having some equity at stake makes it optimal for banks to monitor. Here the cost of monitoring is the cause of what they call the bank capital channel for the amplification of a productivity shock. When such a shock happens the profitability of investing falls, making it harder for banks to attract funds. To counterbalance this effect, banks need more capital relative to total loans to further reduce the asymmetric information problem with the investors. Since capital is accumulated through retained earnings, increasing this ratio means reducing the amount of loans issued and consequently earnings and again loans in the following period, producing a vicious circle.

Bank capital requirements, though, are not only a channel for the amplification and propagation of shocks generating in the production sector, but also of shocks generating in the financial markets. Iacoviello (2011) tries to quantify the extent to which the output contraction in the Great Recession was caused by shocks generated in the financial markets. He estimates a DSGE model with a banking sector which existence is purely a technological matter, since without it agents would not be able to transfer resources across each other and over time. In his model a redistribution shock, a shock that transfers resources from lenders to borrowers (e.g. default on loans) reduces the banks' equity. An externally imposed capital requirement, if binding, forces the bank to deleverage and causes a credit crunch. As before this causes a contraction of investments and a drop in output. Using Bayesian methods, he estimates that these shock accounted for about a half of the output loss. Gerali et al. (2010) arrive at similar conclusions. In their estimated model, the bank capital requirement is not strict. Banks are allowed to violate it, but this violation entails a quadratic cost. They find out that the largest share of the economic contraction of 2008 is due to shocks generating in the banking sector, while other macroeconomic shocks played a relatively little role.

Given the importance of the role played by bank capital, many economists have tried to give recommendations about the optimal regulation of capital requirements, often coming to contradictory conclusions.

On the one hand, some believe that the optimal policy consists in procyclical bank capital requirements, meaning that during a recession banks should be allowed to hold less capital as a fraction of total assets. Holmstrom and Tirole (1997) assume in their model that firms can finance themselves either through informed capital (capital provided directly by investors) or through uninformed capital (indirect investments intermediated by banks).

In either case, banks have to undertake some monitoring activity. The role of monitoring is twofold. In fact, it is needed both to solve the usual asymmetric information problem with indirect investors and as a sort of certification of quality for direct investors. In this sense the banks in the model can also be interpreted as a venture capitalist, a lead investment banks or any other sophisticated investor whose participation in the investments certifies the soundness of the borrower. Moreover, to be credible monitors banks must invest some own money, which defines a market-based capital requirement. It turns out that during a recession the optimal market-determined bank capital requirement falls, given a rise of the return on investments that makes monitoring and the need of being credible monitors less compelling. In the authors opinion this is sufficient to justify a pro-cyclical regulation. Similarly, Van den Heuvel (2008) argues that the current capital requirements are too high. He analyses their welfare costs, and estimates them using US data. He finds out that capital requirements result in a permanent loss in consumption that is between 0.1% and 1%.

On the other hand, other economists lean towards the idea of counter-cyclical capital ratio requirement as the optimal policy. Angeloni and Faia (2009) study the interaction between capital requirements and monetary policy. There are several key assumption in their model. First of all, they separate the banks' management from their ownership. They assume that the goal of the managers is to maximize the return to depositors and shareholders, where the latter have a residual claim once deposits are paid back. Moreover, firms can only fund themselves through banks. The outcome of their activity is random, which implies that the cash flow to banks is risky. Banks are exposed to runs by depositors that are the more likely the higher is their leverage. Moreover they assume that banks are relationship lenders, meaning that by lending they acquire a specialized knowledge about the projects undertaken by the borrowing firms. This determines an advantage in extracting value for shareholders and depositors whenever the project has to be liquidated before its completion. It turns out that the banks' leverage depends positively on the expected return and on the riskiness of firms' projects and on the relationship advantage of the banks. Running several simulations, imposing different capital requirements schemes, they conclude that pro-cyclical requirements tend to accentuate the size of the fluctuation of the main macroeconomic variables. They conclude that the optimal policy requires mildly counter-cyclical requirements, even though they recognize that fixed requirements are enough to contain the amount of risk carried by banks, and thus the likelihood of bankruptcy. Morrison and White (2005) focus on a different aspect. They assume that the banking sector is heterogeneous. There are good banks, with sound and profitable projects, and bad banks. Since depositors cannot observe the type of the bank, the role of the regulator is to solve this adverse selection problem by either auditing the banks before conceding them a license or by imposing capital requirements, making it unprofitable for bad banks to operate. When capital requirements are used to solve this problem, multiple equilibria arises depending on the agents' expectations about the quality of the average bank. They call the switch between an optimistic equilibrium (high expectations) and a pessimistic equilibrium (low expectations) a crisis of confidence. They conclude that if the regulator as a bad reputation as an auditor (low auditing skills) it may be optimal for it to tighten capital requirements in a crisis of confidence, even though it means reducing the size of the banking system that is in general bad for the economy. This result follows from the fact that auditing is a substitute for capital requirements in the solution of the adverse selection problem. In the case of a regulator with a bad reputation then increasing the auditing effort may not be enough.

As it is clear from the previous paragraphs, the question about the optimal capital regulation is not of easy solution. Some economists have noticed that the optimal policy may not be as simple as the trivial imposition of a minimum capital-to-asset ratio. Calem and Rob (1999), for instance, argue that the risk profile of a bank's portfolio is U-shaped and not monotonically decreasing in the capital ratio. This effect is linked to the deposit insurance scheme in force in the US. There banks have to pay an insurance premium to the FDIC that is decreasing in the bank capital ratio. The purpose of this is to discourage banks to be too leveraged. It turns out that at low capitalization levels the riskiness of the bank's portfolio is decreasing in the capital ratio, since the loss in the eventuality of bankruptcy increases with capitalization. Yet this relation is reversed at high levels of capitalization. As the capital ratio increases, the probability of bankruptcy becomes more and more remote and the fear of it is no more able to counterbalance the higher expected return from a riskier portfolio. De Walque et al. (2010), instead, claim that not only the level of the required capital matters, but also the system for its determination. Through the estimation of a DSGE model they focus their attention on the Basel I and Basel II requirements. They find out that the former reduce the long run level of output, making the economy more resilient, while the latter increase business cycle fluctuations.

3. Uncertainty and ambiguity-aversion

3.1 Definition

Knghtian uncertainty takes its name from Frank Hyneman Knight that one of in his books (Knight, 1921) makes a neat distinction between risk and uncertainty:

> Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated. [...] The essential fact is that ”risk” means in some cases a quantity susceptible of measurement [...]. It will appear that a measurable uncertainty, or ”risk” proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We shall accordingly restrict the term ”uncertainty” to cases of the non-quantitative type.

In other words, Knightian uncertainty and risk can be distinguished from each other by the fact that the latter is measurable by some parameters and that this measure can and must be used in the decision making process. For example, the more volatile is the outcome of a lottery (the higher its variance), the riskier it is. The volatility parameter is in general an important information to be used in making decisions involving this lottery. On the contrary, uncertainty in the sense of Knight is pure ignorance, it is the impossibility of quantifying precisely some characteristic (e.g. the mean or the variance) of the random outcome.

Given the possible confusion that the terminology can generate it is better to specify the terms that I will be using in the rest of the essay. I will use the term risk to indicate measurable uncertainty, while Knightian uncertainty (or simply uncertainty) and ambiguity to refer to unmeasurable uncertainty.

As stressed by Machina (1992), the theory of choice under risk can be considered as a "success story" in economic research. For long time the expected utility paradigm has dominated microeconomic research at first, and modern micro-based macroeconomics. In addition to its simplicity and tractability, it could rely on solid axiomatic foundations (Savage, 1972). In a few words the subjective expected utility theory (SEU) assumes that, when facing a decision in an uncertain environment, agents act as if they were maximizing their expected utility, namely the weighted average utility given by their action in all the possible states of the world using the probabilities of these states as weights.

Nevertheless, the expected utility theory is still unable to explain certain behaviors that seem to clash with the Savage's axioms. Probably the most famous example of such behaviors is offered by Ellsberg (1961) , namely the paradox that bears his name. In the experiment he designed[1], subjects are asked to compare different bets involving two urns. The first urn contains 50 red balls and 50 black balls while the second urn contains 100 red and black balls in an unspecified proportion. This design allows to impose an exact probability distribution on the first urn while leaving the probability distribution attached to the second urn under subjective control. According to the SEU an observer could measure the subjective probabilities simply interrogating the subject, asking him to compare different bets about the

[1]Ellsberg never actually run any experiment. In his paper he talks of a mental experiment. Numerous later experiments supported his finding, see Camerer and Weber (1992) for a survey.

color of the ball drawn from the two urns.

Experimental evidence suggests that for many subjects there is no probability distribution that is consistent with all the decisions taken. Assume for instance that subjects are asked to choose between a bet on a red ball from the first urn and the same bet on the second urn. Many people prefer the bet on the first urn, the one with know probabilities, to the bet on the second urn. Given this answer, the SEU would imply that those subjects believe that the second urn contains more black balls than red balls. Yet when asked to choose between a black ball in the first urn and one in the second, they still seem to prefer betting on the first urn. This aspect of agents' behavior, that clearly violates the Savage's axioms, was labeled ambiguity-aversion. For a more exhaustive explanation see Gilboa et al. (2008).

Ambiguity has been also defined as uncertainty about the probabilities (Frisch and Baron, 1988). According to this definition ambiguity-averse agents prefer to bet on the first urn because they know with certainty the distribution of black and red balls, and then the probability of their extraction, while they know nothing about the probabilities for the second urn.

3.2 Multiple Priors and the Maxmin Expected Utility

Following Ellsberg (1961), numerous attempts have been made to develop a decision model that allows for ambiguity-averse behaviors[2]. One of them is the multiple prior model[3] (Gilboa and Schmeidler, 1989). According to this model, an agent that has too little information to form a unique prior over uncertain events bases his decisions considering a whole set of priors deemed admissible. Then, while evaluating a bet an uncertainty averse agent would consider the minimal expected utility over all priors in the set (maxmin

[2]See again Camerer and Weber (1992) for a survey.

[3]See Gul and Pesendorfer (2008) for an alternative theory.

expected utility).

To see how it works, let us consider again the Ellsberg paradox. Suppose as before that an agent is asked to choose between two different lotteries. In the first if a red ball is drawn from the urn with the known number of balls he gets 10$ and zero otherwise. In the second the ball will be drawn from the other urn and the payoff is as before. Since the second urn has an ambiguous distribution of balls, we may assume that in evaluating the two lotteries the agent considers a set of priors, such that the probability of a red ball being drawn from the ambiguous urn lies in the set $[0.5-a, 0.5+a]$ with $0 < a < 0.5$. If we assume, for simplicity that the agent has linear preferences ($u(c) = c$), the maxmin expected utility from the first bet is simply 5 because, since probabilities are known, there is no ambiguity and the maxmin expected utility is equivalent to the standard expected utility. For the second urn the maxmin expected utility is given by the lowest expected utility over the set of priors, namely $10(0.5-a)$. Since a is positive the agent would prefer to bet on the first urn. Similarly if asked to choose between two lotteries about the extraction of a black ball from either one of the two urn, a the same agent would again prefer to bet on the unambiguous urn. As this example shows, the maxmin utility function model can explain the Ellsberg paradox.

Despite the fact that the this theory is not free from critiques (Sims, 2001), its simplicity and versatility made it probably the most used model for decision making under ambiguity. This is also the reason why I am going to use it to model ambiguity-aversion in the next chapter.

Yet, before moving to the model it seems reasonable to review some literature about the application of Knightian uncertainty in macroeconomics and finance.

3.3 Ambiguity in Macroeconomics and Finance

The concept of Knightian uncertainty has found a number of application in finance at first and in macroeconomics later on, especially after the recent crisis. Here I present some related literature.

In portfolio theory, Simonsen and Werlang (1991) show how Knightian uncertainty can produce portfolio inertia with positive quantities held of all assets. In doing so, they rely on nonadditive probability measures to model ambiguity-aversion. Dow and da Costa Werlang (1992) analyze the optimal choice of portfolio of an ambiguity-averse investor[4]. Using the maxmin expected utility model, they argue that the presence of ambiguity creates a range of prices for which an investor does not want to hold any position in that asset.

Epstein and Wang (1994) develop a model of asset pricing involving Knightian uncertainty. They find out that uncertainty can lead to equilibria that are indeterminate. This implies that the determination of a particular equilibrium is left to "animal spirits", which can cause high volatility in the asset market.

Inspired by the current crisis, Routledge and Zin (2009) show that uncertainty reduces the liquidity in security markets. In their paper they notice that some practices in the financial world seem to clash with the Savage expected utility:

> The observed behavior of traders and institutions that places a large emphasis on "worst-case scenarios" through the use of "stress testing" and "Value-at-Risk" seems different than Savage expected utility would suggest.

Caballero and Krishnamurthy (2008) argue that Knightian uncertainty, arising from unusual events and untested financial innovations, can cause

[4] See also Garlappi et al. (2007) for an application of the multi-prior approach to portfolio choice.

episodes of flight to quality. The model they develop describes the financial market when a turmoil period is entered and some financial market specialists receive a liquidity shock. They show that the fear of being hit by a liquidity shock reduces immediately the liquidity in financial markets[5]. They also study the role of a lender of last resort in such a setting.

Pritsker (2013) models Knightian uncertainty in the interbank market to study how it may have contributed to its breakdown during 2007 and 2008. He shows that uncertainty can cause the collapse of the Fed Funds market and that, in such an event, private incentive may be insufficient to recover. He also argues that, with a better publicly available information on core banks aggregate risk exposure, breakdowns are less likely ex-ante and less costly to fix ex-post.

Only recently attempts to allow for Knightian uncertainty in business cycles' models have been made.

Ilut and Schneider (2012) develop a medium-scale DSGE model with an ambiguous TFP process. In the particular way in which ambiguity is modeled, that I will use in my model too, ambiguity has first order effects on the business cycle, allowing its study even under a first order approximation. The variability of the ambiguity level emerges as a major source of business cycle fluctuations.

Finally, Baqaee (2013) argues that information friction, coupled with ambiguity-aversion results in households' expectations of the price level to be more sensible to inflationary then to disinflationary news. He also shows that if households have some bargaining power in the labor market, this asymmetry gives rise to downward wage rigidity.

[5] See also Krishnamurthy (2009) for another example of the relation between liquidity and uncertainty.

4. Model Setup

The model I propose is a modified version of the two-country business cycle model developed by Kollmann et al. (2011). In this economy only one homogeneous final good is produced and there are four agents: a worker, an entrepreneur, a banker and the government. The worker maximizes his expected utility from consumption and work, holding deposits to the bank and deciding how much to work. The entrepreneur owns capital, invests and buys work from the worker to produce the final good, financing himself through bank loans. Each period, part of the loans are defaulted. He maximizes his expected utility from consumption, under the assumption that he consumes all his profits after investments are made. The banker owns the representative bank that accepts deposits from the worker and lends to the entrepreneur. He maximizes his (ambiguous) expected utility from the consumption of his earnings. One of the reasons why I chose this model is that it allows to solve explicitly and in a simple way the banker's optimization problem, as it will be clear in the next pages. The forth agent is the government that raises money through lump sum taxes levied on the other three agents, and spends the tax revenue on general public purchases and possibly on transfers to the bank. It is assumed that the government has no deficit or surplus and pursues no active fiscal policy. All agents are assumed to be price takers.

One peculiarity of this model is that the default rate is stochastic. This kind of modeling choice is not new in the literature. Iacoviello (2011) calls them "redistribution shocks", namely redistribution of wealth from lenders to borrowers. The inclusion of these shocks is useful to account in a simple and intuitive way for all the financial frictions that can cause a disruption of bank capital. In light of the last crisis, the stochastic default can be thought as a parable for investment mistakes made in the past due, for instance, to overoptimism[1]. Moreover, it is easy to construct ambiguity over this parameter. The ambiguity represents the difficulty of estimation of the future losses that the bank has to bear. Financial innovations and the complexity of the credit relations made in fact almost impossible to price some instruments and to evaluate the risk exposure of some debtors.

4.1 Stochastic processes

There are three sources of randomness in this model. The first is TFP (θ_t). It is assumed that

$$\log \theta_t = \rho_\theta \log \theta_{t-1} + \varepsilon_{\theta,t} \tag{4.1}$$

where $\varepsilon_{\theta,t}$ is a i.i.d. random variable with mean 0.
The second is the default rate Δ_t. It is assumed to follow a stationary AR(1) process of the following form

$$\Delta_t = (1 - \rho_\Delta)\Delta + \rho_\Delta \Delta_{t-1} + \varepsilon_{\Delta,t} \tag{4.2}$$

where $\varepsilon_{\Delta,t}$ is a i.i.d. random variable with mean 0.
Unlike the TFP process the latter is not known to all the agents. In particularly it is not know to the banker (see below) which has an ambiguous knowledge. I assume that the conditional mean of Δ_t is ambiguous to the

[1]An example of a default shock is the fall in the aggregate US price index after 2006 that was largely unanticipated.

banker, namely that for him

$$\Delta_t = (1-\rho_\Delta)\Delta + \hat{a}_{t-1} + \rho_\Delta \Delta_{t-1} + \varepsilon_{\Delta,t} \tag{4.3}$$

where $\hat{a}_t \in [-a_t, -a_t + 2|a_t|]$. This way of modeling Knightian uncertainty is taken from Ilut and Schneider (2012). This specification implies that the conditional distribution of Δ_{t+1} given all the information available to the banker at time t is a shifted version of the real one. The collection of all these distributions for different possible values of $\hat{a}_t$ constitutes the set of admissible priors. I will later assume that the banker maximize is maxmin expected utility function, namely that he takes his decisions based on the prior corresponding to the worst-case scenario. To differentiate the banker's expectations from the other agents' expectations, I will use throughout this essay the expectation operator with an hat to indicate the banker's beliefs (e.g. $\hat{E}_t\theta_{t+1} = E_t\theta_{t+1} + \hat{a}_t$) or with a star to indicate the expectations under the optimal prior (a_t^*).

Finally I assume that the ambiguity parameter follows an AR(1) process as well:

$$a_t = (1-\rho_a)A + \rho_a a_{t-1} + \varepsilon_{a,t} \tag{4.4}$$

where $\varepsilon_{a,t}$ is a i.i.d. random variable with mean 0. The ambiguity parameter captures the banker's lack of confidence in his probability assessment of the future default rate. According to this specification, the ambiguity parameter reverts to a long run mean A. Periods of high $a_t > A$ represent unusually low levels of confidence, while low values of a_t are associated with high level of confidence.

4.2 Worker

In optimizing his consumption the worker faces the following budget constraint:

$$c_t = w_t N_t + R_t^D D_t - D_{t+1} - T_t^W \tag{4.5}$$

where D_t is the amount of deposits carried from $t-1$ to t, T_t^W is the lump-sum tax paid by the worker, c_t is consumption, w_t is the wage rate, N_t is hours worked and R_t^D is the gross interest earned on D_t.

The worker then solves the following maximization problem:

$$\begin{aligned} &\max_{\{c_t, D_{t+1}, N_t\}} E_t \sum_{s=0}^{\infty} \beta^s [u(c_{t+s}) + \psi^D u(D_{t+s+1}) - \psi^N N_{t+s}] \\ &\text{sub. } (4.5). \end{aligned} \tag{4.6}$$

where Ψ^D and Ψ^N are positive parameters, and $u(x) = (x^{1-\sigma^W} - 1)/(1 - \sigma^W)$ (when $\sigma^W = 1$, I set $u(x) = \log(x)$). The fact that workers obtain direct utility from holding deposit is a technical requirement to ensure that the worker holds positive deposits. Following Sidrauski (1967), it could be justified assuming that deposits provide some liquidity service which directly gives some utility to the agent. The optimization problem gives the following first order conditions:

$$R_{t+1}^D E_t \beta \frac{u'(c_{t+1})}{u'(c_t)} + \psi^D \frac{u'(D_{t+1})}{u'(c_t)} = 1 \tag{4.7}$$

$$u'(c_t) w_t = \psi^N. \tag{4.8}$$

4.3 Entrepreneur

The entrepreneur faces the following budget constraint

$$d_t^E = L_{t+1} + Q_t - R_t^L L_t(1-\Delta_t) - \xi(I_t) - w_t N_t - T_t^E \tag{4.9}$$

where d_t^E is his consumption at time t, L_t is the loan received at $t-1$ to be repaid in t, R_t the corresponding gross interest rate, Δ_t the portion of that loan that is defaulted, T_t^E is a lump-sum tax and $Q_t = \theta_t K_t^\alpha N_t^{1-\alpha}$ is the production function, where K_t is the capital stock and θ_t the TFP parameter. The function $\xi(\cdot)$ is the cost of investment $I_t = K_{t+1} - (1-\delta)K_t$ where δ is the depreciation rate. Since the model will be linearized around the steady state, it is sufficient to characterize the first and second derivatives of function around the steady state investment $I = \delta K$. In particular it is assumed that $\xi'(I) = 1$ and $\xi''(I) = 1$.

The entrepreneur solves the following optimization problem:

$$\begin{gathered}\max_{\{d_t^E, L_{t+1}, N_t\}} E_t \sum_{s=0}^{\infty} \beta^s \nu(d_{t+s}^E) \\ \text{sub. } (4.9).\end{gathered} \tag{4.10}$$

with $\nu(x) = (x^{1-\sigma^E} - 1)/(1-\sigma^E)$ (when $\sigma^E = 1$, I set $\nu(x) = \log(x)$).
The first order conditions related to this problem are:

$$w_t = (1-\alpha)\theta_t \left(\frac{K_t}{N_t}\right)^\alpha \tag{4.11}$$

$$R_{t+1}^L E_t \beta \frac{\nu'(d_{t+1}^E)}{\nu'(d_t^E)}(1-\Delta_{t+1}) = 1 \tag{4.12}$$

$$E_t \beta \frac{\nu'(d_{t+1}^E)}{\nu'(d_t^E)} \frac{\alpha\theta_{t+1}\left(\frac{K_{t+1}}{N_{t+1}}\right)^{\alpha-1} + q_{t+1}(1-\delta)}{q_t} = 1 \tag{4.13}$$

where in the last equation $q_t = \xi'(K_{t+1} - (1-\delta)K_t)$.

4.4 Bank

The banker owns the representative bank which collects deposits and makes loans to produce dividend for the banker's consumption. The reason for the existence of banks in this economy is purely technological, without it there would be no flow of resources over time or across agents[2]. It is assumed that the bank faces operating costs for holding deposits (Γ_D) and for making loans (Γ_L). In the original model, it is assumed that the bank is required by law to keep a certain amount of own capital as a fraction γ of total loans. Nevertheless, this legal constraint is not binding since the bank can hold less capital, but this is costly[3] (e.g. it has to engage in creative accounting). Defining the amount of capital exceeding the legal requirement as $x_t = (L_{t+1} - D_{t+1}) - \gamma L_{t+1}$, $\phi(x_t)$ is the cost of breaking the legal constraint. It is assumed that $\phi(x_t) = 0$ for $x_t \geq 0$ and $\phi(x_t) > 0$ for $x_t < 0$, $\phi'(\cdot) \leq 0$ and $\phi''(\cdot) \leq 0$. However, this assumption capital requirements will eventually be dropped to disentangle the effects of uncertainty from those of capital requirements.

The bank faces the following budget constraint

$$d_t^B = R_t^L L_t(1-\Delta_t) + D_{t+1} - L_{t+1} - R_t^D D_t - \Gamma_D D_{t+1} - \Gamma_L L_{t+1} - \phi(x_t) + S_t - T_t^B \tag{4.14}$$

where T_t^B is the lump-sum tax paid by the banker and S_t is a transfer from the government.

As anticipated before, the banker has ambiguous beliefs about the future default rate. I assume the banker maximizes his maxmin expected utility

[2]The same modeling choice is made by Iacoviello (2011).

[3]In a similar fashion Gerali et al. (2010) assume that a deviation from an exogenously imposed capital ratio entails a quadratic cost for the bank.

function under the budget constraint, namely he solves:

$$\max_{\{d^B_{t+s}, D_{t+s+1}, L_{t+s+1}\}_{s=0}^{\infty}} \min_{\hat{a}\in[-a_t,-a_t+2|a_t|]} \hat{E}_t \sum_{s=0}^{\infty} \beta^s v(d^B_{t+s}) \quad \text{sub. (4.14).} \tag{4.15}$$

with $v(x) = (x^{1-\sigma^B} - 1)/(1-\sigma^B)$ (when $\sigma^B = 1$, I set $\nu(x) = \log(x)$). The Bellman equation corresponding to the problem is

$$\begin{aligned} V(D_t, L_t, \Delta_t) = \max_{\{D_{t+1}, L_{t+1}\}} &\{v(L_t R^L_t (1-\Delta) + D_{t+1} \\ &- L_{t+1} - D_t R^D_t - \Gamma_D D_{t+1} - \Gamma_L L_{t+1} - \phi(x_t) + S_t - T^B_t) \\ &+ \beta \min_{\hat{a}\in[-a_t,-a_t+2|a_t|]} \hat{E}_t V(D_{t+1}, L_{t+1}, \Delta_{t+1})\}. \end{aligned} \tag{4.16}$$

To be able to solve this problem in a convenient way, we need to find which value of $\hat{a}_t$ corresponds to the worst-case scenario. The next proposition is useful to identify it.

Preposition 1. *The expected value of the value function is decreasing in Δ_t, that is:*

$$\frac{\partial \hat{E} V}{\partial \Delta_t}(D_t, L_t, \Delta_t) < 0$$

Proof. See Appendix A. □

The latter preposition is sufficient to state that the worst-case scenario is obtained for $\hat{a}_t = a^*_t = -a_t + 2|a_t|$, namely for the prior that corresponds to the highest expected default rate. The first order conditions are then

$$R^D_{t+1} E^*_t \beta \frac{v'(d^B_{t+1})}{v'(d^B_t)} = 1 - \Gamma_D + \phi'(x_t) \tag{4.17}$$

$$R^L_{t+1} E^*_t \beta \frac{v'(d^B_{t+1})}{v'(d^B_t)} (1 - \Delta_{t+1}) = 1 + \Gamma_L + (1-\gamma)\phi'(x_t). \tag{4.18}$$

4.5 Goverment

The government collects taxes and can spend the proceeds to make public purchases of the final good. Alternatively the government can directly support the banking sector through a transfer. It is assumed that the government cannot run deficits nor surpluses, namely that

$$S_t + G_t = \sum_i T_T^i \tag{4.19}$$

where G is public spending and $i = W, E, B$. Moreover, it is assumed that each agent funds a constant share of total public spending, that is $T_t^i = \lambda^i(G_t + S_t)$ with $\sum_i \lambda^i = 1$ and $i = W, E, B$. There is no particular reason for these assumptions. They just are the simplest possible in order to gain an insight on the role of the government in the setting of the model.

4.6 Market clearing and GDP definition

The combination of the three budget constraints (4.5), (4.9) and (4.14) with the government equation (4.19) gives the market clearing condition for the homogeneous good:

$$C_t + \xi(I_t) + G_t = Q_t - \Gamma_D D_{t+1} - \Gamma_L L_{t+1} - \phi(x_t) \tag{4.20}$$

where $C_t = c_t + d_t^E + d_t^B$ is aggregate consumption. GDP is defined as either the right hand side (demand) or the left hand side (supply) of the previous equation.

5. Solution and Results

In this section I will discuss some features of the model, in particular the differences with the original one by Kollmann et al., and I will present some graphical output.

5.1 Credit Spread

Let us define the expected effective loan rate as $\widetilde{R^L_{t+1}} = R^L_{t+1}E^*(1-\Delta_{t+1})$. Using a rough approximation, equations (4.17) and (4.18) give the following relation regarding the effective spread expected by the banker:

$$\widetilde{R^L_{t+1}} - R^D_{t+1} = \Gamma_L + \Gamma_D - \gamma\phi'(0) - \gamma\phi''(0)x_t. \tag{5.1}$$

In the original model this equation describes the whole amplification mechanism. In fact it is clear that a shock hitting directly the bank capital, such that the excess capital becomes negative, increases the expected effective loan rate relative to the deposit rate, since $\phi'' > 0$. The basic spread is determined by the administrative cost of deposit and loans. During the cycle it is influenced by the level of capitalization and the capital constraint, just like in Von Peter (2004).

If we compare this to the case without capital requirements ($\phi(x_t) = 0$), where the spread is unaffected by movements in bank capital, loans become relatively too expensive with a consequent fall of the demand for them. The transmission mechanism described here is in line with the literature.

On the contrary, in this essay I am focusing on another mechanism that works through changes in the expectations. Ruling out capital requirements, equation (5.1) shows that the expected spread is constant and predetermined. Yet a shock that increases ambiguity, creates a wedge between the effective loan rate expected by the entrepreneur and the banker. When there is no ambiguity, the expectations of the two agents are the same. If ambiguity rises, the previous equation implies that the bank will charge a higher nominal rate R^L_{t+1}, since the worst case scenario is characterized by an higher default rate. This results in a higher effective loan rate expected by the entrepreneur that, in response, will reduce his demand for loans.

In short, ambiguity creates a wedge between the expectations of the banker and the entrepreneur about the effective loan rate, which results in a reduction of total loans and then of investments and output.

5.2 Linearization and Calibration

To study the dynamics of the model, I linearize the model around a deterministic steady state with no ambiguity. Moreover, to focus the attention on the effects of ambiguity I assume there is no capital requirement. Following Kollmann et al. (2011), the steady state effective loan rate is set to 2.5% p.a., which through equation (4.12) pins down the value for β. This rate implies a loan rate of 3.48%. Similarly the steady state deposit rate is set to 1% p.a.. The resulting spread is 2.48% which is in line with the US and EA data in the past decade. In this economy without capital requirements an equilibrium exists only if the cost of administrative cost of issuing loans is zero (equations (4.12) and (4.18)). The steady state bank capital ratio is set to 5%, matching the average capital ratios of major US commercial banks (D'Hulster, 2009). The default rate is set to 0.95% p.a., equal to the average loan loss rate in US and EA during 1995-2010. Moreover, Ψ^D is set to generate a target loan-to-GDP ratio of 0.5[1], while Ψ^N is chosen arbitrarily since it turns out it only affects the scale of the economy and not the dynamics. Finally, I have set $\sigma^W = \sigma^B = 1$ and $\sigma^E = 0.01$ meaning that the entrepreneur is almost risk neutral.

To calibrate the behavior of the public sector I relied on Kollmann et al. (2012). The baseline public purchases is set to be always equal to the 20% of GDP in every period. The share of taxes paid by each agent is constant and equal to the ratio of own consumption to aggregate consumption.

In line with Kollmann et al. (2011) I have set $\rho_\theta = 0.95$, $\rho_\Delta = 0.97$ and $\Delta = 0.2375$ which corresponds to a 0.95% annualized default rate. For what concerns the stochastic process of the ambiguity parameter I assumed that in the steady state there is no ambiguity ($A = 0$) and that $\rho_a = 0.97$. The latter value has been chosen rather arbitrarily. The reasons that moved me to impose such an high persistence in this process are mainly two. The first is a matter of comparability. In fact one of the goals of this work is to compare the ambiguity shock to the default rate shock and using a similar process for the two exogenous variables seems the best way for a meaningful comparison. The second relates to the difficulty of getting estimates either from data or from other studies. Given this dearth, I relied on the only paper I have found dealing with this kind of process. Ilut and Schneider (2012), in fact, develop a business cycle model with an ambiguous technological process. Using Bayesian techniques they estimate a value of 0.96, indicating a high degree of persistence of ambiguity.

5.3 Results

In the first part of this section I will present and discuss the impulse response functions to a shock in the default rate and in the level of uncertainty. In

[1]The mean ratio between bank loan to non-financial firms and GDP was around 45% between 2000 and 2010.

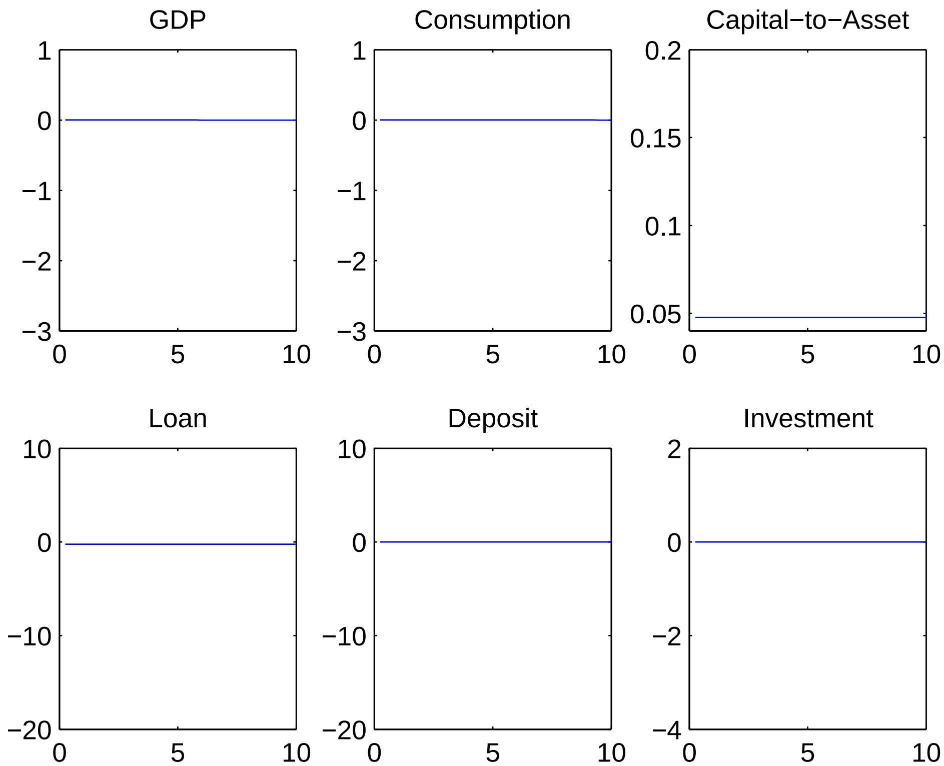

Figure 5.1: Response to a default rate shock. All values, except the capital-to-asset ratio, are in percentage change from the steady state. The capital-to-asset ratio is measured in absolute value.

the second part I will discuss the differences between an increase in public spending versus a direct support to the banking sector in supporting the economy after an ambiguity shock. These will be compared to what obtained by Kollmann et al. (2012).

Impulse Responses

Figure 5.1 shows the effects of an annualized 1% shock in the default rate on some macroeconomic variables. As anticipated, without capital requirements on banks there is no sensible change in economic activity. GDP, aggregate consumption, loans, deposits and investments are unaffected. The bank absorbs the shock by reducing its capital. Since the steady state path is still optimal, no change is needed and the bank has no incentive to restore the initial capital-to-asset ratio. This is in line with what found by Kollmann et al. (2011) and Kollmann et al. (2012). The reason for this is that the expected effective default rate is unaffected both under the banker's and under the entrepreneur's beliefs, implying that their optimal behavior remains unchanged after the shock.

Figure 5.2 shows the responses to an annualized 1% shock in the uncertainty parameter. Here the banker's worst case scenario corresponds to an expected default rate that is 1% higher than before the shock. The uncertainty shock generates much stronger the effects on the economy. Deposits and loans start to decrease, falling by around 5% right after the shock, reaching the lowest level after about four years (roughly -30%). Investments drop immediately by almost 4%. As a consequence aggregate consumption and GDP fall by respectively 2.5% and 3%, starting immediately to catch up with the steady state values. The bank starts deleveraging. The shock causes an increase of the lending rate and a decrease of the deposit rate, that cause a decline of both loans and deposits. In order to smooth consumption the banker accumulates capital that allows him to sustain higher profits.

When uncertainty in the banking system rises, the banker will act according to his worst case scenario, that is the one with the highest expected default rate. Other things equal, the banker will have to charge a higher rate on new loans to keep the equivalence in equation (5.1). Nevertheless this will cause a rise in the effective loan rate expected by the entrepreneur, which will see his funding cost jump up making production less profitable. The result is a reduction in the investing activity and production.

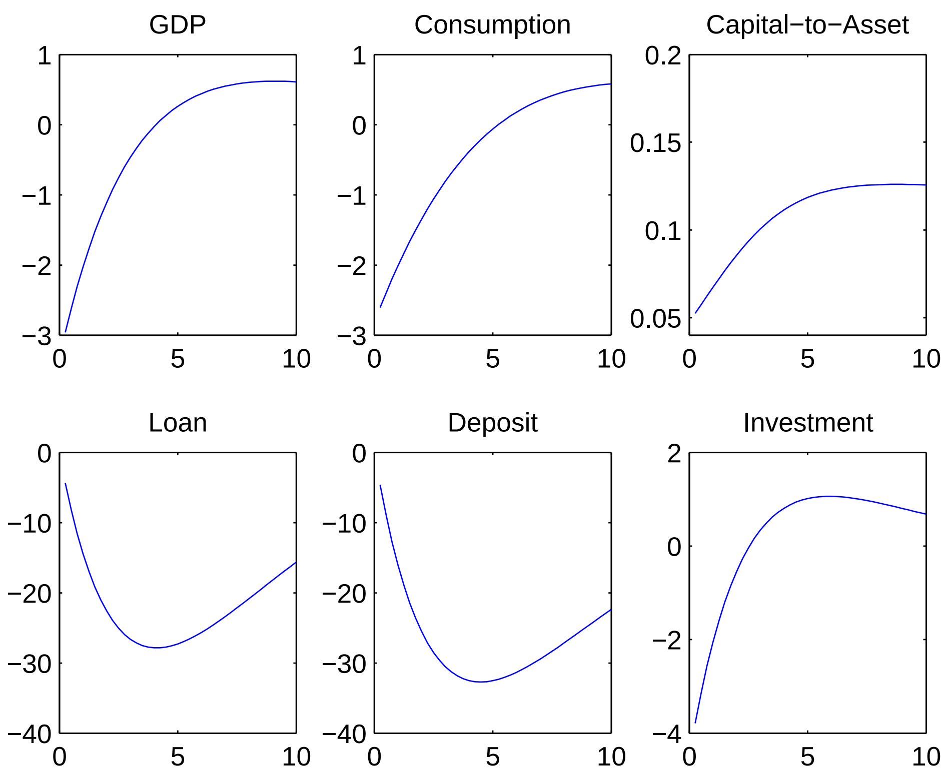

Figure 5.2: Response to an uncertainty shock. All values, except the capital-to-asset ratio, are in percentage change from the steady state. The capital-to-asset ratio is measured in absolute value.

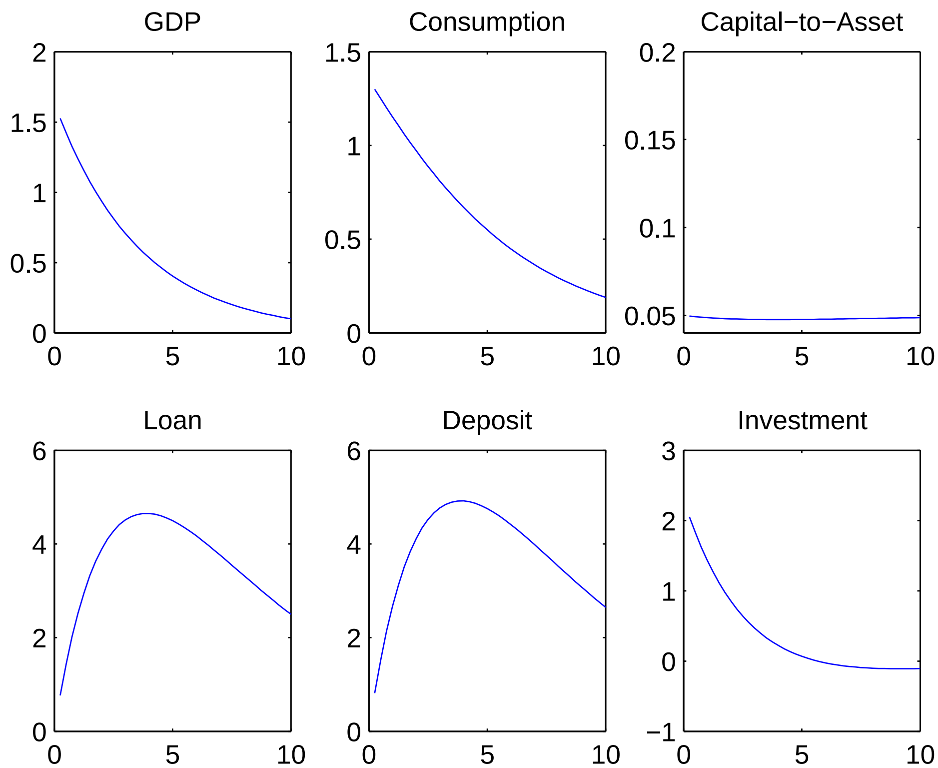

Figure 5.3: Response to a shock to technology. All values, except the capital-to-asset ratio, are in percentage change from the steady state. The capital-to-asset ratio is measured in absolute value.

For the sake of completeness figure 5.3 shows the impulse response functions to a 1% shock to technology. The capital ratio is almost unaffected. Aggregate consumption, savings and GDP raise along with investments that are financed by new loans. Deposits raise as the worker tries to smooth consumption across time.

Policy Experiments

Kollmann et al. (2012) run some policy experiments using a similar model

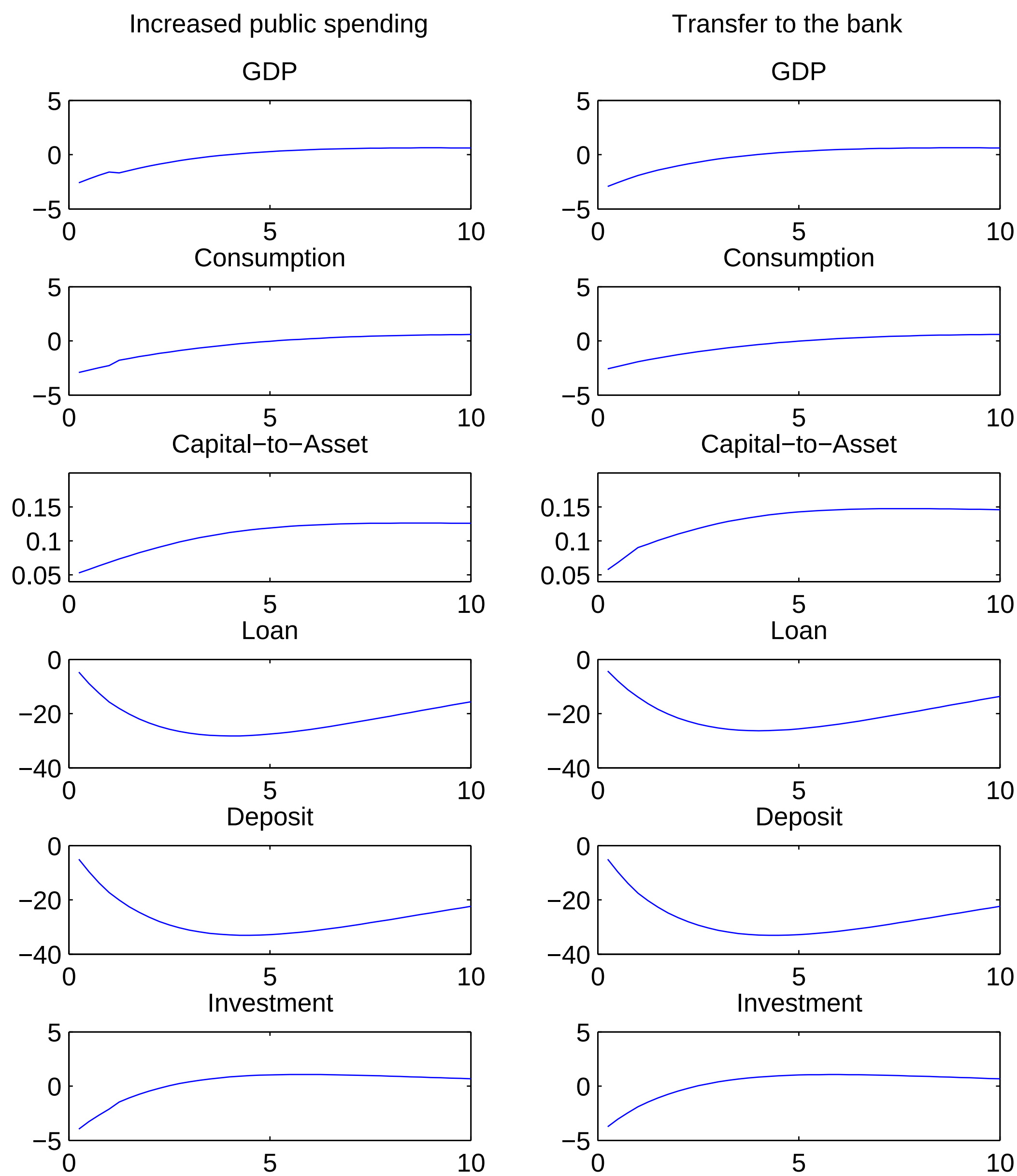

Figure 5.4: Different paths of some macroeconomic variables after an increase in government purchases (left) and after a direct transfer to the banking system (right).

to evaluate the impact of different fiscal policies on an economy stroke by a negative default shock. In particular, they analyze the differences between an increase in public spending and a direct transfer to banks. They find out that in the presence of capital requirements a transfer to the banking system has a stronger impact on GDP than an equivalent increase in public spending. Investments, loans and deposits raise in the first scenario and fall in the second one. The direct transfer to the bank relieves it from the costs associated with a capitals stock that is lower than the minimum required, which reduces the credit spread and restores the bank's capacity to lend.

Here I will run a similar experiment in an economy with no bank capital requirements that has been hit by an ambiguity shock. Figure 5.4 shows the responses of a shocked economy to the two polices. Both the increase in public spending and the transfer amount to 1% of steady state GDP equally spread over one year. This figure shows no substantial difference between the two policies. To make the comparison easier figure 5.5 shows the differences in the same variables between the two policy scenarios and the baseline case without any public intervention.

Looking at the details it is easy to notice that a rise in public spending has a much stronger effect on GDP than a transfer to the banking system. During the year in which the stimulus is applied, the benefit on GDP generated by the first policy is more than five times that generated by the second one. Yet this is mainly due to the direct effect of public purchases on GDP. In fact, this intervention crowds out both consumption and investment. The banking activity shrinks since both loans and deposits fall, following a similar path. With a direct transfer to the banking system, we observe a very little increase in aggregate consumption and a positive effect on investments and loan issuance. Deposits on the other hand decrease just like in the previous case suggesting the main cause of this fall is the increased tax burden to be paid by the worker.

The first conclusion that can be made is that without capital requirements

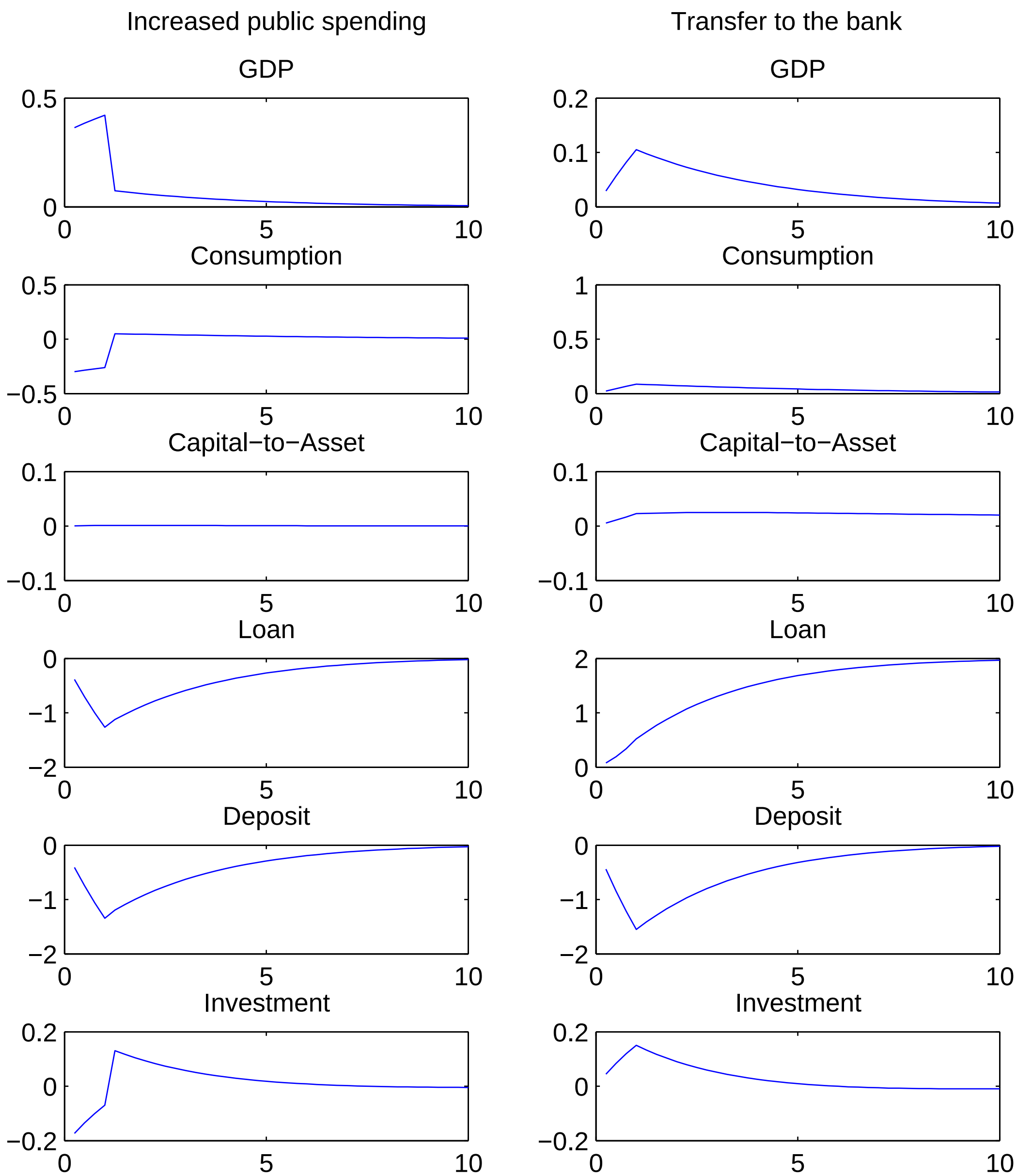

Figure 5.5: Policy scenarios vs. no intervention. Governement spending on the left, bank aid on the right.

the effects of supporting the banking industry on the whole economy are much weaker. Moreover, in this case the results obtained by Kollmann et al. (2012) are reverted, since it is clear that the standard fiscal expansion is more favorable. The reason is that their findings fundamentally depend on the presence of capital requirements. In that case, the direct transfer reduces directly the cost of holding less capital than required allowing bank to lend more. Here without capital requirements the bank does not face such cost by construction.

Nevertheless, the most important observation to be made here is that in both cases the positive effects are limited to the period of intervention, which is the first year. In fact after the stimuli the main macroeconomic variables revert sharply to the pre-intervention path. This suggests that the woes brought by uncertainty cannot be resolved by means of standard fiscal policies, but they are likely to require other specific interventions aiming at the reduction of uncertainty itself. However these are out of the reach of this simple model.

6. Conclusions

The last financial crisis presented some peculiar characteristics. It was generated in the credit market after a relatively small shock in the mortgage business, and resulted in a deep and long-lasting depression of the whole economy. The banking system in particular constituted the main channel through which the shock has been amplified and propagated to the rest of the economy. Several papers have tried to identify the exact mechanisms featuring the transmission of the shock since before the crisis itself. The majority of academic papers focus on credit market frictions and on bank capital requirements. While these mechanism have for sure played an important role, they seems unable to explain completely the depth of the crisis and in particular the size of the credit crunch as described by Ivashina and Scharfstein (2010), and they ignore the one peculiarity of the crisis itself, namely the pervasive uncertainty that impaired the credit system.

I have shown through a very simple model how the uncertainty about the likelihood of a "redistribution" shock moving resources from creditors to debtors can cause a significant drop of new loans' issuance and a consequent weakening of the productive activity. The ambiguity-averse behavior of the banks together with a rise in the level of uncertainty causes them to charge a relatively higher interest rate on loans to the entrepreneur, which depresses credit. Therefore, there is a drop in investments, consumption and GDP. This result is particularly important in relation to the fact that this credit crunch is obtained assuming no capital requirement. It implies that policy talks should not only focus on determining the optimal structure of capital requirements since it would not be sufficient to prevent other crunches, but also on policies preventing sudden surges of uncertainty, like for instance prompt regulation of financial innovations.

Moreover, through two extremely simple experiments of fiscal policy I have found that with a rise in uncertainty in the banking system direct support to banks has a lower effect on GDP that the simple increase of public purchases. This suggest that when the problem is uncertainty, endowing the banking system with resources would not cause much recovery. In other words, macroeconomic problems arising from uncertainty in the banking system cannot be exclusively dealt with standard fiscal policies but requires specific policies aiming at the reduction of uncertainty.

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A. Proof of Preposition 1

To prove Preposition 1 it is sufficient to show that the value function is decreasing in the default rate, namely that

$$\frac{\partial V}{\partial \Delta_t}(D_t, L_t, \Delta_t) < 0. \tag{A.1}$$

Let us assume that we know the optimal sequence of deposits and loans and that we also know that the worst case scenario is obtained at $\hat{a}_t = a^*$. The recursive form of the value function is then

$$V(D_t, L_t, \Delta_t) = v\left(d_t^{B*}\right) + \beta E_t^* V(D_{t+1}^*, L_{t+1}^*, \Delta_{t+1}). \tag{A.2}$$

Deriving the former with respect to Δ_t gives

$$\frac{\partial V}{\partial \Delta_t}(D_t, L_t, \Delta_t) = -v'(d_t^E) D_t R_t^D + \beta E_t^* (1 - \rho_\Delta) \frac{\partial V}{\partial \Delta_{t+1}}(D_{t+1}^*, L_{t+1}^*, \Delta_{t+1}). \tag{A.3}$$

Solving recursively for T periods gives

$$\begin{aligned} \frac{\partial V}{\partial \Delta_t}(D_t, L_t, \Delta_t) = & -E_t^* \sum_{s=0}^{T-1} \beta^s (1 - \rho_\Delta)^s D_{t+s} R_{t+s}^D v'(d_{t+s}^E) \\ & + \beta^T (1 - \rho_\Delta)^T E_t^* \frac{\partial V}{\partial \Delta_{t+T}}(D_{t+T}^*, L_{t+T}^*, \Delta_{t+T}) \end{aligned} \tag{A.4}$$

Taking the limit for $T \to \infty$ and using an improper notation

$$\frac{\partial V}{\partial \Delta_t}(D_t, L_t, \Delta_t) = -E_t^* \sum_{s=0}^{\infty} \beta^s (1-\rho_\Delta)^s D_{t+s} R_{t+s}^D v'(d_{t+s}^E) + \beta^\infty (1-\rho_\Delta)^\infty E_t^* \frac{\partial V}{\partial \Delta_\infty}(D_\infty^*, L_\infty^*, \Delta_\infty) \quad \text{(A.5)}$$

Since the economy converges to a steady state, the variables indexed with ∞ can be thought as the steady state values. Then from (A.3) we can write (omitting the time indexes for the steady state values) that at the steady state

$$\frac{\partial V}{\partial \Delta}(D, L, \Delta) = -v'(d^E) D R^D + \beta(1-\rho_\Delta) \frac{\partial V}{\partial \Delta}(D, L, \Delta)$$
$$\frac{\partial V}{\partial \Delta}(D, L, \Delta) = -\frac{D R^D v'(d^E)}{1-\beta(1-\rho_\Delta)} \leq 0. \quad \text{(A.6)}$$

Combining (A.5) and (A.6), noticing that the first term on the right hand side of equation (A.5) is negative, we obtain the result in (A.1).

B. Matlab code

This appendix contains the Matlab code used to produce this paper. There are four files: Main.m, graph_1.m, graph_2.m and graph_3.m. The first is the main code while the remaining three are the functions used to produce the graphical output.

Main.m

```
%% Definition of parameters and steady state values
global dep C DE DB D L RD RL K G Y_ss x_ass
beta=0.993789;
alpha=0.3;
DELTA=0.002375;
dep=0.025;
CgammaD=0.003727;
CgammaL=0;
gamma=0.05;
psiD=0.003421;
sigma_W=1;
sigma_E=0.01;
sigma_B=1;
rhotheta=0.95;
rhodelta=0.97;
rhoa=0.97;
phi1=0;
phi2=0;

C=0.369064;
```

```
DE=0.029939;
DB=0.000088;
D=0.338771;
L=D/(1-gamma);
N=0.271024;
W=1.845319;
RD=1.0025;
RL=1.008646;
K=6.858863;
G=0.142640;
S_share=0;
Gshare=0.2;
wtw=0.924762;
wte=0.075017;
wtb=0.000220;
Y_ss=K^alpha*N^(1-alpha)-CgammaL*L-CgammaD*D;
TW=wtw*(G+S_share*Y_ss);
TE=wte*(G+S_share*Y_ss);
TB=wtb*(G+S_share*Y_ss);

%% Definition of the matrices describing the system
% 0 = AA x(t) + BB x(t-1) + CC y(t) + DD z(t)
% 0 = E_t [ FF x(t+1) + GG x(t) + HH x(t-1) + JJ y(t+1) +
% + KK y(t) + LL z(t+1) + MM z(t)]
% z(t+1) = NN z(t) + epsilon(t+1) with E_t [ epsilon(t+1) ] = 0
% x(t)=(rd_t+1; d_t+1; rl_t+1; l_t+1; k_t+1)
% y(t)=(c_t; de_t; db_t; n_t; w_t; g_t; tw_t; te_t; tb_t; y_t)
% z(t)=(theta_t; delta_t; a_t; a_t-1; S_t; abs_g_increase)

%AA
A1=1-CgammaD+phi1;
A2=-(1+CgammaL+(1-gamma)*phi1);

AA= [ 0        -1        0        0        0;
      0         0        0        0        0;
      0         0        0        1       -1;
      0         0        0        0        0;
      0         A1       0        A2       0;
      0         0        0        0        0;
      0         0        0        0        0;
      0         0        0        0        0;
      0         0        0        0        0;
      0         0        0        0        1];

%BB
```

```
B1=alpha*(K/N)^(alpha-1)+1-dep;
B2=alpha*(1-alpha)*K^(alpha-1)*N^(-alpha);

BB= [ D        RD        0              0        0;
      0        0         0              0        0;
      0        0   -L*(1-DELTA)  -RL*(1-DELTA)  B1;
      0        0         0              0        B2;
     -D       -RD   L*(1-DELTA)    RL*(1-DELTA)  0;
      0        0         0              0        0;
      0        0         0              0        0;
      0        0         0              0        0;
      0        0         0              0        0;
      0        0         0              0   -(1-dep)];

%CC
C1=(1-alpha)*(K/N)^alpha-W;
C2=-alpha*(1-alpha)*K^alpha*N^(-1-alpha);

CC= [ -1      0      0      W      N      0     -1      0      0      0;
    -W/(C^2) 0      0      0     1/C     0      0      0      0      0;
       0     -1      0      C1    -N      0      0     -1      0      0;
       0      0      0      C2    -1      0      0      0      0      0;
       0      0     -1      0      0      0      0      0     -1      0;
       0      0      0      0      0     wtw    -1      0      0      0;
       0      0      0      0      0     wte     0     -1      0      0;
       0      0      0      0      0     wtb     0      0     -1      0;
       0      0      0      0      0     -1      0      0      0 Gshare;
       1      1      1      0      0      1      0      0      0     -1];

%DD
D1=K^alpha*N^(1-alpha);
D2=(1-alpha)*(K/N)^alpha;

DD=[  0      0      0      0      0      0;
      0      0      0      0      0      0;
      D1    L*RL    0      0      0      0;
      D2     0      0      0      0      0;
      0    -L*RL    0    -L*RL    1      0;
      0      0      0      0     wtw     0;
      0      0      0      0     wte     0;
      0      0      0      0     wtb     0;
      0      0      0      0      0      1;
      0      0      0      0      0      1];

%FF
```

```
FF=[ 0      0      0      0      0;
     0      0      0      0      0;
     0      0      0      0 beta*(1-dep);
     0      0      0      0      0;
     0      0      0      0      0];

%GG
G1=-psiD*(C^sigma_W)/(D^(1+sigma_W))*sigma_W;
G2=beta*(alpha*(alpha-1)*K^(alpha-2)*N^(1-alpha)...
    -(1-dep)^2-(alpha*(K/N)^(alpha-1)+(1-dep)));

GG=[ beta          G1            0            0             0;
     0             0      beta*(1-DELTA)      0             0;
     0             0             0            0            G2;
     beta         phi2           0     -phi2*(1-gamma)      0;
     0   (1-gamma)*phi2 beta*(1-DELTA) -(1-gamma)^2*phi2  0];

%HH
H1=(1-dep)*beta*(alpha*(K/N)^(alpha-1)+1-dep);

HH=[ 0      0      0      0      0;
     0      0      0      0      0;
     0      0      0      0      H1;
     0      0      0      0      0;
     0      0      0      0      0];

 %JJ
J1=-RD*beta*sigma_W/C;
J2=RL*beta*sigma_E/DE*(1-DELTA);
J3=beta*(alpha*(K/N)^(alpha-1)+1-dep)*sigma_E/DE;
J4=beta*alpha*(1-alpha)*K^(alpha-1)*N^(-alpha);
J5=beta*RD*sigma_B/DB;
J6=beta*RL*(1-DELTA)*sigma_B/DB;

JJ=[   J1     0      0      0      0      0      0      0      0      0;
       0     -J2     0      0      0      0      0      0      0      0;
       0     -J3     0      J4     0      0      0      0      0      0;
       0      0     -J5     0      0      0      0      0      0      0;
       0      0     -J6     0      0      0      0      0      0      0];

%KK
K1=RD*beta*sigma_W/C+psiD*sigma_W*C^(sigma_W-1)/D^sigma_W;

KK=[ K1     0      0      0      0      0      0      0      0      0;
     0     J2      0      0      0      0      0      0      0      0;
```

```
     0    J3     0     0     0     0     0     0     0     0;
     0     0    J5     0     0     0     0     0     0     0;
     0     0    J6     0     0     0     0     0     0     0];

%LL
L1=alpha*beta*(K/N)^(alpha-1);

LL=[ 0     0     0     0     0     0;
     0 -RL*beta  0     0     0     0;
    L1     0     0     0     0     0;
     0     0     0     0     0     0;
     0 -beta*RL  0 -beta*RL  0     0];

%MM
MM=zeros(5,6);

%NN
NN=[rhotheta 0     0     0     0     0;
       0  rhodelta 0     0     0     0;
       0     0   rhoa    0     0     0;
       0     0     1     0     0     0;
       0     0     0     0     0     0;
       0     0     0     0     0     0];

%% Solution to the model
% This part is extrapolated from the Uhlig's toolkit.

[~,m_states] = size(AA);
[~,n_endog ] = size(CC);
[l_equ,k_exog  ] = size(DD);

CC_plus = pinv(CC);
CC_0 = (null(CC'))';
Psi_mat   = [ zeros(l_equ-n_endog,m_states)
              FF - JJ*CC_plus*AA           ];
Gamma_mat = [ CC_0 * AA
              JJ*CC_plus*BB - GG + KK*CC_plus*AA ];
Theta_mat = [ CC_0 * BB
              KK*CC_plus*BB - HH                 ];
Xi_mat    = [ Gamma_mat,     Theta_mat
              eye(m_states), zeros(m_states) ];
Delta_mat = [ Psi_mat,       zeros(m_states)
              zeros(m_states), eye(m_states) ];
```

```
[Xi_eigvec,Xi_eigval] = eig(Xi_mat,Delta_mat);

[Xi_sortabs,Xi_sortindex] = sort(abs(diag(Xi_eigval)));
Xi_sortvec = Xi_eigvec(1:2*m_states,Xi_sortindex);
Xi_sortval = diag(Xi_eigval(Xi_sortindex,Xi_sortindex));
Xi_select = 1 : m_states;
Lambda_mat = diag(Xi_sortval(Xi_select));
Omega_mat  = [Xi_sortvec((m_states+1):(2*m_states),Xi_select)];
PP = Omega_mat*Lambda_mat/Omega_mat;
PP = real(PP);

RR = - CC_plus*(AA*PP+BB);
VV = [ kron(eye(k_exog),AA),   kron(eye(k_exog),CC)
       kron(NN',FF)+kron(eye(k_exog),(FF*PP+JJ*RR+GG)), ...
                          kron(NN',JJ)+kron(eye(k_exog),KK) ];

LLNN_plus_MM = LL*NN + MM;
   QQSS_vec = - VV \ [ DD(:)
                        LLNN_plus_MM(:) ];

QQ = reshape(QQSS_vec(1:m_states*k_exog),m_states,k_exog);
SS = reshape(QQSS_vec((m_states*k_exog+1): ...
                    ((m_states+n_endog)*k_exog)),n_endog,k_exog);
WW = [ eye(m_states)         , zeros(m_states,k_exog)
       RR*pinv(PP)           , (SS-RR*pinv(PP)*QQ)
       zeros(k_exog,m_states), eye(k_exog)            ];


%% Impulse response functions

length=40; %10 years
x_ass=[1:length]./4;

%Shock to technology
Z_theta=zeros(size(QQ,2),length+1);
X_theta=zeros(size(AA,2),length+1);
Y_theta=zeros(size(CC,2),length+1);
epsilon_theta=[[0.01; 0; 0; 0; 0; 0] zeros(size(QQ,2),length-1)];

for i=1:length;
    Z_theta(:,i+1)=NN*Z_theta(:,i)+epsilon_theta(:,i);
    X_theta(:,i+1)=PP*X_theta(:,i)+QQ*Z_theta(:,i+1);
    Y_theta(:,i+1)=RR*X_theta(:,i)+SS*Z_theta(:,i+1);
end
```

```
name='Responce to a shock in technology';
graph_1(X_theta,Y_theta,name,[0 2],...
                    [0 1.5],[0.04 0.2],[0 6],[-1 3]);

%Shock to default rate
Z_delta=zeros(size(QQ,2),length+1);
X_delta=zeros(size(AA,2),length+1);
Y_delta=zeros(size(CC,2),length+1);
eps_delta=[[0; 0.0025; 0; 0; 0; 0] zeros(size(QQ,2),length-1)];

for i=1:length;
    Z_delta(:,i+1)=NN*Z_delta(:,i)+eps_delta(:,i);
    X_delta(:,i+1)=PP*X_delta(:,i)+QQ*Z_delta(:,i+1);
    Y_delta(:,i+1)=RR*X_delta(:,i)+SS*Z_delta(:,i+1);
end
name='Responce to a shock in default';
graph_1(X_delta,Y_delta,name,[-3 1],...
                    [-3 1],[0.04 0.2],[-20 10],[-4 2]);

%Uncertainty shock
ep_a=[[0; 0; 0.0025; 0; 0; 0] zeros(size(QQ,2),length-1)];

%redefine NN
NN_s=[rhotheta    0       0    0    0   0;
          0    rhodelta  0    0    0   0;
          0       0    rhoa   0    0   0;
          0       0       0    0    0   0;
          0       0       0    0    0   0;
          0       0       0    0    0   0];


Z_a=zeros(size(QQ,2),length+1);
X_a=zeros(size(AA,2),length+1);
Y_a=zeros(size(CC,2),length+1);

for i=1:length;
    Z_a(:,i+1)=NN_s*Z_a(:,i)+ep_a(:,i);
    X_a(:,i+1)=PP*X_a(:,i)+QQ*Z_a(:,i+1);
    Y_a(:,i+1)=RR*X_a(:,i)+SS*Z_a(:,i+1);

end

name='Responce to an uncertainty shock';
graph_1(X_a,Y_a,name,[-3 1],[-3 1],[0.04 0.2],[-40 0],[-4 2]);
```

```
%% POLICY EXPERIMENTS

%Public Purchases
Z_e1=zeros(size(QQ,2),length+1);
X_e1=zeros(size(AA,2),length+1);
Y_e1=zeros(size(CC,2),length+1);
eps_e1=[[zeros(2,4);
         0.0025 0 0 0;
         zeros(2,4);
         ones(1,4)*0.00250*Y_ss] zeros(size(QQ,2),length-4)];

for i=1:length;
    Z_e1(:,i+1)=NN_s*Z_e1(:,i)+eps_e1(:,i);
    X_e1(:,i+1)=PP*X_e1(:,i)+QQ*Z_e1(:,i+1);
    Y_e1(:,i+1)=RR*X_e1(:,i)+SS*Z_e1(:,i+1);
end

%Bank aid
Z_e2=zeros(size(QQ,2),length+1);
X_e2=zeros(size(AA,2),length+1);
Y_e2=zeros(size(CC,2),length+1);
eps_ex=[[zeros(2,4);
         0.0025 0 0 0;
         0 0 0 0;
         ones(1,4)*0.00250*Y_ss;
         0 0 0 0] zeros(size(QQ,2),length-4)];

for i=1:length;
    Z_e2(:,i+1)=NN_s*Z_e2(:,i)+eps_ex(:,i);
    X_e2(:,i+1)=PP*X_e2(:,i)+QQ*Z_e2(:,i+1);
    Y_e2(:,i+1)=RR*X_e2(:,i)+SS*Z_e2(:,i+1);
end


name='Public spending vs. Bank aid absolute';
graph_2(X_e1,Y_e1,X_e2,Y_e2,name,[-5 5],[0.04 0.2]);
name='Public spending vs. Bank aid relative';
graph_3(X_e1,Y_e1,X_e2,Y_e2,X_a,Y_a,name,[0 1],[-0.1 0.1]);
```

graph_1.m

```
function graph_1(X,Y,name,y1,y2,y3,y4,y5)
global dep C DE DB D L K Y_ss x_ass

N=size(X,2);

OUTPUT=Y(10,2:N)./Y_ss*100;
A_C=(Y(1,2:N)+Y(2,2:N)+Y(3,2:N))./(C+DE+DB)*100;
LOAN=X(4,2:N)./L*100;
DEPOSIT=X(2,2:N)./D*100;
INVESTMENT=(X(5,2:N)-(1-dep).*X(5,1:(N-1)))./(dep*K)*100;
CAP_ASS=(X(4,2:N)+L-X(2,2:N)-D)./(X(4,2:N)+L);

figure('name',name)
subplot(2,3,1), plot(x_ass,OUTPUT), ylim(y1)
title('GDP')
subplot(2,3,2), plot(x_ass,A_C), ylim(y2)
title('Consumption')
subplot(2,3,3), plot(x_ass,CAP_ASS), ylim(y3)
title('Capital-to-Asset')
subplot(2,3,4), plot(x_ass,LOAN), ylim(y4)
title('Loan')
subplot(2,3,5), plot(x_ass,DEPOSIT), ylim(y4)
title('Deposit')
subplot(2,3,6), plot(x_ass,INVESTMENT), ylim(y5)
title('Investment')
set(gcf,'color','w')
```

graph_2.m

```
function graph_2(X1,Y1,X2,Y2,name,y1,y2)
global dep C DE DB D L K Y_ss x_ass
```

```
N=size(X1,2);

OUTPUT_1=Y1(10,2:N)./Y_ss*100;
A_C_1=(Y1(1,2:N)+Y1(2,2:N)+Y1(3,2:N))./(C+DE+DB)*100;
LOAN_1=X1(4,2:N)./L*100;
DEPOSIT_1=X1(2,2:N)./D*100;
INVESTMENT_1=(X1(5,2:N)-(1-dep).*X1(5,1:(N-1)))./(dep*K)*100;
CAP_ASS_1=(X1(4,2:N)+L-X1(2,2:N)-D)./(X1(4,2:N)+L);


OUTPUT_2=Y2(10,2:N)./Y_ss*100;
A_C_2=(Y2(1,2:N)+Y2(2,2:N)+Y2(3,2:N))./(C+DE+DB)*100;
SPREAD_2=(X2(3,2:N)-X2(1,2:N))*400;
LOAN_2=X2(4,2:N)./L*100;
DEPOSIT_2=X2(2,2:N)./D*100;
INVESTMENT_2=(X2(5,2:N)-(1-dep).*X2(5,1:(N-1)))./(dep*K)*100;
CAP_ASS_2=(X2(4,2:N)+L-X2(2,2:N)-D)./(X2(4,2:N)+L);


figure('name',name,'NumberTitle','off')
subplot(6,2,1), plot(x_ass,OUTPUT_1)
title('GDP')
subplot(6,2,2), plot(x_ass,OUTPUT_2)
title('GDP')
subplot(6,2,3), plot(x_ass,A_C_1)
title('Consumption')
subplot(6,2,4), plot(x_ass,A_C_2), ylim(y1)
title('Consumption')
subplot(6,2,5), plot(x_ass,CAP_ASS_1), ylim(y2)
title('Capital-to-Asset')
subplot(6,2,6), plot(x_ass,CAP_ASS_2), ylim(y2)
title('Capital-to-Asset')
subplot(6,2,7), plot(x_ass,LOAN_1)
title('Loan')
subplot(6,2,8), plot(x_ass,LOAN_2)
title('Loan')
subplot(6,2,9), plot(x_ass,DEPOSIT_1)
title('Deposit')
subplot(6,2,10), plot(x_ass,DEPOSIT_2)
title('Deposit')
subplot(6,2,11), plot(x_ass,INVESTMENT_1)
title('Investment')
subplot(6,2,12), plot(x_ass,INVESTMENT_2)
title('Investment')
set(gcf,'color','w')
```

graph_3.m

```
function graph_3(X1,Y1,X2,Y2,Xb,Yb,name,y1,y2)
global dep C DE DB D L K Y_ss x_ass

N=size(X1,2);

OUTPUT_1=Y1(10,2:N)./Y_ss*100;
A_C_1=(Y1(1,2:N)+Y1(2,2:N)+Y1(3,2:N))./(C+DE+DB)*100;
LOAN_1=X1(4,2:N)./L*100;
DEPOSIT_1=X1(2,2:N)./D*100;
INVESTMENT_1=(X1(5,2:N)-(1-dep).*X1(5,1:(N-1)))./(dep*K)*100;
CAP_ASS_1=(X1(4,2:N)+L-X1(2,2:N)-D)./(X1(4,2:N)+L);


OUTPUT_2=Y2(10,2:N)./Y_ss*100;
A_C_2=(Y2(1,2:N)+Y2(2,2:N)+Y2(3,2:N))./(C+DE+DB)*100;
SPREAD_2=(X2(3,2:N)-X2(1,2:N))*400;
LOAN_2=X2(4,2:N)./L*100;
DEPOSIT_2=X2(2,2:N)./D*100;
INVESTMENT_2=(X2(5,2:N)-(1-dep).*X2(5,1:(N-1)))./(dep*K)*100;
CAP_ASS_2=(X2(4,2:N)+L-X2(2,2:N)-D)./(X2(4,2:N)+L);

OUTPUT_b=Yb(10,2:N)./Y_ss*100;
A_C_b=(Yb(1,2:N)+Yb(2,2:N)+Yb(3,2:N))./(C+DE+DB)*100;
LOAN_b=Xb(4,2:N)./L*100;
DEPOSIT_b=Xb(2,2:N)./D*100;
INVESTMENT_b=(Xb(5,2:N)-(1-dep).*Xb(5,1:(N-1)))./(dep*K)*100;
CAP_ASS_b=(Xb(4,2:N)+L-Xb(2,2:N)-D)./(Xb(4,2:N)+L);


figure('name',name,'NumberTitle','off')
subplot(6,2,1), plot(x_ass,OUTPUT_1-OUTPUT_b)
title('GDP')
subplot(6,2,2), plot(x_ass,OUTPUT_2-OUTPUT_b)
title('GDP')
subplot(6,2,3), plot(x_ass,A_C_1-A_C_b)
title('Consumption')
subplot(6,2,4), plot(x_ass,A_C_2-A_C_b), ylim(y1)
title('Consumption')
subplot(6,2,5), plot(x_ass,CAP_ASS_1-CAP_ASS_b), ylim(y2)
title('Capital-to-Asset')
subplot(6,2,6), plot(x_ass,CAP_ASS_2-CAP_ASS_b), ylim(y2)
```

```
title('Capital-to-Asset')
subplot(6,2,7), plot(x_ass,LOAN_1-LOAN_b)
title('Loan')
subplot(6,2,8), plot(x_ass,LOAN_2-LOAN_b)
title('Loan')
subplot(6,2,9), plot(x_ass,DEPOSIT_1-DEPOSIT_b)
title('Deposit')
subplot(6,2,10), plot(x_ass,DEPOSIT_2-DEPOSIT_b)
title('Deposit')
subplot(6,2,11), plot(x_ass,INVESTMENT_1-INVESTMENT_b)
title('Investment')
subplot(6,2,12), plot(x_ass,INVESTMENT_2-INVESTMENT_b)
title('Investment')
set(gcf,'color','w')
```