From agent-based models to artificial economies: the Eurace approach for policy design in economics

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Abstract

The aim of this thesis is to propose and illustrate an alternative approach to economic modeling and policy design that is grounded in the innovative field of agent-based computational economics (ACE). The recent crisis pointed out the fundamental role played by macroeconomic policy design in order to preserve social welfare, and the consequent necessity of understanding the effects of coordinated policy measures on the economic system. Classic approaches to macroeconomic modeling, mainly represented by dynamic stochastic general equilibrium models, have been recently criticized for they difficulties in explaining many economic phenomena. The absence of interaction among heterogeneous agents, along with their strong rationality, are two of the main of criticisms that emerged, among others. Actually, decentralized market economies consist of large numbers of economic agents involved in local interactions and the aggregated macroeconomic trends should be considered as the result of these local interactions. The approach of agent-based computational economics consists in designing economic models able to reproduce the complicated dynamics of recurrent chains connecting agent behaviors, interaction networks, and to explain the global outcomes emerging from the bottom-up. The work presented in this thesis tries to understand the feedback between the microstructure of the economic model and the macrostructure of policy design, investigating the effects of different policy measures on agents behaviors and interactions. In particular, the attention is focused on modeling the relation between the financial and the real sides of the economy, linking the financial markets and the credit sector to the markets of goods and labor. The model complexity is increasing with the different chapters. The agent-based models presented in the first part evolve to a more complex object in the second part, becoming a sort of complete "artificial economy". The problems tackled in the thesis are various and go from the investigation of the equity premium puzzle, to study of the effects of classic monetary policy rules (as the Taylor rule) or to the study of the macroeconomic implications of bank's capital requirement or quantitative easing.

Contents

Preface

The global financial crisis started in 2007 has led to an intense debate about how to further improve the modelling tools currently available for describing and understanding economic developments and policy measures [Caballero, 2010, Trichet, 2010]. The key reference point for this debate is the framework of Dynamic Stochastic General Equilibrium (DSGE) models that has become the standard in macro-economic modeling [Ratto et al., 2009, Smets and Wouters, 2003, Vogel, 2010]. Both in the academic world and, especially, in the world of financial institutions, DSGE models represent the common theoretical set-up. This fact can be easily observed by looking at the recent studies presented by central banks or by international organizations performing policy analysis and financial advising. For instance, the topic of evaluating the macroeconomic impact of different capital requirements for banks, which will be treated in detail in chapter 5, has been intensively examined after the last financial crisis [1] using a variety of models that mainly belong to the DSGE theoretical account.

These models take into account the Lucas critique of earlier econometric models as well as the need to represent explicitly the stochasticity of economic systems. They provide a common ground shared by firmly anti-Keynesian researchers (who started the DSGE research program) as well as by new Keynesians (who have come to share it). They are typically large models including different kinds of players in the economy (consumers, producers, the government sector, the central bank, etc.) who interact within a defined framework (preferences, technology and institutions). These different elements are interrelated such that the behavior of every player has an impact on the behavior of other players as well as on the global economic outcome. The use of DSGE models has increased systematically over the years in part due to the development of larger computers and powerful software and applications that allow to solve these models (Matlab, Dynare, etc.).

One the most attractive features of DSGE models is they can be estimated and validated using empirical data. As a result, interesting policy conclusions can be drawn (see for instance Uhlig [2005]), and it is certainly worth mentioning that the benchmark model for the European Economy is the one proposed by Smets and Wouters [2003]. DSGE models have several appealing features, which have made them so popular among both researchers and policy makers. First, they are micro-founded models. That is, the behavioral equations describing the economy are derived from a utility maximization problem at the micro level, i.e. each agent is rational at the individual level. Second,

[1] See, among others, the reports on capital requirements implications by the Basel Committee on Banking Supervision (*http://www.bis.org/publ/bcbs173.htm*); by the Institute of International Finance (*http://www.iif.com/press/press+151.php*); by the Bank of Canada (*http://www.bank-banque-canada.ca/en/publication/strengthening.html*); or by Banca d'Italia [Angelini et al., 2011].

DSGE models generally assume that agents have rational expectations (RE). That is, agents use the full information set to make unbiased forecasts about the future value of relevant economic variables, like investment or consumption, and they compute their present value in order to make decisions rationally. The last key assumption of DSGE models is that the average agent behaves in the same way as the typical individual living in the economy. This is the representative agent assumption by which the micro and the macro levels of the model are obviously equal. The implication of these building blocks is that DSGE models are said to be consistent. In other words, the rational behavior of agents at the micro level is consistent with the behavior of the economy as a whole at the macro level.

Despite their popularity, these models have been widely criticized (see e.g. Caballero [2010] and De Grauwe and Honkapohja [2009]). Both versions of the DSGE models, the Real Business Cycle [Kydland and Prescott, 1982, Prescott, 1986] models and the New Keynesian models [Galí and Gertler, 2007, Smets and Wouters, 2003, 2004, 2007], when tested against empirical data face important difficulties in explaining many economic phenomena [Del Negro and Schorfheide, 2007, Franchi and Juselius, 2007, Nelson, 1998]. As a consequence, several lines of critique have emerged.

One of the most important ones are related to the assumptions of the DSGE models. Their strong reliance on the full rationality of the economic agents does not seem appropriate in the light of the findings provided by behavioral economics [Kahneman and Tversky, 1979, 1984, Benartzi and Thaler, 1995a, Fehr and Tyran, 2008]. Economic agents are capable of performing strategic and rational thinking in some situations as well as to panic in others. In this context data on economic sentiments seem of particular relevance; as shown by Lux (2009) there is an important degree of interaction between economic agents. An interesting alternative in the field of DSGE models to extreme rationality and rational expectations is the literature on learning agents [Evans and Honkapohja, 2001, Slobodyan and Wouters, 2009]. In another line of critique, because of the assumed equivalence between the micro and the macro behavior, phenomena like coordination failures and the fallacy of composition cannot take place in DSGE models [Caballero, 1992]. In this context, the heterogeneous agent model approach has offered an interesting alternative to general equilibrium models in finance [Brock and Hommes, 1997, 1998, Lux and Marchesi, 1999] and more recently in macroeconomics [Dosi et al., 2006, De Graeve et al., 2008]. Other lines of critique of DSGE models include the lack of a full fledge financial and banking system within a network that allows for bankruptcy cascades and the lack of non-linearities in the models structure. When included in standard DSGE models, banks do not perform maturity transformation. As a consequence the intrinsic fragility of the banking system is not present in these models [Diamond and Rajan, 2001]. Models should ideally include a complete banking network in the lines of Allen and Gale [2001], Battiston et al. [2007] and Rotemberg [2008]. Banks in macroeconomic models should therefore be allowed to transform the maturity of assets and liabilities, such that the inherent fragility of the banking system is formally studied. In this context data on the interbank market plays a crucial role in order to define the banking network. Finally, the fact that, mainly for reasons of analytic tractability, DSGE models are generally linear is clearly limiting.

What emerges from this description of assets and flaws of DSGE models is the need for an alternative approach able to generalize or complement the standard macroeconomic framework. The main objective of this thesis is to show that agent-based modelling in economics represents an valid alternative to DSGE models that can be used as an effective tool for policy analysis and decision making.

It can be argued that agent-based (or multi-agent) models generalize the DSGE structure; this generalization comes in two steps. First, the individual agents are faced with decision problems that may allow for several solutions; the behaviour by single agents does still include optimization, but it also includes more pragmatic decision rules, for example imitation. This adds a layer of complexity to the model that many consider as a step towards increased realism. Second, the network structure linking different agents becomes essential for the dynamics of the system [Acemoglu et al., 2010, Jackson and Watts, 2002]. This seems particularly relevant for financial markets [Giannone et al., 2011].

The study of the economy by means of agent-based computational models is a relatively new field and dates back to the 90s, when the increasing availability of cheap computing power made possible to undertake the computationally expensive experiments required to model the interactions of large numbers of bounded rational, heterogeneous agents (see Tesfatsion and Judd [2006] for a review). Agent-based models are based on the simulation of large number of agents allowing the modeller to study the emergent aggregate statistical regularities in the economy, which cannot be originated by the behaviour of a "representative" individual [Kirman, 1993], but is the result of agents heterogeneity and interaction. The individual behaviour of an agent is assigned by means of (generally simple) rules, and each agent is therefore able to make decisions based on these rules. As a result of various and repeated interactions among the agents an aggregate behaviour at population-level can emerge. This kind of approach is typically called the "bottom-up" approach.

The most common building strategy of agent-based models is based on mimicking complex natural systems, i.e. foraging systems of social insects, molecular behaviour in cells and tissues, economic activity in multiple markets and social system. The objective is learning theoretical insights according to the results of model's simulations, or testing different scenarios by means of what-if analysis. During the last decade, a number of research papers using Agent-based Computational Economics (ACE) methodology focused on different fields of economic theory, such as finance (see, e.g., Raberto et al. [2001], LeBaron [2006], Ussher [2008]), industrial organization [E. Kutschinski and Polani, 2003], labour market (see e.g. [Tassier, 2001]), innovation [Dawid et al., 2008], and the relationship between financial fragility of firms and business cycles [Delli Gatti et al., 2009, 2007]. Generally speaking, these studies are able to drop the unrealistic assumptions of general equilibrium theory, i.e., perfect competition, centralized exchange and full information. The outcome of market failures, which may depend on asymmetric information among agents, imperfect competition and coordination failures, are therefore easily observed and investigated. Furthermore, the agent-based approach offers a realistic environment that is well suited for studying the out-of-equilibrium transitory dynamics of the economy caused by changes of policy parameters. A number of studies have in fact appeared recently on the issue of policy analysis (see e.g., two special issues: Dawid and Fagiolo, eds, 2008 and LeBaron and Winker, eds, 2008). Some studies are focused on the design of regulatory policies for financial markets [Pellizzari and Westerhoff, 2009], other on the design of appropriate fiscal and monetary policies [Russo et al., 2007, Cincotti et al., 2010, Raberto et al., 2008b].

It can be argued that, by constructing agent-based computer simulations of heterogeneous entities, one opens Pandora's Box. Instead of the unique and stable equilibrium point of General Equilibrium Theory immediately a highly ductile environment appears. A high number of heterogeneous assumptions has to be made and has to be quantitatively (and with respect to time) specified. Results of simulation runs can never be considered to be analytic truths and preliminary suggestions replace the proof of (sometimes redundant) theorems. The agent-based method therefore constitutes an epistemological break, a radical innovation that could eventually lead to a stronger insight into economic phenomena, and in particular into the deepest global financial crisis since the Great Depression of the 1930s. More to the detail, this methodology is able to consider different model-buildings for each type of economic agent, and the consequent implications on the global evolution can be studied quantitatively. Omnipresent non-linearity and diverging processes are not insurmountable difficulties any more and can be incorporated into the models. The performance of institutional rule systems, even the emergence of institutions can be studied by using simulations. But surely the researcher has to be very cautious and careful when interpreting models outcomes. No certainty, comparable to some of the proofs of a theorem in the highly stylized formal worlds of

GET, can be expected. But who expects certainty in a world of continuously growing knowledge?

Agent-based models are by now widespread in many areas, but still less so in economics and finance than in other fields. While the virtues of the microstructural approach of multi-agent simulations have been highly appreciated in transportation research and business applications, the dissemination of this new research strategy in economics and finance is still hampered by the tradition of representative agent modeling in these fields. However, the recent financial crisis and the inability of "orthodox" neoclassical models to understand ongoing events makes clear the need for a major reorientation of the focus in the research economists undertake. The backbone of agent-based approaches is the modeling of interactions of different types of agents (traders in a financial market, banks and other institutions in the global financial network). Phenomena like bubbles and crashes, or domino effects of financial contagion defy an explanation within a representative agent approach, but are the very direct consequences of various types of interactions and linkages between agents [Colander et al., 2009].

The work presented in this thesis proposes an agent-based approach to macroeconomics, presenting a set of models where the integration between the real and the financial sectors of the economy plays a crucial role. In fact, the models presented from Chapter 1 to Chapter 5 are characterized by increasing complexity, but the rationale behind all of them is the aim to detect and implement a structure of relations between the dynamics of financial and real markets.

In particular, part I presents two models that integrate real and financial markets. The first one, described in chapter 1, is a production economy with a financial market where firm's assets are traded, whereas the second one (Chapter 2) is a financial market model where traders take decisions considering a fundamental price based on firms equity capital and expected retained earnings.

In Part II a detailed banking system is introduced in the models. This is particularly important because the credit market is highly central due to its structural capability of linking the real, the financial and the monetary sides of the economy. It therefore permits to better describe the role of money in the economic system and to take into account its creation and destruction cycles. The adopted perspective is that money can be considered as credit-money originated by loans which are created from nothing as long as the borrower is credit-worthy and some institutional constraints are not violated. Apart from incorporating a credit market, the models presented in Chapters 4 and 5 are characterized by a quantitative difference with respect to the previous ones (that, can be argued, becomes a qualitative difference) in the sense that they are far more complete, including much more agent types and communication mechanisms. Consequently it is probably more correct to speak of an "artificial economy" rather than "economic models", due to the completeness and complexity of the interactions that are taken into account.

The artificial economy presented in Part II represents a fully integrated macroeconomic model including the main economic agents acting in the main economic spheres, as explained in chapter 3 where the Eurace simulator is presented. Chapters 4 and 5 present two studies that address the recent financial crisis by means of the Eurace simulator, testing the impact of different policies on the economic system. In particular, the focus of the analysis is centered on the effects of policies based on quantitative easing and on the regulation of banks capital requirement.

Part I

Integrating real and financial economy: an agent-based approach

Introduction

Until the crisis there was a broad divide between the study of financial economics and the study of macroeconomics. The crisis has made it abundantly clear that this divide must be bridged. A number of researchers are now trying to integrate these two distinct fields using a variety of approaches. This thesis is explicitly designed to provide an integrated view of the financial system and the macroeconomy, and to yield insights on the two-way interactions and transmission mechanisms between the two. The combination of rational expectations and equilibrium constraints in traditional DSGE models means that phenomena such as bubbles, panics, contagion, and financially triggered recessions are difficult if not impossible to model. Freed from such constraints, the agent-based approach will enable to model such phenomena and explore policy options for addressing them.

Modern mainstream economic theory of finance is characterized by an abundance of rather sophisticated technicalities and a rather archaic skeleton of assumptions connecting the elements of formalization with the main body of accumulated economic theory. This does not mean that standard financial theory is not concerned with practical questions, quite the opposite is the case. As a look into any modern textbook shows (e.g. [Mishkin F.S., 2004], [Walsh C.E., 2000]) the theory is very ready to link its issues to the processes observed in financial markets. However, it is clear that the usual assumptions of perfect and fully efficient markets, unlimited liquidity, and full rationality and information of economic agents are not realistic. Furthermore, a deficiency of the standard theory of finance is its inability to root itself in the core paradigms of economic theory proper. Mainstream financial theory is characterized by modelling financial agents with complicated and formalized descriptions about their own existing practices, and at the same time is by a certain poverty of theory concerning the essence of its central variables: interest rates, money, evolution of institutions, production processes, and internal model-building of agents. As pointed out by [Flaschel, Franke, and Semmler, 1997], the theory of finance has almost completely cut the links to dynamic macroeconomic theory by dropping the problems of endogenous determination of interest rates. It has assumed its major economic pillars – which reside in what today often is called the real side of the economy – to be exogenously given, i.e. outside the world of finance. At best some theoretical fragments hint at a vague link to the concept of innate time preferences of human individuals – but without any consequences beyond the empty statement that whatever occurs might be explained as being "rational" in the sense of Paul Samuelson's revealed preferences.

Complex economic systems are not suitable for simulation experiments relying on equation-based deterministic or better stochastic modelling. In fact, socio-economic systems are characterized by the interaction among independent agents with limited and local information; besides, the self-organized patterns which emerge through these interactions are based on differences, rather than similarities, among the interacting economic agents. As a consequence, models based on equations representing the average behaviour of representative agents are inadequate for describing socio-economic systems. In this respect, the agent-based approach based on multi-agent simulations is a breakthrough in modelling complex phenomena, because it captures the distributed and independent decision making in real systems (Jennings et.al 1998), and allows the simulation of systems with a volatile, rather than stable, environment. The development of an agent-based model which addresses the interplay of the economy with the financial sector allows to study and to better define, in a controlled and simulated environment, the influence of financial markets on real sector and the impact of macro level regulations.

Modeling approaches combining agent-based simulation and a complex network structure are especially suitable for the analysis of this kind of phenomena. By building up scenarios defined by relatively simple individual behaviors and complex patterns of interaction among them, it would be possible foresee whether a certain institutional setting can favor long-term stability in financial and other economic systems. Such a research perspective can be highly useful to address policy issues. First, it can be directly applied to assess different existing financial and economic theories and models of regulatory regimes, and analyze their societal impact over time. More concretely, the influence of public policy factors like taxation, the structure of the financial sector or regulatory competition can be studied in detail. Secondly, in a more general way, it can contribute to our better understanding of the evolving role of finance in the economy and society in general. Finally, an agent-based approach based on a complex network structure allows testing different scenarios about the regulation system. Such kind of models will capture both the behaviors of individual actors and the interactions among them in the framework of different institutional settings, making therefore possible to study the role of non-trivial phenomena (oscillations and state transitions, for instance) in the interplay between the financial and the real sector of economy.

Chapter 1

Modeling a financial economy

During the last decade,several research papers have appeared focusing on different fields of economic theory with an agent-based approach. In particular, many studies regarded finance, see LeBaron [2006] for a review, while others focused on labour and goods market [Tassier, 2001, Tesfatsion, 2001] and industrial organization E. Kutschinski and Polani [2003]. However, only a few partial attempts have been made in order to model a multiple-market economy as a whole Basu et al. [1998], Bruun [1999], B. Sallans [2003]. Basu et al. [1998] developed an agent-based computer simulator of the US economy characterized by a detailed financial sector including a banking system and a bond market, simulating agent learning by means of genetic algorithms. Bruun [1999] studied an agent-based macroeconomic model with Keynesian features which included both the production and the financial sector of the economy. B. Sallans [2003] presented a model of coupled financial and consumers markets, populated by agents with sophisticated learning features, and gave emphasis on the validation technique. In this respect, the model presented in this chapter integrates the real, the monetary and the financial sectors of the economy by considering four different markets, i.e, a labor and a goods market, representing the real side of the economy, a credit market and a stock market. The distinctive feature of this study consists in modeling agents according to well-established optimizing behaviors, or to simple and parsimonious rules of thumb. Furthermore, prices in real markets are not governed by a Walrasian tattonment process, but depend on price-setting agents on the supply side; this feature allows potential short term real effects of monetary policy. In this respect, the proposed model is utilized for purposes of monetary policy design.

The agent-based framework provides a powerful computational facility for economics, where performing experiments on scientific hypotheses and policy design issues. It offers a realistic environment, characterized by non-clearing markets and bounded rational agents, well suited for studying the out-of equilibrium transitory dynamics of the economy caused by policy parameters' changes. Previous works of the author of this thesis studied the effect of monetary [Raberto et al., 2006a] and fiscal [Raberto et al., 2006b] policies in agent-based models characterized by price-taking agents. It is worth noting that, in the context of price-setting agents, prices may not be set to their market clearing value; this can be due to insufficient information owned by the price setters, or to price decision mechanisms that do not necessarily pursue the markets' clearing. These features offer a microfoundation of nominal rigidities, that in the new Keynesian literature are a well known source of monetary non-neutrality [Mankiw and Romer, 1991]

We present in this chapter a discrete-time, agent-based, economic model composed by a monopolistic firm, a trade union, a central bank and N heterogeneous agents, that are at the same time consumers, workers, and financial traders. The firm produces a single homogeneous good using labor as the only input, and is characterized by a Cobb-Douglas technology. Households posses cash and stocks, earn labor and financial income, take consumption decisions and act as traders in the stock market. The bank borrows money from households and lends it to the firm, while the trade union's main role is to set the optimal wage for the workers community.

The real economy side of the model includes a labor market and a goods market. The trade union sets a wage at the beginning of the period and households decide if to apply for a job or not, according to their reserve real wages. The firm knows the aggregate labor supply and forms its expectations about goods demand in order to set the good's price and the quantity to be produced. Then labor market clears and households can be rationed. Considering their labor and financial incomes, households formulate their demand, trying to smooth consumption over time [Deaton, 1991]. Given demand and supply, goods market clears and both the households and the firm can be rationed.

Once transactions in the goods and labor markets are completed, the stock market opens. Households/traders are characterized by an endowment of cash, which derives from the dynamics of the real economy, and an endowment of a single asset, which is the equity of the monopolistic firm of the system. The market is characterized by a clearing house for the price formation and a Markovitz portfolio selection mechanism.

It is worth noting that the bank plays a central role, because it sets the borrowing rate, that is the instrument for conducting monetary policy in the model.

The central problem of theory of monetary policy is to provide principles that can be used to select a desirable rule for setting a central bank's interest rate [Woodford, 2003, Taylor, 1993]. In this respect, the model is used to analyze the implications of the nominal interest rate as the operational instrument of monetary policy. In particular, we investigate how the interest rate set by the central bank influences the economy, when the system is close to full employment. It can be observed that, when a full employment state is reached, and consequently the output can not be further increased, the firm tends to rise prices, generating an higher inflation rate. This may give rise to instability which undermine the economy. In order to keep the inflation monitored and to guarantee stability, a monetary policy that keeps the output somewhat below the maximum potential output, given by full employment, should be pursued. Consequently, we propose an interest rate setting rule based on the control of output gap, i.e., the difference between current output and full employment output. It is worth noting that, in the optimizing sticky price model of the new Keynesian literature [R. Clarida, 1999], a concept of output gap, defined as he deviation of output from its level under flexible prices, plays a central role both as a source of fluctuations in inflation (represented by the new Keynesian Phillips curve), and as a policy target (e.g. the well-known Taylor's rule). It worth noting that the output gap, irrespective to the different definition provided in our model, has a similar role here both as a determinant of inflation dynamics and as key policy variable.

The chapter is organized as follows. The model is outlined in Section 1.1, while computational experiments and results are discussed in Section 1.2. Section 1.3 provides some concluding remarks.

1.1 The economic agents

The model is characterized by four markets.

- A labor market, where households supply labor and are organized in a trade union that sets the wage. The labor force is hired by the monopolistic firm in order to produce the scheduled quantity of output.
- A goods market, where the firm acts as a price setter and supplies the output according to a profit maximizing behavior. The aggregate demand is the sum of each household's demand, which depends on his past income stream in order to smooth consumption over time.
- A credit market, where the firm borrows money from the bank in order to pay wages, and the bank sets an the interest rate according to the policy rule.
- A stock market, where a number of shares of the monopolistic firm are traded by the households.

It follows a detailed description of agent's behavior in each market.

1.1.1 The trade union

Households are represented by a trade union that sets the nominal wage in order to optimize the aggregate real labor income U, given by $(w/p)N$, where N is the number of workers, with $N \leq M$, being M the total number of households, and w/p is the real wage.

The trade union looks at the past, according to a fixed time window T^U, to verify the effectiveness of its wage policy. If the correlation $\rho(dU, dw)$, computed in T^U, is positive, it means that nominal wage increments dw led to aggregate utility increments dU, and the trade union will confirm the past policy by a rise of the nominal wage. Whereas, if the correlation is negative, the trade union will not change the nominal wage. In case of increment, the wage will be adjusted according to an inflation rate equal to planned inflation π^*, set by the central bank. The trade union decision rule can be summarizes as

$$w_t = \begin{cases} w_{t-1}(1+\pi^*) & \text{if} \quad \rho(dU, dw) \geq 0 \\ w_{t-1} & \text{if} \quad \rho(dU, dw) < 0 \end{cases}$$

1.1.2 The households

Each household possesses a real reserve wage, under which he is not willing to work. After the trade union has decided current period's nominal wage w_t, each household decides whether to apply for a job or not, considering the previous period goods price p_{t-1} for the evaluation of the current real wage. The labor supply N_t^s is then given by the number of households willing to work.

Households consumption choice follows a rule proposed by Deaton [1991], modified to take into account the price inflation, that is based on the comparison between the current income and past income stream realized in the last time window T^i. Let us define the cash-on-hand X_{t-1}^i as the quantity of cash at household's ith disposal before his consumption choice c_t^i at period t. Households's disposable income for consumption I_t^i is composed by the previous period wage, w_{t-1}, and the dividends of profits that the firm made in the previous period, i.e., $I_t^i = \delta_{t-1}^i w_{t-1} + m_{t-1}^i d_{t-1}$, where δ_{t-1}^i is equal to 0 or 1, depending on the employment status of the household at time $t-1$ and the integer m_{t-1}^i is the number of shares in the portfolio of household i in the previous period. Dividends d_{t-1} are given by $p_{t-1}\Pi_{t-1}/S$, where Π_{t-1} are the real profits realized by the firm in the previous period and S is the total number of shares of the monopolistic firm. .

Households's target is to keep a stable rate of consumption; saving when income is high in order to accumulate cash for periods of low income. Deaton assumes that individuals consume cash-on-hand as long as current nominal income is less in real terms than the average past real income $\bar{I}_t^i$, while, if the income exceeds in real terms $\bar{I}_t^i$, households save a constant fraction $(1-\upsilon)$ of the excess income. Formally, given the price p_t set by the firm in the current period, Deaton's decision rule can be written as:

$$c_t^i = \begin{cases} \min\left(\bar{I}_t^i, (I_t^i + X_{t-1}^i)/p_t\right) & \text{if } I_t^i/p_t \leq \bar{I}_t^i\,, \\ \bar{I}_t^i + \upsilon(I_t^i/p_t - \bar{I}_t^i) & \text{if } I_t^i/p_t > \bar{I}_t^i\,. \end{cases} \tag{1.1}$$

Aggregate goods demand Y_t^d is then given by $Y_t^d = \sum_i c_t^i$.

1.1.3 The monopolistic firm

The model includes a single monopolistic firm that produces an homogeneous perishable good according to a production function that has labor as the only input:

$$Y_t = \zeta N_t^\alpha \tag{1.2}$$

The parameters $\zeta > 0$ and $\alpha > 0$ are determined by the current technology and are kept fixed in this study.

The firm knows the nominal wage w_t that has been already set by the trade union, and acts as a price setter, facing the problem to decide the price p_t of the good and the quantity Y_t of goods to be produced. It is assumed that firms adjust adaptively the price and the quantity of goods, according to the following steps,

- The firm knows the labor supply N_t^s and has a perfect knowledge of the demand's elasticity.
- The firm takes into consideration a set of hypothetical prices p_t^h, that lie in a neighborhood of the last market price p_{t-1}. The prices p_t^h are chosen inside a grid parameterized by $(1+j\delta)p_{t-1}$, with $j = -n, -n+1, \ldots, n-1, n$, where δ represents the minimum relative variation of the price and δn is the higher bound for variation. Consequently, the firm calculates the exact goods' demand relative to each price, i.e., $Y_t^d(p_t^h)$.
- The firm computes, for each pair $\left(p_t^h, Y_t^d(p_t^h)\right)$, the value of real profits, considering nominal costs given by:

$$C_t = (1 + r_t^B) w_t N_t \tag{1.3}$$

  where r_t^B is the interest that have to be paid on the loan $w_t N_t$, where $N_t = (Y_s/\zeta)^{-\alpha}$, with the constraint $N_t \leq N_t^s$.

- A price and quantity couple (p_t, Y_t) is therefore chosen as the one that corresponds to the higher real profits, i.e.,

$$(p, Y)_t = \text{argmax}_{(p,Y)_t} \Pi_t \,, \tag{1.4}$$

where

$$\Pi_t = Y_t - C_t/p_t \,. \tag{1.5}$$

Finally, the firm distributes profits to households. Each household will receive dividends at the beginning of the next period, proportionally to the number of stocks in his possession.

1.1.4 Labour and goods market clearing

The goods market always clear, because the firm produces to match the demand. On the other hand, households may be rationed in the labor market, because $N_t \leq N_t^s$. In that case, a priority list of individuals is randomly generated according to a uniform distribution; agents' demand for labor is therefore satisfied according to the priority list, until the total quantity Y_t is sold out. After the clearing of the goods market, households cash is reallocated for the next period, i.e., for the ith agent:

$$X_t^i = X_{t-1}^i + \delta_{t-1}^i w_{t-1} + m_{t-1}^i d_{t-1} - p_t c_t^i + r^L X_{t-1}^i \,, \tag{1.6}$$

where r^L is the fixed lending rate of the bank. Then the stock market opens.

1.1.5 The central bank

The model encloses a bank, which incorporates the functions of both a commercial bank and a central bank. The bank performs the following actions

- sets a programmed inflation π^*
- remunerates the household's cash account at a fixed lending rate r_L
- provides credit to firms at a borrowing rate r_t^B
- sets r_t^B according to a monetary policy rule

Lending rate r^L is set by the bank at the same level of programmed inflation, in order to let grow the money aggregate of the households at the same pace of inflation.

Two monetary policy rules, that use the nominal interest rate r^B as the operational instrument, have been designed. The first one, henceforth random policy rule, sets r^B as,

$$r_t^B = r^{Bmin} + \xi_t \phi \,, \tag{1.7}$$

where r^{Bmin} is the fixed minimum value for the interest rate, generally set somewhat higher than r^L, ϕ is the policy strength, while ξ_t is a random value extracted from a uniform distribution in the interval $[0, 1]$. The random policy rule aims to investigate firm's reactions to random variation of the interest rate. These reactions are mainly studied in terms of correlations, as shown in table 1.1 of section 1.2. In eq.

The second policy rule, henceforth output gap control rule, is based on the control of the output gap,

$$r_t^B = r^{Bmin} + \phi \exp\left(-\beta \frac{Y^p - Y_t}{Y^p} \right), \tag{1.8}$$

where β is a policy tuning parameter and Y^p is the potential output, in case of full employment, i.e., $Y^p = \zeta M^\alpha$.

1.1.6 The stock market

The stock market is populated by M agents, as each household of the economic model becomes a trader in the stock market. Traders are characterized by an endowment of cash, which derives from the dynamics of the real economy, and an endowment of a single asset, which is the equity of the monopolistic firm of the system.

The essential steps performed in the stock market can be resumed in:

- Traders form beliefs on the asset's risk and returns
- Traders decide their optimal wealth allocation and formulate their limit prices
- Traders issue orders
- Market clears (rationing and financial wealth allocation)

Let us now examine more in detail how the stock market works.

Traders are characterized by heterogeneous time windows T^i through which they can look at the past, in order to form their expectations on the future. Each trader calculates the historical volatility

$\sigma_t^i(T^i)$ of the stock price s according to his time window. Therefore, the price returns estimation by the ith trader is calculated by means of a MA(0) model, and corresponds to $\varrho_t^i = zN(0, \sigma_t^i)$, where z is a parameter. Consequently, each trader sets a limit price, above which she is not willing to buy, if she is a buyer, or below which she is not willing to sell, if she is a seller, according to:

$$s_{lim,t}^i = s_{t-1}(1 + \varrho_t^i)\,. \tag{1.9}$$

However, when agents have to decide the share of their financial wealth to allocate in stocks, they will consider the overall stock return ρ that takes into account also the dividends paid by the stock. In this respect, traders have a full knowledge of the value d_t of the dividend paid by the firm for holding stocks. Traders beliefs on overall stock returns, considering both expected dividends and a component related to the standard deviation of historical price returns, are given by

$$\rho_t^i = \frac{d_t}{s_{t-1}} + \varrho_t^i \tag{1.10}$$

Concerning the decision on portfolio allocation, each agent is characterized by a specific attitude toward risk, represented by his risk aversion value ν^i. Given this heterogeneous risk aversion, the trader takes into consideration the expected stock returns, the risk free interest rate r^L, and the stock's price volatility, in order to allocate his portfolio. According to Markowitz portfolio selection theory [Markowitz, 1952], the percentage of total financial wealth that the trader invests in the stock is given by the weight ω_t^i,

$$\omega_t^i = \frac{\rho_t^i - r_t^L}{\nu^i \sigma_t^i} \tag{1.11}$$

These weights are then mapped on a (0,1) range

$$\omega_t^{*i} = \begin{cases} \frac{2}{\pi}\arctan(w_t^i) & \text{for } \omega_t^i \geq 0 \\ 0 & \text{for } \omega_t^i < 0 \end{cases} \tag{1.12}$$

This choice is useful in a simulation perspective, because it smoothes fluctuations on the stock demand, and avoids extreme behaviors that would be given by weights values bigger than 1, while it does not alter significantly lower weights.

When the portfolio selection is completed, traders check their current wealth allocation and compare it with the desired one given by weights ω_t^{*i}. Being the financial wealth of agent i, W_t^i, given by

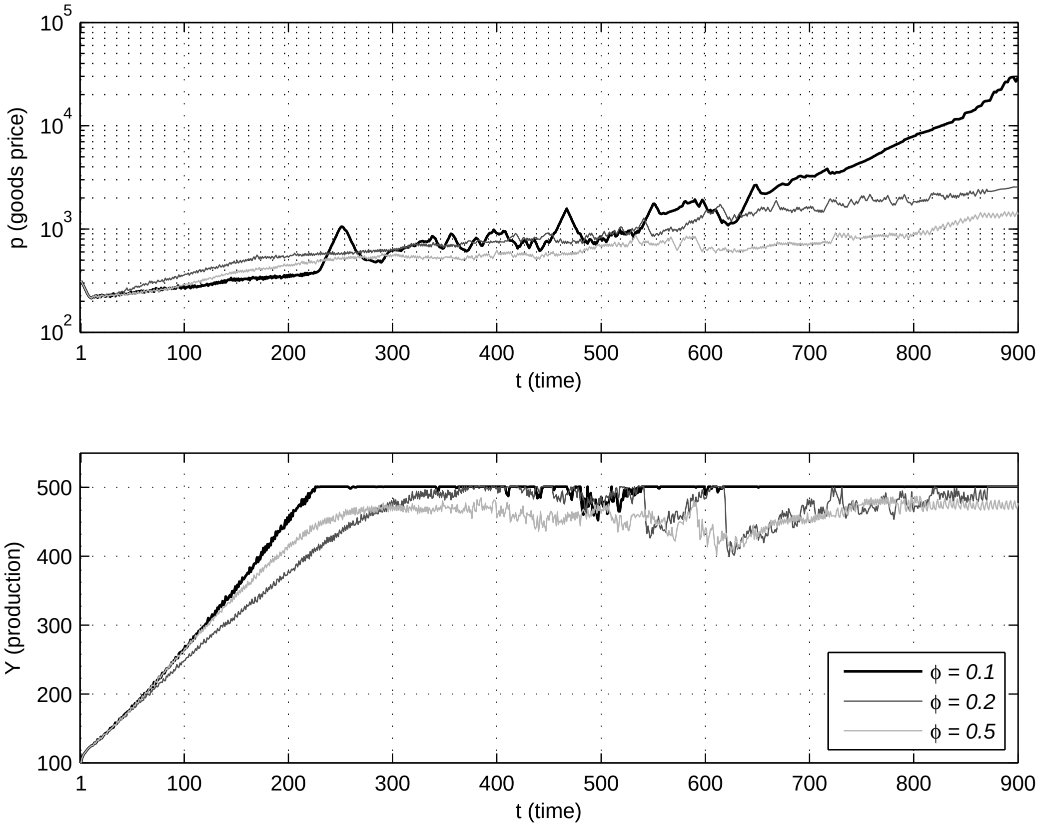

Figure 1.1: Time series of goods price and production for different values of policy strength ϕ

$W_t^i = X_t^i + m_{t-1}^i s_{t-1}$, where m_{t-1}^i is the number of stocks hold in portfolio, current wealth allocation in equity is equal to $m_{t-1}^i s_{t-1}/W_t^i$. Consequently each agent decides to issue buy or sell orders to cancel the gap between what they have m_{t-1}^i and what they want m_t^{*i}, where m_t^{*i} is the integer of $\omega_t^{*i} W_t^i$. Each order can then be identified by the limit price $s_{lim,t}^i$ and the associated quantity q_t^i of shares, given by $q_t^i = m_t^{*i} - m_{t-1}^i$. If the $q_t^i > 0$, the order is a buy order, otherwise, it is a sell order. The price formation process is centralized and modeled according to a clearing house mechanism. Buying and selling orders are collected by the clearing house that builds a demand curve and a supply curve on a common price grid. The price s_t that clears the market, at the crossing between demand and supply, is chosen in order to maximize the transaction's amount.

All the traders whose limit prices are compatible with the clearing price ($s_{lim,t}^i \geq s_t$ for buyers, $s_{lim,t}^i \leq s_t$ for sellers) are selected for the transaction; however some of them will be rationed. A priority order is randomly generated and agents carry out their transactions following the order. When all the amount of stocks is traded, agents in the successive positions ar rationed.

Table 1.1: Correlation values between interest rate variations Δr^B and percentage variation of good's price, production and real profits. All correlation values are significantly different from zero, as shown by the correspondent p-value, given in brackets.

	$\rho(\Delta r^B, \frac{\Delta p}{p})$	$\rho(\Delta r^B, \frac{\Delta Y}{Y})$	$\rho(\Delta r^B, \frac{\Delta \Pi}{\Pi})$
$\phi = 0.1$	0.28 (10^{-17})	-0.14 (10^{-5})	-0.35 (10^{-28})
$\phi = 0.2$	0.34 (10^{-25})	-0.36 (10^{-29})	-0.89 (~ 0)
$\phi = 0.5$	0.56 (10^{-76})	-0.26 (10^{-15})	-0.91 (~ 0)

1.2 A monetary policy experiment

We present, as a main result, a study on the effects of using a nominal interest rate as the operational instrument of monetary policy.

The interest rate r^B has an influence on the economy through the decision making of the firm, which borrows money to pay wages. Given the nominal wage set by the trade union, nominal costs incurred by the firm in order to hire the labor input depend directly on the interest rate level, as equation 1.3 clearly shows. As an example, a rise of the interest rate at time t implies an increase of costs, and determines in the same time step an upward shift of the firm's supply curve in the (Y,p) plane. Due to the fact that the aggregate demand curve at time t is not affected by this interest rise [1], the goods market clears at a higher price and at a lower quantity. It is worth noting that, given the general equilibrium framework of the model, in the long run this effect could be canceled by second order effects, e.g. downward shifts of the demand curve or employment reduction.

In order to empirically investigate the consequences of interest rate changes, we have computed the correlation ρ between the time series of interest rate variations and the time series of percentage variations of some macroeconomic variables, related to the same simulation trajectories. Table 1.1 reports these correlations for different values of the policy strength α, in the case of a random monetary policy rule, see eq. 1.7. The random rule was preferred to avoid spurious statistical effects due to serial correlation in the interest rates.

Results show, as expected, that interest rate changes Δr^B are significantly correlated with price relative variations $\Delta p/p$ and anti-correlated with output relative variations $\Delta Y/Y$. Furthermore, the anti-correlation values between interest rate changes and real profit variations $\Delta \Pi/\Pi$ are even more significant, due to the firm's risen costs for paying higher interests on debt.

Figures 1.1, 1.2 and 1.3 present three different trajectories, starting with the same initial conditions, of six economic variables. The monetary policy rule employed in the simulations is based on the

[1] Households demand depends on the income stream of the economy up to the previous time step, see eq. 1.1

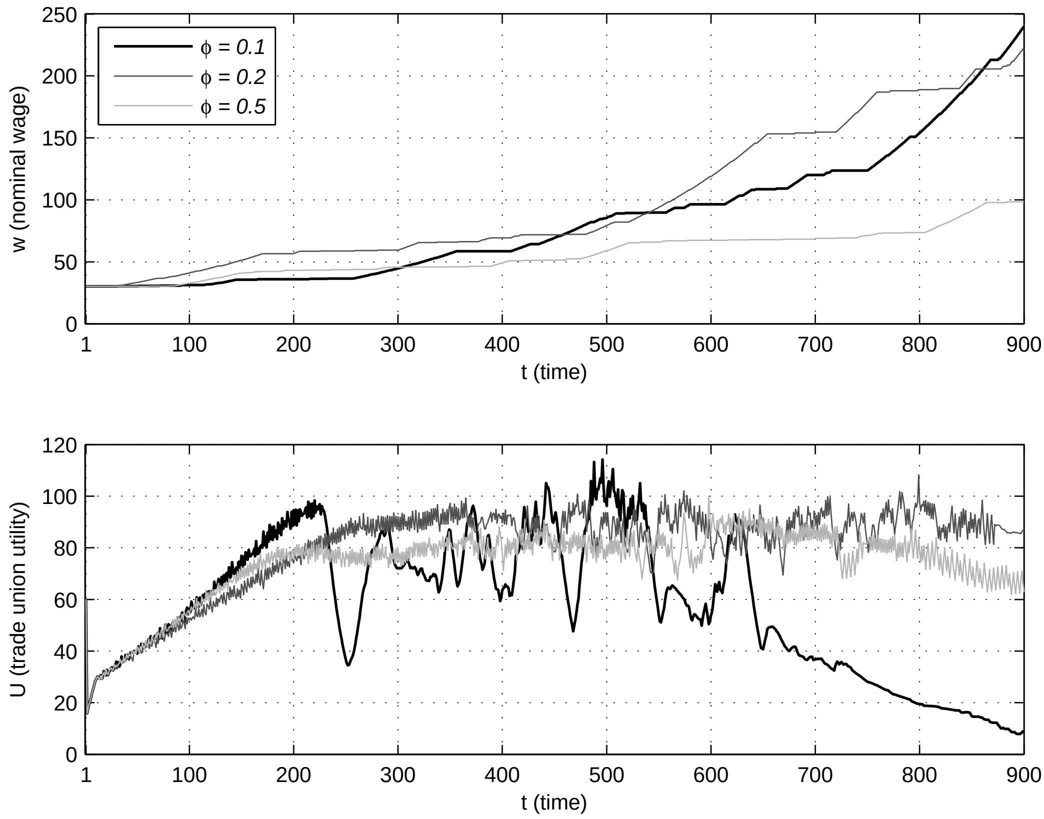

Figure 1.2: Time series of nominal wage and trade union utility for different values of policy strength ϕ

output gap control (see eq. 1.8), and each trajectory refers to a different policy strength parameter ϕ. These computational experiments have been performed with the following parameter's values: $M = 1000$, $T^U = 20$, $\pi^* = 0.5\%$, $\zeta = 1$, $\alpha = 0.9$, $\delta = 0.1$, $n = 50$ (implying a maximum price variation of $\pm 5\%$, $r^L = 0.005$, $r^{Bmin} = 0.01$. Moreover, the reserve wages of households are set to 0, implying a constant labor offer set to M. For what concerns the stock market, $z = 16$, the time window T^i varies from 20 to 100, and the risk aversion of traders varies from 1 to 5.

As figure 1.1 clearly shows, the trajectories start from the same initial conditions of market price and production, and are characterized by an output growth and inflation. Production's trajectories are bounded by an upper value, which corresponds to the maximum number of employable workers, i.e., M. The output dynamics evidences two main phases; a first initial phase of steady growth and a second phase of fluctuations close to the production's upper bound. It can be noted that, for higher values of the policy strength, i.e., higher interest rate values, production is depressed: in case of $\phi = 0.5$ output never reaches the maximum level. This evidence confirms the effectiveness of the output gap control rule, which uses r^B as a policy instrument, in driving the production level. The importance to keep the economy under its maximum level of output is clearly evident examining the price trajectories.

The price evolution, in case of weak output gap control ($\phi = 0.1$), exhibits two main patterns: a first pattern of low steady growth and a second pattern characterized by a high growth and strong fluctuations. The pattern's change occurs after production achieves the upper bound; in particular this event triggers a sudden inflation rise. Indeed, the incentive for the monopolistic firm to rise price is stronger when it faces an high demand but can not increase output, i.e, it is constrained in employment of labor input. However, an high inflation regime can not be sustained indefinitely, as shown by the evident price falls in the figure, because it depresses real wages and consequently the aggregate demand. In this respect, the cap on nominal wage updates which equals the planned inflation $\pi^\star$ plays an important role, determining the maximum value of sustainable price inflation. Nominal wage trajectories are shown in figure 1.2. The decrease in aggregate demand and thus in production is particularly evident in the trajectory of $\phi = 0.1$ before time step $t = 500$. This hyperinflation has a very strong effect on the trade union utility, i.e., on the welfare of the workers community, as shown in figure 1.2. The fall of real wages, due to high inflation, together with the decreased employment, due to the lowered demand, determines strong negative fluctuations in the trade union utility which end up with a downward trend, generated by the final steady price's growth. Higher values of the policy strength parameter may be used in order to prevent these negative outcomes. The monetary policy strategies corresponding to $\phi = 0.2$ and $\phi = 0.5$, have a relevant impact on inflation control. Indeed, price growth exhibits an increase in the first phase, i.e, before output gap cancels, and a significant reduction in the second phase. These apparently incongruous price reactions to interest rate are actually given by precise economic reasons. The behavior in the first phase can be explained according to the relation between interest rate and production costs, i.e., the firm supply curve, whose underlaying mechanism has been already clarified. On the other hand, the behavior in the second phase depends on the fact that a tighter monetary policy is able to keep the economy under its maximum capacity, preventing the inflation peaks caused by the the labor input constraint. A tight output gap monetary policy rule, preventing the fall of the real wage by controlling inflation, guarantees a higher and more stable utility for workers. However, some caution has to be used in the tightening monetary policy, as shown by both the lower production level and the lower trade union utility level correspondent to the policy $\phi = 0.5$.

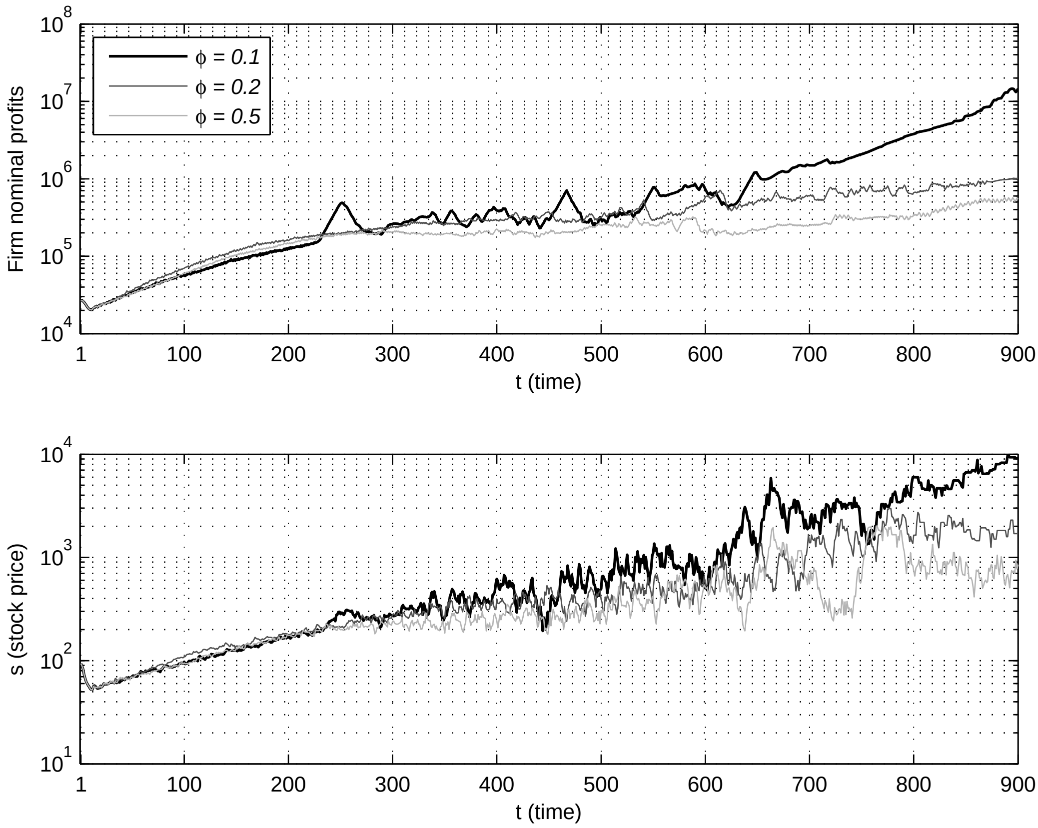

Figure 1.3: Time series of nominal profits and stock price for different values of policy strength ϕ

Tables 1.2 and 1.3 present the average values and the standard error of four economic time series, obtained applying an output gap control policy rule and a random policy rule, respectively. A comparison of the two tables shows that for low ϕ values the output gap control rule does not clearly outperform the random rule: it keeps an higher output but also an higher inflation, lowering worker's welfare. This is due to the weak impact of monetary policy for low values of ϕ. For higher values of ϕ, i.e., a strong policy impact, it emerges that generally the output gap rule have a better performance than the output gap rule, both in term of superior output and higher utility; price and wage inflation are also better controlled. Considering the values reported in table 1.2, let us point out that an output gap control monetary policy permits to increase the worker's utility and to keep inflation under control, without implying substantial output losses. In this respect, the random rule is not able to obtain similar results.

Figure 1.3 shows the trajectories of nominal profits realized by the firm and the stock market

Table 1.2: Output gap control policy rule: average values and standard error of four economic time series

	μ_Y ($\hat{\sigma}_Y$)	μ_U ($\hat{\sigma}_U$)	μ_π ($\hat{\sigma}_\pi$)	μ_{π^w} ($\hat{\sigma}_{\pi^w}$)
$\phi = 0.05$	448.5 (3.5)	59.3 (0.8)	0.51 (0.10)	0.31 (0.01)
$\phi = 0.10$	447.4 (3.6)	57.6 (0.9)	0.56 (0.10)	0.23 (0.01)
$\phi = 0.15$	445.7 (3.5)	72.6 (0.6)	0.36 (0.11)	0.25 (0.01)
$\phi = 0.20$	421.8 (3.5)	80.0 (0.6)	0.31 (0.13)	0.22 (0.01)
$\phi = 0.25$	421.6 (3.4)	79.7 (0.6)	0.28 (0.12)	0.19 (0.01)
$\phi = 0.30$	428.3 (3.3)	77.0 (0.5)	0.28 (0.13)	0.18 (0.01)
$\phi = 0.35$	405.1 (3.1)	78.3 (0.6)	0.28 (0.12)	0.20 (0.01)
$\phi = 0.40$	413.3 (3.4)	71.5 (0.6)	0.22 (0.13)	0.16 (0.01)
$\phi = 0.45$	398.3 (2.9)	76.5 (0.5)	0.29 (0.13)	0.19 (0.01)
$\phi = 0.50$	415.4 (3.1)	74.0 (0.5)	0.25 (0.14)	0.13 (0.01)

price. According to the model of the stock market, the expected return of firm's equity is equal to the expected dividend yield plus a gaussian random variable with zero average, see eq. 1.10. Besides, being portfolio allocation weights based on Markowitz portfolio selection theory, the level of investment in stocks increases along with expected dividend yields. This feature is confirmed by examining figure 1.3, where the stock market price is clearly driven by nominal profits. Nominal profits trajectories are strictly related to the dynamics of the price level, implying that the stock market price is influenced by the monetary policy strategy through the dynamics of inflation. However, the high stock market price for low values of ϕ does not necessarily mean a higher profitability of the firm's equity in real terms. Indeed, the level of prices in the goods market must be taken into account to form a correct evaluation of stock market profitability.

The distribution of stock returns is characterized by fat tails. The presence of the random component in the expected returns formation, together with the volatility feedback effect, give rise to the well-known stylized facts in the distribution of returns, as pointed out in previous works of some of the authors [Raberto et al., 2001, 2003]. The Jarque-Bera test and the Kolmogorov-Smirnov test reject the null hypothesis of Gasussian distribution for returns at the 5% significance level. The ARCH test rejects the null hypothesis that the time series of returns is characterized by independent and identically distributed Gaussian disturbances, therefore pointing out the existence of ARCH effects.

1.3 Some concluding remarks

The main attempt of the work presented in this chapter is to contribute to the development of the field of agent-based computational economics, by providing an integrated model of a real economy and a financial market, and by showing how an agent-based model can be a very useful instrument

Table 1.3: Random policy rule: average values and standard error of four economic time series

	$\mu_Y\ (\hat{\sigma}_Y)$	$\mu_U\ (\hat{\sigma}_U)$	$\mu_\pi\ (\hat{\sigma}_\pi)$	$\mu_{\pi^w}\ (\hat{\sigma}_{\pi^w})$
$\phi = 0.05$	421.6 (3.7)	75.1 (0.8)	0.34 (0.12)	0.29 (0.01)
$\phi = 0.10$	434.1 (3.6)	65.4 (0.7)	0.49 (0.13)	0.27 (0.01)
$\phi = 0.15$	421.4 (3.8)	64.6 (0.8)	0.32 (0.12)	0.26 (0.01)
$\phi = 0.20$	429.9 (3.7)	78.3 (0.7)	0.41 (0.14)	0.29 (0.01)
$\phi = 0.25$	248.8 (1.8)	48.3 (0.4)	0.39 (0.15)	0.28 (0.01)
$\phi = 0.30$	381.8 (3.2)	70.5 (0.6)	0.27 (0.15)	0.14 (0.01)
$\phi = 0.35$	378.9 (3.2)	68.1 (0.6)	0.35 (0.15)	0.20 (0.01)
$\phi = 0.40$	250.3 (1.5)	45.2 (0.3)	0.33 (0.15)	0.21 (0.01)
$\phi = 0.45$	271.8 (2.0)	45.8 (0.4)	0.29 (0.15)	0.21 (0.01)
$\phi = 0.50$	210.7 (2.6)	36.3 (0.5)	0.32 (0.15)	0.23 (0.01)

for performing monetary policy experiments.

The field of macroeconomics has witnessed in recent years a marked increase in the interest on monetary policy and there has been a considerable improvement in the underlying theoretical frameworks used for policy analysis. New generation of small-scale monetary business cycle models, generally referred to as New Keynesian models, incorporate the techniques of dynamic general equilibrium theory with explicit consideration of frictions such as nominal rigidities there are very important to evaluate the effectiveness of monetary policy. Indeed, the new Keynesian analytical framework is based on a log-linear approximation of agents' optimizing behavior and represents monetary policy by a rule for setting the nominal rate of interest. A notable feature of this recent approach to monetary policy is the emphasis given to the objective of maintaining a low and stable rate of inflation.

The present model addressed these issues from a different perspective: an agent-based model within a general equilibrium framework. Our approach permits to avoid the approximations of small-scale analytical models, by means of performing computer simulation of large-scale interacting agents models. Results show that, through a monetary policy strategy based on the output gap control, it has been possible to target the objective to maintain a low and stable rate of inflation. Moreover, results show that the monetary policy can have a positive effect on welfare, provided a proper calibration of the degree of policy tightness.

This research program aims at making significant progress towards the development of a framework with the purpose of evaluating alternative monetary policies. Furthermore, future research in this fiels should also investigate in depth the influence of assets traded in financial markets on monetary policy design.

Chapter 2

A financial market with real expectations

The combination of high equity premium, low risk free rate, and smooth consumption, which has been observed in real data, is difficult to explain with plausible levels of risk aversion within the rational-expectations consumption-based asset pricing models, as first pointed out by the seminal paper of Mehra and Prescott [1985]; see also Mehra and Prescott [2008] for a comprehensive survey.

In this chapter, the equity premium puzzle is analyzed by means of an artificial financial economy where households behavior under uncertainty is modeled according to findings and assumptions of prospect theory [Kahneman and Tversky, 1979, Tversky and Kahneman, 1992]. In particular, households financial preferences encompass important behavioral assumptions, namely, loss aversion (losses cause a disutility which is higher than the utility due to an equal gain) and mental accounting of portfolio gains and losses. A model by Barberis et al. [2001] showed interesting results in encompassing two prospect theory insights, i.e., loss aversion and reference points, within the standard agents' utility framework based on the inter-temporal maximization of consumption. In this respect, the difference is that our approach is agent-based instead of being based on the analytically-tractable general equilibrium modeling paradigm and that we separate portfolio allocation decisions by households from their consumption decisions, which are modeled according to an empirically grounded rule-of-thumb [Deaton, 1992]. Consumption decisions affect only the size of portfolio investment through the budget constraints, but not the weights of assets in the portfolio, see our former contribution [Cincotti et al., 2007] to appreciate how the dynamics of consumption may affect asset prices in an agent-based model.

Households portfolio allocation is then modeled according to a preference structure based on a key prospect theory insight, i.e., the myopic loss aversion, which depends on the limited foresight capabilities characterizing humans when forming beliefs about financial returns. Benartzi and Thaler [1995b] showed that loss aversion combined with mental accounting, i.e., frequent evaluation of portfolio, is able to explain the equity premium puzzle. That combination has been dubbed myopic loss aversion. It is worth noting that myopic loss aversion, due to its algorithmic nature, can be hardly addressed within a general equilibrium analytical model; the agent-based approach seems then to be the suitable framework to model this behavioral feature; see e.g. Tesfatsion and Judd [2006] for a recent survey on this approach.

Besides households, the model is populated by firms, a commercial bank, a central bank and a government, which interact with households through a multi-asset financial market. As portfolio allocation for households, also decisions by firms about dividends payment are endogenously determined and constrained by two exogenous stochastic processes, namely labor wages for households and returns on investments for firms. The Government and the Central Bank make fiscal and monetary policy decisions by setting tax and interest rates, respectively. A particular attention is devoted to the balance sheets, considering the dynamics of the financial flows among agents. Firms and bank's equity are divided into shares among households and traded in the financial market. Firms also recur to debt financing, asking for bank loans. The bank collects households deposit and accesses to the standing facilities of the central bank, that sets the interest rate. The government collect taxes and pays bonds coupons to bondholders.

The chapter is divided into sections as follows. In Section 2.1, we present the agent-based model, Section 2.2 reports computational experiments, while the last Section presents some conclusions.

2.1 The Model

The distinctive feature of the model is that agents' financial decisions are endogenously determined by behavioral rules. Conversely, due to the absence of a labor market, the wage level is exogenously determined by means of a stochastic process.

Two nested time units characterize the time structure of the model, namely, the day, indexed by t, and the month, indexed by τ. Firms, the commercial bank, the Government and the central bank make decisions on a monthly basis, while the financial market operates daily as well as households' financial investment decisions. Each month is divided into a given number of days.

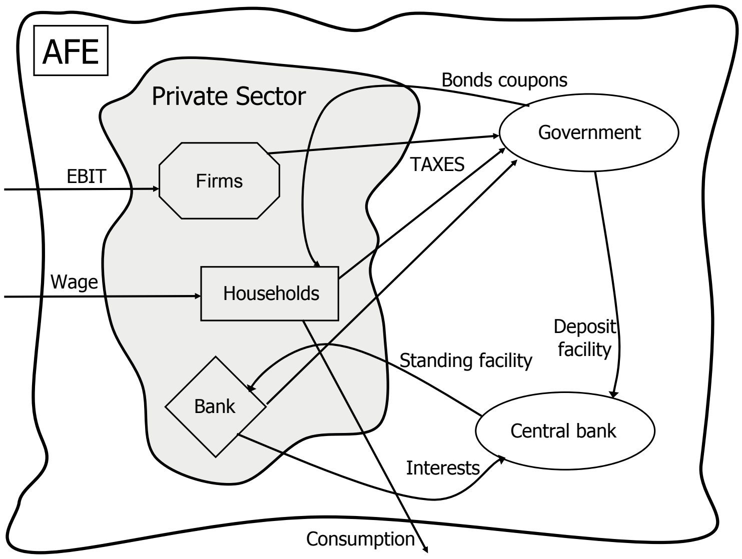

Figure 2.1: General scheme of the main interactions in the model of an Artificial Financial Economy (AFE). Exogenous flows, along with flows between the private sector and the external institutions are represented.

2.1.1 Firms

Each firm, indexed by j, is described by a balance sheet, characterized by a fixed endowment of physical capital A^j on the asset side, and both equity E^j_τ and debt D^j_τ as liabilities. Given the dynamics of debt, the book value of equity at any time τ is given by:

$$E^j_\tau = A^j - D^j_\tau \,, \tag{2.1}$$

where the endowment of physical capital is supposed to be measured in term of the same monetary numeraire of both equity and debt liabilities. Claims on firm equity capital and future profits stream are dividend into $\mathcal{N}^j$ shares, and traded by households in the stock market. The initial price of each firm share p^j_0 is set to $E^j_0/\mathcal{N}^j$. The debt is a loan provided by the commercial bank.

Each firm is also characterized by a time-varying return on physical capital (ROA) ξ^j_τ, modeled according to an exogenous autoregressive stochastic process, i.e.,

$$\xi^j_\tau = \alpha\xi^j_{\tau-1} + \sigma\epsilon^j_\tau \,, \tag{2.2}$$

where ϵ^j_τ is a Gaussian white noise, i.e., $\epsilon_\tau \sim N(0,1)$, and α and σ are parameters uniform across firms, characterized by the usual constraints, i.e., $0 < \alpha < 1$ and $\sigma > 0$. Noises are uncorrelated across firms. The quantity $\xi^j_\tau A^j$ sets the earnings obtained by the firm, before interests and taxes. Net earnings π^j_τ are then given by:

$$\pi^j_\tau = \xi^j_\tau A^j - r^L_{\tau-1} D^j_{\tau-1} - T^j_\tau \,, \tag{2.3}$$

where T^j_τ are taxes paid to the Government on gross earnings, after deducing interest payment, and r^L is the commercial bank lending rate. A constant fraction θ^j of net earnings, if positive, is paid to shareholders by means of dividends, while the remaining part is retained to reduce debt. Per share dividends d^j_τ are then given by $\theta^j \max(\pi^j_\tau, 0)/\mathcal{N}^j$ and the dynamics of firm debt is determined as follows,

$$D^j_\tau \;\; = \;\; D^j_{\tau-1} - \pi^j_\tau + \mathcal{N}^j d^j_\tau \,. \tag{2.4}$$

The book value of equity at month τ is then computed according to Eq. 2.1. $\mathcal{E}^{|}_\tau$ denotes the market value of equity at month τ and is given by $\mathcal{E}^{|}_\tau = \mathcal{N}^j p^j_\tau$, where p^j_τ is the stock price observed during the last day of month $\tau - 1$. In principle, the values of $\mathcal{E}^{|}_\tau$ and E^j_τ can be very different; however, fundamentalist trading behavior is based on the difference between stock market capitalization and the book value of equity, see paragraph 2.1.2, thus determining a not diverging behavior in the long run.

2.1.2 Households

Households are simultaneously taking the roles of workers, consumers and market traders. They receive an exogenously given labor income, if employed, and an unemployment subsidy from the government, if unemployed. Savings-consumption decision has been modeled within the framework of the buffer-stock theory of consumption [Carroll, 2001, Deaton, 1992] (see section 1.1.3 for a more detailed description). The main attractive feature of this approach is that consumption behavior can be articulated in very simple and intuitive terms. Consumers have a target level of cash on hand to income ratio $\bar{x}^i$, i.e., a target buffer stock of liquid assets with respect to permanent income, that they use to smooth consumption in the face of an uncertain income stream. If their buffer stock falls below target, their consumption level C^i_τ will be lower than their expected income and liquid assets will rise, while if they have assets in excess of their target they will spend freely and assets will fall.

Households can either invest their savings in the asset market, by trading stocks or bonds, or can put them in a saving account that pays a fixed, risk-free interest rate. They form beliefs about assets future returns considering a common forward horizon of three months. The implied idea is that households are able to foresee assets trends only for short periods of time, also if they plan to hold their assets for a longer period. Besides, each household i is characterized by an evaluation period ϵ_i which is a multiple of the forward horizon and is used to compute preferences and evaluate investments, see Benartzi and Thaler [1995b] for a discussion about the importance of the evaluation period. Beliefs are formed according to three stylized behavior, i.e., random, chartist and fundamental. In particular, expected asset returns for each asset j, issued by the j-th firm, are given by a linear combination of three terms: a scalar random component $\rho^r_{j,i}$, a set of past returns $\rho^c_{j,i}$ computed in a backward time window, and a fundamentalist scalar term $\rho^f_{j,i}$. In order to compute the fundamental return, each household estimates a fundamental price

$$p_{j,i} = (E^j_\tau + \widehat{\pi}^j)/\mathcal{N}^j \tag{2.5}$$

taking into account the equity capital of firm j and the expected retained earnings $\widehat{\pi}^j$ in the forward horizon. Given the fundamental price and considering the last market price, the household derives the expected fundamental return $\rho^f_{j,i}$. Composing the three terms and adding expected cash flow yields $y^e_{j,i}$ (i.e., dividends for stocks and coupons for bonds), households determines a set of total expected returns $\rho_{j,i}$ as

$$\rho_{j,i} = \alpha^r_i \rho^r_{j,i} + \alpha^c_i \rho^c_{j,i} + \alpha^f_i \rho^f_{j,i} + y^e_{j,i} \tag{2.6}$$

where α^r_i, α^c_i and α^f_i are household's weights that sum to one. Then households build a normalized histogram $H[\rho_{j,i}]$ where the set of total expected returns is grouped in M_i bins. It is worth noting that a large number of bins M_i means that the household is more careful when examining the asset's past performance, taking into account more elements (it uses a higher resolution to build the histogram).

The histogram $H[\rho_{j,i}]$ can be seen as a prospect $\mathcal{P} = [\rho^H_{j,i}, p^H_{j,i}]$ where $\rho^H_{j,i}$ are the bins center values of the expected total returns histogram and $p^H_{j,i}$ are the associated probabilities, i.e., the level of the normalized histogram. If the evaluation period of the household is longer than the forward horizon used in the beliefs formation, it means that the prospect should be iterated accordingly. To this aim, we modelled how the structure of a prospect varies when the evaluation period changes. Following the concepts of myopic loss aversion, we introduce a new prospect $\mathcal{P}^n$ that represents the mental accounting [Benartzi and Thaler, 1995b] of the agent when considering the risky investment, that means an n times iteration of prospect $\mathcal{P}$. Accordingly, the number of elements of the iterated prospect $\mathcal{P}^n$ will pass from M_i to $\mathcal{M}_i$. Thus, each household will face a new prospect $\mathcal{P}^n = [\rho_{j,i}^{H_n}, p_{j,i}^{H_n}]$ depending on its evaluation period.

In order to clarify this aspect we show one iteration of a belief structure where the household expects, for a given asset, a negative return of 1% with 50% probabilities and a positive return of 2% with 50% probabilities.

Initial Prospect: $\big[$(-0.01,0.5) , (0.02,0.5)$\big]$

Utility: $U = 0$ ($\lambda = 2$)

Iterated Prospect: $\big[$(-0.02,0.25) , (0.01,0.5) , (0.04,0.25)$\big]$

Utility: $U = 0.005$ ($\lambda = 2$)

It can be noted how, in the example, a single iteration can determine a raise in the utility of the asset, and therefore in the relative demand for it.

Prospect theory utility is defined over gains and losses, i.e., returns ρ^{H_n}, rather than levels of wealth. The value function for the ith household has the following form:

$$v_i\big(\rho_{j,i}^{H_n}\big) = \begin{cases} (\rho_{j,i}^{H_n})^{\alpha} & \text{if} \quad \rho_{j,i}^{H_n} \geq 0\,, \\ -\lambda_i(-\rho_{j,i}^{H_n})^{\beta} & \text{if} \quad \rho_{j,i}^{H_n} < 0\,, \end{cases} \tag{2.7}$$

where λ_i is the coefficient of loss aversion of household i.

Given the histogram of composed expected returns, the ith household may calculate the utility of asset j as,

$$U_{j,i} = \sum_{\mathcal{M}_i} p_{j,i}^{H_n}\ v(\rho_{j,i}^{H_n}), \tag{2.8}$$

where $p_{j,i}^{H_n}$ are the probabilities associated to $\rho_{j,i}^{H_n}$. These utilities are finally normalized and mapped into assets weights by means of a linear transformation. Once the assets weights are available, the household can build its desired portfolio and emit orders consequently. Orders are therefore submitted to a clearing house that determines assets new prices.

2.1.3 The banking sector

The commercial bank collects households deposits B_τ, provides loans L_τ to firms, and holds a buffer account C_τ at the central bank, which can be positive or negative. The commercial bank sets the lending rate r^L to firms according to a mark-up rule on the central bank policy rate r, i.e., $r_\tau^L = \mu_L r_\tau$, where $\mu_L > 1$ is the mark-up. The rate on households deposits r^B is determined by $r_\tau^B = \mu_B r_\tau$

where μ_B is lesser than one. Net earnings are given by

$$\pi_\tau^b = r_{\tau-1} C_{\tau-1} + r_{\tau-1}^L L_{\tau-1} - r_{\tau-1}^B B_{\tau-1} - T_\tau^j \tag{2.9}$$

where T_τ^j are taxes as a fraction of gross earnings paid to the Government. The capital structure of the bank is composed by both equity capital E^b and debt financing, i.e., the Central Bank account and households deposits. The bank equity is divided into shares among households and traded in the financial market. Given the amount of L and B set by firms and households, respectively, and the dynamics of equity $E_\tau^b = E_{\tau-1}^b + \widehat{\pi}_\tau^b$, where $\widehat{\pi}^b$ are the retained earnings, the bank adjusts C according to the budget constraint $C_\tau = E_\tau^b + B_\tau - L_\tau$.

The central bank implements monetary policy decisions by means of a policy rate r_τ which is used both as a borrowing or lending rate for the commercial bank account.

2.1.4 The government

The Government runs a financial budget. Income is given by a mixture of different taxation policies, that include taxes on households wages, on corporate earnings, and on capital income. Expenditures depend on unemployment benefits, that are expressed as a percentage of the current wage level, and on the interest rates on government debt. Taxation is adjusted adaptively in order to finance expenditures, running a zero budget target. The government may issue both short-term or long-term bonds in order to finance the budget deficit. Bonds have a face value which is paid at the maturity date, and pay fixed coupons to bondholders anchored to the central bank policy rate.

2.2 Explaining the equity premium puzzle

The model described in section 2.1 has been simulated on a cluster of 24 parallel processors and the current section shows some of the computational results. In particular, we focused our investigation on the effects of households psychological traits (i.e., loss aversion and evaluation period) on the financial market. Loss aversion represents the idea that the damage caused by a loss overcomes the utility produced by an equally large gain. The evaluation period is the length of time over which an agent aggregates and evaluates returns, that in the case of the model coincides with the period an agent intends to hold an asset. We propose a set of experiments where we verify the effects of variations in households loss aversion and evaluation period on the financial market and,

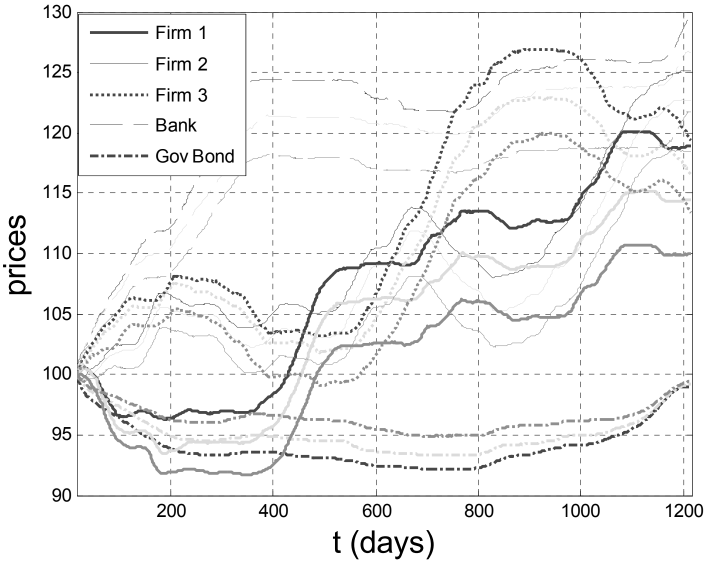

Figure 2.2: Assets price level for different values of loss aversion: $\lambda = 1.5$ (black line), $\lambda = 2$ (light gray line), $\lambda = 2.5$ (dark gray line)

in particular, on the equity premium.

In order to interpret these results, the reader should reckon with two essential aspects of the model. The first aspect is that households have three different available solution for their financial investments: a risk free bank account, government bonds with a low risk profile, and firms stocks which are characterized by a higher risk. It is reasonable to expect that changes in households loss aversion or evaluation period should modify the distribution of agents wealth among these different assets. The second aspect to keep in mind is that the total number of assets in the model is constant over time, because the government does not issue new bonds during the simulation. Considered that the entirety of the assets is distributed among households, it is worth noting that, in average, the percentage of a specific asset in households portfolio turns out to be fixed, and in particular, this implies that, in average, the ratio between stocks and bonds in households portfolio is constant.

We present the results of computational experiments performed with a model populated by 2000 households, 3 firms, a commercial bank, a central bank and a government. Firms are endowed with a constant physical capital and make no new investments. They adopt different dividends pay-out strategies and use retained earnings to increase their equity base. Traders are divided among fundamentalists (10%), chartists (10%) and random traders (80%). The commercial bank dividend policy consists in paying 100% of its net earnings. The government applies a fixed tax rate both on capital income of households and on corporate earnings of the firms and the bank. In the financial

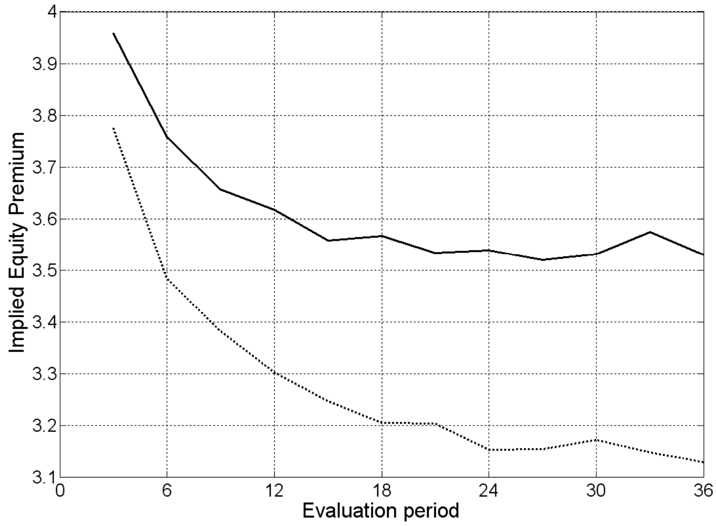

Figure 2.3: The implied equity premium for different values of the evaluation period. Stocks/bonds ratio is 50% (dotted line) or 66% (continuous line)

market 3 stocks and one government bond are traded. There is no issuing of new government bonds, and their maturity date is set at the end of the simulation.

Figure 2.2 shows assets prices trajectories for a sample simulation where the central bank interest rate is $r = 0.05$ and households evaluation period corresponds to 2 times the forward looking window, i.e., $\epsilon = 6$ months. The three gray levels identify three different values for loss aversion: $\lambda = 1.5$ (black), $\lambda = 2$ (light), $\lambda = 2.5$ (dark).

Let us make some general observations on the plot. The government bond price is far less volatile than stocks prices; this is mainly due to the the bond face value, which strongly anchors the expectations of price dynamics, and to the bond cash flow, that corresponds to a constant coupon. The different price trajectories among firms depend on their different dividends pay-out strategies. If a firm pays high dividends, at the beginning of the simulation the price of its asset grows faster, but later this effect tends to be compensated by the higher equity base of firms that have a lower dividends pay-out policy, and whose price will raise pushed by fundamentalists traders. Finally, it is worth noting that the price processes exhibit jumps, crashes and periods of low volatility, realistic features which clearly depend on the interplay of random, chartist and fundamental strategies.

Figure 2.2 shows that in the presence of higher values of loss aversion stocks price levels decrease, while in contrast the price of the government bond grows. This effect is given by the higher volatility of stocks, because households overestimate the risk of loosing money, when their loss aversion is

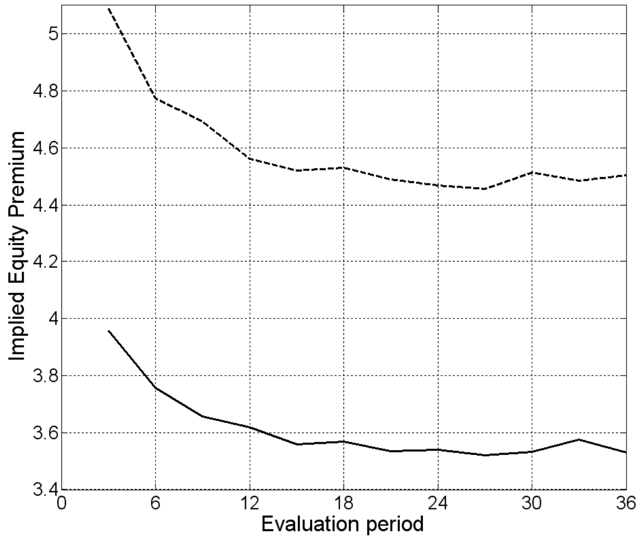

Figure 2.4: The implied equity premium for different values of the evaluation period. Central bank interest rate is set at 3% (dashed line) or at 4% (continuous line).

stronger, and therefore prefer to buy government bonds.

What we would like to show, with the help of Figures 2.3 and 2.4, is that the magnitude of the equity premium strongly depends on the evaluation period. Of course other variables, like the interest rate, or the loss aversion, contribute to set the equity premium, but this could have been easily foreseen. On the other hand, the dependence on the evaluation period is more subtle and interesting because, given certain standard values of the interest rate and of the loss aversion, the model permits to infer how frequently households are supposed to evaluate their investments in order to explain an observed empirical value of the equity premium. Using a similar approach Benartzi and Tahler find that, in order to justify the historical value of the equity premium, households should have an evaluation period of one year [Benartzi and Thaler, 1995b].

Figure 2.3 shows a dotted line, referred to a stock/bonds ratio of 50% and a continuous one referred to a ratio of 66%. What emerges looking at the downward slope of these curves is the following concept: if we suppose that households have a shorter evaluation period, we should expect a higher equity premium in order to justify a given stocks/bonds ratio. This supports the thesis of myopic loss aversion as a determinant of a very high level of equity premium, because if a short evaluation is supposed, a high equity premium should be expected.

The continuous line (66% ratio) exhibits the same trend of the dotted (50% ratio) but for higher values of the equity premium. Obviously, if we suppose households holding more stocks, we should

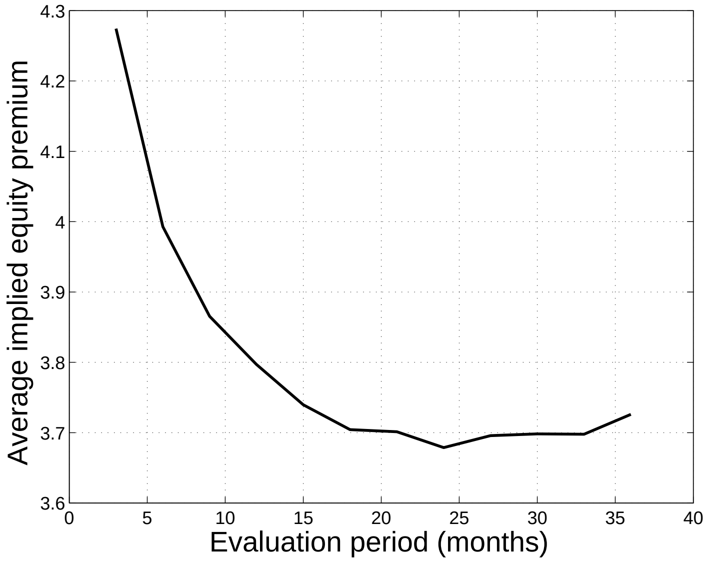

Figure 2.5: The average implied equity premium for different values of the evaluation period.

also expect the presence of higher stock returns attracting them.

Figure 2.3 compares the continuous line of figure 2.3, with a dashed one (66% stocks/bonds ratio) corresponding to a central bank interest rate that decreases from 4% to 3%. The increase of the equity premium is evident and it appears to compensate the decrease in interest rates, but it also should be remarked that this increase is slightly less that the reduction of the central bank policy rate (corresponding to 1%). This is probably due to second order effects that still has to be investigated. Actually, the impact of the interest rate on the equity premium is probably a thorny policy issue that we will take in more exhaustive consideration in future works.

Figure 2.5 has been obtained by averaging, for each evaluation period, the value of the equity premium using 10 different seeds for the underlying stochastic processes (ROA and wages). Again, it clearly shows that, if we suppose that households have a shorter evaluation period, we should expect a higher equity premium in order to justify a given stocks/bonds ratio in their portfolio.

2.3 Conclusions

The explanation of equity excess returns with respect to relatively risk free treasury bills has been quite a thorny issue for the economists since the problem has been raised from Mehra and Prescott. Among several possible solution that have been proposed in the last decades, Benartzi and Tahler suggested that the nature of the mental accounting that characterizes traders could explain this apparent contradiction derived from the rational expectations asset pricing approach. In particular, according to Benartzi and Tahler, the length of time over which an agent aggregates and evaluates returns, called evaluation period, plays a crucial role in the matter.

The work presented in this chapter is based on a agent-based model of a financial economy where the behavioral decisions of agents are endogenously taken. The model incorporates the main actors of the financial scenario, including households, firms, banks and government, and is particularly complete in terms their economic interaction.

A particular attention has been dedicated to the beliefs formation mechanism of households trading in the asset market, and on their preferences structure that is designed in order to take into account some of the main features of prospect theory.

The computational experiments presented in the section 2.2 show that households distinctive parameters (like loss aversion and evaluation period) clearly influence asset prices. In particular, the equity premium turns out to be appreciably dependent on households evaluation periods. In this respect, we show that households with a short evaluation period are not inclined to buy risky assets (firms stocks in our case) and tend to look for government bonds, or to keep their money in the bank account. This determines a strong presence of relatively non-risky assets in their portfolio, despite the higher returns of stocks. Results are coherent with the analysis of Benartzi and Tahler and support their explication of myopic loss aversion as a determinant of the equity premium puzzle.

Part II

Towards an artificial economy: the Eurace model

Introduction

The agent-based approach seems better suited to take into account the complex pattern of agents behavior and interactions that take place in financial markets, like herding behavior and information cascades, and in credit markets, like networks effects, credit rationing and bankruptcy waves, and to figure out their influences on the real side of the economy. Part of mainstream research in economics, usually named as new-Keynesian economics, showed how the financial and liability structure of the economy may influence aggregate economic activity and amplify business cycles. The credit channel, i.e., the financing of business investment, has been pointed out as the main linkage between finance and the real economy. The seminal paper by Stiglitz and Weiss [1981] showed that informational asymmetries in the credit markets may prevent firms, even ones with good investment projects, to obtain credit. Further research highlighted the so-called financial accelerator mechanism, i.e., a balance sheet channel through which monetary policy has real effects in the economy [Bernanke and Gertler, 1990, Greenwald and Stiglitz, 1993, Bernanke and Gertler, 1995]. The credit channel regards both the balance sheet of banks and firms. The balance sheet of credit institutions conditions the potential supply of loans, due to the capital adequacy ratios, while firms net worth influence the willingness of bank to lend to highly leveraged firms. Furthermore, Kiyotaki and Moore [2002] stressed the importance of asset prices and the role of net worth as collateral. It is worth noting however that in the new-Keynesian literature the investment-finance linkage is considered as a propagator mechanism of shocks which are exogenous with respect to the economy. On the contrary, the agent-based approach is able to emphasize the role of the investment-finance link not just as a propagator of exogenous shocks but as the main source of financial instability and business cycles, in line with the Minskyťs financial instability hypothesis [Minsky, 1986, Fazzari et al., 2008].

Deployment of the multi-agent approach for simulating the interplay between the financial and the real sector of the economy will require the modelling and the validation of agent behaviour, and consequently the calibration of artificial populations and the validation of macro-economic outcomes.

Although there exists meanwhile a broad range of behavioral models and the literature on agent-based approaches is more and more seen as a valuable alternative to the orthodox efficient market paradigm, such models have hardly been rigorously estimated and tested with empirical data. This is mainly due to the fact that application of traditional econometric methodology is cumbersome for complex models with a large number of interacting agents. Since most available models in the pertinent literature could be interpreted formally as (highly complex) Markov processes, the market could be described by a continuously changing overall configuration of macroscopic characteristics with Markov properties (for a probabilistic approach to the study of economics see Garibaldi and Scalas [2010]). Even without being able to derive closed-form solutions for the distribution of this configuration, simulation-based methods could be used for parameter estimation.

A clear taxonomy of the most common procedures of validation has been proposed by Fagiolo et al. [2007]. According to them, three are the most influential approaches to empirical validation developed in the ABM literature. The approaches considered are: the Werker–Brenner approach [Werker and Brenner, 2004], the history-friendly approach [Malerba et al., 2001, Malerba and Orsenigo, 2002] and the indirect calibration approach (see for example Dosi et al. [2003]). The approach followed within this thesis can be considered similar to the one of Werker–Brenner and of history-friendly approaches. One can first select among parameters by calibrating the model (e.g., by directly estimate parameters, when possible, with micro or macro data) and then judge to which extent the calibrated model is able to reproduce the stylized facts of interest. This latter method is so-called ex ante input validation. In other words, the researcher tries to introduce the correct parameters in the model before running it, analyzing actual data.

The Eurace model has been actually calibrated by using realistic empirical values both for the parameters of the agents and for the state variables initialization. However, it has been introduced a characteristic feature, that has been called "balance sheet approach" which means that financial state variables of the various agents have been submitted to a crossed balance sheet consistency test in order to check the overall coherence of the model (see Teglio et al. [2010] for details). This balance sheet approach is alternative to the mainstream paradigm, which is based on the inter-temporal optimization of welfare by individual agents, and introduces a new methodology for studying how institutions (firms, banks, governments and households) create flows of income, expenditure and production together with stocks of assets (including money) and liabilities, thereby determining how the whole economy evolves through time. Indeed, the crucial assumption is that the model, as any realistic representation of a monetary economy, must be grounded in a fully articulated system of income and flow of funds accounts.

The development of an artificial economy is a step forward with respect to isolated agent-based models, and requires strong computing resources. An agent is basically a computer system that is situated in some environment and that is capable of autonomous action in this environment in order to meet its design goals (Wooldridge and Jennings, 1995). Once the lowest-level components of a system are identified as agents, simple or complex rules governing their real behaviour are applied, which facilitates interactions between the agents and leads to emergent behaviour over time. In highly complex systems where there are multiple temporal and geometric scales, agent-based systems can provide the basis for a more complex modelling capability by interfacing with multiple solvers and other agent-based systems providing a coherent multi-dimensional and multi-scale model that replicates the key phenomena and structural details of the system under study. With growing complexity and multiple facets of these models it is important that parallel supercomputers are used.

As researchers attempt to understand more and more complex systems by building large-scale models and running extensive simulations it is becoming clear that most of these systems involve activities and components that act at a variety of scales both spatial and temporal. Since many of these components interact and affect each other it is impossible to ignore these different scale effects and thus the need for multi-scale modelling and software environments to support this. Some of the early work in this area is in physics and materials where the effects of different scale can have significant impact on the properties and behaviour of these materials (Baeurle 2009). In operations research the approach informs decision theory and the analysis of such systems (Wernz, 2010). The current state of the art has demonstrated the feasibility of building certain types of multi-scale models, however, these are generally on–off models that are hand crafted for the specific investigation. This has led to the idea of developing a multi-scale modelling language that could support the development of a systematic and general method of building such models. An early attempt has been made to do this in the field of land-use modelling (Carneiro 2003) using nested cellular automata. Paszyñski (2010) used ideas from UML to describe an approach to multi-scale simulations.

In terms of agent-based modelling this limits the technology to one highly successful and flexible system, FLAME (Flexible Large-scale Agent-based Modelling Environment – www.flame.ac.uk). This technology is word leading and it has been used in the EURACE project.

A critical priority in implementation of complex system simulation is also to provide modellers with different expertise a way to express state and behavior of agents in a way as simple as possible without pruning abilities to express complex behavior. As a consequence, such systems must also provide the means for modelers to author test cases for their designs. Hence the overall architecture of the simulation software is expected to present a layered interface to model designers which allows a progressive path for both laying out and testing their design, and for learning the facilities of the software system. FLAME is a tool which allows modellers from all disciplines, economics, biology or social sciences to easily write their own agent-based models. The environment is a first of its kind which allows simulations of large concentrations of agents to be run on parallel computers without any hindrance to the modellers themselves.

The main advantages of this kind of approach over traditional modelling approaches, including Cellular Automata are asynchrony and spatiality; where asynchrony means that agents do not need to simultaneously perform actions at constant time-steps, rather they can follow discrete event queues or a sequential schedule of interactions; while spatiality implies that the environment does not necessarily need to be grid-based, nor the agents need to tile the environment, which allows cohabitation of agents with different environmental experiences

Chapter 3

The EURACE simulator

Between 2006 and 2009 I've been involved in the development of a European project called Eurace, whose aims were to design and implement an agent-based macroeconomic simulation platform integrating different sectors and markets, in particular, goods markets, labor markets, financial markets and credit markets. The Eurace project proposed an innovative approach to macroeconomic modelling and economic policy design according to the new field of agent-based computational economics.

The EURACE model is probably by far the largest and most complete agent-based model developed in the world to date. It represents a fully integrated macroeconomy consisting of three economic spheres: the real sphere (consumption goods, investment goods, and labour market), the financial sphere (credit and financial markets), and the public sector (Government, Central Bank and Eurostat).

The main source of the contents exposed in this chapter is Eurace [2009], where further details about the EURACE implementation can be found. Some general information on EURACE can be also found in Deissenberg et al. [2008].

3.1 General features of Eurace

In the following some of the main distinguishing features of EURACE are resumed.

- Closure: Eurace is one of the very rare fully-specified agent-based models of a complete economy. Eurace is dynamically complete, that is, it specifies all real and financial stocks and flows and will allow us to aggregate upward from the micro-specifications to the macroeconomic variables of interest.

- Encompassing types of real and financial markets and economic agents are taken into consideration.
- Wide use of empirically documented behavioural rules.
- Different levels of time and space granularity. It is possible to investigate the impact of real-life granularity on the economic outcomes, and to analyse the consequences of a modification of this granularity.
- Treatment of time: asynchronous decision-making across different agents.
- Explicit spatial structure, allowing to take into account not only regional and land-use aspects, but also more generally the fact that all human activities are localized in geographical space.
- Evolving social network structure linking the different agents.
- Very large number of agents, possibly allowing to discover emerging phenomena and/or rare events that would not occur with a smaller population.
- Use and development of innovative software frameworks, code parallelization in order to employ super-computers, allowing very large-scale simulations.
- Calibration on European economic data and the focus on European policy analysis.
- Use of a balance sheet approach as a modelling paradigm.

In figure 3.1 a general picture containing the agents populating the Eurace model is represented along with the main markets where they are involved. For a specific description of agents behaviours and market mechanism, Eurace [2009] is currently the most complete source. This chapter presents a description of the main modelling choices of Eurace. When needed, agents interactions and market rules will be also presented in chapters 4 and 5 in order to understand simulations outcomes. In section 3.1.2 the focus is on the explanation of a modelling and validating strategy that has been called "the balance sheet approach", which should be considered as a useful tools for agent-based computational economics.

3.1.1 Model design strategies

Number and types of agents

It is one of the main goals of EURACE to analyze how far qualitative properties of the phenomena arising in economies with (locally) interacting heterogeneous agents change as the number of

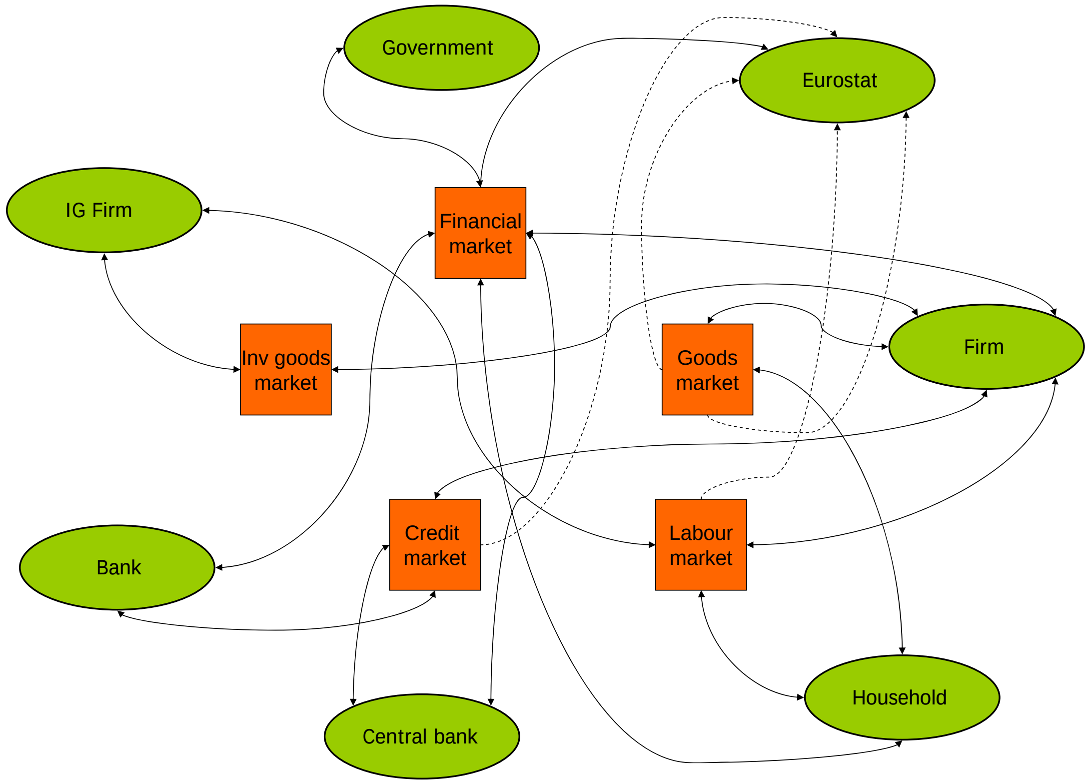

Figure 3.1: A generale scheme of the main agents and markets included in the Eurace model. The arrows show the main communication network of the agents through the different markets.

involved agents goes up. A research topic that has been to a large extent ignored in previous work in agent-based computational economics. Based on this goal, the implementation of the Eurace platform is designed to be scalable to a large number of agents.

Spatial structure and local interaction

The decision to give the model an explicit spatial structure and to let the agents locally interact within this structure was motivated by theoretical, empirical, and policy-related considerations. At the theoretical level, an explicit local interaction structure in space and time is arguably the most salient feature of an agent-based model. At the empirical level, it permits to take into account the main elements of heterogeneity between different economic regions, for instance the distribution of economic activity and of wealth. At the policy level, many issues of major concern are of a spatial nature: how to distribute funds to poorer areas, in which regions to invest, what regional labour market policies to set, and what land use policy to promote, and so on.

Market interaction types

Casual empirical observation about how each market is functioning, rather than an in-depth empirical study, let us chose specific interaction patterns for the way agents interact on the different markets: local or global interaction, centralized or decentralized market mechanisms. The appropriate interfaces needed to integrate the different markets have been defined on the base of, in addition to accounting constraints, on plausibility and practicability consideration.

Timing of decisions

The choice of time scales for the agents' decision making has been made in order to reflect the real time scales in economic activities. The agents' financial decisions are made on a shorter time scale (day) than the economic decision making, e.g., consumption and production, where the proper time horizon can be a week, a month, or a quarter.

Asynchronous interactions

In reality, most human decision-making and interaction is asynchronous, due to the autonomous decisions of the agents. We model this asynchronous decision making by letting agents have different activation days. This means that on a single market different agents are active on different days. Thus, who interacts with whom changes from day to day. Some activities, however, are synchronized. This is in particular the case when they are institutionally initiated. Think, for example, of yearly tax payments, or monthly wage payments. We use synchronous decision making/interactions whenever it reflects the reality.

Market protocols

The modelling of the market protocols is empirically inspired by real-world markets. For the consumption goods market all consumer-firm interactions go through the local outlet malls. Households go shopping on a weekly basis. This closely mimics reality and is a simple form to model localized markets with potential rationing on both sides. In particular the market protocols used capture important market frictions based on problems of search, matching and expectation formation in turbulent environments that are present in real world labour and goods markets. The labour market functions by way of a local search-and-matching protocol that likewise resembles a real world job search by unemployed workers. For the artificial financial market we model a real-world market protocol: the clearinghouse. Government bonds are usually sold by auction. For the credit market we use a firm-bank network interaction mechanism. Firms can apply for loans with at most n banks, where n is a parameter that can be set by the modeller. This reflects how real-world firms appear to manage their credit lines as comes out from the empirical data that have been examined concerning firm-bank network interactions.

Decision processes

In modelling agent decision processes, the model follows the usual and realistic assumptions of agent-based economics about bounded rationality, limited information gathering and storage capacities, and limited computational capabilities of the economic agents. These assumptions lead us to use simple heuristics to model the agents' behaviour, derived from the management literature for firms, and from experimental and behavioural economics for consumers/investors. We also make use of experimental evidence from the psychological literature on decision making. For example, for the modelling of the households' portfolio decisions on the financial market, Kahneman and Tversky's Prospect Theory is considered. The rules used by the agents are simple but not necessarily fixed. Their parameters can be subject to learning, and thus adapted to a changing economic environment. Here we can make a distinction between adaptive agents and learning agents: the first use simple stimulus-response behaviour to only adapt their response to their environment, while the last use a conscious effort to learn about the underlying structure of their environment.

Incremental model development

The submodules have been, and still are developed incrementally, starting with a simplified version of a model and adding new features only after the simplified version has been shown to work. This guards against an important modelling fallacy, which is to start with the most complete model first, only to discover along the way that things are too complicated. It also allows for continuous model validation, one feature at a time, which is a part of the philosophy of agile engineering.

Market interfaces

The separate submodules are connected by market interfaces which define how the markets are interconnected. A market interface is given by the input and output variables and messages that are used by the agents acting on the market. If markets need to be run in a particular sequence (given by the order of the internal function dependencies), then this is also reflected in the market interface.

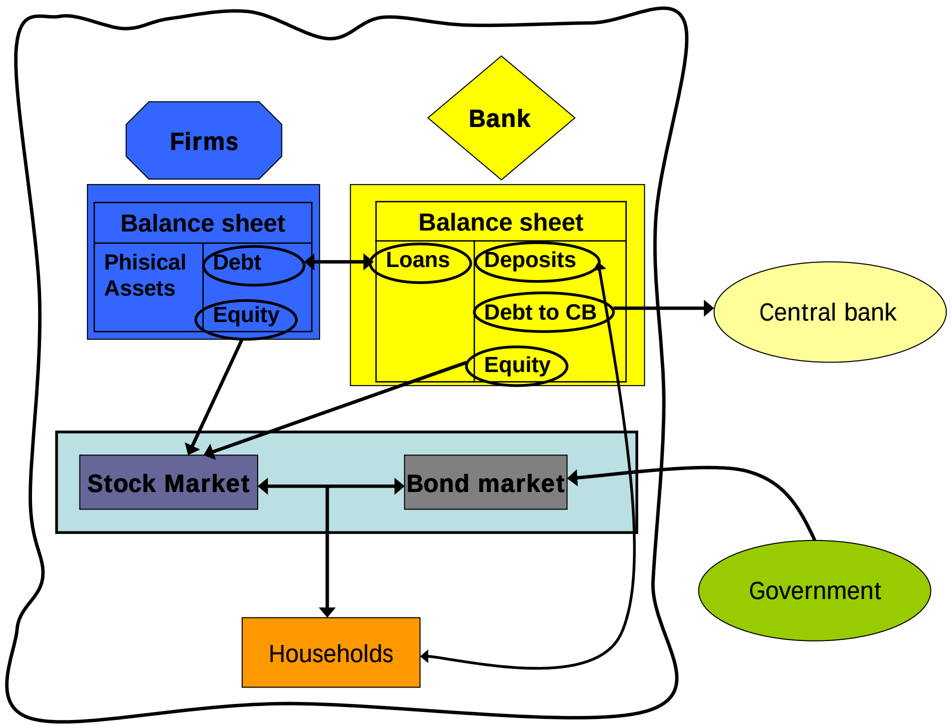

Figure 3.2: A representation of firms and banks balance sheets.

3.1.2 The balance sheet approach

In the Eurace model, a double-entry balance sheet with a detailed account of all monetary and real assets as well as monetary liabilities is defined for each agent. Monetary and real flows, given by agents' behaviors and interactions, determine the period by period balance sheet dynamics. A stock-flow model is then created and used to check that all monetary and real flows are accounted for, and that all changes to stock variables are consistent with these flows. This provides us with a solid and economically well-founded methodology to test the consistency of the model.

In order to explain our approach, let us consider the balance sheets of the different agents of the model.

Household's balance sheet is reported in Table 3.1. Its financial wealth is given by

$$W = M^h + \sum_{f \in \{firms\}} n_f^h p_f + \sum_{b \in \{banks\}} n_b^h p_b + \sum_{g \in \{governments\}} n_g^h p_g$$

where p_f, p_b are daily prices of equity shares issued by firm f and bank b, respectively; while p_g is the daily price of the bond issued by government g.

Firm's balance sheet is shown in Table 3.2. M^f and I_m^f are updated daily following firms' cash

Table 3.1: Household (H): balance sheet overview

Assets	**Liabilities**
M^h: liquidity deposited at a given *bank* n_g^h: government bonds holdings n_f^h, n_b^h: equity shares holdings of firm f and bank b	(none)

Table 3.2: Firm (f): balance sheet overview

Assets	**Liabilities**
M^f: liquidity deposited at a given *bank* I_m^f: inventories at *malls* K^f: physical capital	D_b^f: debts to *banks* E^f: equity

flows and sales, while K^f and D_b^f are updated updated monthly. The equity E^f is also updated monthly according to the following rule:

$$E^f = M^f + p_C \sum_{m \in \{malls\}} I_m^f + p_K K^f - \sum_{b \in \{banks\}} D_b^f$$

where p_C is the average price level of consumption goods and p_K is the price of capital goods.

Table 5.1 reports the balance sheet of the bank. M_h^b, M_f^b, L_f^b are updated daily following the private sector deposits changes and the credit market outcomes. M^b and E^b are updated daily following banks cash flows and keeping into account the balance constraint:

$$M^b = D^b + \sum_{h \in \{households\}} M_h^b + \sum_{f \in \{firms\}} M_f^b + E^b - \sum_{f \in \{firms\}} L_f^b$$

If M^b becomes negative, D^b is increased to set $M^b = 0$. If both M^b and D^b are positive, D^b is partially or totally repaid.

In order to understand the functioning of money creation, circulation and destruction in EURACE, we first need to explain the outlay of bank's balance sheet.

Let's start with the money creation issue: four channels of money formation are open. The first,

Table 3.3: Bank (b): balance sheet overview

Assets	**Liabilities**
M^b: liquidity (reserves) deposited at the *central bank* L_f^b: loans to firms	D^b: standing facility (debts to the *central bank*) M_h^b: households' deposits at the bank M_f^b: firms' deposits at the bank E^b: equity

Table 3.4: Government (g): balance sheet overview

Assets	**Liabilities**
M^g: liquidity deposited at the central bank	D^g: standing facility with the central bank n^g: number of outstanding bonds

and most important one, activates when banks grant loans to firms, and new money (M1) appears in the form of firm's increased payment account (and, thus, increased deposits). The second channel operates when the central bank is financing commercial banks through lending of last resort, and money creation (Fiat money) translates in augmented bank's reserves. Government Bond issuing constitutes the third channel: it is at work whenever the quantitative easing (QE) feature is active, allowing the CB to buy government bonds in the financial market. Finally, the fourth and last channel is represented by bailouts of commercial banks by the CB.

So far we have dealt with money creation, let us now comment money circulation and destruction. Since there is no currency, that is no money is present outside the banking system, when agents (firms, households or Government) use their liquid assets to settle in favor of other agents, money should simply flow from payer's bank account to taker's bank account, obviously keeping itself constant (such cash movements are accounted at the end of the day, when agents communicate to banks all their payments). On the contrary, whenever a debt is repaid, money stock has to decrease accordingly. For technical details and a more exhaustive discussion on these issues, see Eurace [2009].

Finally, the balance sheets of the government and of the central bank are reported in Tables 3.4 and 3.5, respectively.

The government budget is composed by taxes on corporate profits, household labor and capital income, as revenues, and unemployment benefits, transfer and subsidies, as expenses.

Since the Central Bank is not allowed to make a profit, its revenues from government bonds and bank advances are distributed to the government in the form of a dividend. In case of multiple governments, the total dividend payment is equally divided among the different governments.

These modelling hypothesis lead to the definition of a precise "EURACE time invariant" feature, consisting in a fundamental macroeconomic accounting identity:

Table 3.5: Central Bank (c): balance sheet overview

Assets	**Liabilities**
n_g^c: Government bonds (QE)	M^c: fiat money due to QE
M^c: liquidity	M_g^c: Governments liquidity
L_b^c: loans to banks	M_b^c: banks reserves
L_g^c: loans to governments	E^c: equity

$$\underbrace{\Delta\Big(\sum_h M^h + \sum_f M^f\Big)}_{\text{private sector deposits}} + \underbrace{\Delta\Big(\sum_b E^b\Big)}_{\text{banks equity}} + \underbrace{\Delta\Big(\sum_g M^g + M^c\Big)}_{\text{public sector deposits}} = \underbrace{\Delta\Big(M^c + \sum_b L_b^c + \sum_g L_g^c\Big)}_{\text{fiat money}} + \underbrace{\Delta\Big(\sum_b \sum_f L_f^b\Big)}_{\text{credit money}}$$

This accounting identity ensures the coherence of the aggregate stock-flow in the EURACE model. For policy considerations, it is clearly important to consider the monetary endowment of agents in the private sector, i.e.,

$$\sum_h M^h + \sum_f M^f + \sum_b E^b$$

A higher monetary endowment due, e.g., to a loose fiscal policy and QE, leads to a higher nominal demand. Depending on the behavior of prices, the higher nominal demand could translate into a higher real demand.

3.1.3 The stategraph

This section aims at giving a basic explanation, through an example, about the way economic agents interact within the model. A portion of the stategraph of the Eurace model, shown in figure 3.3 will be used for the purpose. The whole stategraph is generated automatically when parsing the Eurace model, and represents the activity flows of each agent type, from the beginning of the day to the end of the day. This clearly does not mean that each agent performs the same set of actions each day of the year; there are of course some actions that are activated weekly, or monthly, or that are simply triggered by other events. Nevertheless, this kind od information compares explicitly in the stategraph, that shows the activation frequency of each agent's function. Looking at stategraph therefore allows one to visualize agents interactions and to understand the model structure. The main information which is not contained in the stategraph is functions content (or code), i.e., the

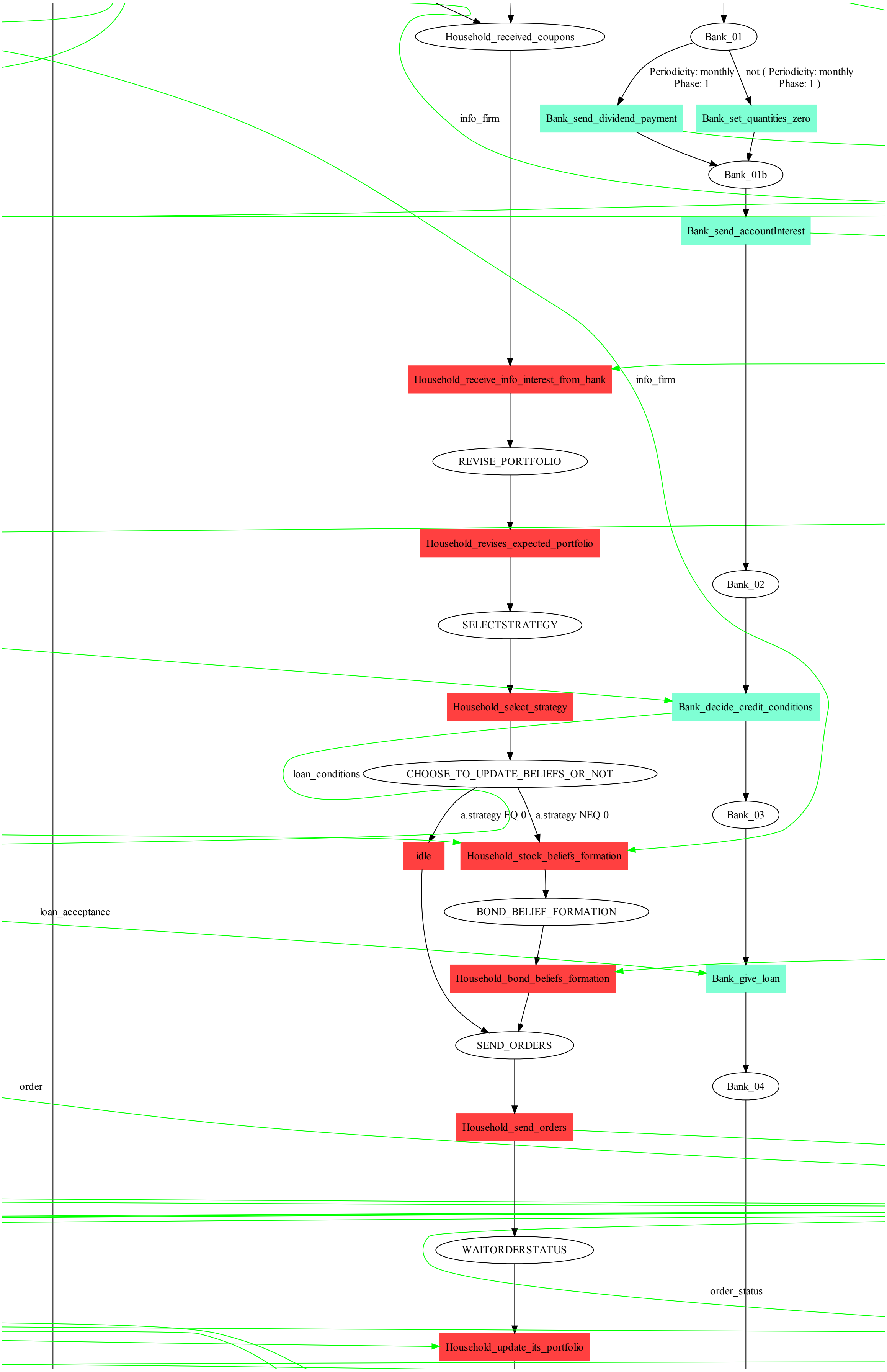

Figure 3.3: Zoomed particular of the stategraph of the Eurace model, representing the household taking portfolio decision (left line) and the bank examining loan requests (right line).

description of agents behaviours.

Showing the entire stategraph is not possible due to its large dimension. It contains the flow of 10 agents typologies distributed in 90 temporal layers, with a total of nearly 500 functions. Thus, a small portion of the stategraph is shown in figure 3.3, in order to illustrate a sample of the interaction structure. This portion includes about 12 functions and 10 temporal layers, just to give the idea of proportions with respect to the whole original picture.

The two vertical lines represent the household (left) and the bank (right). The rectangular boxes are agent's functions, while the ellipses represent different states of the agent. The green curved arrows are messages that agents exchange among themselves. Bank's transition between state *Bank_01* and state *Bank_01b* depends on the periodicity. Each bank pays dividends once per month and so the function *Bank_send_dividends_payment* is activated only the day of the month when that particular bank has to pay its dividends. The function Bank_decide_credit_conditions is activated when a bank receives a message (msg: *loan_request*) from a firm that is asking for a loan. Within the function, the bank evaluates firm's characteristics and associated risk and proposes its loan conditions, sending a message to the firm (msg: *loan_conditions*). The firm decides if accepting or rejecting bank's conditions, communicating its positive answer (if any) in the message *loan_acceptance*. Later the bank grants the loan in the function *Bank_give_loan*. Note that this function does not need any message because each agent involved in the transaction, i.e., the firm and the bank, will simply adjust its balance sheet accordingly; thus, in *Bank_give_loan* the bank only updates its financial accounting.

Another example of agent's state flow is given by the vertical line in the left part of the figure, where some of the household's choices in the financial market are represented. In particular, households receive messages from other agents of the model about some relevant variables in order to make financial decisions, as bank deposit rates or historical asset prices. According to this information and according to their individual characteristics and activation times, households make their financial decisions. For instance, households do not update beliefs every time they send a financial order but only when the internal variable *strategy* is different from zero (NEQ 0); this condition is checked in the function *Household_select_strategy* and determines two different path for the household. These two paths meet again in the state *send_orders* where each trading household sends a message with its buy and sell orders to the clearing house. Finally the household waits until a response message from the clearing house is delivered, containing the information about the occurred transactions, and he can therefore move to a function where updating correspondingly its (local) financial portfolio.

The software framework that permits to design the different components of the Eurace model according to the interactions scheme represented in figure 3.3 is quite complex, and a detailed analysis of it is beyond the scope of this thesis. On the other hand, it can be useful to spend some words on the main principles that inspired the development of the software tools which have been used for modeling Eurace. This will be the subject of section 3.7.

3.2 The production sector

3.2.1 Type of producers

Two types of producers are considered in the Eurace model: capital goods producers and consumption goods producers. Capital goods producers employ energy and raw materials to produce capital goods following a job production process. Consumption goods producers use capital goods and labor to produce homogenous consumption goods that will be sold to households. Contrary to consumption goods producers, capital goods producers do not have production inventories as well as financing needs because of the job production process and the variable production factors employed. Capital goods producers can then be represented as stylized agents with both real and financial inputs and output. Conversely, consumption goods producers are much more complex agents characterized by both flows and stocks (e.g., inventories, physical capital, etc..) and will be described in details in the following.

3.2.2 Consumption goods producer (firms)

Consumption goods producer, henceforth firms, are the bulk of the production sector in the Eurace model. The employ labor and capital goods to produce consumption goods by means of a Cobb-Douglas technology. Quantity and price decisions are based on standard inventory planning and mark-up pricing rules. Firms ask loans to the banking system in order to finance their production plans and fulfill their payments commitments, i.e., taxes, dividends, interests, and loan repayments. If firms are rationed in the credit market, they issue new shares to raise the required money in the equity market.

Table 3.6 presents the typical balance sheet of a firm f at a given month. M_f and I_f are updated daily following firms' cash flows and sales, while K_f and D_f are updated monthly following capital investments and the outcomes in the credit market, i.e., new loans and repayment of old loans. Once the balance sheet entries are updated, the equity E_f is also updated monthly according to the usual

Assets	Liabilities
M^f: liquidity deposited at a given bank	$D^f = \sum_l \lambda^{f,i}$: total debt
I^f: inventories	(sum of outstanding loans)
K^f: physical capital	E^f: equity

Table 3.6: Balance sheet snapshot of firm f at the end of its sale month.

accounting rule:

$$E^f = M^f + p^C I^f + p^K K^f - \sum_{b \in \{banks\}} D^f_b \tag{3.1}$$

where p^C is the general price index of consumption goods and p^K is the price of capital goods, both referred to the accounting month.

Production, investment and financing decisions are taken, processed and completed by firms once a month at their specific activation day. Activations days are different and specific to every firm. Sales of new produced goods, together with inventories, occur during the activation day as well as during the $n-1$ business days following any activation day. A month is then defined as a set of n business days, henceforth simply days, therefore, any activation day sets the starts of a sale month which is specific for every firm and does not correspond to calendar months which have a duration of n days but start at day 1, n +1, 1, 2n +1, etc.... Consider firm f at the activation day which sets the beginning of month τ. Firm f plans the quantity $\hat{q}_\tau$ of new consumption goods to produce and decides their new sale price p^f_τ. The new produced goods should be sold during month τ, along with the inventories $I^f_{\tau-1}$ remaining from the previous month τ-1. Given the production plan $\hat{q}_\tau$, the firm determines its factor demand, i.e., the amount of labor $\hat{N}^f_\tau$ and capital $\hat{K}^f_\tau$ needed to fulfill the production plans. If the amount of needed physical capital is higher then the present endowment of physical capital, i.e, if $\hat{K}^f_\tau > (1-\xi)K^f_{\tau-1}$, where $K^f_{\tau-1}$ is the capital endowment of firm f at the end of the previous sale month and η is the monthly capital depreciation rate, then the firm demands an investment $\hat{I}^f_\tau = \hat{K}^f_\tau - (1-\eta)K^f_{\tau-1}$ in new physical capital to fill the gap. It is worth noting that the hat symbol denotes a planned or desired amount and not a realized one. The effective amount will depend on market and simulation outcomes.

Besides production, pricing and investment decisions, each firm computes at the same activation day the amount of liquidity needed to finance the production and investment plans as well as the scheduled financial payments. In particular, scheduled financial payments consist in the interest bill B^f_τ, i.e., the interest payments on the amount of previous debt, the loan installments to repay the outstanding debt, taxes T^f_τ and the dividends payout. The interest bill B^f_τ is given by:

$$B^f_\tau = \sum_i \frac{r^i}{12} \lambda^{f,i}_{\tau-1} \, , \tag{3.2}$$

where $\lambda^{f,i}_{\tau-1}$ is the amount of the i-th loan, received by firm f from any bank, that has still to be repayed, and r^i is the yearly interest rate specific to loan i. B^f_τ is a monthly interest bill and this explains the division by 12. The loan installments sum is given by $\rho \sum_i \lambda^{f,i}_{\tau-1}$ where ρ is the constant fraction of loans to be repayed at any month. The tax bill is a constant fraction ξ of previous month gross earnings (or gross profits) $\Pi^f_{\tau-1}$, i.e., $T^f_\tau = \xi \Pi^f_{\tau-1}$, while the dividends payout is a variable fraction of previous month net earnings (or net profits) $\Pi^f_{\tau-1} - T^f_\tau$. In particular, the firm decides the planned per-share dividend $\widehat{d}^f_\tau$, then the dividends payout is simply given by $e^f \widehat{d}^f_\tau$ where e^f is the number of outstanding equity shares of firm f. It is worth noting that both taxes and dividends are set to zero in the case of negative gross earnings. Gross earning at sale month $\tau - 1$ are given by revenues $R^f_{\tau-1}$ earned during the month minus labor costs and the interest bill $B^f_{\tau-1}$. Revenues are computed as $R^f_{\tau-1} = p^f_{\tau-1} q^f_{\tau-1}$ where $q^f_{\tau-1}$ is the quantity sold during the previous month and $p^f_{\tau-1}$ the sale price. Labor costs are given by $w_{\tau-1} N^f_{\tau-1}$ where $w_{\tau-1}$ is the money wage and $N^f_{\tau-1}$ the number of employees of firm f during month $\tau - 1$.

The total foreseen liquidity needs L^f_τ of firm f at month τ are therefore given by summing all scheduled financial payments, the foreseen production and investment costs referred to the production planned for month τ. Costs include both the foreseen labor costs, i.e., $w_\tau \hat{N}^f_\tau$, where $\hat{N}^f_\tau$ is the labor demand, and investments costs $p^k_\tau \hat{I}^f_\tau$. It is worth noting that effective costs may be lower than the foreseen ones, because $N^f_\tau \leq \widehat{N}^f_\tau$ due to possible rationing of firm f in the labor market and thus its inability to hire all the planned employees. On the contrary, given that we stipulate a job production for capital goods producers, effective investments I^f_τ should be expected to be always equal to planned ones, unless the firm f is unable to collect the necessary liquidity needs L^f_τ. The foreseen liquidity needs are then given by:

$$\mathsf{L}^f_\tau = B^f_\tau + T^f_\tau + \rho \sum_i \lambda^{f,i}_{\tau-1} + + e^f \widehat{d}^f_\tau + w_\tau \widehat{N}^f_\tau + p^k_\tau \widehat{I}^f_\tau \, . \tag{3.3}$$

Finally, it is worth noting that the interest bill, taxes and loans repayments are certain and out of the firm control, while dividends, labor and investments costs, determined also by the given money wage and unit capital cost, are under the control of the firm and can therefore can be scaled down in the case the firm is unable to raise the necessary monetary resources in the credit market and in the stock market.

Details on the firm' decision process about production, pricing, factor demand, and financing will be given in the next paragraphs.

Production and price decision

Each firm keeps a stock of its unsold production as inventories I_f. Once every period, during its activation day, the firm checks if its stock needs to be refilled. According to the approach of using standard managerial methods wherever it is applicable, a standard inventory rule for managing the stock holding is employed.

Let us suppose that at day t, when the firm has to plan production for the next month, firm f has got a stock level of $I_{f,\,t}$, and that firm's expected demand for next period τ is $\hat{Q}_{f,t}$. Then, standard results from inventory theory suggest that the firm should choose to produce its desired replenishment quantity $\tilde{Q}_{f,\,t}$ for period τ according to the following rule:

$$\tilde{Q}_{f,\,t} = \begin{cases} 0 & I_{f,\,t} \geq \hat{Q}_{f,\,t} \\ \hat{Q}_{f,\,t} - I_{f,\,t} & I_{f,\,t} < \hat{Q}_{f,\,t}, \end{cases} \tag{3.4}$$

where $\hat{Q}_{f,t}$ is chosen such that the firm expects to be able to satisfy the market demand with some probability $1-\chi$. Demand in the current period is estimated using a linear regression based on previous sales. Put formally,

$$\hat{Q}_{f,t} = \hat{a}_{f,t} + (\tau+1)\hat{b}_{f,t} + \bar{q}_{1-\chi} \cdot \sqrt{\hat{\delta}_t^2}, \tag{3.5}$$

where $\bar{q}_{1-\chi}$ is the $1-\chi$ quantile of the standard normal distribution and the parameters $\hat{a}_{f,t}$ and $\hat{b}_{f,t}$ are estimated using standard linear regression methods. Thus, considering the vector of past sales $\{\hat{S}_{f,t-\tau}, ..., \hat{S}_{f,t-1}\}$, we have

$$\hat{b}_{f,t} = \frac{\tau \sum_{s=1}^{\tau} s\hat{S}_{f,t-\tau+s} - \frac{1}{2}(\tau(\tau+1)) \sum_{s=1}^{\tau} \hat{S}_{f,t-\tau+s}}{\frac{1}{6}(\tau^2(\tau+1)(2\tau+1)) - \frac{1}{4}(\tau^2(\tau+1)^2)} \tag{3.6}$$

and

$$\hat{a}_{f,t} = \frac{1}{\tau} \sum_{s=1}^{\tau} \hat{S}_{f,t-\tau+s} - \frac{1}{2}\hat{b}_{f,t}(\tau+1), \tag{3.7}$$

and for the variance

$$\delta^2 = \frac{1}{(\tau-1)} \sum_{s=1}^{\tau} (\hat{S}_{f,t-\tau+s} - (\hat{a}_{f,t} + s \cdot \hat{b}_{f,t}))^2. \tag{3.8}$$

To avoid excessive oscillations of the quantities that the firm desires to produce in period τ, the replenishment quantity ($\tilde{Q}_{f,t}$) is smoothed. On this account, the consumption goods producer shows some inertia in adapting the actual production quantity to the desired quantity. In particular, the planned production quantity is

$$\bar{Q}_{f,t} = \xi \cdot \tilde{Q}_{f,t} + (1-\xi) \cdot \frac{1}{T} \cdot \sum_{k=t-T}^{t-1} Q_{f,k}, \tag{3.9}$$

where the second addend is the average production quantity of past period T. As discussed in more detail below, the realized production volume $Q_{f,t}$ can deviate from the planned output $\bar{Q}_{f,t}$ due to rationing on the factor markets.

Production times of consumption goods are not explicitly taken into account and the produced quantities are delivered on the same day when production takes place. The local stock level is therefore updated accordingly.

Consumption good producers employ a standard approach from the management literature, the so-called 'break-even analysis' to set their prices. The break-even formula determines at what point the change in sales becomes large enough to make a price reduction profitable and at what point the decrease in sales becomes small enough to justify a rise in the price. Basically, this managerial pricing rule corresponds to standard elasticity based pricing.

Assuming that all firms have constant expectations $\varepsilon_f^e < -1$ of the elasticity of their demand, they set the price according to the standard rule

$$p_{f,\tau} = \frac{\bar{c}_{f,\tau-1}}{1 + 1/\varepsilon_f^e}, \tag{3.10}$$

where units costs $\bar{c}_{f,\tau}$ are calculated as a weighted average between unit costs of current production ($\tilde{c}_{f,\tau}$) and past unit costs of goods already stocked in the inventories, i.e.,

$$\bar{c}_{f,\tau} = \frac{\bar{c}_{f,\tau-1} I_{f,\tau} + \tilde{c}_{f,\tau} Q_{f,\tau}}{I_{f,\tau} + Q_{f,\tau}}.$$

Once the firm has determined the updated prices $p_{f,\tau}$, the new prices are posted for the following period.

Factors demand

Consumption good producers, denoted by i, need physical capital and labor to produce the consumption goods. The accumulation of physical capital by a consumption good producer follows

$$K_{f,\,t+\tau} = (1-\delta)K_{f,\,t} + I_{f,\,t} \tag{3.11}$$

where $K_f(0) = 0$ and $I_{f,\,t} > 0$ is the gross investment.

Every worker w has a level of general skills $b_w^{gen} \in \{1, ..., b_{\max}^{gen}\}$ and a level of specific skills $b_{w,\,t}$. The specific skills of worker w indicate how efficiently the corresponding technology is exploited by the individual worker. Building up those specific skills depends on collecting experience by using the technology in the production process. The shape of the evolution of productivity follows a concave curve, the so-called learning curve, when the organizational productivity is recorded after implementing a new production method or introducing a new good. Concavity in this context means that the productivity rises with proceeding use of the production method or production of the new good, but this increase emerges at a decreasing rate. We transfer this pattern of organizational learning on the individual level and assume that the development of individual productivity follows a learning curve. The specific skills are updated once in each production cycle of one month. Further, we assume that updating takes place at the end of the cycle.

A crucial assumption is the positive relationship between the general skills b_w^{gen} of a worker and his ability to utilize his experiences. Building up worker's technology specific skills depends on a worker's level of general skills, i.e. his education and the other general abilities which are not directly linked to the particular technology. Taking the relevance of the general skill level into account the specific skills of a worker w for technology j is assumed to evolve according to

$$b_{w,\,t+1} = b_{w,\,t} + \chi(b_w^{gen}) \cdot (A_{f,\,t} - b_{w,\,t}),$$

where we denote with $A_{f,\,t}$ the average quality of the capital stock. The function χ is increasing in the general skill level of the worker. Note that this formulation captures the fact that in the absence of technology improvements marginal learning curve effects per time unit decrease as experience is accumulated and the specific skills of the worker approaches the current technological frontier.

The production technology in the consumption goods sector is represented by a Cobb-Douglas type production function with complementarities between the quality of the investment good and the specific skills of employees for using that type of technology. Factor productivity is determined by the minimum of the average quality of physical capital and the average level of relevant specific skills of the workers. Capital and labor input is substitutable with a constant elasticity and we assume constant returns to scale. Accordingly, output for a consumption goods producer is given by

$$Q_{f,\,t} = \min[B_{f,\,t},\, A_{f,\,t}] \times L^{\alpha}_{f,\,t} K^{\beta}_{f,\,t}, \tag{3.12}$$

where $B_{f,\,t}$ denotes the average specific skill level in firms and $\alpha + \beta = 1$.

Firms aim to realize a capital to labor ratio according to the standard rule for CES production functions. Let us recall that $\lambda^{f,i}_{\tau-1}$ is the unpaid amount of the i-th loan received by firm f from any bank, and that r^i is the yearly interest rate specific to loan i. The weighted average loan interest rate for firm f at time t (that is at the beginning of period τ) is therefore

$$\bar{r}^f_\tau = \frac{\sum_i \lambda^{f,i}_{\tau-1} r^i}{\sum_i \lambda^{f,i}_{\tau-1}}$$

The monthly cost of capital for firm f can be expressed as the cost of debt plus capital depreciation rate, i.e.,

$$c^{f,t}_K = \frac{\bar{r}^f_\tau}{12} + \delta^f, \tag{3.13}$$

where depreciation δ^f is considered as a monthly rate. It is worth noting, to clarify the use of temporal indexes, that the decisions about production, including factors demand, are taken at time t, at the beginning od period τ, while sales occur during the whole duration of period τ. Hence, the indexes t and τ are substantially equivalent when a decision is taken once every period, like in this case.

We can express the ratio of quantity to price of the two factors as proportional to the corresponding intensity parameter. Accordingly,

$$\frac{\tilde{K}_{f,\,t}}{c^{f,t}_K} / \frac{\tilde{L}_{f,\,t}}{w^e_t} = \frac{\beta}{\alpha}, \tag{3.14}$$

where $c^{f,t}_K$ has been defined in 3.13 and w^e_t is the expected wage, that is calculated as the average wage currently paid by the firm to its employees.

Let us point out that firm f has already calculated its planned production quantity by eq. 3.9. Taking into account the production function of eq. 3.12, according to standard theory of cost minimization, this yields under the assumption of positive investments to the following optimal values for capital and labor.

$$\begin{aligned}\hat{K}_{f,\,t} &= \frac{(\beta w_t^e)^\alpha \bar{Q}_{f,\,t}}{(\alpha c_K^{f,\,t})^\alpha \min[A_{f,\,t},\, B_{f,\,t}]} \\ \hat{L}_{f,\,t} &= \frac{(\alpha c_K^{f,\,t})^\beta \bar{Q}_{f,\,t}}{(\beta w_t^e)^\beta \min[A_{f,\,t},\, B_{f,\,t}]}\end{aligned} \tag{3.15}$$

If the optimal value of capital is lower than the available capital, considering depreciation, i.e., if $\hat{K}_{f,\,t} < (1-\delta^f)K_{f,\,t-1}$, then the available capital $(1-\delta^f)K_{f,\,t-1}$ should be used because its cost is always paid. Moreover, given the supposed technological constraint, a maximum increase of physical capital κ is foreseen, i.e, if $\hat{K}_{f,\,t} > (1+\kappa)K_{f,\,t-1}$ then $\tilde{K}_{f,\,t} = (1+\kappa)K_{f,\,t-1}$. Given the desired capital $\hat{K}_{f,\,t}$, the needed labor is therefore calculated as

$$\tilde{L}_{f,\,t} = \left(\frac{\bar{Q}_{f,\,t}}{(\tilde{K}_{f,\,t})^\beta \min[A_{f,\,t},\, B_{f,\,t}]}\right)^{1/\alpha} \tag{3.16}$$

For simplicity credit constraints are not incorporated in this version of the model. All desired investments can be financed.

The monthly realized profit of a consumption goods producer is the difference of sales revenues during the previous period and costs as well as investments (i.e. labor costs and capital good investments) borne for production in the current period. Wages for the full month are paid to all workers at the day when the firm updates its labor force. Investment goods are paid at the day when they are delivered.

Financing

According to the pecking-order theory [Myers and Majluf, 1984], any firm f meets its liquidity needs first by using its internal liquid resources P^f_τ, i.e., the cash account deposited at a given bank; then, if $\mathsf{P}^f_\tau < \mathsf{L}^f_\tau$, the firm asks for a loan of amount $\lambda^f_\tau = \mathsf{L}^f_\tau - \mathsf{P}^f_\tau$ to the banking system so to be able to cover entirely its foreseen payments. Credit linkages between firm f and any bank b are defined by a connectivity matrix which is randomly created whenever a firm enters the credit market in search for funding. In order to take search costs as well as incomplete information into account, each firm links with a limited number of banks, which are chosen in a random way.

Firms have to reveal to the linked banks information about their current equity and debt levels, along with the amount of the loan requested λ^f_τ. Using this information, each contacted bank b communicates the amount of money $\ell^{b,f}_\tau$ is is willing to lend to the firm f, where $\ell^{b,f}_\tau \leq \lambda^f_\tau$. $\ell^{b,f}_\tau$ is determined according to the decision rules outlined in the next section. Each contacted bank calculates also the interest rate $r^{b,f}_\tau$ associated to the loan offer and communicates it to the firm. Then the firm f agrees to get teh loan from the bank applying the lowest interest rate. On banks' hand, they receive demands by firms sequentially and deal with them in a “first come, first served” basis. As explained with more detail in the following section, the firm can be credit rationed. If a firm can not obtain a sufficient amount of credit from the bank that is offering the best interest rate, the firm will ask credit to the bank offering the second best interest rate, until the last connected bank of the list is reached. It is worth noting that, although the individual firm asks loans to the bank with the lowest lending rate, the total demand for loans does not depend directly on the interest rates of loans.

When firm f receives a loan, its cash account P^f_τ is then increased by the amount of it. If the firm is not able to collect the needed credit amount, i.e., if P^f_τ is still lower than L^f_τ, the firm has still the possibility to issue new equity shares and sell them on the stock market. If the new shares are not sold out, the firm enters a state called *financial crisis*. When a firm is in financial crisis, we mainly distinguish two cases: if the firm’s available internal liquidity is still sufficient to meet its committed financial payments, i.e., taxes, the debt instalment and interests on debt, then these financial payments are executed and the dividend payout and the production schedule are rearranged to take into account the reduced available liquidity; otherwise, the firm is unable to pay it financial commitments and it goes into bankruptcy.

3.2.3 Investment goods producers (IG firms)

There exists a single type of technology for investment goods. The investment good is offered with infinite supply by investment goods producers which produce on job and have no inventories and financing needs. Energy and raw materials are the only factor of production and are assumed to be imported from abroad. The price of energy and raw materials is exogenously given. The price of capital goods p^K is a mark-up on energy prices. Profits of investment good producer are distributed in equal shares among all households. Put differently, it is assumed that All households own equal shares of capital goods producers and that shares are not traded in the market. Therefore, the amount payed by consumption goods producers to for investment goods is partially, the part related to mark-up, channeled back into the economy, while the part related to energy costs leaves the Eurace economy.

3.3 Households

Households are simultaneously taking the roles of workers, consumers and financial market traders. Households’ total monthly income is made by both labor and capital income. Gross labor income

Assets	Liabilities
M^h: liquidity deposited at a given *bank* n_g^h: government bonds holdings n_f^h, n_b^h: equity shares holdings of firm f and bank b	(none)

Table 3.7: Household (H): balance sheet overview

is given by the monthly money wage w_τ, payed by the employer, or by an unemployment benefit received from the Government. The unemployment benefit is set at a fixed percentage η of the last salary received. Households receive gross capital income from the equity shares and government bonds held in their financial portfolio. Capital income is given by dividends payed by firms on a monthly basis and by monthly government bonds coupons. Households pay taxes on both labor and capital income. Labor and capital income taxes are a fixed percentages, ξ^{H_w} and ξ^{H_K}, respectively, of the gross income. Households financial wealth is given by their assets portfolio and by the liquidity deposited at a give bank. We stipulate that households have no liabilities. Table 3.7 presents the typical balance sheet of a household.

Once households receive their labor income or unemployment benefit, at the activation day of the firm they are employed, they set the consumption budget for the entire duration of the month. Saving-consumption decision is modelled according to the theory of buffer-stock saving behaviour [Carroll, 2001, Deaton, 1992], which states that households consumption depends on a precautionary saving motive, determined by a target level of wealth to income ratio. Consider household h receiving a gross money wage w_τ at a particular day. Consider the total net income of the household y_τ^h which include the after taxes money wage as well the net capital income earned during the previous month. Consider also the financial wealth W_τ^h of household h at month τ which includes the assets portfolio, value at the most recent market values, as well as liquidity. Following the buffer stock theory of consumption, the household sets the budget for consumption c_τ^h in the following month as:

$$c_\tau^h = \bar{y}^h + \phi^H \left(W_\tau^h - x\bar{y}^h \right), \tag{3.17}$$

where $\bar{y}^h$ is the average total net income of household h in the last 5 months and x is the target wealth to income ratio. The rationale of the rule is that if for instance the present wealth to average income ratio is higher then the target one, i.e., $W_\tau^h / \bar{y}^h > x$, then the household spend more then his or her income in order reach the target value. The parameter ϕ^H sets the adjustment speed.

Households can either invest their savings in the asset market, by trading stocks or bonds, or can put them in a saving account that pays a fixed, risk-free interest rate. The financial market operates on a daily basis and is characterized by a clearing house mechanism for price formation which is based on the matching of the demand and supply curves. Households portfolio allocation is modeled according to a preference structure designed to take into account the psychological findings emerged in the framework of behavioral finance and in particular of prospect theory [Kahneman and Tversky, 1979, Tversky and Kahneman, 1992]. In particular, a key prospect theory insight, i.e., the myopic loss aversion, is considered. Myopic loss aversion depends on the limited foresight capabilities characterizing humans when forming beliefs about financial returns [Benartzi and Thaler, 1995b]. Further details about the belief formation and the preference structure are provided in Raberto et al. [2008a], Teglio et al. [2009].

Once the monthly consumption budget c_τ^h has been determined, household h samples on a weekly basis the prices of different consumption goods producers and then decides which goods to buy. We assume that the decision is random and that follows a probability distribution given by a logit model. This approach is standard in the marketing literature where logit models are intended to represent the stochastic influence of factors not explicitly taken into account. Denote by F_h the set of consumption goods producers whose goods has been sampled by household h in the given week. Since in our setup there are no quality differences among consumption goods, the choice probability $\text{Prob}_{h,f}$ of good $f \in F_h$ produced by the f-th consumption goods producer depends solely on relative prices as follows:

$$\text{Prob}_{h,f} = \frac{\exp\big(-\lambda \log p^f\big)}{\sum_{f \in F_h} \exp\big(-\Lambda \log p^f\big)}\,, \tag{3.18}$$

where Λ parameterizes the intensity of market competition, i.e., the bigger Λ is, the more price sensitive probabilities are and the more competitive the market is. Once the consumer has selected a particular consumption good producer f, he spends his entire weekly consumption budget, i.e., $c_\tau^h/4$ for good f provided that the inventory is sufficiently large. In case the consumer can not spend all his budget on the product selected first, he spends as much as possible, removes that product from the list F_h, updates the logit values and selects another product to spend the remaining consumption budget there. If he is rationed again, he spends as much as possible on the second selected product and rolls over the remaining budget to the following week.

3.4 The banking sector

The primary purpose of banks is to channel funds received from deposits towards loans to firms. Any bank meets the demand for a loan from a firm, provided that the risk-reward profile of the loan

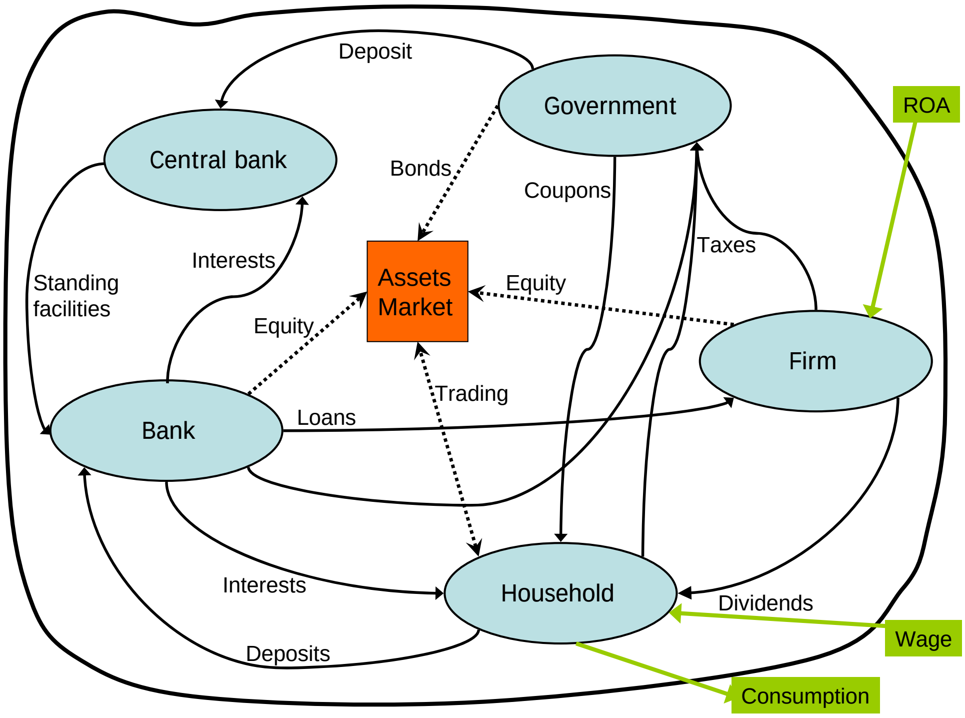

Figure 3.4: The financial market of the Eurace model. The picture shows connections among the agents involved, and their respective roles in the financial market.

is considered acceptable by the bank. The reward is given by the interest rate which is charged and the risk is defined by the likelihood that the loan will default. Given the loan request amount λ^f by firm f, bank b calculates the probability π^f that the firm will not be able to repay its debts as:

$$\pi^f = 1 - \exp\left(-\frac{D^f + \lambda^f}{E^f}\right). \tag{3.19}$$

The default probability π^f correctly increases with the firm's leverage and is used as a risk weight in computing the risk-weighted loan portfolio of banks, henceforth W^b. According to the computed credit worthiness of the firm, the bank informs it about the interest rate that would be applied to the requested loan:

$$r^{b,f} = r^{cb} + \gamma^b \pi^f, \tag{3.20}$$

where r^{cb} is the base interest rate set by the central bank and $\gamma^b \pi^f$ is the risk spread depending on the firm's credit risk π^f. The parameter γ^b sets the spread sensitivity to the credit worthiness of the firm. The central bank acts as the "lender of last resort", providing liquidity to the banking sector at the base interest rate r^{cb}. Finally, it is worth noting that banks lending rate does not depend on

Assets	Liabilities
M^b: liquidity deposited at the *central bank*	S^b: standing facility (debt to the *central bank*)
$\mathcal{L}^b$: bank's loan portfolio	D^b: total (households' and firms') deposits at the bank
	E^b: equity

Table 3.8: Bank's balance sheet

the expected demand for loans but only on the evaluation of firm's credit risk.

Banks can then lend money, provided that firms wish to take out new loans and that their regulatory capital requirement are fulfilled. It is worth noting that granting new loans inflates the balance sheet of the banking system because it generates also new deposits[1].

The model regulatory capital requirement are inspired by Basel II accords and state that the capital ratio of banks, given by the equity E^b divided by the risk-weighted assets W^b, has to be higher than a given threshold, defined as $\frac{1}{\alpha}$, where α is the key policy parameter used in this study. Hence, if firm f asks for a loan λ^f, bank b supplies a credit amount ℓ^{bf} determined as follows:

$$\ell^{bf} = \begin{cases} \lambda^f & \text{if} \quad \alpha E^b \geq W^b + \pi^f \lambda^f \,, \\ \frac{\alpha E^b - W^b}{\pi^f} & \text{if} \quad W^b < \alpha E^b < W^b + \pi^f \lambda^f \,, \\ 0 & \text{if} \quad \alpha E^b \leq W^b \,. \end{cases} \tag{3.21}$$

The value of risk-weighted assets W^b is computed by the weighted sum of outstanding loans of bank b where the weights are given by the default probability (the default risk) of each loan defined in Eq. 5.1. Bank's liquidity, i.e., M^b as in Table 3.8, is an asset but its default risk shall be considered zero, therefore it does non enter in the computation of W^b.

The parameter α can be interpreted as the leverage level banks are allowed to have. Equations 5.3 state that bank b is available to satisfy entirely the loan demand λ^f if it does not push W^b above the Basel II threshold, set at α time the net worth (equity) of the bank, otherwise the bank can satisfy the loan demand only partially or even is not available to lend any money at all, and firm f is rationed in the credit market. Thus, it can be argued that banks are quantity takers and price setters in the loans market, with the policy constraint of a fixed capital adequacy ratio.

In order to better visualize the stock-flow accounts for banks, a typical balance sheet of a bank is reported in table 3.8. For any bank b, the stocks of total deposits D^b and loans $\mathcal{L}^b$ are updated daily following the changes in their stock levels, i.e., changes in the private sector (households and firms)

[1]When a loan is taken and spent, it creates a deposits in the bank account of the agent to whom the payment is made. In particular, firms pay wages to workers and pay new physical capital to investment firms, that are owned by households and redistribute net earnings to them.

Assets	Liabilities
M^g: liquidity deposited at the central bank	long-term debt (n^g: number of outstanding bonds)

Table 3.9: Government's balance sheet

deposits due to payments (i.e. flows of money among private sector agents) and changes in the loan portfolio due to the granting of new loans and old loan repayments. The stock of liquidity M^b of bank b is then updated accordingly following the standard accounting rule $M^b = S^b + D^b + E^b - \mathcal{L}^b$. If M^b becomes negative, S^b, i.e., the standing facility with the Central Bank, is increased to set $M^b = 0$. If M^b is positive and the bank has a debt with central bank, i.e. $S^b > 0$, S^b is partially or totally repaid for a maximum amount equal to M^b. Finally, at the end of the trading day, both liquidity M^b and equity E^b are updated to take into account in the same way of any money flows which regards the bank b, i.e., interest revenues and expenses, taxes and dividends. The bank can choose if to pay or not to pay dividends to shareholders and this choice is crucial for driving its equity dynamics. In particular, if a bank is subject to credit supply restriction due to a low net worth compared to the risk-weighted assets portfolio, then it stops paying dividends so to raise its equity capital and increaser the chance to match in the future the unmet credit demand. Finally, loans are extinguished in a predetermined and fixed number of constant installments.

3.5 The Government

The Government is responsible of the fiscal and and the welfare policy. The Government collect taxes on corporate profits, household labor and capital income and set the three corresponding tax rates. Taxes are collected on a monthly basis while tax rates are revised yearly downward or upward by a given percentage tick in order to pursue a zero budget deficit goal. Taxes constitute the revenues side of government budget.

Government expenses are made by unemployment benefits, households transfers and the interest rates on the outstanding government debt, all payed on a monthly basis. Unemployed benefits are set to a percentage of the last salary of the unemployed worker, while transfers are payed to all households and are set to a given fraction of the price index. The government debt is made by infinitely-lived government bonds that pays a fixed monthly coupon, determined by the nominal bond interest rate and the bond face value. The nominal bond interest rate is anchored with a mark-up to the central bank base interest rate. Government bonds are owned by households and

traded in the financial market. Government deficit is financed by issuing and selling in the market new infinitely-lived bonds. Government liquidity M^g is deposited at the Central bank.
Table 3.4 presents the sketch of assets, i.e. liquidity, and liabilities, i.e., bonds of the Government in Eurace.

3.6 The Central Bank

The Central Bank plays several important role in the Eurace economy. It provides a standing facility to provide liquidity in infinite supply to commercial banks when they are in short supply and sets the base interest rate (or policy rate), which is the the cost of liquidity provided to banks and the lowest reference value considered by banks when setting interest rates of loans to firms. Furthermore, the Central Bank may purse an unconventional monetary policy, named quantity easing, consisting in buying Government bonds directly in the market, easing the funding conditions for the budgetary authorities. Table 3.6 shows the typical balance sheet of a Centra Bank.

3.7 A note on Eurace technological framework

FLAME (Flexible Large-scale Agent-based Modelling Environment) is a tool which allows modellers from all disciplines, economics, biology or social sciences to write their own agent-based models. The environment is a first of its kind which allows simulations of large concentrations of agents to be run on parallel computers without any hindrance to the modellers themselves. Coakley et al. [2006] offer a survey of agent-based modelling using FLAME, while Jackson et al. [2004] present an application describing ants behaviors. Coakley and Kiran [2007] show how FLAME works in the Eurace framework.

FLAME is specifically designed to provide a formal and very flexible approach to agent-based modelling. Also the use of high performance computing was an integral part of the design as the

Assets	**Liabilities**
n_g^{CB}: government bonds (QE)	outstanding fiat money
M^{CB}: liquidity	M_g^{CB}: governments liquidity
L_b^{CB}: loans to banks (standing facility)	M_b^{CB}: banks reserves
	E^{CB}: equity

Table 3.10: Central Bank's balance sheet

goal was to perform simulations contain many millions of agents. No other currently available platform is designed to utilise high performance computing. Some platforms like A-Globe, ABLE, Cougaar, and Zeus, use common network protocols to send communication between computers and are written in Java. Although this is a very portable approach Java implementation are not very efficient. EcoLab provides a way for users to try and implement HPC routines themselves using the MPI library. FLAME introduces formal methods and mark-up language for models to be written, allowing these applications to be automatically created to work on both serial and parallel systems through the FLAME Xparser. Echo, Swarm, and Repast don't obey these principles. Indeed, Echo was for ecological modelling and is now obsolete. Repast and the most recent versions of Swarm are platforms based on Java language, which is an interpreted language. The models we are developing need much more computer power to perform realistic simulations, of up to hundreds thousand, or millions, agents. FLAME, being based on C language can exploit the computation efficiency of the language and can easily ported on most target machines.

3.7.1 The FLAME framework for modeling economic systems

The initial FLAME framework was based around the needs of biological systems modelling, specifically tissue models where agents are biological cells. The agents were quite simple needing only a list of variables for memory that are single fundamental data types. The agents functions could be defined as a simple list and agent communication was restricted by Cartesian space. Economic models for EURACE require more complex agents with multidimensional memory and functions that depend on a magnitude of other functions either via communication or the change of agent memory. For this purpose, a number of additional features have been designed and added to the FLAME framework to make it more friendly for economic modellers. These have been listed below:

- Additional features for economic systems includes the use of abstract data types and arrays in agent memory.
- Agent functions are not just linear but are dependent on numerous markets and different types of agents. This has required the use of function dependencies to order the execution of functions and the timing of communication synchronisation to make the execution of a simulation as efficient as possible.
- Communication is no longer restricted to Cartesian space but can be dependent on the relationship between any message variable and any other variable, possibly agent memory variables. This allows communication to be restricted to specific markets and networks of regions.

Each agent function has defined input and output messages. Any input to a function is dependent on the output coming from other functions, this is called a communication dependency. Whenever there is a communication dependency between functions there needs to be a synchronisation across the agents so the that message boards are fully updated. In the parallel implementation this is a very complex task and is discuss in a later section.

The FLAME model design

The FLAME framework is a tool which enables creation of agent-based models that can be run on high performance computers (HPCs). The framework is based on the logical communicating extended finite state machine theory (X-machine) which gives the agents more power to enable writing of complex models for large complex systems.

The agents are modelled as communicating X-machines allowing them to communicate through messages being sent to each other as per designed by the modeller. This information is automatically read by the FLAME framework and generates a simulation program which enables these models to be parallelised efficiently over parallel computers.

The simulation program for FLAME is called the Xparser. The Xparser is a series of compilation files which can be compiled with the modeller's files to produce a simulation package for running the simulations. Various tools have to be installed with the Xparser to allow the simulation program to be produced.

Various parallel platforms like SCARF, (add more) have been used in the development process to test the efficiency of the FLAME framework.

Traditionally specifying software behaviour has used finite state machines to express its working. Extended finite state machines (X-machines) are more powerful than the simple finite state machine as it gives the model more flexibility than a traditional finite state machine.

FLAME uses X-machines to represent all agents acting in the system. Each would thus possess the following characteristics:

- A finite set of internal states of the agent.
- Set of transitions functions that operate between the states.
- An internal memory set of the agent.
- A language for sending and receiving messages among agents.

The machines communicate through a common message board, to which they post and read from their messages. Using conventional state machines to describe the state-dependent behaviour of a system by outlining the inputs to the system, but this fails to include the effect of messages being read and the changes in the memory values of the machine. X-Machines are an extension to conventional state machines that include the manipulation of memory as part of the system behaviour, and thus are a suitable way to specify agents.

Describing a system in FLAME includes the following stages:

- Identifying the agents and their functions.
- Identify the states which impose some order of function execution with in the agent.
- Identify the input messages and output messages of each function (including filters on inputs).
- Identify the memory as the set of variables that are accessed by functions (including conditions on variables for the functions to occur).

Chapter 4

Addressing the crisis: the impact of quantitative easing

This chapter presents a study on the interplay between monetary aggregates and macroeconomic performance in an artificial economy setting, based on the Eurace model and simulator.

A description of the general characteristics of Eurace can be found in chapter 3, while the main features of the Eurace model which are relevant to this study are given in section 4.1. This introductive part points out some general aspects that are related to the specific topic investigated in this chapter, that is centered on the understanding of output and prices variabilities in the Eurace economic environment and their interplay with the amount of credit in the economy.

This central topic has been addressed by Bernanke [2004] in a well known speech at the Federal Reserve Board in 2004, but after the crisis it surely needs to be revisited. The talk of Bernanke regarded the so called "Great Moderation", i.e., the decline in the variability of both output and inflation in the previous twenty years, and argued that it could be explained by the improved ability of the economy to absorb shocks. Shocks are considered, in line with the dynamic stochastic general equilibrium modeling approach, as the main source of economic instability. In section 4.2 we show that instability can also endogenously arise as a consequence of agents decision making. The issue is of primary importance because, as Bernanke says, reducing macroeconomic volatility has numerous benefits. Lower volatility of inflation improves market functioning, makes economic planning easier, and reduces the resources devoted to hedging inflation risks. Lower volatility of output tends to imply more stable employment and a reduction in the extent of economic uncertainty confronting households and firms. Unfortunately, the recent crisis pointed out the times we are living are not so "moderate" as the FED chairman and many mainstream economists showed to think. Moreover, the effectiveness of monetary policies based on a "Taylor rule" structure is seriously in question.

This study investigates the interplay between monetary aggregates and the dynamics and variability of output and prices by considering both the money supplied by commercial banks as credit to firms and the fiat money created by the central bank through the quantitative easing monetary policy. Different amount of credit money have been produced in the system by setting different dividends payout policies and so different bank financing policies by firms. Quantitative easing has been implemented by letting the central bank intervening in the bond market. Quantitative easing is an extraordinary monetary policy measure that has been largely used by the Federal Reserve and the Bank of England during the recent crisis [1], and has also been recently adopted by the European Central Bank.

In concrete terms, our experiments on the Eurace platform consist of different simulations for different parameter values. We take into consideration the effects of two critical parameters of the model.

The first one, as said above, regards the financial management decision making of the firms, and corresponds to the fraction of net earnings paid by the firm to shareholders in form of dividends. The dividends decision impacts on many sectors of the model. In the financial market, for instance, agents beliefs on asset returns take into account corporate equity and expected cash flows, establishing an endogenous integration between the financial side and the real side of the economy. In particular, fundamentalist trading behavior is based on the difference between stock market capitalization and the book value of equity, therefore generating an interaction between the equity of the firm and the price of its asset in the financial market. Concerning the credit market, the dividends payment is strongly correlated with the request of loans by firms and consequently influences the amount of credit created by commercial banks; as our results show in section 4.2, the credit amount proves to be decisive for its effects on the variability of output and prices.

The second parameter of our study is a binary flag that activates the possibility for the central bank to buy treasury bills in the financial market, when a government asks for it. In practical terms, the central bank expands its balance sheet by purchasing government bonds. This form of monetary policy, widely adopted during the global financial and economic crisis of the years 2007-10, which is used to stimulate an economy where interest rates are close to zero, is called quantitative easing. The money creation channel through quantitative easing is intended to facilitate the funding of the

[1] See, for instance, Willem Buiter blog at FT for a report on Bank of England balance sheet explosion (http://blogs.ft.com/maverecon/2009/09/what-can-be-done-to-enhance-qe-and-ce-in-the-uk-and-who-decides/)

government budget deficit in a situation of depressed economy, when a raise of taxes should be avoided. In synthesis, two alternative ways to finance government budget deficit are analyzed: fiscal tightening (FT) and quantitative easing (QE).

From a theoretical point of view, the interplay between monetary factors and the real economy is not new and has been extensively investigated by many economists. However, both in the old [Hicks, 1937] and in the new Keynesian economics [R. Clarida, 1999], as well as in the monetarist tradition [Friedman and Schwartz, 1963], the attention has been mainly devoted to monetary aggregates and interest rates set exogenously by central banks, disregarding the important role of the credit sector in setting the overall money supply by the endogenous creation of credit money. Notable exceptions in this respect have been Fisher [1933] during the Great Depression era, the circuitist school of economics, represented e.g. by Graziani [2003], and the now celebrated Hyman Minsky [1986]. They pointed out the importance of the endogenous nature of credit money, and of the nominal level of debts as opposed to the price level of real assets, in originating business cycles and depressions.

In the agent-based literature, a few attempts have been made to study the interplay between monetary policy, credit and business fluctuations. Raberto et al. [2006a] show the long-run monetary neutrality of an agent-based Walrasian-like macro-model characterized by price-taking agents subject to changes in the money supply. Raberto et al. [2008a] study a Taylor-like monetary policy rule in an agent-based integrated model of a real, financial, and monetary economy with price, wage and interest setting agents and show the effectiveness of the policy in limiting inflation and increasing welfare. Delli Gatti et al. [2009] show the emergence of business cycles from the complex interaction of agents heterogeneous financial conditions in a three-sector network economy characterized by credit relationships.

The EURACE model is by far more complete and realistic than the ones outline above. It encompasses price-making agents, a heterogenous production sector instead of the monopolistic firm considered in Raberto et al. [2008a], and an explicit modelling of the households consumption behavior instead of the passive final consumers considered in Delli Gatti et al. [2009]. Therefore the EURACE model and simulator promises to deliver more meaningful and precise results for any of the computational experiments considered.

The chapter is organized as follows. In section 4.1 an overall description of the model is given, with particular attention to the features that are relevant to this article. Section 4.2 presents the computational results of our study and a related discussion. Conclusions are drawn in Section 4.3.

4.1 The Model

4.1.1 The Eurace Simulator

The EURACE model is probably by far the largest and most complete agent-based model developed in the world to date. It represents a fully integrated macroeconomy consisting of three economic spheres: the real sphere (consumption goods, investment goods, and labour market), the financial sphere (credit and financial markets), and the public sector (Government, Central Bank and Eurostat).

Given the complexity of the underlying technological framework and given the considerable extension of the Eurace model, it is not possible to present an exhaustive explanation of the economic modelling choices, together with a related mathematical or algorithmic description (see chapter 3 for some more detail). Consequently, we will limit our approach to a general qualitative explanation of the main key features of the model, treating in a concise way each different market, and giving prominence to those modelling aspects that attain to the argument of the specific analysis we are presenting here. In particular, we will explain in details the so-called balance-sheet approach followed in the Eurace modeling, an approach we think is very important for our purposes and in the agent-based modeling in general.

If the reader will need more details about the Eurace implementation, he will find a quite exhaustive summary in the Eurace [2009]. Moreover, when needed, we will cite specific Eurace deliverables. Some general information on Eurace can be found in Deissenberg et al. [2008].

Before proceeding with the description of agents and markets of Eurace, we introduce some general aspects of the model.

4.1.2 General setting

The choice of time scales for the agents' decision making in Eurace has been made in order to reflect the real time scales in economic activities, and interactions among households are generally asynchronous. This means that different agents are active on the same markets on different days. Synchronous decision making or synchronous interactions are used whenever they reflects what happens in reality.

Both the modelling of agents behaviors and the modelling of markets protocols are empirically inspired by the real world.

Agent decision processes follow the usual and realistic assumptions of agent-based economics about bounded rationality, limited information gathering and storage capacities, and limited computational capabilities of the economic agents; see e.g. Tesfatsion and Judd [2006] for a comprehensive survey on this approach. These assumptions lead us to use simple heuristics to model the agents' behaviour, derived from the management literature for firms, and from experimental and behavioural economics for consumers/investors [Deaton, 1992, Benartzi and Thaler, 1995b]. We also make use of experimental evidence from the psychological literature on decision making. For example, the modelling of households' portfolio decisions on the financial market is based on Prospect Theory [Kahneman and Tversky, 1979, Tversky and Kahneman, 1992].

The rules used by the agents are simple but not necessarily fixed. Their parameters can be subject to learning, and thus adapted to a changing economic environment. Here we can make a distinction between adaptive agents and learning agents: the first use simple stimulus-response behaviour to only adapt their response to their environment, while the last use a conscious effort to learn about the underlying structure of their environment.

Different market protocols characterize the markets of the Eurace model. For the consumption goods market all consumer-firm interactions go through the local outlet malls. Households go shopping on a weekly basis. This closely mimics reality and is a simple way to model localized markets with potential rationing on both sides. In particular the used market protocols capture important market frictions based on problems of search, matching and expectation formation in turbulent environments that are present in real world labour and goods markets. The labour market functions by way of a local search-and-matching protocol that likewise resembles a real world job search by unemployed workers. For the artificial financial market we model a clearinghouse. For the credit market we use a firm-bank network interaction mechanism where firms can apply for loans with at most n banks, where n is a parameter that can be set by the modeler.

4.1.3 The Goods Market

For detailed information about the economic modelling choices characterizing the goods and the labor markets, see Eurace Project D7.1 [2007], Eurace Project D7.2 [2008]. See also Dawid et al. [2008] and Dawid et al. [2009] for additional explanations and for some discussion and analysis of computational experiments directly involving the two markets. What follows is a qualitative description of the main aspects that are relevant to the study.

The goods markets are populated by IGFirms (investment goods firms) that sell capital goods to CGfirms, that produce the final consumption good. Stocks of firms product are kept in regional malls that sell them directly to households. A standard inventory rule is employed for managing the stock holding. Standard results from inventory theory suggest that the firm should choose its desired replenishment quantity for a mall according to its expectations on demand, calculated by means of a linear regression based on previous sales.

Consumption good producers need physical capital and labor to produce. The production technology in the consumption goods sector is represented by a Cobb-Douglas type production function with complementarities between the quality of the investment good and the specific skills of employees for using that type of technology. Factor productivity is determined by the minimum of the average quality of physical capital and the average level of relevant specific skills of the workers. Capital and labor input is substitutable with a constant elasticity and we assume constant returns to scale. The monthly realized profit of a consumption goods producer is the difference of sales revenues achieved in the malls during the previous period and costs as well as investments (i.e. labor costs and capital good investments) borne for production in the current period. Wages for the full month are paid to all workers at the day when the firm updates its labor force. Investment goods are paid at the day when they are delivered. Pricing is based on a fixed mark-up rule.

Once a month households receive their income. Depending on the available cash, that is the current income from factor markets (i.e. labor income and dividends distributed by capital and consumption goods producers) plus assets carried over from the previous period, the household sets the budget which it will spend for consumption and consequently determines the remaining part which is saved. This decision is taken according to the buffer-stock saving theory [Deaton, 1992, Carroll, 2001].

At the weekly visit to the mall in his region, each consumer collects information about the range of goods provided and about the prices and inventories of the different goods. In the marketing literature it is standard to describe individual consumption decisions using logit models. These models represent the stochastic influence of factors not explicitly modelled on consumption.We assume that a consumer's decision about which good to buy is random, where purchasing probabilities are based on the values he attaches to the different choices he is aware of. Since in our setup there are no quality differences between consumer goods and we also do not take account of horizontal product differentiation, choice probabilities depend solely on prices. Once the consumer has selected a good, he spends his entire budget for that good if the stock at the mall is sufficiently large. In case the consumer cannot spend all his budget on the product selected first, he spends as much as possible, removes that product from its list, and selects another product to spend the remaining consumption budget there. If he is rationed again, he spends as much as possible on the second selected product and rolls over the remaining budget to the following week.

4.1.4 The Labor Market

The labor market is governed by a matching procedure that relates directly workers looking for a job and firms looking for labor force. On the demand side, firms post vacancies with corresponding wage offers. On the supply side, unemployed workers or workers seeking for a better job, compare the wage offers with their actual reservation wages. Then the matching algorithm operates by means of ranking procedures on the side both of firms and households (see Eurace [2009] for more details).

The algorithm might lead to rationing of firms on the labor market and therefore to deviations of actual output quantities from the planned quantities. In such a case the quantities delivered by the consumption good producer to the malls is reduced proportionally. This results in lower stock levels and therefore it generally increases the expected planned production quantities in the following period.

4.1.5 The Financial Market

For more detailed information on the financial market, see Eurace Project D6.1 [2007] and Eurace Project D6.2 [2008]. Teglio et al. [2009] shows also economic results obtained by means of computational experiments in the financial market, mainly regarding the problem of the equity premium puzzle.

The EURACE artificial financial market operates on a daily basis and is characterized by a clearing house mechanism for price formation which is based on the matching of the demand and supply curves. The trading activity regards both stock and government bonds, while market participants are households, firms and the governments. Both firms and governments may occasionally participate to the market as sellers, with the purpose to raise funds by the issue of new shares or governments bonds. Households provide most of the trading activity in the market, to which they participate both for saving and speculation opportunities. Household preferences are designed taking into account the psychological findings emerged in the framework of behavioral finance and in particular of prospect theory [Kahneman and Tversky, 1979, Tversky and Kahneman, 1992]. Households portfolio allocation is then modeled according to a preference structure based on a key prospect theory insight, i.e., the myopic loss aversion, which depends on the limited foresight capabilities characterizing humans when forming beliefs about financial returns (see Benartzi and Thaler [1995b]).

A very relevant aspect with respect to the presented analysis, is the fraction of earning d that firms pay to shareholders in form of dividends. In this model it is treated as a constant and varied in the different computational experiments.

4.1.6 The Credit Market

Concerning the credit market of Eurace, in the project deliverables Eurace Project D5.1 [2007], Eurace Project D5.2 [2008] the modelling philosophy and the technical details can be found.

Firms finance investments and production plans preferably with internal resources. When these funds are not sufficient, firms rely on external financing, applying for loans to the banks in the credit market. The decision about firms loan request is taken by the bank to which the firm applies and depends on the total amount of risk the bank is exposed to, as increased by the risk generated by the additional loan. If a firm is credit-rationed in the credit market, then it has other possibilities of financing, i.e. issuing new equity on the financial market.

Commercial banks have two roles: one consists in financing the production activities of the firms, operating under a Basel II-like regulatory regime. The other role is to ensure the functioning of the payment system among trading agents. Finally, firms and households deposit entirely their liquid assets in the banks.

In the model banks are at the core of the system of payments: each transaction passes through the bank channel. Firms and households do not hold money as currency but under the form of bank deposits. Hence, the sum of payment accounts of bank's clients is equal to bank's deposits. As a consequence, every transaction (payment) between two non-financial agents translates into a transaction between two banks. At the end of every day, agents communicate the consistency of their liquid assets to their banks; then each bank can account for the net difference between inflows and outflows of money from and to the other banks and, if its reserves are negative, a compensating lending of last resort by the central bank is always granted. Thus, a sort of Deferred Net Settlement System has been implemented.

The Central Bank has several function in the Eurace model. It helps banks by providing them with liquidity when they are in short supply. It has the role of monitoring the banking sector setting the maximum level of leverage each bank can afford. It decides the lowest level of the interest rate, which is a reference value for the banking sector. If the quantitative easing feature is active, the central bank expands its balance sheet by purchasing government bonds in the financial market.

4.2 Computational Experiments

A number of computational experiments has been performed in order to study the interplay between the stock of liquidity (credit money + fiat money) and the performance of the economy, measured by the dynamics of the gross domestic product (GDP), the unemployment level, the dynamics of prices and the accumulation of physical capital in the economy.

The dynamics of credit money is fully endogenous and depends on the supply of credit from the banking system, which is constrained by its equity base, and on the amount of loans demanded by firms to finance their activity. Alternative dynamic paths for credit money have been produced by setting different firms' dividend policies. The ratio d of net earnings that firms pay out as dividends has been exogenously set to five different values, namely, 0.5, 0.6, 0.7, 0.8, and 0.9. It is clear that for higher values of d, firms' investments and hiring of new labor force must be financed more by new loans than by retained earnings, thus determining a higher amount of credit money in the economy.

The dynamics of fiat money depends on the central bank monetary policy. In particular, the non conventional monetary policy practice called quantitative easing is considered. The central bank policy rate is kept fixed at low levels, however, if the quantitative easing (QE) policy is active, the central bank may buy government bonds directly on the market, thus increasing the overall amount of fiat money in the economy. Under quantitative easing, we set that the government budget deficit is funded just by the issue and sale of bonds on the market. In this case, the intervention of the central bank is finalized to sustain bond prices and thus to facilitate the financing of government debt. If quantitative easing is not active, we set that the government budget deficit is funded both by the issue of new bonds in the market and by an increase of tax rates. This second policy case has been named as FT, an acronym that refers to "fiscal tightening".

Each parameters' setting is then characterized by one of the five values of d and by a flag which denotes whether the quantitative monetary (QE) policy or the fiscal tightening (FT) one has been adopted. The total number of parameters settings then sums up to 10. In order to corroborate the significance of results, for each parameters setting, 10 different simulation runs have been considered, where each run is characterized by a proper seed of the pseudorandom numbers generator. The same set of 10 random seeds has been employed for all parameters' settings.

The agents' population is constituted by 1000 households, 10 consumption goods producing firms, 1 investment goods producing firms, 2 banks, 1 government and 1 central bank. The duration of each simulation is set to 240 months (20 years).

Tables 4.1 and 4.2 report the simulation results for the main real and nominal variables of the

d	policy	Private sector money endowment growth rate (%)	price inflation rate (%)	wage inflation rate (%)
0.5	FT	-0.47 (0.03)	-0.052 (0.004)	0.012 (0.001)
	QE	-0.39 (0.02)	-0.020 (0.007)	0.052 (0.009)
0.6	FT	-0.37 (0.02)	-0.048 (0.004)	0.008 (0.001)
	QE	-0.33 (0.03)	0.02 (0.01)	0.11 (0.02)
0.7	FT	-0.29 (0.02)	-0.038 (0.004)	0.016 (0.004)
	QE	-0.24 (0.03)	0.02 (0.01)	0.10 (0.02)
0.8	FT	-0.14 (0.03)	-0.011 (0.008)	0.036 (0.008)
	QE	-0.10 (0.03)	0.03 (0.01)	0.07 (0.02)
0.9	FT	0.16 (0.03)	0.11 (0.02)	0.13 (0.02)
	QE	0.18 (0.03)	0.14 (0.02)	0.16 (0.02)

Table 4.1: Ensemble averages (standard errors are in brackets) over 10 different simulation runs of mean monthly rates. Each run is characterized by a different random seed. FT and QE cases are characterized by the same seeds. For each simulation run, mean monthly rates are computed over the entire simulation period, except for the first 12 months which have been considered as a transient and discarded.

economy, respectively, obtained with the 10 parameters' settings considered. Figures from 4.1 to 4.4 in the appendix show two representative time paths, respectively for $d = 0.6$ and $d = 0.9$, for the main real and nominal variables, both in the FT and the QE policy cases. A clear and important empirical evidence that emerges from the path of GDP is that the EURACE model is able to exhibit endogenous short term fluctuations, i.e., business cycles, as well as endogenous long-run growth.

The main cause of long-run economic growth is the positive growth rate of aggregate physical capital that is present in the economy, despite the existence of a capital depreciation rate, see the first column of Table 4.2. Endogenous investment decisions in physical capital by firms are responsible of the growth of physical capital in the economy. The increase of labor productivity due to the improvement of the skills of workers is the other reason which explains the long-run growth.

Main reasons explaining business cycles are the coordination failure between demand and supply of consumption goods, strong fluctuations in the investment in physical capital, and disruptions in the supply chain as well as mass layoffs due to firms bankruptcies. In particular, investment decisions as well as firms bankruptcies strongly depend on the availability of internal liquidity or bank credit. Therefore, there is a strict relation between real economic activity and its financing through the credit sector. The following analysis of simulation results will outline in details this relationship. Simulation results will be interpreted with respect to the different values of d and the two policies, namely FT and QE, considered.

Nominal variables, as shown in table 4.1, exhibit similar qualitative behavior with respect to the value of d in the two policy cases considered. However, the QE case is characterized by a more

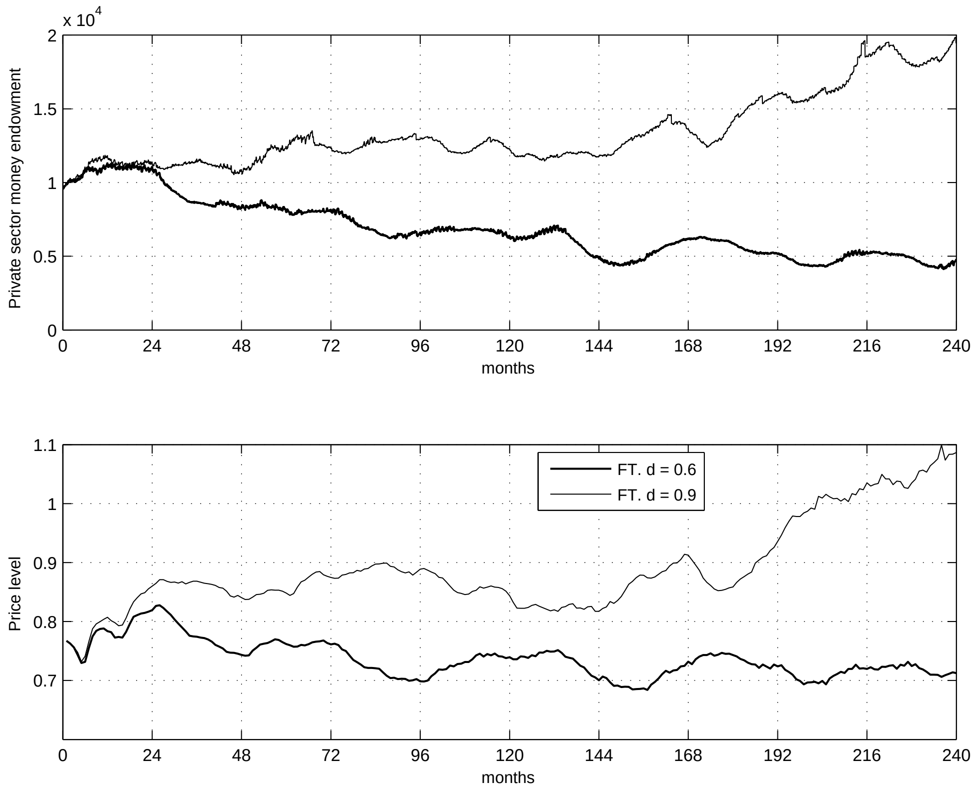

Figure 4.1: Results of a simulation path for the private sector money endowment and the price level in the FT case. Two values of d are considered, i.e., $d = 0.6$ (thick line) and $d = 0.9$ (thin line).

pronounced increase of nominal variables as d increases. The table shows that as the value of d increases, i.e., firms raise their dividends payout ratio, then the growth rate of the private sector money endowment also increases in the two policy cases considered. It is worth noting that the credit money supplied by the banking system is the source, together with the fiat money supplied by the central bank, of the endowment of liquid resources held by both the private sector (households, firms and banks) and the public sector (government and central bank). An increase in the demand for bank credit by firms then increases the amount of liquid resources in the economy as a whole, and consequently the private sector's liquidity. The higher growth rates of nominal variables in the QE case, can indeed be explained by the additional contribution of the increase of fiat money in this case.

The effects of different parametrization of d on nominal variables is also evident from the Figures 4.1 and 4.2, where the simulation paths for two different values of d, i.e., $d = 0.6$ and $d = 0.9$ are reported. The paths are in fact diverging over time in any of the four panels considered.

d	policy	physical capital growth rate (%)	real GDP growth rate (%)	unemployment rate (%)
0.5	FT	0.140 (0.006)	0.023 (0.006)	20.3 (0.5)
	QE	0.19 (0.01)	0.052 (0.008)	10.68 (0.08)
0.6	FT	0.135 (0.006)	0.007 (0.01)	20.5 (0.8)
	QE	0.25 (0.02)	0.07 (0.02)	10.7 (0.1)
0.7	FT	0.157 (0.006)	0.036 (0.005)	19 (1)
	QE	0.25 (0.02)	0.07 (0.01)	10.4 (0.1)
0.8	FT	0.20 (0.01)	0.04 (0.01)	15.4 (0.6)
	QE	0.24 (0.02)	0.04 (0.02)	10.0 (0.1)
0.9	FT	0.28 (0.02)	0.06 (0.01)	13.2 (0.7)
	QE	0.29 (0.02)	0.05 (0.01)	8.5 (0.2)

Table 4.2: Ensemble averages (standard errors are in brackets) over 10 different simulation runs of mean monthly rates. Each run is characterized by a different random seed. FT and QE cases are characterized by the same seeds. For each simulation run, mean monthly rates are computed over the entire simulation period, except for the first 12 months which have been considered as a transient and discarded.

d	policy	lag -1	lag 0	lag 1
0.5	FT	0.00 (0.02)	0.50 (0.02)	0.42 (0.02)
	QE	0.24 (0.02)	0.30 (0.02)	0.37 (0.03)
0.6	FT	0.39 (0.02)	0.52 (0.01)	0.43 (0.01)
	QE	0.32 (0.02)	0.41 (0.02)	0.48 (0.03)
0.7	FT	0.39 (0.01)	0.52 (0.02)	0.45 (0.02)
	QE	0.31 (0.02)	0.43 (0.02)	0.49 (0.02)
0.8	FT	0.40 (0.02)	0.53 (0.02)	0.50 (0.03)
	QE	0.34 (0.03)	0.45 (0.03)	0.47 (0.05)
0.9	FT	0.19 (0.03)	0.30 (0.03)	0.39 (0.02)
	QE	0.18 (0.05)	0.27 (0.06)	0.36 (0.04)

Table 4.3: Ensemble averages (standard errors are in brackets) over 10 different simulation runs of cross-correlations between percentages variations of the private sector money endowment and of the price level, respectively. High values al lag 1 are an indication that percentage variations of the private sector money endowment lead percentage variations of the price level.

Table 4.1 also shows that higher inflation and wage rates are associated to higher values of d. It is worth noting, however, that higher inflation rates for higher values of d can not be directly explained in this framework according to the quantity theory of money, i.e., referring to the higher amount of liquidity in the economy. This because prices are not set by a fictitious Walrasian auctioneer at the cross between demand and supply, but they are set by firms, based on their costs, which are labor costs, capital costs and debt financing costs. Higher credit money means higher debt and higher debt financing costs. Higher credit money induces also higher wage inflation, and thus again higher price inflation through the cost channel. The wage inflation can be explained by the labor market conditions, i.e., the level of unemployment, as it will be clear in the following.

Finally, table 4.3 reports the cross-correlation between the percentages variations of the private

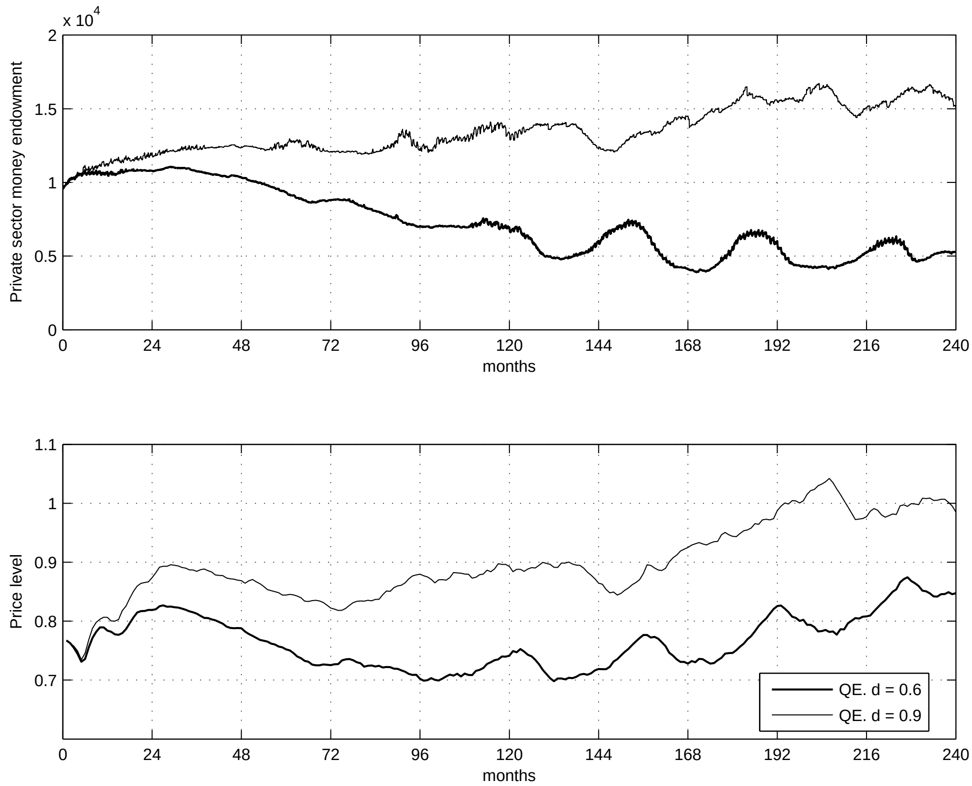

Figure 4.2: Results of a simulation path for the private sector money endowment and the price level in the QE case. Two values of d are considered, i.e., $d = 0.6$ (thick line) and $d = 0.9$ (thin line).

sector money endowment and the ones of the price level, respectively. Reported values, which are higher than the 95 % noise band set at 0.13, indicates positive meaningful cross-correlation. In particular, changes in the monetary aggregates seems to lead changes in the price level, thus indicating a clear influence of money on prices.

Table 4.2 presents the outcomes of the simulation concerning the real variables of the economy, i.e., the unemployment level and the growth rates of physical capital and of real GDP. In the FT policy case, a clear indication emerges for a better macroeconomic performance, i.e., lower unemployment, and higher growth rate of real GDP and physical capital, related to higher levels of credit money in the economy, i.e., higher values of d. On the contrary, no clear indication in this respect emerges in the QE policy case, where the performance of real variables is very similar irrespective of the value of d. Another possible way to read the results is to compare the outcomes of the FT policy with the ones of the QE for each value of d. In this respect, results shows that the QE policy provides better macroeconomic performance for low values of d, while it gives results

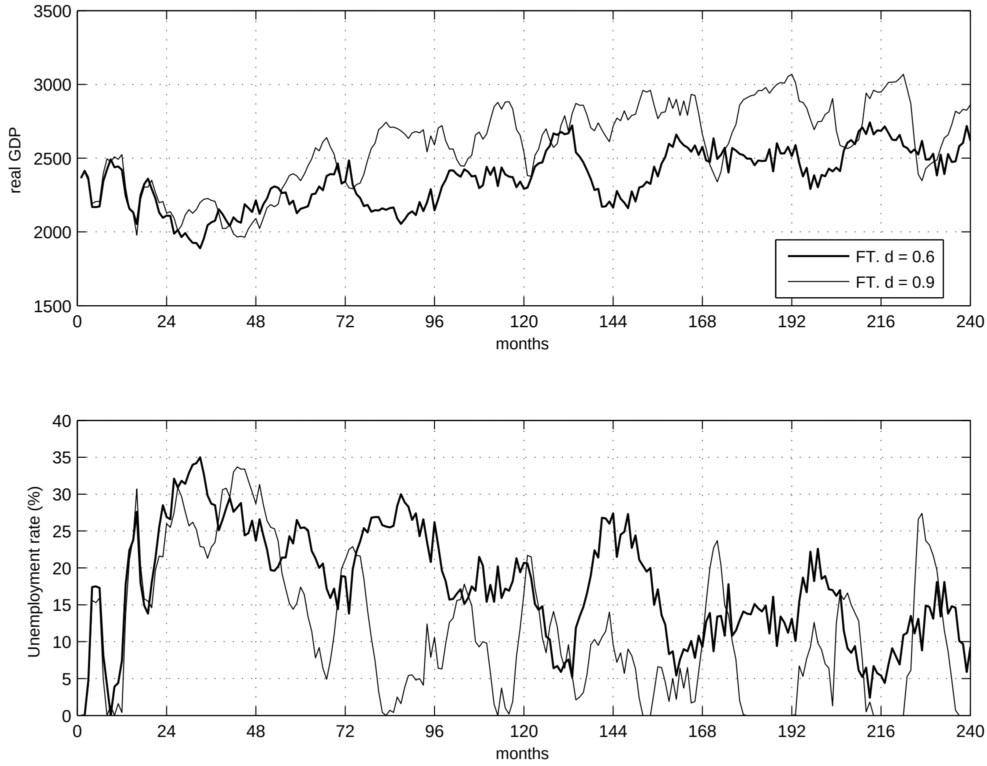

Figure 4.3: Results of a simulation path for the real gross domestic product (GDP) and the unemployment rate in the FT case. Two values of d are considered, i.e., $d = 0.6$ (thick line) and $d = 0.9$ (thin line).

similar to the FT policy, except for lower unemployment records, for values of d equal or close to 0.9. A possible explanation of these findings is that for low values of d, the QE policy outperforms the FT policy because of the injection of fiat money created by the central bank, as also testified by the higher level of private sector monetary endowment shown in table 4.1, while for high values of d the higher amount of credit money supplied by commercial banks results to be a close substitute of the fiat money created by the central bank, then providing comparable outcomes for the real variables.

This indication is also graphically evident by inspecting Figures 4.3 and 4.4, where two simulation paths for the real GDP and the unemployment levels are reported in both the FT and the QE policy cases for different values of d, i.e., $d = 0.6$ and $d = 0.9$. Finally, table 4.4 reports the cross-correlation between the percentages variations of the private sector money endowment and the ones of GDP, respectively. Reported values, which are higher than the 95 % noise band set at 0.13, indicates positive meaningful cross-correlation, thus confirming the non-neutrality of money in the EURACE

d	policy	lag -1	lag 0	lag 1
0.5	FT	0.21 (0.02)	0.20 (0.01)	0.06 (0.01)
	QE	0.22 (0.02)	0.01 (0.02)	0.15 (0.02)
0.6	FT	0.27 (0.02)	0.25 (0.01)	0.07 (0.01)
	QE	0.38 (0.04)	0.27 (0.03)	0.27 (0.05)
0.7	FT	0.28 (0.01)	0.27 (0.01)	0.10 (0.02)
	QE	0.38 (0.04)	0.29 (0.03)	0.26 (0.03)
0.8	FT	0.35 (0.02)	0.27 (0.02)	0.13 (0.02)
	QE	0.34 (0.04)	0.27 (0.03)	0.17 (0.03)
0.9	FT	0.34 (0.03)	0.31 (0.02)	0.14 (0.02)
	QE	0.31 (0.03)	0.26 (0.03)	0.10 (0.02)

Table 4.4: Ensemble averages (standard errors are in brackets) over 10 different simulation runs of cross-correlations between percentages variations of the private sector money endowment and of the GDP, respectively. High values al lag -1 are an indication that percentage variations of GDP lead percentage variations of the private sector money endowment.

d	policy	GDP (first half)	GDP (second half)	Bankruptcies (first half)	Bankruptcies (second half)
0.5	FT	- 16.1 (0.004)	- 16.1 (0.005)	0 (0)	0.3 (0.3)
	QE	- 14.0 (0.006)	- 16.8 (0.009)	0 (0)	0 (0)
0.6	FT	-17.1 (0.003)	-16.4 (0.005)	0.6 (0.4)	0,7 (0,4)
	QE	-14.5 (0.005)	-24.9 (0.021)	0 (0)	0.3 (0.3)
0.7	FT	-18.5 (0.003)	-19.3 (0.006)	1.3 (0.5)	4.5 (0.7)
	QE	-15.3 (0.008)	-22.8 (0.018)	0 (0)	1 (0.5)
0.8	FT	-18.8 (0.003)	-19.4 (0.011)	2.9 (0.4)	9.3 (1.5)
	QE	-14.2 (0.005)	-19.9 (0.019)	1.1 (0.4)	6.6 (1)
0.9	FT	-20.3 (0.006)	-20.3 (0.011)	4.9 (0.9)	22.4 (1.5)
	QE	-13.6 (0.005)	-18.0 (0.011)	1.9 (0.5)	20.6 (1)

Table 4.5: Values in the first two columns report the ensemble average (standard errors are in brackets) over 10 different simulations runs of the maximum percentage variability over a moving window of 36 months (3 years) of the real GDP. Values in last two columns report the average number of bankruptcies.

framework. In particular, changes in GDP seems to lead changes in the money endowment of the private sector.

Table 4.5 shows the maximum percentage variability over a moving window of 36 months (calculated as $(min - max)/mean$) of the real GDP. Let us point out some evident features related to this table. In the case of fiscal tightening policy, the output variability clearly depends on dividends pay-out, rising when d is higher; this is no more true when the quantitative easing mechanism is active. GDP variability is constant along time (first and second half) in the case of FT, while in the case of QE the economy seems to become much more instable in the second half of the simulation: in fact, in the first part of the simulation, GDP variability values under QE policy are always higher than in the case of FT policy, while in the second part they are lower.

How can we interpret the information of the table? We can easily argument that the raising of output variability for higher d values is mainly due to the higher debt load of firms that produces more bankruptcies (see the last two columns of table 4.5). In the first half of the simulation a QE policy seems to stabilize the economy, probably because firms are not subject to a strong fiscal pressure and can afford to pay their debts. However, in the long run the effect is the opposite: the high amount of credit money injected in the system in the case of QE policy tends to increment the economic fluctuations, while fluctuations don't change in the case of fiscal policy. This phenomenon is probably due to the higher money supply that generates in the long run a higher price inflation rate (as shown in table 4.1). This higher inflation rate is probably the cause of the increase of economic instability in the case of QE. It is also worth noting that, when the QE policy is active, the number of bankruptcies in the first half is quite low but in the second half it raises to a level comparable to FT, especially for high values of d. This shows that for high levels of firms debt a QE policy may not be effective in the long run. The reason probably relies on the fact that for high values of firms dividends payout, a strong money supply is already guaranteed by commercial banks and therefore, the effect of quantitative easing is significantly weakened.

We could argue that table 4.5 is warning about an extended use of quantitative easing. It shows us that QE can be used with the purpose of economic stabilization but in the long run the excess of money in the economy could also produce some counter reaction probably through the inflation channel.

4.3 Concluding Remarks

The study of chapter 4 presented a set of results provided by the agent-based model and simulator Eurace. In particular, results point out the strict dependence of output and prices dynamics on monetary aggregates. Credit money supplied by commercial banks as loans to firms and fiat money created by the central bank through quantitative easing determine the dynamics of monetary aggregates. The dynamics of credit money is endogenous, different dynamic paths can be obtained by exogenously setting different firms dividend policies. Results show the emergence of endogenous business cycles which are mainly due to the interplay between the real economic activity and its financing through the credit market. In particular, the amplitude of the business cycles strongly raises when the fraction of earnings paid out by firms as dividends is higher, that is when firms are more constrained to borrow credit money to fund their activity. This interesting evidence can be explained by the fact that the level of firms leverage, defined as the debt-equity ratio, can be considered ad a proxy of the likelihood of bankruptcy, an event which causes mass layoffs and decrease

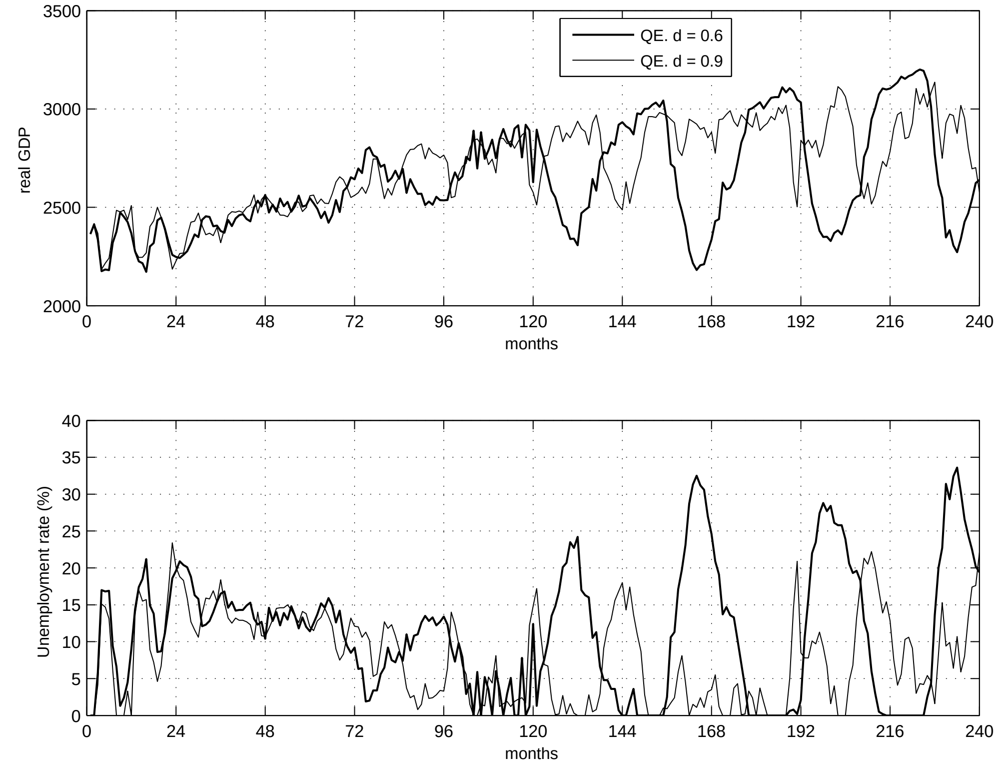

Figure 4.4: Results of a simulation path for the real gross domestic product (GDP) and the unemployment rate in the QE case. Two values of d are considered, i.e., $d = 0.6$ (thick line) and $d = 0.9$ (thin line).

in supply. A quantity easing monetary policy coupled with a loose fiscal policy has been shown to generally provide better macroeconomic performance with respect to a tight fiscal policy and no central bank intervention in the bond market. However, the QE policy causes more inflation both in the short and in the long run and seems responsible in the long run of a higher variability of output.

Finally, from a more general perspective, the results show the possibility to explain the emerge of business cycles based on the complex internal functioning of the economy, without considering any ad-hoc exogenous shocks. The adopted agent-based framework has been able to address this complexity, and these results reinforce the validity of the Eurace model and simulator for future research in economics.

Chapter 5

Addressing the crisis: macroeconomic implications of capital requirement

The work presented in this chapter investigates the impact of bank lending regulation on macroeconomic activity by considering a set of economic variables as indicators. The regulatory parameter considered is the leverage ratio of commercial banks, i.e. the ratio between the value of the loan portfolio held by banks, weighted with a measure of the loan riskiness, and banks net worth or equity, along the lines of capital adequacy ratios set by the Basel II agreement [BIS, 2006].

The debate on implications and consequences of capital adequacy requirements for banks has been growing in the last three decades [Berger et al., 1995, Blum and Hellwig, 1995] and has drawn particular attention after the financial crisis of 2007-2009 [Hellwig, 2010, Adrian and Shin, 2010]. The discussion focuses on the beneficial effects of equity requirements compared to the disadvantages in terms of economic costs and credit market effectiveness. Some of the main controversial aspects about the implications of higher equity requirements are clearly resumed in Admati et al. [2010]. The main benefit of increased equity capital requirements is claimed to be the weakening of systemic risk, while potential drawbacks are, among others, the reduction of return on equity (ROE) for banks, the restriction of lending, and the increase of funding costs for banks. This study focuses on the macroeconomic implications of capital adequacy regulation, studying its effect on banks' lending activity and therefore on the main economic indicators such as GDP, unemployment and inflation. In particular, three different time horizons are considered (short, medium and long run) in order to analyze the macroeconomic outcomes of the Eurace artificial economy so to take into account also the long-term effects.

The long-term macroeconomic impact of capital requirements has been intensively examined after the last financial crisis, see BCa [2010], BIS [2010], IIF [2010] and Angelini et al. [2011] for some complete and representative studies by central banks or by international institutions performing policy analysis and financial advising, like the BIS[1] or the IIF[2]. An analysis of these reports, along with a critical assessment of the used models, is beyond the scope of this thesis. Let us simply summarize the main common results. Firstly, higher capital requirements reduce the probability of banking crises. Secondly, it emerges that an increase in the capital ratio causes a decline in the level of output; the magnitude of the effect depends on the specific model. Thirdly, a higher capital ratio tends to dampen output volatility, especially if counter-cyclical capital buffers schemes are adopted. These main results have been obtained using a variety of models (see BIS [2010] for a list), mainly Dynamic Stochastic General Equilibrium (DSGE) models or semi-structural models. DSGE can be considered as the standard type of model currently used in macroeconomics, even though they have been widely criticized both for their difficulties in explaining some economic phenomena (see for instance Caballero [2010], Juselius and Franchi [2007]) and for the fact that the assumed equivalence between the micro and the macro behavior in DSGE models does not allow to take properly into account interaction and coordination among economic agents [Caballero, 1992].

The aim of this study is to present an alternative approach based on a fully endogenous agent-based model whose dynamics does not depend on external stochastic processes but mainly on the interaction of economic agents populating the artificial economy. See Tesfatsion and Judd [2006] for a comprehensive survey on agent-based computational economics and chapter 3 or Eurace [2009] for an overview of the Eurace model.

In concrete terms, a set of computational experiments have been carried out with the objective to study the performance of the economic system according to different values of the capital ratio requirement. The outcomes of this what-if analysis show how the main macroeconomic variables characterizing the Eurace economy, i.e. both real variables (such as GDP, unemployment and capital stock), and nominal variables (such as wage and price levels) are affected by the aggregate amount of loans provided by banks, which in turn depends on banks net worth or equity and on the allowed leverage ratio.

The interpretation of results can be possibly done in accordance with the lines of the endogenous credit-money approach of the post-Keynesian tradition Fontana [2003], Arestis and Sawyer [2006], Kriesler and Lavoie [2007]. Contrary to the neoclassical synthesis, where money is an exogenous

[1] The Bank for International Settlements; http://www.bis.org
[2] The Institute of International Finance, Inc.; http://www.iif.com/

variable controlled by the central bank through its provision of required reserves, to which a deposit multiplier is applied to determine the quantity of privately-supplied bank deposits, the essence of endogenous money theory is that in modern economies money is an intrinsically worthless token of value whose stock is determined by the demand of bank credit by the production or commercial sectors and can therefore expand and contract regardless of government policy. Money is then essentially credit-money originated by loans which are created from nothing as long as the borrower is credit-worthy and some institutional constraints, such as the Basel II capital adequacy ratios, are not violated. As the demand for loans by the private sector increases, banks normally make more loans and create more banking deposits, without worrying about the quantity of reserves on hand, and the central bank usually accommodates the demand of reserves at the short term interest rate, which is the only variable that the monetary authorities can control.

The modeling architecture of the Eurace economy, which has been conceived in order to closely mimic the functioning of a modern credit-driven economy, strongly confirms the endogenous theory view. Based on this conceptual framework, we investigate the relationship between endogenous credit money and macroeconomic activity, by examining computational experiments where the institutional (e.g. Basel II) constraints on bank leverage are exogenously set.

The chapter is organized as follows. In section 5.1 an overall description of the credit market model is given, both considering the firms and the banks sides. Section 5.2 presents the computational results of our study and a related discussion. Conclusions are drawn in section 5.3.

5.1 The credit market model

In the following, we outline the main features of the Eurace credit market model by describing how the demand of credit by firms arises to finance their production and liquidity needs, how the supply of credit by banks is conditioned by their capital adequacy ratio and how borrowers (firms) and lenders (banks) match their respective demand and supply schedules in the market.

5.1.1 Firms' side

Two types of firms are considered in the Eurace model: capital goods producers and consumption goods producers. Capital goods producers employ labor to produce on job capital goods that will be used as production factor together with labor by consumption goods producers. Given job production and only labor as production factors, capital goods producers, contrary to consumption goods producers, have not inventories as well as financing needs. In the following we will describe in more detail consumption goods producers, henceforth generally identified as firms.

Once a month, every firm computes its total liquidity needs, given by the liquidity necessary to meet its financial payments and by the expected cost of the planned production schedule. In particular, firm f at month t is subject to the following financial payments: the interest payments on its debt, henceforth R_t^f, the debt installment, henceforth I_t^f, taxes T_t^f and dividends payments D_t^f. The total liquidity needs L_t^f of firm f are therefore given by $\mathsf{L}_t^f = \mathsf{C}_t^f + \mathsf{R}_t^f + \mathsf{I}_t^f + \mathsf{T}_t^f + \mathsf{D}_t^f$, where C_t^f are the the expected costs of the planned production schedule.

Firms plan the monthly production schedule by considering the stock of inventories kept by the different malls selling their products, and by estimating the demand using a linear regression based on previous demands. Production is carried out according to a Cobb-Douglas type function, with two factors of production, i.e. labor and capital; a desired capital to labor ratio is calculated considering the marginal rate of substitution of the two factors, which depends on the given money wage and the cost of capital. Given the planned monthly production schedule and the desired capital to labor ratio, the desired capital endowment and the labor demand are determined by inverting the Cobb-Douglas production function. Demand for investments then depends on the difference between the desired and the actual capital endowment (see Dawid et al. [2009, 2007] for details).

According to the pecking-order theory Myers [1984], any firm f meets its liquidity needs first by using its internal liquid resources P_t^f, i.e., the cash account deposited at a given bank; then, if $\mathsf{P}_t^f < \mathsf{L}_t^f$, the firm asks for a loan of amount $\mathsf{L}_t^f - \mathsf{P}_t^f$ to the banking system so to be able to cover entirely its foreseen payments. Credit linkages between firm f and bank b are defined by a connectivity matrix which is randomly created whenever a firm enters the credit market in search for funding. In order to take search costs as well as incomplete information into account, each firm links with a maximum of n banks of the same region, which are chosen in a random way.

Firms have to reveal to the linked banks information about their current equity and debt levels, along with the amount of the loan requested λ_t^f. Using this information, according to the decision rules outline din the next section, each contacted bank b determines the amount of money available for lending to firm f (henceforth ℓ_t^f, where $\ell_t^f \leq \lambda_t^f$), calculates the interest rate i_t^{bf} associated to the loan and communicates it to the firm. After this first consulting meeting where firm's credit worthiness has been assessed by the bank, each firm asks for credit starting with the bank with the lowest interest rate. On banks' hand, they receive demands by firms sequentially and deal with them in a "first come, first served" basis. As explained with more detail in the following section, the firm can be credit rationed. If a firm can not obtain a sufficient amount of credit from the bank that is offering the best interest rate, the firm will ask credit to the bank offering the second best interest rate, until the last connected bank of the list is reached. It is worth noting that, although the individual firm asks loans to the bank with the lowest lending rate, the total demand for loans does not depend directly on the interest rates of loans.

When firm f receives a loan, its cash account P_t^f is then increased by the amount of it. If the firm is not able to collect the needed credit amount, i.e., if P_t^f is still lower than L_t^f, the firm has still has the possibility to issue new equity shares and sell them on the stock market. If the new shares are not sold out, the firm enters a state called *financial crisis*. When a firm is in financial crisis, we mainly distinguish two cases (see Eurace [2009] for further details): if the firm's available internal liquidity is still sufficient to meet its committed financial payments, i.e., taxes, the debt instalment and interests on debt, then these financial payments are executed and the dividend payout and the production schedule are rearranged to take into account the reduced available liquidity; otherwise, the firm is unable to pay it financial commitments and it goes into bankruptcy.

5.1.2 Banks' side

The primary purpose of banks is to channel funds received from deposits towards loans to firms. When a firm f contacts a bank b to know its credit conditions, the firm has to inform the bank about its equity level E_t^f and its total debt D_t^f, defined as the sum of the loans that the firm has received from every bank and that it has not yet payed back. Any bank meets the demand for a loan, provided that the risk-reward profile of the loan is considered acceptable by the bank. The reward is given by the interest rate which is charged and the risk is defined by the likelihood that the loan will default. Given the loan request amount λ_t^f by firm f, bank b calculates the probability that the firm will not be able to repay its debt as:

$$\pi_t^f = 1 - e^{-\left(\frac{D_t^f + \lambda_t^f}{E_t^f}\right)}. \tag{5.1}$$

The default probability π_t^f correctly increases with the firm's leverage and is used as a risk weight in computing the risk-weighted loan portfolio of banks, henceforth W_t^b. According to the computed credit worthiness of the firm, the bank informs it about the interest rate that would be applied to the requested loan:

$$i_t^{bf} = i_t^c + \gamma_t^b \cdot \pi_t^f, \tag{5.2}$$

where i_t^c is the interest rate set by the central bank and $\gamma_t^b \cdot \pi_t^f$ is the risk spread depending on the firm's credit risk. The parameter γ_t^b sets the spread sensitivity to the credit worthiness of the firm and is an evolving parameter that basically adjusts in order to reinforce the previous choices that were successful in increasing the bank's profits. The central bank acts as the "lender of last resort", providing liquidity to the banking sector at the interest rate i_t^c. Finally, it is worth noting that banks lending rate does not depend on the expected demand for loans but only on the evaluation of firm's credit risk.

Banks can then lend money, provided that firms wish to take out new loans and that their regulatory capital requirement are fulfilled. It is worth noting that granting new loans inflates the balance sheet of the banking system because it generates also new deposits[3].

The model regulatory capital requirement are inspired by Basel II accords and state that the capital ratio of banks, given by the equity E_t^b divided by the risk-weighted assets W_t^b, has to be higher than a given threshold, defined as $\frac{1}{\alpha}$, where α is the key policy parameter used in this study. Hence, if firm f asks for a loan λ_t^f, bank b supplies a credit amount ℓ_t^{bf} determined as follows:

$$\ell_t^{bf} = \begin{cases} \lambda_t^f & \text{if} \quad \alpha E_t^b \geq W_t^b + \pi_t^f \lambda_t^f \,, \\ \frac{\alpha E_t^b - W_t^b}{\pi_t^f} & \text{if} \quad W_t^b < \alpha E_t^b < W_t^b + \pi_t^f \lambda_t^f \,, \\ 0 & \text{if} \quad \alpha E_t^b \leq W_t^b \,. \end{cases} \tag{5.3}$$

The value of risk-weighted assets W_t^b is computed by the weighted sum of outstanding loans of bank b where the weights are given by the default probability (the default risk) of each loan defined in Eq. 5.1. Bank's liquidity, i.e., M^b as in Table 5.1, is an asset but its default risk shall be considered zero, therefore it does non enter in the computation of W_t^b.

The parameter α can be interpreted as the leverage level banks are allowed to have. Equations 5.3 state that bank b is available to satisfy entirely the loan demand λ_t^f if it does not push W_t^b above the Basel II threshold, set at α time the net worth (equity) of the bank, otherwise the bank can satisfy the loan demand only partially or even is not available to lend any money at all, and firm f is rationed in the credit market. Thus, it can be argued that banks are quantity takers and price setters in the loans market, with the policy constraint of a fixed capital adequacy ratio.

In order to better visualize the stock-flow accounts for banks, a typical balance sheet of a bank is reported in table 5.1. For any bank b, the stocks of total deposits D^b and loans $\mathcal{L}^b$ are updated daily following the changes in their stock levels, i.e., changes in the private sector (households and firms) deposits due to payments (i.e. flows of money among private sector agents) and changes in the loan

[3]When a loan is taken and spent, it creates a deposits in the bank account of the agent to whom the payment is made. In particular, firms pay wages to workers and pay new physical capital to investment firms, that are owned by households and redistribute net earnings to them.

Assets	Liabilities
M^b: liquidity deposited at the *central bank*	S^b: standing facility (debt to the *central bank*)
$\mathcal{L}^b$: bank's loan portfolio	D^b: total (households' and firms') deposits at the bank
	E^b: equity

Table 5.1: Bank's balance sheet

portfolio due to the granting of new loans and old loan repayments. The stock of liquidity M^b of bank b is then updated accordingly following the standard accounting rule $M^b = S^b + D^b + E^b - \mathcal{L}^b$. If M^b becomes negative, S^b, i.e., the standing facility with the Central Bank, is increased to set $M^b = 0$. If M^b is positive and the bank has a debt with central bank, i.e. $S^b > 0$, S^b is partially or totally repaid for a maximum amount equal to M^b. Finally, at the end of the trading day, both liquidity M^b and equity E^b are updated to take into account in the same way of any money flows which regards the bank b, i.e., interest revenues and expenses, taxes and dividends. The bank can choose if to pay or not to pay dividends to shareholders and this choice is crucial for driving the equity dynamics. In particular, if a bank is subject to credit supply restriction due to a low net worth compared to the risk-weighted assets portfolio, then it stops paying dividends so to raise its equity capital and increaser the chance to match in the future the unmet credit demand. Finally, loans are extinguished in a predetermined and fixed number of constant installments.

For a more detailed explanation of the stock-flow accounts in the Eurace model and of its "balance sheet approach", see Teglio et al. [2010].

5.2 Results and discussion

Computational experiments have been performed considering a simulation setting characterized by 2,000 households, 20 consumption goods producers, 3 banks, 1 investment goods producer, 1 government, and 1 central bank. The experiments consist in running several simulations of the Eurace model, varying the values of the capital adequacy ratio and observing the macroeconomic implications of the different bank regulation settings. Values of α have been set in the range from 4 to 9, where $\alpha = 4$ corresponds to the case of the tightest capital requirement and $\alpha = 9$ to the most permissive case.

Figure 5.1 presents typical time series paths referred to the production and sales of consumption goods (top panel) and investments in capital goods (bottom panel). Considering that the Eurace model foresees a job production of investment goods, demand of capital goods always coincides with supply as evidenced by the single line in the bottom of figure 5.1. On the contrary, the consumption goods case in the top panel shows two lines, a black one, representing sales, and a gray one for production. The existence of inventories, not represented in the figure, explain while sometime sales may be higher than production. The Gross Domestic Production (GDP) of the Eurace economy should be then considered as the sum of the consumption goods (top panel) and capital goods (bottom panel) production.

It is worth noting that the time series showed in Figure 5.1 are characterized by realistic graphical patterns. First, values referred to aggregate investments are much smaller than values assumed by aggregate consumption and, nevertheless, much more volatile. Second, the time series considered in Figure 5.1 clearly exhibit irregular cycles which are mainly characterized by steep ascents and descents as well as periods of steady and moderate growth, with a varying periodicity whose duration could be measured in years. Third, long-run growth can be observed both in the production and sales time series as well as in the investments path. The cycles in the investments time series are clearly correlated with the ones in the two time series referred to production and sales, and can be easily interpreted as business cycles. It is also worth noting that the sources of these business cycles are endogenous, i.e., Eurace business cycles are the product of agents' behavior and interaction, as no stochastic exogenous shock is foreseen in the model setting. We argue the important role played in this respect by fluctuations in investments and disruptions in the supply chain caused by firms bankruptcies and consequent inactivities. As outlined in Section 5.1.1, demand for investments depends, among other things, on expected aggregate demand for consumption goods; therefore an increase of unemployment reduces the aggregate demand as well as demand for investments, which in turn, like in a positive feedback mechanism, increase unemployment by reducing the employment also at investment good producers. Furthermore, in the bankruptcy[4] case, a reduction of aggregate supply also occurs due to the inactivity of the firm for a while.

Figure 5.2 presents the typical simulation paths of the key real economic variables, i.e., the firms' aggregate stock of physical capital (top panel), the unemployment rate (central panel) and the real GDP (bottom panel). For any of the three economic variables considered, we represent the time path related to two different values of α, i.e., $\alpha = 5$ and $\alpha = 9$. The time series have been represented *ceteris paribus*, including the same seed of the pseudo-random number generator. Consistent with the two components of GDP represented in Figure 5.1 for the same seed and $\alpha = 5$, i.e. production

[4]The bankruptcy for insolvency occurs when the net worth of the firm becomes lower than zero. In that case, firm' shareholders are wiped out and all workers are fired; the debt is also restructured and loans are partially written-off in the lending banks' portfolios; the firm's physical capital is frozen and the firm remains inactive as long as new financial capital is raised in the stock market.

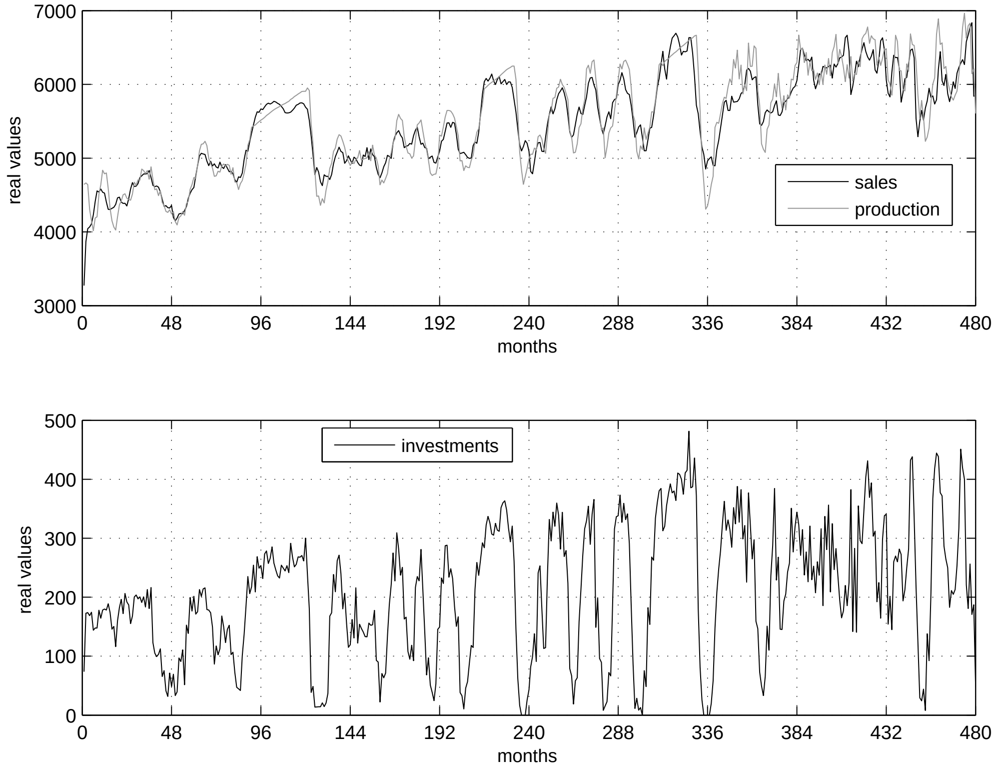

Figure 5.1: Top panel: aggregate production of consumption goods and sales (aggregate households' consumption). Bottom panel: investments in capital goods by the production sector. Values reported in the y-axis are real values, i.e., nominal values at current prices divided by the price index. The value of α is set to 5.

of consumption goods and investments in capital goods, the real GDP time series (bottom panel) exhibits long-run growth and irregular business cycles. The unemployment rate time series (central panel) is characterized by peaks which occur simultaneously with the bottoms of GDP cycles as well as steep drops (or increases) when the economy is booming (or in recession). Aggregate firms' physical capital (top panel) exhibits a steady growth characterized by relatively small fluctuations which, considering the capital depreciation and the fluctuations of investments, are consistent with the cycles in the bottom panel of Figure 5.1 and the real GDP in Figure 5.2.

A clear difference emerges in the long run between the paths with $\alpha = 5$ and the ones with $\alpha = 9$. In particular, the Eurace economy with $\alpha = 5$ is characterized by higher long-run growth of both production and physical capital, and consequently lower unemployment. This is actually a quite general result as shown in Tables 5.2 to 5.5, where the ensemble average over 10 random seeds has been considered and the complete set of 6 α values is shown.

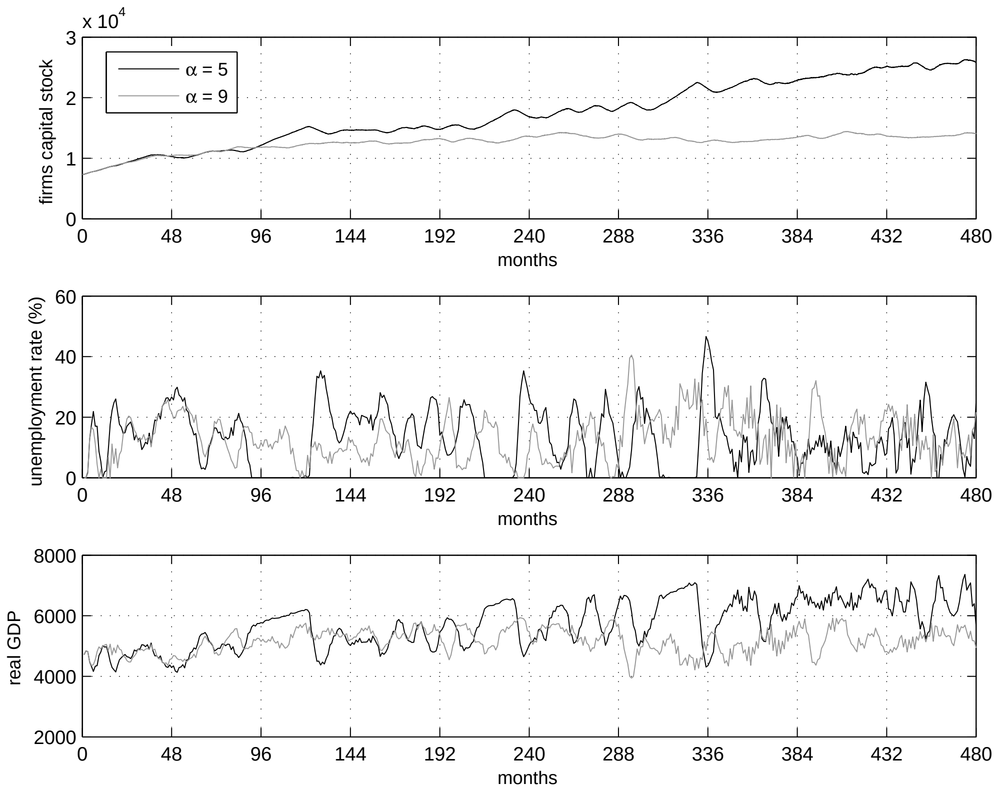

Figure 5.2: Firms' aggregate stock of physical capital (top panel), unemployment rate (central panel) and real GDP (bottom panel). Two different values of α have been considered for the same seed, i.e., $\alpha = 5$ (black line) and $\alpha = 9$ (gray line).

Tables from 5.2 to 5.5 consider eight important economic variables, related to both the level of economic activity, such as the real GDP, the unemployment rate, and the aggregate capital stock in the economy, and to banks' balance sheets and lending activity, such as the equity stock, the total credit supplied and the percentage of credit rationing suffered by firms. Tables include also two main nominal variables, namely the price and the wage levels. With regard to prices, it should be noticed that in a non money-neutral economy prices depend both on real and monetary variables and that the monetary aggregate in the Eurace model is endogenous, because it depends on the total credit supply. Three different periods have been considered, i.e., the first 5 years of the simulation (the short run), the central part of the simulation (the medium term) and the last 20 years (the long run). The time averages of the variables have been considered in any period and, in order to increase the robustness of results, the values in the tables report the ensemble averages of the time averages. The ensemble averages have been computed over 10 different seeds of the pseudo-random number generator. Standard errors are shown in brackets.

α	Real GDP 1 - 5	Real GDP 6 - 20	Real GDP 21 - 40	Total credit 1 - 5	Total credit 6 - 20	Total credit 21 - 40
4	4629 (28)	5509 (45)	6239 (106)	18057 (250)	19897 (340)	18986 (729)
5	4608 (22)	5466 (31)	6064 (81)	18458 (157)	19533 (152)	17781 (609)
6	4669 (9)	5390 (40)	5859 (75)	20130 (133)	19799 (246)	16844 (447)
7	4725 (20)	5429 (33)	5918 (82)	20808 (222)	20200 (298)	16733 (933)
8	4767 (26)	5382 (33)	5715 (139)	21006 (216)	20083 (210)	16326 (927)
9	4714 (12)	5457 (36)	5920 (124)	20770 (178)	19989 (228)	16621 (780)

Table 5.2: Ensemble averages and standard errors (in brackets) of real GDP and total credit for different values of α. Statistics are computed over 10 seeds of the random number generator.

α	Banks' equity 1 - 5	Banks' equity 6 - 20	Banks' equity 21 - 40	Credit rationing (%) 1 - 5	Credit rationing (%) 6 - 20	Credit rationing (%) 21 - 40
4	4048 (64)	4610 (103)	2560 (203)	12.2 (0.1)	0.2 (0.1)	10.5 (0.2)
5	3664 (79)	3851 (242)	1954 (433)	4.3 (0.1)	0.0 (0.0)	13.8 (1.7)
6	3588 (87)	3699 (232)	1621 (423)	0.5 (0.0)	0.0 (0.0)	8.3 (1.1)
7	3279 (94)	3032 (248)	1436 (622)	0.0 (0.0)	0.9 (0.7)	15.1 (3.3)
8	3072 (31)	2941 (162)	1319 (510)	0.0 (0.0)	0.0 (0.0)	14.1 (3.1)
9	2957 (46)	2902 (258)	1192 (334)	0.0 (0.0)	0.1 (0.1)	13.5 (2.8)

Table 5.3: Ensemble averages and standard errors (in brackets) of banks' aggregate equity and credit rationing (%) for different values of α. Statistics are computed over 10 seeds of the random number generator.

The tables show how the ensemble average values of the economic variables change with respect to the different values of the allowed leverage level α. Furthermore, the three reference periods permit to interpret the macroeconomic implications of the different strategies of leverage regulation, according to the considered time span. In particular, a major difference is evident comparing the short run (the first 5 years) and the long run (the last 20 years). The results observed in the first 5 years can be interpreted considering that the risk weighted assets of each of the three banks have been initialized to be five times the initial level of equity. This implies that for values of α lower or equal to 5, the constraint on bank leverage is binding and it is not possible for banks in the short run to increase the supply of credit in order to match the demand by firms. The limitation of banks' loans explains the high percentage values we observe for credit rationing in the first 5 years for $\alpha = 5$ and in particular for $\alpha = 4$, see Table 5.3, and the consequent lower level of credit-money in the economy as observed in Table 5.2. The lower level of credit supply reduces the opportunities for firms to invest, to increase production and to hire new workers, and this is clearly evident in the short-run values of GDP, employment and firms' capital stock which are the lowest for the values of α less or equal to 5 and increase more or less monotonically as α increases, see Tables 5.2 and 5.4. On the contrary, the aggregate equity level of banks is monotonically decreasing with the leverage level α in the short run. In fact, in the case banks face a credit demand higher than their supply

α	Firms' capital stock			Unemployment (%)		
	1 - 5	6 - 20	21 - 40	1 - 5	6 - 20	21 - 40
4	9307 (20)	14881 (354)	20916 (880)	15.6 (0.6)	12.7 (0.4)	12.5 (0.3)
5	9446 (33)	14128 (282)	19959 (677)	16.9 (0.5)	11.7 (0.5)	13.9 (0.5)
6	9495 (12)	13690 (356)	17983 (638)	15.3 (0.2)	11.8 (0.5)	13.6 (0.6)
7	9573 (23)	13802 (276)	18302 (577)	14.2 (0.4)	11.6 (0.3)	13.2 (0.5)
8	9634 (26)	13414 (357)	16737 (1036)	13.5 (0.6)	11.5 (0.4)	13.1 (0.7)
9	9575 (19)	13946 (325)	18489 (1000)	14.5 (0.3)	11.5 (0.3)	13.4 (0.5)

Table 5.4: Ensemble averages and standard errors (in brackets) of firms' aggregate capital stock and unemployment rate (%) for different values of α. Statistics are computed over 10 seeds of the random number generator.

α	Price index			Wage level		
	1 - 5	6 - 20	21 - 40	1 - 5	6 - 20	21 - 40
4	0.76 (0.00)	0.87 (0.02)	1.07 (0.03)	1.53 (0.02)	2.0 (0.05)	2.82 (0.11)
5	0.76 (0.00)	0.84 (0.01)	1.05 (0.03)	1.53 (0.02)	1.88 (0.05)	2.74 (0.10)
6	0.77 (0.00)	0.82 (0.01)	0.97 (0.02)	1.53 (0.01)	1.81 (0.04)	2.43 (0.09)
7	0.78 (0.00)	0.83 (0.01)	0.98 (0.02)	1.54 (0.00)	1.83 (0.04)	2.47 (0.08)
8	0.78 (0.00)	0.81 (0.02)	0.92 (0.04)	1.54 (0.00)	1.77 (0.06)	2.25 (0.14)
9	0.78 (0.00)	0.83 (0.02)	0.98 (0.04)	1.55 (0.00)	1.86 (0.05)	2.51 (0.15)

Table 5.5: Ensemble averages and standard errors (in brackets) of aggregate price and wage levels for different values of α. Statistics are computed over 10 seeds of the random number generator.

constraints, as fixed by the institutional arrangements (α) and their equity level, they stop the payment of dividends to raise their net worth and to become able to meet the demand of credit in excess of supply.

The short run macroeconomic implications of the different values of α fade if the medium term time span is considered (years between 6 and 20) and disappear in the long run. Indeed, it emerges that the short run implications are somehow reversed in the second half of the simulation, where we observe a better economic welfare on average for the highest capital requirements (low values of α), and in particular for $\alpha = 4$. The values of real GDP in table 5.2 actually show that lower capital requirements do not allow for economic expansion in the long run. We state that banks' equity plays again a crucial role in determining these findings. In fact, firms' failures occurring in the course of the simulation and the consequent debt write-offs reduce considerably the equity of banks, see Table 5.3. Furthermore, the consequences of firms' failure are more severe when the value of α is high. The reasons is twofold: first in the case of low capital requirements (high α), banks do not stop dividends' payments, due to the absence of credit rationing in the short run; therefore, they keep their net worth at the initial relatively low levels; second, debt write-off are higher for more indebted firms, and firms' indebtedness is higher for high α, due to the easier access to credit in the short run. In fact, as it is clearly evident in Table 5.3, banks' equity levels in case of lower capital requirements are small in the first part of the simulation and are also subject to the biggest reduction.

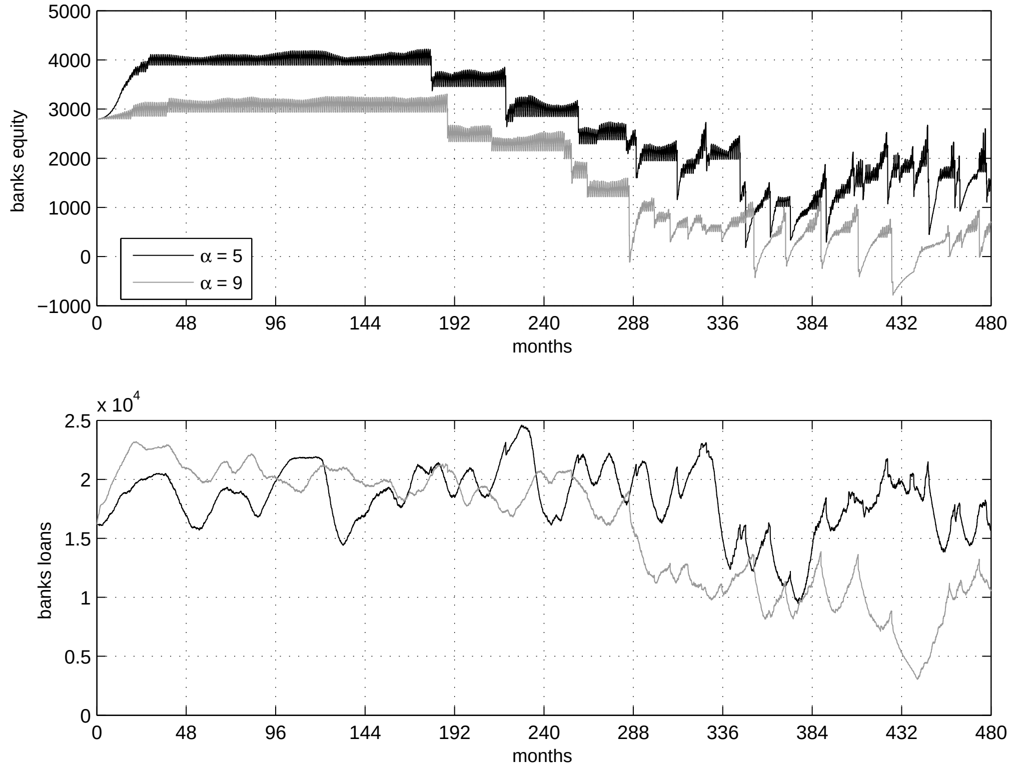

Figure 5.3: Banks' aggregate equity level (top panel) and aggregate amount of outstanding loans (bottom panel). Two different values of α have been considered for the same seed, i.e., $\alpha = 5$ (black line) and $\alpha = 9$ (gray line).

Figure 5.3 shows the dynamics of the aggregate equity of banks (top panel) and the total level of loans supplied by banks to firms (bottom panel). It is worth reminding that the dynamics of the equity of any bank depends on dividends' payments and on the eventuality of debt write-offs, due to firms' bankruptcy. In normal conditions, banks usually pay out all their profits as dividends to shareholders; however, in the case the Basel II-like institutional constraint set by α is binding, i.e., the demand for credit at a bank is higher than the allowed supply at the present equity level, then the bank stops dividends payments in order to increase its equity and thus being able to satisfy the entire loan demand in the future. This behavioral feature explains the increase in the aggregate level of equity that is occurring in the case of low αs. In particular, it is worth noting the rise in the aggregate equity level that can be observed in the figure (top panel) at the beginning of the simulation for $\alpha = 5$, i.e., when the constraint is more binding and therefore credit rationing is expected to occur. This effect can be examined also by looking at banks' equity values of the first 5 years in table 5.3, considering that bank's equity is always initialized at a value close to 3000 (as shown also by figure 5.3). The subsequent large drops of equity in figure 5.3 are therefore explained by firms' bankruptcy and consequent debt write-offs.

The dynamics of the aggregate amount of loans (bottom panel) is consistent with the equity paths represented in the top panel, in particular whenever the demand for loans is rationed by insufficient levels of equity on the side of banks. In fact, at the beginning of the simulation the aggregate amount of outstanding loans in the $\alpha = 5$ case is lower than the amount in the $\alpha = 9$ case, consistently with the aggregate equity increase occurring for $\alpha = 5$ which indicates credit rationing. Furthermore, in the second part of the simulation, the higher amount of outstanding loans for $\alpha = 5$ can be explained by the lower severity of credit rationing in that case, as the higher equity level for $\alpha = 5$ should clearly indicate.

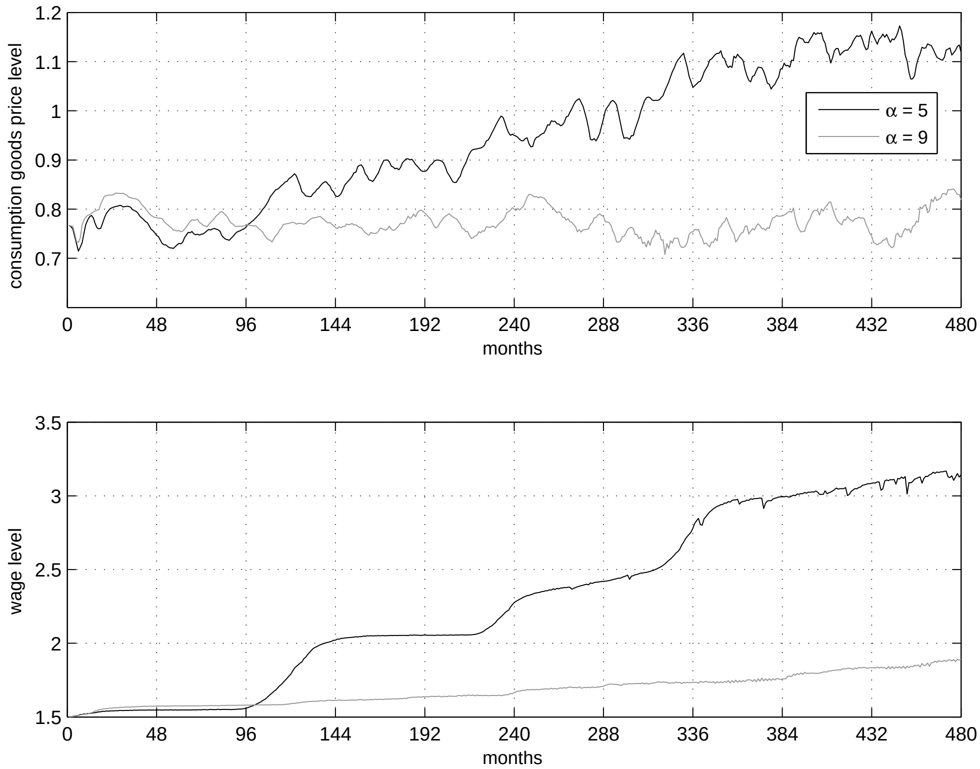

Figure 5.4: Price level (top panel) ana wage level (bottom panel). Two different values of α have been considered for the same seed, i.e., $\alpha = 5$ (black line) and $\alpha = 9$ (gray line).

Figure 5.4 shows the dynamics of two key nominal variables of the economy, i.e., the price (top panel) and the wage level (bottom panel). The paths of the two variables exhibit a general upward trend with some volatility, in particular for prices. It is worth noting that the steepness of the upward trend depends on α and on the period considered. In particular, in the short run the price and wage values are generally higher for $\alpha = 9$, while in the long run the upward trend of prices and wages is clearly steeper for $\alpha = 5$. This result is consistent with the figures showed in the tables and with economic intuition, i.e., the dynamics of prices and wages positively depends on the one of monetary aggregates and on the conditions of the real side of the economy.

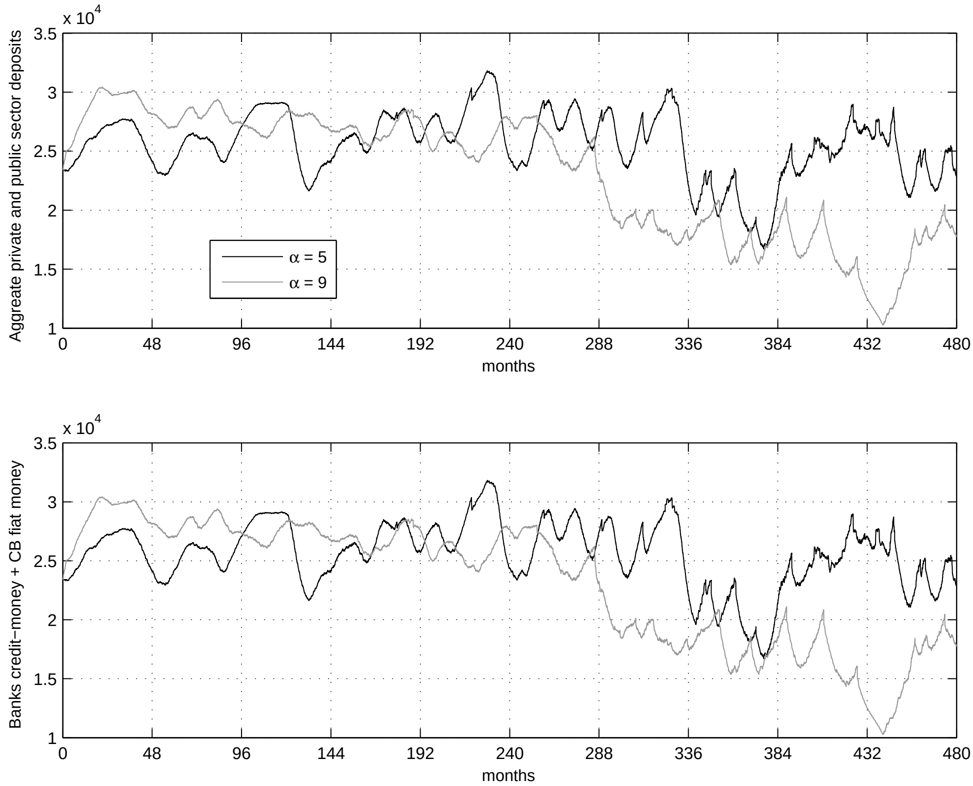

Figure 5.5: Aggregate amount of liquid monetary resources (top panel) and aggregate amount of outstanding loans plus central bank liabilities (bottom panel). Two different values of α have been considered for the same seed, i.e., $\alpha = 5$ and $\alpha = 9$.

Figure 5.5 shows in the top panel the dynamics of the monetary aggregate, i.e. the aggregate amount of liquid monetary resources in the Eurace economy, and presents in the bottom panel the sum of the aggregate amount of outstanding loans and of central bank liabilities. The monetary aggregate is defined at any time as the sum of all private (i.e., held by households and firms) and public (i.e., held by the Government and the Central Bank) deposits plus banks' equity. The initial value of the aggregate amount of outstanding loans is given by the sum of the debt of any firm, where firms' debt has been uniformly initialized so to have a leverage, i.e., a debt to book value of equity ratio, equal to 2, considering also the assigned book value of assets. In real economies the amount of outstanding banknotes is part of the central bank liabilities. In Eurace, the initial value of central bank liabilities is defined as residual, i.e., as the difference between the initial value of the previously defined monetary aggregate and the initial aggregate amount of outstanding loans. The high-powered money provided by the central bank is therefore the part of the monetary aggregate not explained by banks' loans. In absence of a quantitative easing policy performed by the central bank, i.e., if the central bank does not inflate its balance sheet by purchasing government bonds, as it is the case for the results presented in this study[5], central bank liabilities has to be considered constant, and the variation of the monetary aggregate should be eventually explained only by the dynamics of the aggregate amount of outstanding loans. Figure 5.5 confirms the above argument, as the time value of the monetary aggregate (top panel) is identical to the time series presented in the bottom panel, i.e., to the value of outstanding loans plus central bank liabilities, the latter to be considered constant in the simulations. This result further corroborates the rationale behind the theory of endogenous money. The different behavior observed with respect to the two values of α is consistent with the figures presented in the tables and with previous considerations. In particular, the values of the monetary aggregate and its counterpart, i.e. the aggregate outstanding loans plus the central bank liabilities, are characterized by higher values in the short run for $\alpha = 9$, while in the long run the situation is reversed and the time series referred to $\alpha = 5$ dominate.

Figure 5.6 shows the empirical probability distribution function of the monthly output levels during the 40 years of simulation for $\alpha = 5$ and $\alpha = 8$. They are grouped according to three different time spans: the first five years (top panel), from year 6 to year 20 (central panel), from year 21 to year 40 (bottom panel). For each α, all the 15 simulations corresponding to different random seeds have been included. Comparing the three panels it emerges that the economy is characterized by a long-run growth both in the case of $\alpha = 5$ and $\alpha = 8$. However, significative differences come out when considering the two curves within the same panel. In the case of higher capital requirement, i.e., $\alpha = 5$, the output level is lower and characterized by more variability in the first 5 years (top panel). This can be explained keeping into account that the risk weighted assets of each of the three banks have been initialized to be five times the initial level of equity, with the implication that for $\alpha = 5$ the constraint on bank leverage is binding and it is not possible for banks in the short run to increase the supply of credit in order to match the demand by firms. Table 5.2 corroborates this interpretation showing that the outstanding bank credit in the first period is significantly lower

[5] A study about the effects of quantitative easing in the Eurace economy can be found in Cincotti et al. [2010].

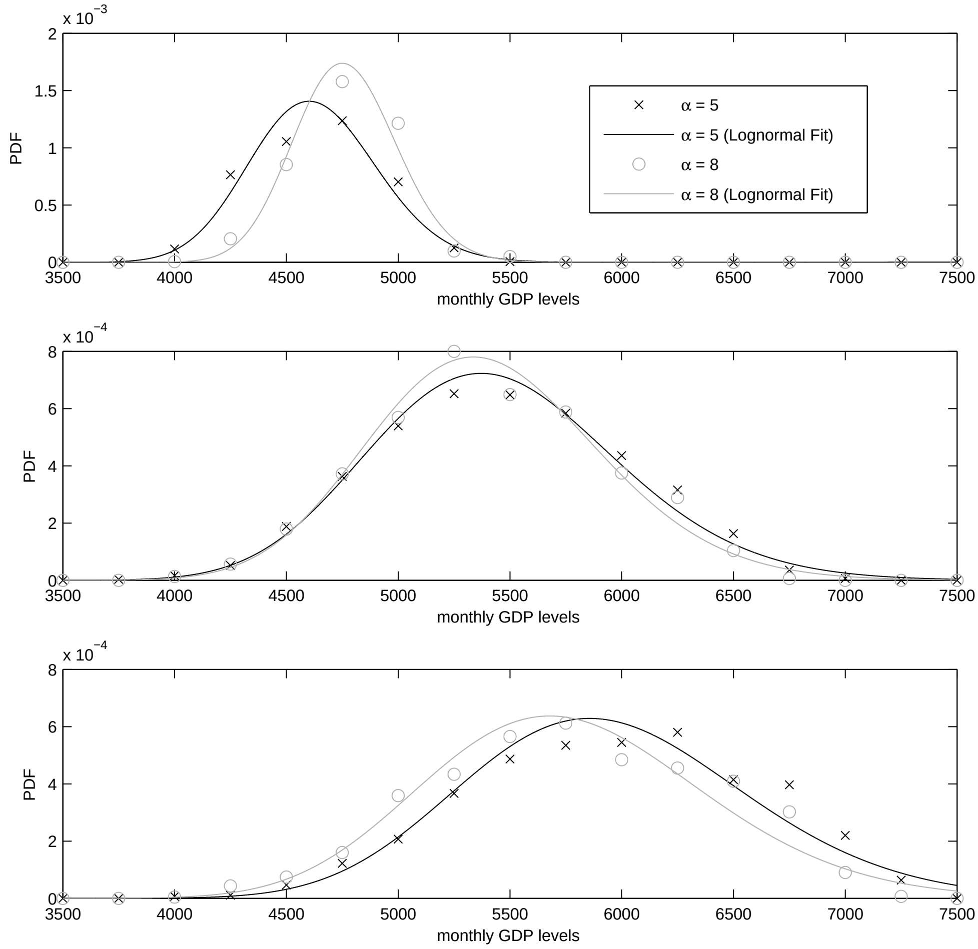

Figure 5.6: Empirical PDF of monthly real GDP levels computed over 15 different seeds of the random number generator. Top panel represents GDP levels for the first 60 months. Central panel includes months from 61 to 240, and bottom panel from 241 to 480. Two values of α have been considered, i.e., $\alpha = 5$ (black line) and $\alpha = 8$ (gray line).

for $\alpha = 5$ than for $\alpha = 8$. The lower level of credit supply reduces the opportunities for firms to invest and to increase production, therefore affecting the short-run values of GDP and creating more instability.

The central panel of figure 5.6 clearly shows that in the medium term (6 - 20 years) the loss of output given by credit rationing is completely recovered. This can be interpreted again by looking at tables 5.3 and 5.2, showing that the aggregate equity level of banks is decreasing with the leverage level α in the short run. This is due to the fact that when banks face a credit demand higher than their supply constraints (low α), they stop to payout dividends in order to raise net worth so to meet the future demand of credit.

The bottom panel of figure 5.6 shows that the short run implications are reversed in the second half of the simulation, where a better economic welfare is observed in the case of higher capital requirement ($\alpha = 5$). Table 5.2, examined along with table 5.3, shows that lower capital requirements reduce banks' equity and limit economic expansion in the long run. Banks' equity is reduced when firms go bankruptcy, and debt write-offs are clearly higher for more indebted firms. The higher level of debt accumulated in the short run in the case of high α therefore causes a more severe reduction of banks' equity. Moreover, a low capital requirement reduces credit rationing in the short run, inducing banks to payout their dividends and to keep low equity levels, being more exposed to further equity reductions due to firms' bankruptcies in the long run.

The clear evidence of results presented in this study is that the monetary aggregate plays a key role in determining the real variables of the economy. Furthermore, the monetary aggregate is made by two components, an endogenous one, or endogenous money, which is given by the aggregate outstanding loans created by the banking sector, and an exogenous one which is set by the monetary authorities, i.e., by the central bank. The first component should be considered as endogenous because is determined by the self-interested interaction of private agents, i.e., banks and firms, while the second component can be considered as exogenous because may depend on discretionary unconventional monetary policies, like quantitative easing. The rate of growth and long-run dynamics of endogenous money, however, depends also on parameters or institutional constraints, like α, which can be considered as exogenous because set by the regulatory authorities. Actually, the main result of the study regards the role of a policy setting, like banks' capital adequacy ratio, on the dynamics of endogenous money and therefore on the growth of the economy.

Investigating the role played by the monetary aggregate in the real economy has been the subject of research in economics for many years and is still the topic of a wide debate, as testified by the controversy between endogenous and exogenous money theorist Arestis and Sawyer [2006], Fontana

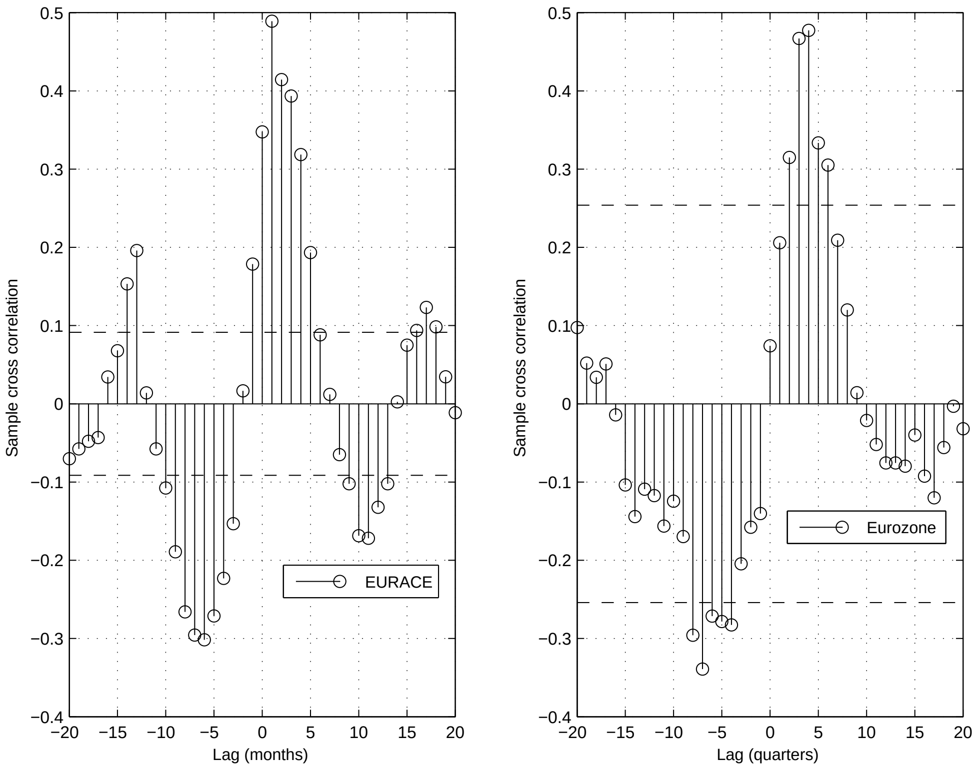

Figure 5.7: Cross-correlation diagram between Eurace real GDP and monetary aggregate data (left panel) and between Eurozone real GDP and M3 data. The dashed symmetric bounds refers to the 95 % confidence level interval for the sample cross-correlation under the null hypothesis of zero theoretical cross-correlation. The bounds values are given by $\pm\frac{2}{\sqrt{N}}$, where N is the sample size. This explains the difference between the left panel bounds, where we have 480 monthly data, i.e., 40 years of simulation, and the Eurozone case (right panel) characterized by only 64 quarterly data, i.e., the 16 years from 1995 to 2010.

[2003], Godley and Lavoie [2007]. The results presented in this chapter point out an interesting similarity between Eurozone economic data and Eurace data concerning the cross-correlation between the percentage variations of GDP and percentage variations of M3, as shown in figure 5.7. The left panel shows the cross-correlation diagram between the percentage variations of real GDP, shown in Figure 5.2 (bottom panel), and the monetary aggregate, shown in Figure 5.5 (top panel), both for $\alpha = 5$. The right panel presents again the cross-correlation diagram computed now considering the percentage variations of Eurozone real GDP and the percentage variation of a broad measure of the monetary base, the so-called M3. Eurozone cross-correlation diagram has been computed on a quarterly base, contrary to the Eurace case, where data are all macroeconomic data are conventionally generated on a monthly time scale. In fact, Eurone GDP are provided on a quarterly base, therefore also M3 data, which are recorded on a monthly base, has been transformed to a quarterly time series, by considering the quarterly average. Eurozone GDP data are working day and seasonally adjusted as well as chain-linked to adjust for inflation with the 2000 as reference year. Eurozone GDP data refers to the period I quarter 1995 - IV quarter 2010, while M3 data to the period January 1995 - December 2010. All data are available on Internet at the European Central Bank statistical data warehouse[6].

It is worth noting that, apart the different time scales involved, the two cross-correlation diagrams are characterized by a similar pattern, as in both cases the percentage variations of real GDP lead the percentage variations of the monetary aggregate. This finding further confirm the rationale behind the theory of endogenous money, stating that the stock of money is determined by the demand for bank credit, which is in turn induced by the economic variables that affect the GDP.

5.3 Concluding remarks

After start of the global financial crisis in 2007, an increasing attention has been devoted to the design of proper regulation systems of the banking sector. A great effort has been done in order to understand and foresee the consequences of different regulation strategies on the stability of the financial system, on growth, and on the main macroeconomic variables. As pointed out in the introduction, many reports on this topic are available, mainly produced by central banks research centers or by international organizations. One of the central themes is the assessment of the long-term impact of different capital requirements for banks. The methodology is typically based on a set of economic models that originate in the DSGE class, which are estimated or calibrated according

[6] `http://sdw.ecb.europa.eu`

to data sets belonging to specific countries or areas.

The aim of this chapter is to tackle the same topic using an agent-based approach. The Eurace model provides with a complex economic environment where to run computer simulations and to perform what-if analysis related to policy issues. The model has been calibrated by using realistic empirical values both for the parameters of the model and for the state variables initialization.

Capital adequacy ratio, i.e., the ratio between banks' equity capital and risk-weighted assets, has been chosen as the key varying parameter that assumes six different values. For each value a set of ten simulations with different random seeds has been run, and the results have been reported and analyzed.

The outcomes of the models consist of time series that are characterized by quite realistic graphical patterns. In particular long-run growth and endogenous business cycles are observed. The capital adequacy ratio proved to have significant macroeconomic implications that depend critically on the considered time horizon.

In the short run (up to five years) a lower leverage policy, restricting the credit supply, has negative macroeconomic consequences, reducing growth, investments and employment. Actually, the limited credit supply determines firms' rationing, whereas a higher leverage allows firms to get loans without incurring in credit rationing. However, the higher debt load that firms acquired in the short run in the case of less restrictive policies, i.e., low capital adequacy ratio, turns out to have significative implications if considered along with the lower equity capital of banks. Indeed, in the case of low capital adequacy ratio, firms financial fragility becomes higher and consequently firms bankruptcies are more frequent. These bankruptcies undermine the equity capital of banks, that in the case of high leverage has not been sufficiently raised by banks, determining a severe reduction of the lending capacity of the banking sector in the long run. On the other hand, if capital adequacy ratio is higher, firms experience less opportunities to increase production and hire new workers in the short run, but later, due to the higher equity of banks, that needs to raise it by retaining dividends in order to face the credit demand, the banking system proves to be more stable, with lower values of credit rationing and a higher level of total loans.

According to the outcomes of the Eurace model, the credit dynamics markedly influences the macroeconomic activity. The banking system is therefore crucial, and an appropriate set of regulations seem to have great potential benefits for growth and economic stability. The model we presented reproduces in detail the interaction among economic agents, and shows that it can already be effectively used as an environment where performing economic analysis and forecast, and where testing policy strategies.

Conclusions

Some concluding remarks are presented at the end of each chapter of the thesis, resuming the main economic outcomes of the correspondent model. Therefore i will point out here some general aspects that emerged from this thesis.

The used methodology proved to be robust and able to reproduce macroeconomic stylized facts, in particular long term growth and business cycles. Long-run economic growth can be explained by the the positive growth rate of aggregate physical capital, despite the existence of a capital depreciation rate. Endogenous investment decisions in physical capital by firms are responsible of the growth of physical capital in the economy. The increase of labor productivity due to the improvement of workers skills is the other reason which explains the long-run growth.

Business cycles appear to be caused by the coordination failure between demand and supply of consumption goods, by strong fluctuations in the investment in physical capital, and by disruptions in the supply chain as well as mass layoffs due to firms bankruptcies. In particular, investment decisions strongly depend on the availability of internal liquidity or bank credit. Therefore, it emerges a strict relation between real economic activity and its financing through the credit sector

Another evidence of results presented in this thesis is that the monetary aggregate plays a key role in determining the real variables of the economy. In particular, endogenous money, given by the aggregate outstanding loans created by the banking sector, strongly influences the macroeconomic activity. The rate of growth and long-run dynamics of endogenous money, however, depends also on parameters or institutional constraints, like the capital adequacy ratio, which can be considered as exogenous because set by the regulatory authorities.

It can be stated that the Eurace model is able to capture both the behaviors of individual actors and the interactions among them in the framework of different institutional settings, allowing to study the feedback between the economic microstructure and the more aggregated or centralized level. Moreover, the role of non trivial phenomena deriving by agents heterogeneity and direct interaction can be analyzed in detail by means of the Eurace simulator.

Finally, the artificial economy presented in this thesis shows that it can be already used as an environment where performing economic analysis and forecast, and where testing policy strategies.

Resumen y conclusiones en castellano

Resumen

El objetivo de esta tesis es proponer un enfoque alternativo para la modelización económica y el estudio de políticas económicas, en el marco de la economía computacional multi-agente (Agent-based Computational Economics). La reciente crisis ha evidenciado el papel fundamental que tienen las políticas macroeconómicas para proteger el bienestar social, y la consiguiente necesidad de entender los efectos de medidas políticas coordinadas sobre el sistema económico. Los enfoques clásicos de la modelización económica, principalmente representados por los modelos de equilibrio general dinámico estocástico (DSGE), han sido recientemente criticados por sus dificultades para explicar muchos hechos empíricos. La ausencia de interacción entre agentes económicos heterogéneos, conjuntamente con la alta racionalidad de los agentes, son dos de las mas importantes criticas. En efecto, las economías con mercados descentralizados se componen de un gran número de agentes económicos que participan interactuando localmente, y por ello, las tendencias macroeconómicas agregadas son el resultado de estas interacciones locales. El enfoque de la economía computacional multi-agente consiste en desarrollar modelos económicos que puedan reproducir las complicadas dinámicas de los vínculos recurrentes que conectan el comportamiento de los agentes, formando redes de interacción y tendencias globales que emergen desde abajo. El trabajo presentado en esta tesis intenta comprender la relación entre la micro estructura del modelo económico y la macro estructura de las políticas económicas, investigando el efecto de diferentes políticas sobre el comportamiento de los agentes y sus interacciones. En particular, la atención se enfoca sobre la modelización de la reciprocidad entre la parte real y la parte financiera de la economía, tratando de enlazar los mercados financieros y el sector crediticio al mercado de bienes y al mercado del trabajo. La complejidad del modelo económico crece a lo largo de los capítulos. El modelo presentado en la primera parte se vuelve mucho más complejo en la segunda parte, convirtiéndose en una "economía artificial" muy completa. Los temas considerados en este trabajo de tesis son muy varios y van desde la investigación del enigma del premio accionario (equity premium puzzle), hasta el estudio de los efectos de reglas clásicas de política monetaria (como la Taylor rule), o el estudio de las implicaciones macroeconómicas de los requisitos de capital de los bancos o de la flexibilización cuantitativa (quantitave easing).

Conclusiones

Al final de cada capítulo de la tesis he presentado algunos comentarios conclusivos que resumen los principales resultados económicos del modelo correspondiente al capítulo. Por lo tanto, quisiera remarcar aquí algunos aspectos generales que emergen de la tesis.

Se ha comprobado que la metodología utilizada es robusta y capaz de reproducir hechos macroeconómicos estilizados, en particular el crecimiento a largo plazo y los ciclos económicos. El crecimiento a largo plazo puede ser explicado con la tasa de crecimiento positivo del capital agregado de las empresas, no obstante la existencia de una tasa de depreciación del capital. Decisiones endógenas de inversión en capital físico por las empresas son responsables del crecimiento del capital en la economía. El aumento de la productividad del trabajo, debida a la mejora de las habilidades de los trabajadores, es otro de los factores detrás del crecimiento a largo plazo.

Los ciclos económicos parecen causados por falta de coordinación entre oferta y demanda de bienes de consumo, por fuertes fluctuaciones de la inversión en capital físico, y por la destrucción de la cadena de la oferta, que causa despidos masivos debidos a las bancarrotas de empresas. En particular, las decisiones de inversión dependen significativamente de la disponibilidad de liquidez de la empresa o del crédito bancario. Como consecuencia, emerge una relación fuerte entre la actividad económica real y su financiación a través del sector crediticio.

Otro resultado que ha sido presentado en esta tesis es que al agregado monetario tiene un papel fundamental en la determinación de las variables reales de la economía. Especialmente, la moneda endógena, que consiste en la agregación de los préstamos del sector bancario, es determinante sobre la actividad macroeconómica. La tasa de crecimiento y la dinámica de largo plazo de la moneda endógena, sin embargo, dependen también de parámetros o vínculos institucionales, como el capital adequacy ratio (CAR), que se puede considerar exógeno, ya que es establecido por autoridades reguladoras.

Como conclusión se puede afirmar que el modelo Eurace es capaz de representar el comportamiento de los agentes económicos individuales, y las interacciones entre ellos en diferentes contextos institucionales, permitiendo el estudio de la reciprocidad entre la estructura microeconómica y el nivel mas agregado y centralizado. Además, el papel de fenómenos no triviales, consecuencia de la heterogeneidad de los agentes y de sus interacciones directas, pueden ser analizados en detalle por medio del simulador Eurace.

Finalmente, la economía artificial presentada en esta tesis se demuestra un interesante instrumento para efectuar análisis y previsiones económicas, y para comprobar estrategias de políticas económicas.

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