Doctoral Thesis
博士論文

Crisis, growth and heterogeneities of firms in economic systems: agent-based simulations and empirical evidence

(経済システムにおける危機、成長と企業の異質性：エージェントベースシミュレーション及び実証研究)

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鄭　文智

Graduate School of Frontier Sciences

The University of Tokyo

Acknowledgement

First of all, I would like to express my sincerest gratitude to my supervisor Prof. Yu Chen for his patient, enthusiastic and excellent instructions on my research.

I thank the members in Chen's lab for interesting and helpful discussions.

I am deeply grateful to Dr. Yuting Lou for her careful review of this thesis and for her many important suggestions on the revision of this thesis.

I would also like to express sincere gratitude to Prof. Sasaki, Prof. Okuda, Prof. Nishino and Prof. Matsuda for their attention and patience to my thesis defense, and proposing many critical but very constructive and inspiring questions and suggestions.

At last, my special thanks go to my family for their trust and love.

Content

Chapter 1 Introduction

The economy is an organic and evolving system. Many kinds of economic indicators have been developed to describe the performances of various aspects of it, and are used by researchers and policy makers to diagnose the overall health of the economy.

When there appears a symptom of a worsening economy, the policy makers would use their policy tools, usually the monetary and fiscal policies, to improve it. However, unlike patients to doctors, the policy makers would not have enough samples or opportunities to do experiments. Therefore, macroeconomic models are developed so that the policy makers can test the possible effects of polices in the models before implementing the policies. These traditional macroeconomic models usually adopt a representative agent framework for the sake of simplicity and thus overlook the heterogeneity of firms. However, various researches on statistical physics and complex systems have shown that a system composed of heterogeneous particles or agents could have very different macroscopic properties from the one composed of homogeneous particles or agents. The bottom-up methodology of agent-based modelling makes it possible to study the macroeconomic implications of firms' heterogeneity, which will be the main topic of this thesis.

This chapter is organized as follows. Section 1.1 describes the main economic problems concerned by policy makers such as governments and central banks. Section 1.2 discusses the relevance between heterogeneity of firms and economic problems. Section 1.3 gives a brief introduction to the macroeconomic models. In Section 1.4, I will discuss the motivations and objectives of this research. Section 1.5 provides an outline.

1.1 Economic problems for a policy maker

1.1.1 Growth

Thanks to the tremendous progresses in science and technology, we have witnessed a trend of worldwide economic growth with expanding population and capitalization in the past decades. Although there have been recessions, crises, even natural disaster and wars, real GDP per capita has increased at an annual of about 2% over the last one hundred years (Figure 1). In this development process, people benefit from the growth of quantity and diversity of goods.

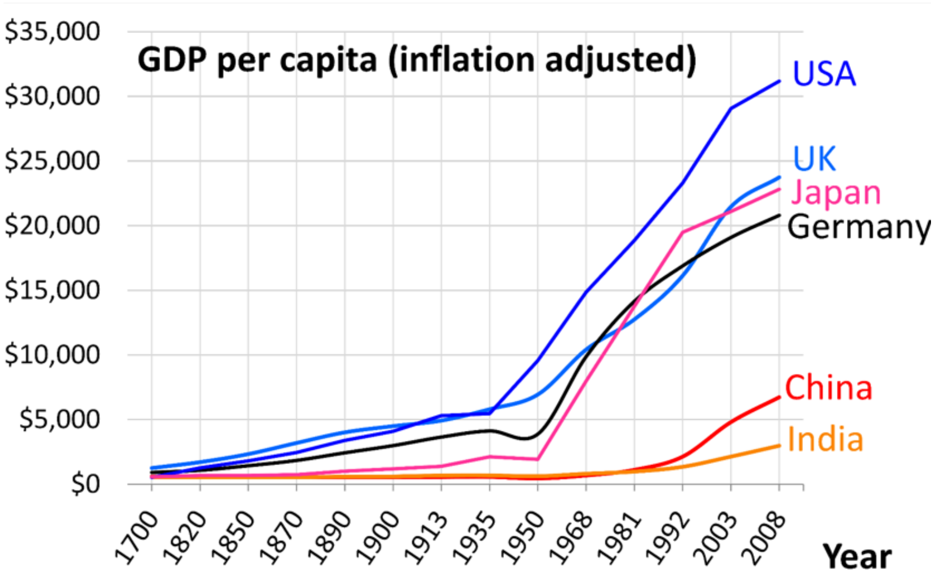


Figure 1 the trend of GDP per capita (inflation adjusted) for U.S.A, U.K., Japan, Germany, China and India over 300 years. (Angus Maddison, 2015)

The long-term economic growth is mainly because of the creation, combination and synthesis of knowledge, and the transformation from knowledge to technology.

Generally, the relationship between the output and input of an economy can be summarized by the aggregate production function:

$$Y = \alpha * K^{\beta} * L^{\gamma}; \tag{1}$$

where Y represents the total production output (i.e., GDP), K and L are the capital and labor input, respectively, β and γ give the corresponding factor shares, and α is the total factor productivity (TFP). A natural logarithm of the Equation (1) gives:

$$\ln Y = \ln \alpha + \beta \ln K + \gamma \ln L; \tag{2}$$

For small changes in any variables:

$$\frac{\Delta Y}{Y} \approx \frac{\Delta \alpha}{\alpha} + \beta \frac{\Delta K}{K} + \gamma \frac{\Delta L}{L}. \tag{3}$$

From the perspective of this Equation (3), the change of an economy's total production can be contributed by the change of labor force (for example, population increase has positive effect while aging tendency has a negative effect, on conditions of the current technology), and the change of capital investment. On the other hand, when the aggregate production changes at a different rate than the changes predicted by the capital and the labor force, the change in TFP can be determined as noted by Equation (3). Therefore, TFP, as suggested by its name, gives a measure of the productivity level. Growth in TFP of an economy can be the result of adoption of advanced technology, for example, steam engine, electricity, chemical engineering, ICT (Information and communications technology) and so on have contributed significantly to growth in TFP in history.

Bergeaud, Cette and Lecat (2015) gives a summary of the periodic contributions to economic growth in different economies (Figure 2 and Figure 3). It can be found that TFP was the most significant factor for the economic growth in all of the four economies, and meanwhile the negative contributions of the “Hours worked” was an evidence that people in general were getting more work done in less time during the last century.

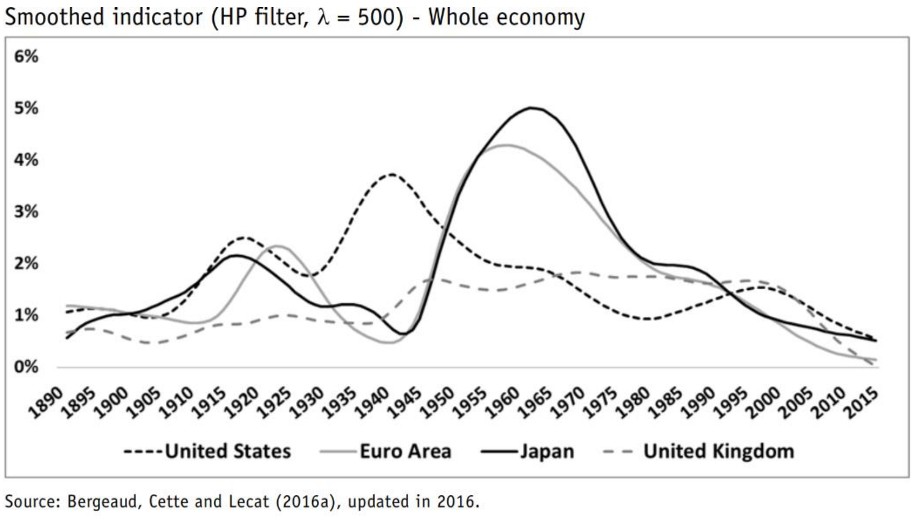
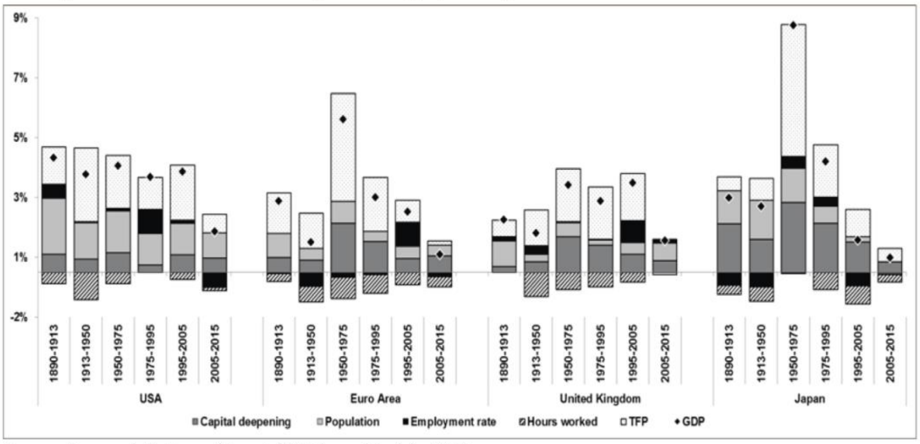


Figure 2 Trend of TFP (total productivity factor) growth in the United States, the Euro Area, United Kingdom and Japan, 1890~2015 (average annual growth rate)

Average annual contributions (percentage points)



Source: Bergeaud, Cette and Lecat (2015), updated in 2016.

Figure 3 Contributions to the economic growth in U.S.A, the Euro Area, Japan and U.K., 1890 ~ 2015. the "Capital deepening" bar corresponds to $\Delta K/K$ in Equation (3), the summation of "Population", "Employment rate" and "Hours worked" corresponds to $\Delta L/L$ in Equation (3).

Figure 3 economy may also benefit from short- /mid-term factors and have good macroeconomic performance. This is especially true when the growth of the economy is related to the prosperity of a specific industry (usually the production of natural resources). However, such short-/mid-term factors cannot help the economy achieve long-term and sustainable growth, or even worse, lead to structural defects of the economy, i.e. "Dutch disease".

Beyond that, political and economic structures can also strongly influence TFP. The economic liberalization (transition from planned economy to market economy) in China in the late 20th century leads to a rapid growth of not only the accumulation of capital stock but also the TFP (Figure 4). In Figure 4, it can be found that while the GDP growth before 1980s was mainly contributed by capital and labor, since 1980s, the growth of TFP contributed significant portion of the overall GDP growth (the two waves of economic liberalization in China started from 1979 and 1992).

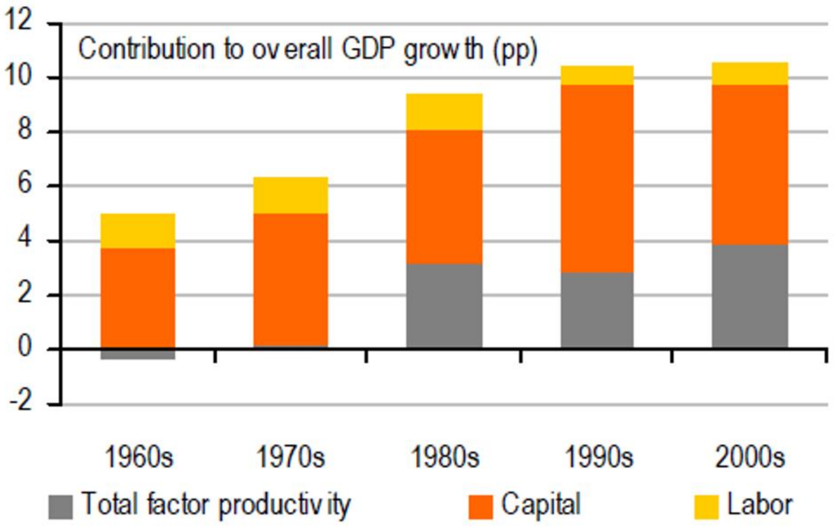


Figure 4 Contributions to economic growth in China. Source: CEIC/UBS report.

The economic liberalization promoted the state-owned firms to reform their organizational structures and incentive mechanisms so that they could compete with the private firms which were more flexible and innovative. The ownership structure of the stated-owned firms may still hinder the productivity growth but this also reserves some room for future growth.

The significant change brought by the economic liberalization in China highlights the fact that policy makers could also play a crucial role in the productivity growth in an economy, although they would not engage in any actual production or knowledge creation process. However, this does not mean that economic liberalization could always automatically result in an idealzied free-market economy where the total benefit of the participants is maximized at the equilibrium. Instead, it should be the duty of policy makers to implement policies to improve the market efficiency, for example, reduce market friction of transactions and the powers that hinders market competition.

1.1.2 Stability

Figure 5 gives the time series of GDP per capita in more recent years. It can be noticed that the growth trend is decorated with fluctuations, which are usually defined as business cycles by economists. This brings us to the second problem – stability.

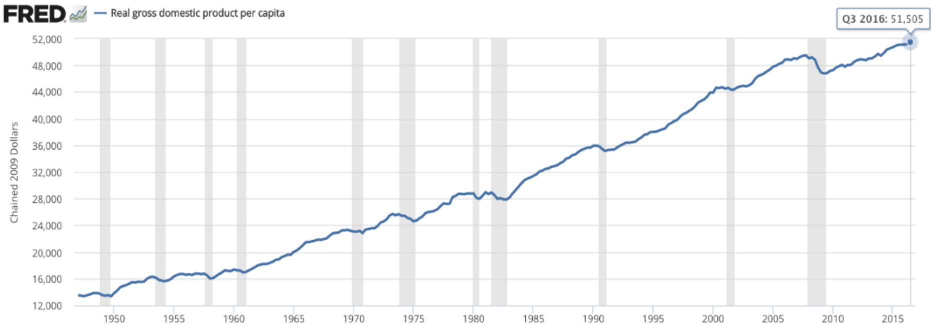


Figure 5 the real GDP per capita of U.S.A since 1945. The recession periods are indicated by shaded areas. Source: Federal Reserve Economic Data

The main indicators related to economic stability include employment data (unemployment rates, nonfarm payroll employment, etc.) and inflation data (consumer price index, producer price indices, GDP deflator etc.). For policy makers, an optimal situation is that the full-employment is achieved and the inflation rate is on a moderate level (depending on the country, 1% ~ 5% for most of countries). However, during the expansions and contractions in business cycles, the inflation rates could go to unexpected high or low levels (Figure 6), which might further lead to hyperinflation and deflation, disrupt economic activities and invalidate conventional policy tools. When these drastic fluctuations were accompanied with high level of debt ratio in the economy, the probability of an economic/financial crisis would rise. For example, a high inflation rate could stimulate over-borrowing and over-investment or make it difficult for firms to do production planning as the price of raw materials went up too fast. On the other hand, a deflation could suppress the desire to consume, and thus reduce capital investment and future economic growth. Increase of unemployment rates could increase the risk of mortgage default and further lead to cascade of bankruptcies.

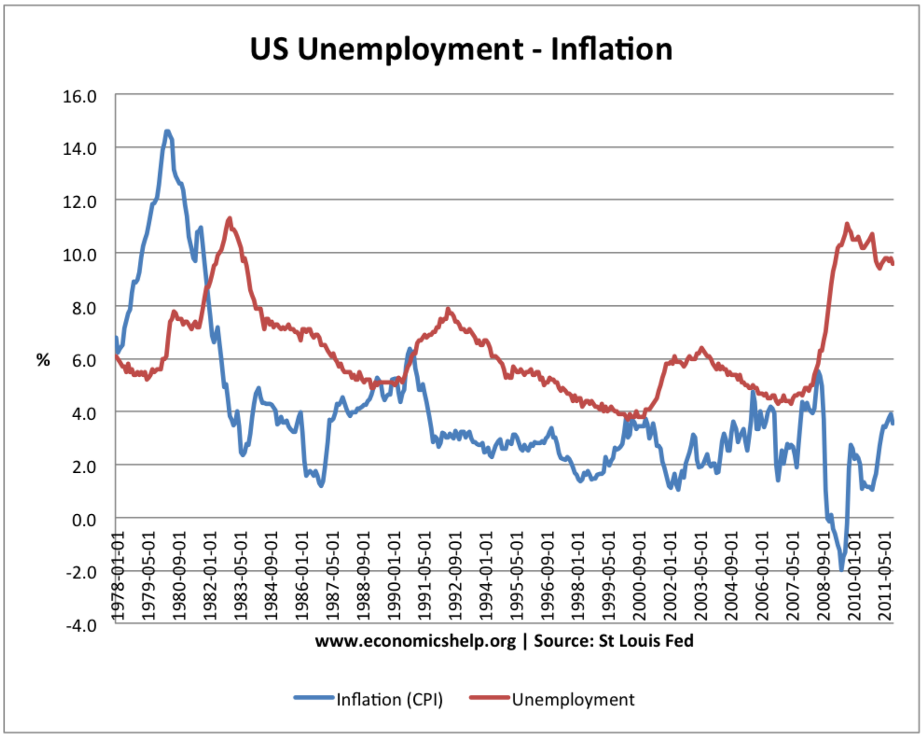


Figure 6 Inflation (blue line) and unemployment (red line) in U.S. Source: Federal Reserve Economic Data.

Therefore, a modern central bank would observe carefully the change of both employment data and inflation data, run their macroeconomic models (for example, the dynamic stochastic general equilibrium model) to give predications and adjust the monetary policies to smooth the fluctuations of the economy. The effects of the central banks' actions could be positive, when the targets of employment and inflation were achieved, or be negative, when the economy is still in deflation but the monetary policy has reached its limitation (for example, zero interest rates) or a speculative bubble collapse in an unbearable way. Ray Dalio collected numerous records of the recessions/crises and the corresponding effects of the central banks' actions in history in his book, "Principles for Navigating Big Debt Crises" (Dalio 2018).

1.1.3 Welfare

Welfare is a system of the government for the citizens to meet basic human needs, and to have opportunities to receive necessary social services, for example, education and healthcare.

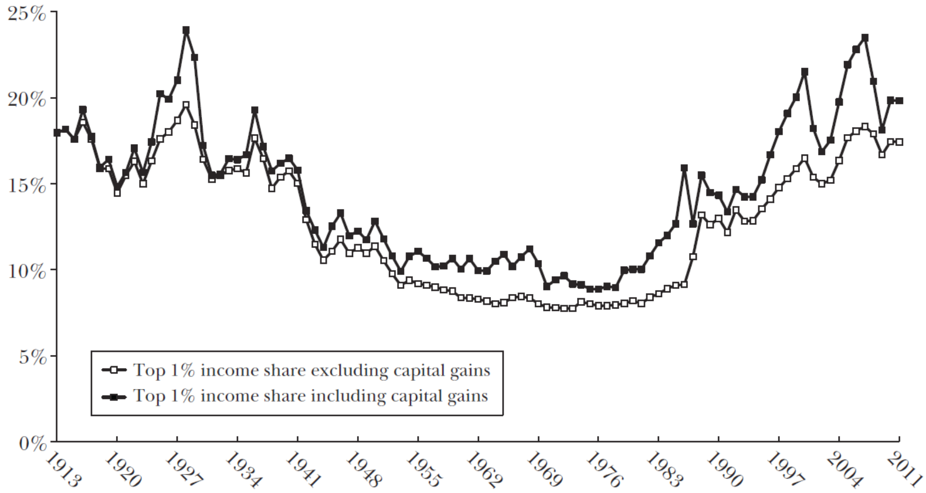


Figure 7 Top 1 Percent Income Share in the United States. Source: Alvaredo, Facundo, et al 2013 and the World Top Incomes Database.

Broadly defined, the welfare has a role as the wealth redistributing system which is intended to balance the benefits among people located at different positions of the wealth distribution.

As the increasing trend of wealth inequality in the past decades (Figure 7), trimming the welfare system so that it could be acceptable and affordable has become a complicated task in many countries. Furthermore, recent researches (Perugini et al. 2015; Stockhammer and Engelbert 2015) have studied the relevance between increasing inequality and economic crisis.

An extreme case of the welfare system is the one in a socialism economy. Karl Marx, in his famous "Capital: A Critique of Political Economy" proposed that because of the nature of capitalism to pursue the profit, the capital will continuously exploit "surplus value" by paying lower wages relative to the profit growth, or by finding cheaper labors. Because of this nature of capital, it is inescapable for the socio-economic system consisting of proletariats and capitalists to fall into economic crises (recession, depression, etc.). In Marx's social-economic picture, only if the capitalism were replaced by an ideal system, namely the socialism, the economy could get rid of the recurring crises. A socialism resolves the wealth polarization problem in the capitalism through the social ownership of the means of production so that the "surplus value" could always be shared by all of the citizen. However, this ideal system could not be established in most of economies because of the absence of conditions.

In fact, even the current operating welfare has been criticized as affecting work incentives. The researches done by the laureate of 2019 Nobel Prize (Banerjee et al. 2011) in economics may shed lights on the design of welfare policy. Their innovative field studies show that the polices which were intended to help the poor, for example, high investment in educational resources, cheap vaccine and micro loans, might not have the expected effects. One important reason is the misjudgments of the behavioral patterns of the people in poverty by the policy makers.

1.1.4 Competitiveness

For a nation, its competitiveness has been defined as the ability to provide a high and rising standard of living to all the nation's citizens (Scott et al. 1985; Porter 1990). From this perspective, competitiveness of a nation is highly related to the productivity growth, economic stability and welfare. Productivity growth and economic stability are the conditions for the citizens to increase the real income and welfare ensures that the fruits of growth would not be distributed in a too biased way. For example, the World Economic Forum gives the global competitiveness report annually (*https://www.weforum.org/*), based on over 100 factors including the adoption of technology, productivity change, social inequality and so on.

Along with the development of industrialization, nations are increasingly participating in the trading and competition with the others. Therefore, from a mesoscopic point of view, the competitiveness of a nation can be measured by the ability of the firms in one or several industries in the nation to produce products or services with lower cost, higher quality and even irreplaceability than its foreign competitors. M. Cristelli, A. Tacchella and L. Pietronero (2012) measure the competitiveness of an economy through the diversity and complexity of its product portfolio and find that their indictor can predict the sustainability of future growth of the economy in some extent.

For policy makers, their actions could also influence the competitiveness of an economy. A "favorable" exchange rate can be good for exports and make its products seem to be competitive but may also reduce the living standard of the domestic households and hinder the evolution of the industry. Also, a government may provide subsidies to some industries because the government wants to avoid a forthcoming crisis in the industry or wants to support some new technologies in the industry. But on the other side, the subsidies may lead to misallocation of resources and slow down the advance of the economy.

1.2 Heterogeneity of firms and the economic problems

In the recent decade, there has been increasing concerns of the inequality trends. Ranciere, R., et al. (2012) shows the trends of top 5 percent households' income share in different countries over about one hundred year (Figure 8). In general, we can find that the income inequality (measured by the top 5 percent income share) got to its first peak level in the beginning of the last century, and then declined until 1980. Since 1980, the income inequality has been increased for decades. The increasing income inequality could have implications on the economic problems which have been discussed in the last section. For example, high level of income inequality could limit the access to education for the middle and poor class and thus, impede the future economic growth in a country. Also, evidence (Gu, X., & Huang, B. , 2014; Wisman, J. D., 2013; Bazillier, R., & Hericourt, J., 2017; Stockhammer, E., 2015; Stiglitz, J. E., 2012) suggests that the increase of income inequality was usually accompanied with an increase of households' debt, which could lead to economic instability eventually. Moreover, income inequality could also result in poor health care system, high crime rate and even political instability and thus, damage the welfare and competitiveness of an economy.

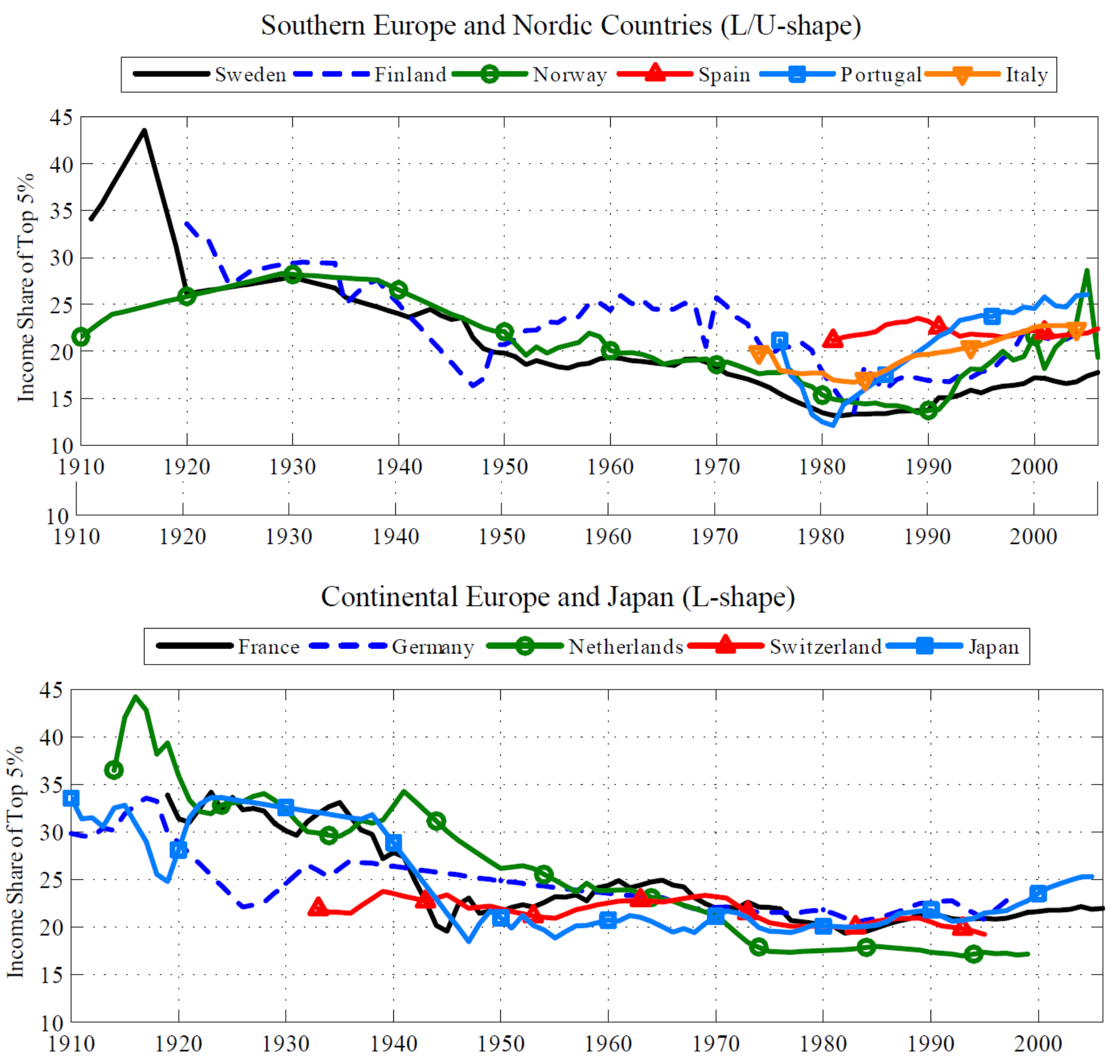


Figure 8 Top 5 Percent Income shares in the Cross-Section (Ranciere, R., et al., 2012)

Therefore, economists have made attempts to explain the increasing income inequality and understand the possible outcomes from different theoretical and empirical perspectives. In Kumhof, M., Rancière, R., & Winant, P. (2015), the authors argued that the increasing income inequality reflected a loss of bargaining power of the workers in the long-term. Ranciere, R., et al. (2012) proposed that the economic liberalization since 1980 (known as Reaganomics in U.S., the economic policies included reduction of tax and government regulation), which steered U.S. economy back to growth, reverse the trend of income inequality since 1930 in U.S. Other authors (Alvaredo, F., et al., 2013; Piketty, T., Saez, E., & Atkinson, A. B., 2011) found that the rich benefited a lot from capital gains in terms of wealth growth while the middle and poor class benefited little. Ranciere, R., et al. (2012) proposed two growth models, debt-led growth and export-led growth, to understand the difference in income inequality between countries from the perspective of international trade and financial deregulation. In fact, in the famous work "Das Kapital" (Marx, K., 1867), Karl Marx argued that the internal contradictions of the capitalist system would cause poverty of workers and would further lead to crisis. Goda, T. (2013) reviews and contrasts the theoretical frameworks of Marxian, Post Keynesian, neo-classical economics and new-Keynesianism, regarding the root of income inequality and how the income inequality could cause economic crisis.

Generally, households' income includes basic wage, bonus and capital gain. Therefore, an increasing trend of income inequality could also be a reflection of the different economic status of the firms or industries that they work for or benefit from. In fact, if measured by various indicators, the economic performance of firms can be very heterogeneous, even for the firms in the same sector. For example, after the release of the first iPhone in 2007, Apple took about 15% market shares among the major smart phone producers, nevertheless, Apple's profit share in the smart phone market was more than 50%. This fact reflects a much stronger profitability of Apple than other smart phone producers (which can also be supported by a comparison of Apple's and the other listed producers' financial statement).

From the DuPont formula (Phillips, M., 2015):

$$Return\ on\ equity = Net\ income/Sales \times Sales/assets \times Assets/Equity$$

we can find that the profitability of a firm can be decomposed into three components, that is, the profit margin ($Net\ income/Sales$), the asset turnover ($Sales/assets$) and the financial leverage ($Assets/Equity$). Therefore, if one firm wants to achieve a higher profitability, the firm will need to increase either of the three components. For example, if the firm was able to decrease its cost per unit of product and keep the sales at the same level, the firm would get a higher profit margin. The costs of Apple's smartphones were less than 50% of their retail price, while the costs of its competitors' smartphones usually accounted for more than 80% of the retail price. Thus, the high profit margin is one of the sources for the high profitability of Apple. Besides profit margin, the firm could also try to increase the asset turnover. Indeed, the asset turnover can be understood as a measure of the firm's productivity. For example, the products sold in a Walmart or on Amazon usually have a very low profit margin, nonetheless, both Walmart and Amazon are able to sell their inventories much faster than their competitors. Therefore, the high productivity (small profits but quick turnover) can also help a firm achieve high profitability. At last, if a firm could utilize a higher financial leverage in a sustainable way, the firm would be able to improve its profitability.

The DuPont formula is a quantitative approach to understand the different heterogeneous profitability of firms. The Porter's five forces analysis (Porter, M. E., 1989), which is very popular in the business school textbooks, provides a qualitative framework to understand why the profitability of firms can be so different.

Some characteristics of the products or services can also make the firm which provides the products/services possible to achieve high profitability. For example, the social network provided by Facebook has the characteristic that, if more users join the network, the network would be more attractive to the current users and the potential users (a positive feedback of demand creating demand) and would be more profitable and valuable (considering that Facebook makes profit through advertising service and the massive data generated in the network). On the other hands, due to the rapid spread of information, it is more likely to create popularity of products/services (another type of positive feedback of demand creating demand, maybe in an irrational way) so that some "lucky" firms are able to grow very rapidly.

As a result of the heterogeneity of firms, we can find not only a skewed distribution of the firms' market capitalization (Figure 9, Segarra, A., & Teruel, M., 2012 for a review of the firm size distributions), but also a huge gap between the people work for different firms. For example, while the mean annual wage of a waiter or waitresses in New York is 25280 dollars, the annual wage of a common employee in Facebook can be more than 200 thousand dollars (Bureau of Labor Statistics, U.S.)

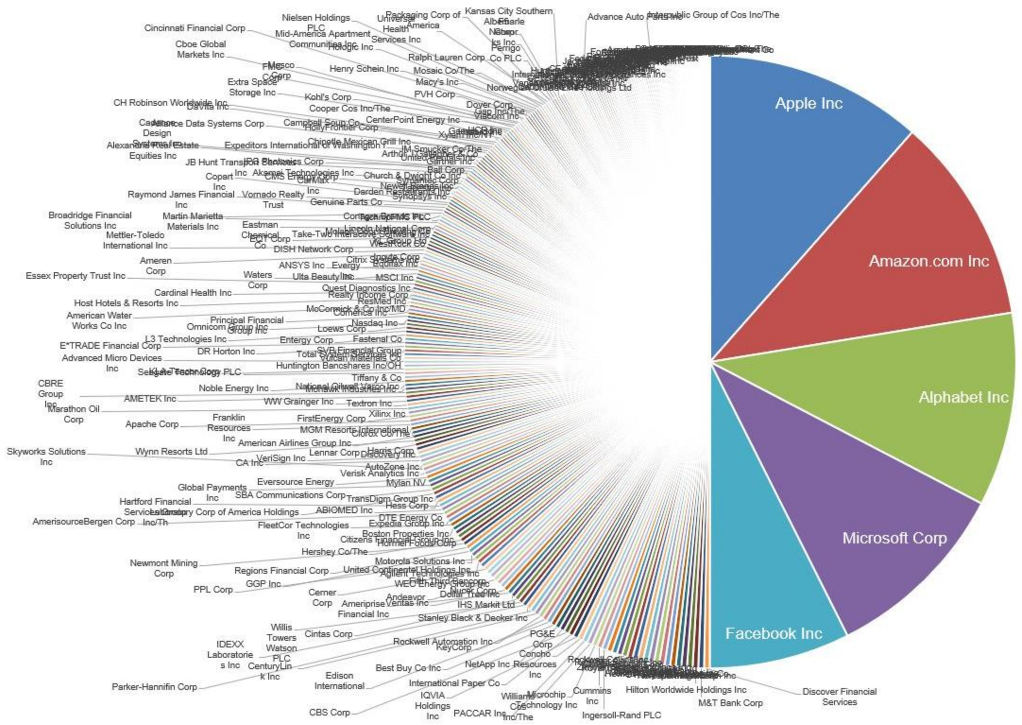


Figure 9 the market capitalization: top 5 and bottom 282 in S&P 500 (Jul., 2018, done by "the Fortune Teller" on *www.seekingalpha.com*)

The heterogeneity of firms is usually considered as a quite natural phenomenon in traditional economic theories. The mainstream economics has a belief on the free market. Thus, any outstanding firms would be eliminated quickly so that the relevant issues should not be a major concern. From the knowledge of statistical physics and the studies on complex systems, usually, the macroscopic properties of a system can be inferred from its components if: the properties of components are homogeneous; the interactions or correlations between the components are weak. In the early stages of industrialization, the manufacturing contributed a large share to the economy, the assumption of representative agent for firms in the mainstream economics might be suitable. This is because: (1) the difference of products in one category was small; (2) the business models for the firms were similar; (3) most were made to meet simple and basic demands; (4) the gaps of productivity between workers were relatively low.

However, in the late industrialization, the share of manufacturing is small for a modern economy. As the accumulation of knowledge and technology, instead of physical capital, human capital has become the most important resource for production.

This means that a low variable cost and thus a very high profit margin can be achieved. Moreover, the difference in management, organizational structure and incentive systems can make the productivity of human very different. Last but not least, today, consumers buy products or service not only for basic needs, but also for mental needs and social needs. For example, with the help of the network effect and the modern information and communications technology, the Internet Giants are able to build very wide "moats" (a term in the investment analysis, popularized by Warren Buffett) to sustain their high profitability, which is very robust against market competition. Some governments have started to discuss new tax policies for the Internet Giants.

Overall, in the late industrialization, the heterogeneity of firms has been strengthened in various aspects, which may have important economic implications on the basic economic problems.

1.3 Methodology

1.3.1 Traditional macroeconomic model for policy makers

The mainstream macroeconomic models used by central banks and governments are the dynamic stochastic general equilibrium (DSGE) models. Based on a set of differential equations describing dynamic relations among many macroeconomic measures under appropriate assumptions, standard DSGE models excel in quantitative prediction of macroeconomic measures for systems in business cycles or economic growth but perform poorly at out-of-equilibrium phenomena such as economic bubbles and crisis (Stiglitz 2015; Colander et al. 2008; Bookstaber 2017; Ormerod 2004, 2010). In standard DSGE models, a severe economic crisis can only be triggered by a large exogenous shock (Kirman 1992; Gali 2008; Fagiolo and Roventini 2012) rather than endogenously occur, while in reality, it seems that large shocks are the result of an economic crisis. Moreover, each sector of DSGE-modeled economy is described as a representative agent, for instance, firms or households, whose behaviors are formulated by a set of ordinary differential equations based on the economic rationale. Such practice of modeling implicitly assume that the aggregation of multiple firms or households should be equivalent to the corresponding representative agents, which is justifiable only if the interactions among the group of agents are weak enough and meanwhile, the rationality of the agents' behavior must be perfectly ensured. However, during the periods of bubbles and crises, the interactions among agents could be significantly enhanced by the contagion effect and the rationality in decision making could be distorted due to the herding behavior (Ormerod 2004, 2010; Blanchard 2016). In past decades, many sophisticated modifications have been made to improve DSGE models in these two aspects (Christiano et al. 2014; Korinek and Simsek 2016; Bilbiie 2017) to strengthen their quantitative credibility for better policy-making.

1.3.2 Full-scale ABM on macroeconomy

The agent-based approach has been extensively used in physical, chemical, biological and social systems (Gatti et al. 2008; Pogson et al. 2006; Batty 2007; Bonabeau 2002) to understand unexpected phenomena emerging from a group of heterogeneous and adaptive interacting agents. As a set of powerful tools in linking micro-behaviors to macro-phenomena in a class of complex adaptive systems, agent-based modeling and simulation have also been applied to the analyses of macroeconomic phenomena (Gualdi et al. 2015,2017; Gatti et al., 2008, 2011; Aoki, and Yoshikawa 2011; Caiani et al. 2016; Dawid et al. 2012; Deissenber et al. 2008; Dosi et al. 2010; Bouchaud et al. 2017; Tesfatsion, 2002). Generally, we can differentiate the previous ABM studies into two categories. In the first genre, ambitious researchers are building the full-scale ABMs which includes as many different types of economic agents and their complicated interactions as possible.

A famous example of the full-scale models is Eurace (Dawid et al. 2012; Deissenberg et al. 2008), which is designed to recover various economic processes and is an early attempt to provide a platform for testing policies for decision-makers. The Eurace have been developed for more than 10 years and by about 70 researchers. The types of agents which are included in the baseline model of the Eurace are households, consumer-goods firms, a capital goods firm, commercial banks, a government and a central. The household agents would act as consumers, workers and investors (Figure 10 the Framework of Eurace (*http://www.eurace.org/*). The baseline model focuses on the role of credit creation as a driving force of business cycles (Cincotti et al. 2010, 2012; Holcombe et al. 2013; Teglio et al. 2012). Their simulations also give the effects of fiscal policy, unconventional monetary policy and austerity policies on different phases of business cycles.

The baseline Eurace model has been further developed to include new modules. In papers by

Raberto et al. (2016) and Ozel et al. (2019), a real estate market is incorporated and the commercial banks are endowed with mortgage lending capability. As the mortgage loans become a new approach of credit creation, the related economic issues such as the real estate bubble and collapse can be studied in the simulator. Eurace model has also be extended to study low-carbon transition and the related policy issues by introducing an energy sector (Tonelli et al., 2016, Raberto et al., 2019, Ponta et al., 2016). Recently, an information sector has been incorporated in the model to study the impacts of digital transformation on the labor market and the other sectors.

One important feature of Eurace is the stock-flow-consistency (SFC). This is realized by implementing a double-entry balance sheet system for each agent. Therefore, the model can be checked at levels from items in individual agents' balance sheet to macroeconomic variables in a way just like audit process. As described above, various extensions have added much complexity to Eurace. The SFC makes it easier to find if there were any unexpected changes or errors introduced by new modifications.

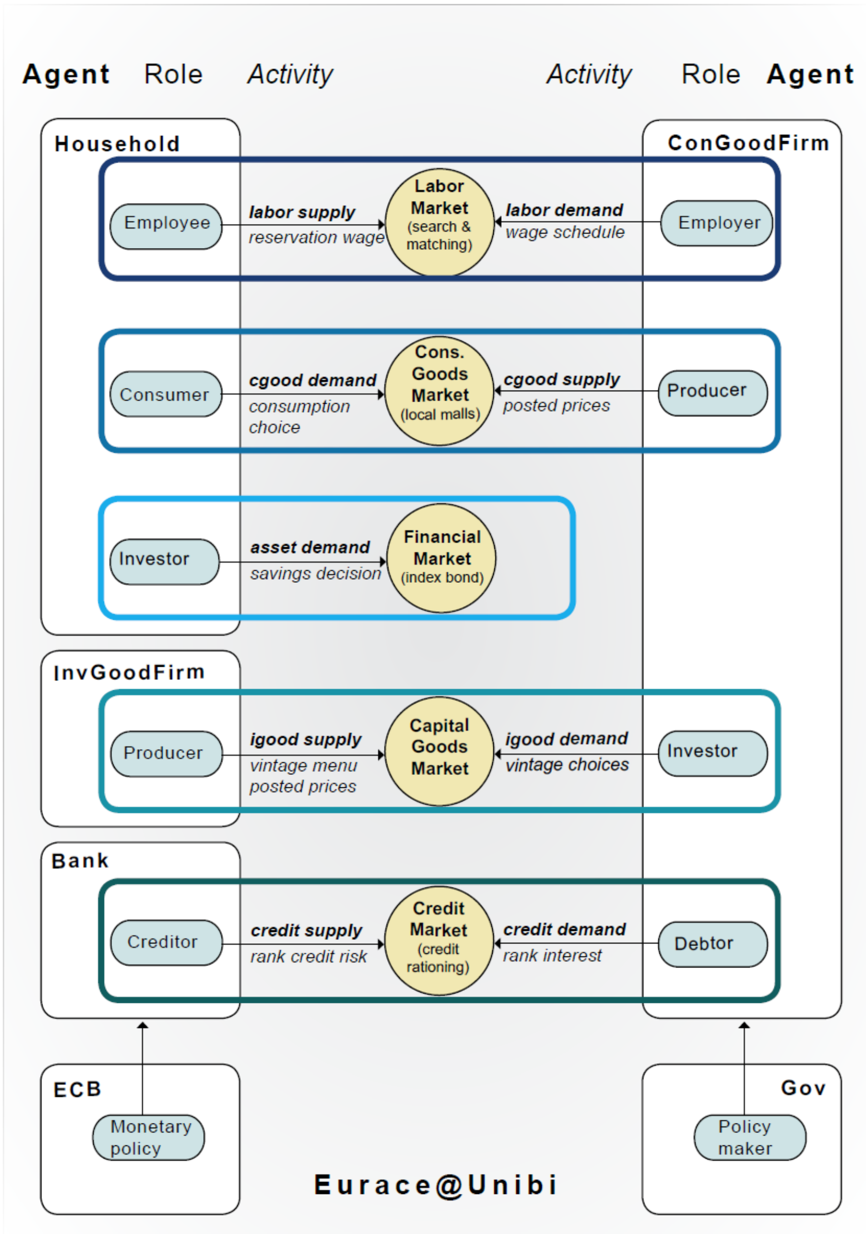


Figure 10 the Framework of Eurace (*http://www.eurace.org/*)

Dosi et al. (2006, 2011, 2013) developed a model which has a similar framework to Eurace, consisting of households, producers, banks and a government. They have two sectors, that is, capital firms and consumption firms, for the producers. The capital firms perform R&D and produce capital goods for the consumption firms. The consumption firms are able to update their productivity through a selection process of the capital goods and produce homogeneous consumption goods for the households.

A huge set of empirical stylized facts, including correlations and auto correlations of macroeconomic variables and distributions of firms and households, are used to calibrate Dosi et al's model. Their model is used as a platform to do a series of "what-if" analysis of polices. In Dosi et al. (2013), they find that the effects of monetary and fiscal policy will be dependent on the shapes of the income distribution and profit distribution. In Dosi et al. (2006), their study shows that "Schumpeterian engine" (the policies related to firms' innovation behaviors) cannot sustain a near full-employment and high growth state alone, "Keynesian" demand-generating engine, usually referring to fiscal policies, is a necessary complementarity keep the economy in the right path.

A recent large project related to the agent-based modelling on economic and financial systems is CRISIS (Complexity Research Initiative for Systemic Instabilities, *http://www.crisis-economics.eu/*), which aims to develop a new approach for economic modelling to understand global economic risk. The project is divided into eight sub projects including, database construction, agent-based model of the financial system, agent-based model of the macro-economy, economic experiments, online economic game, a user-friendly economic simulator, stylized complex systems models and integration and coordination of agent-based models. It was obviously a very ambitious project so that eleven universities and institute joined the project and the researchers in the fields of financial economics, macroeconomics, agent-based modelling, physics (econophysics) and behavioral and experimental economics make up the team.

In the sub project of agent-based model of the macro-economy, several versions of models, that is, mark I, mark II, mark 0+, were established and it could be understood as a process of improvement. In mark I (Gatti et al. 2008), only households, banks, and firms producing consumption goods are included. In mark II (Gatti et al. 2010), capital investment and capital investment are incorporated in the model (Figure 11). In mark 0+ (Grazzini, J., and Gatti 2013), the production network among the firms is taking into consideration.

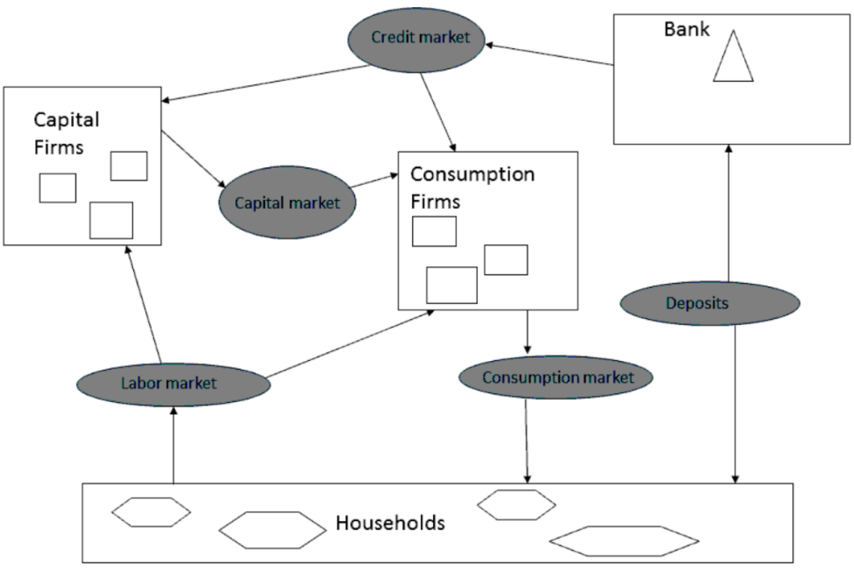


Figure 11 the framework of mark II in project CRISIS (Grazzini, J., and D. Delli Gatti, 2013)

However, there appears "regime transitions" from a low regime era to a high regime-low volatility era, then to a high regime-high volatility era, which are found to be robust against many changes of the model in their simulations (Figure 12). The original mark I model is too complicated to illuminate the underlying mechanism of the transitions. Therefore, the physicists in the stylized complex systems model group (another sub project in CRISIS) simplify the structure and behavioral roles of mark I to develop a so-called “mark0” model. As a result, they find that the phenomenon observed in mark I can be summarized in a phase diagram, which is ruled by only two control parameters, and furthermore, can be understood analytically. Section 1.2.3 and Chapter 2 will give a brief introduction to mark0 and its basic results, respectively.

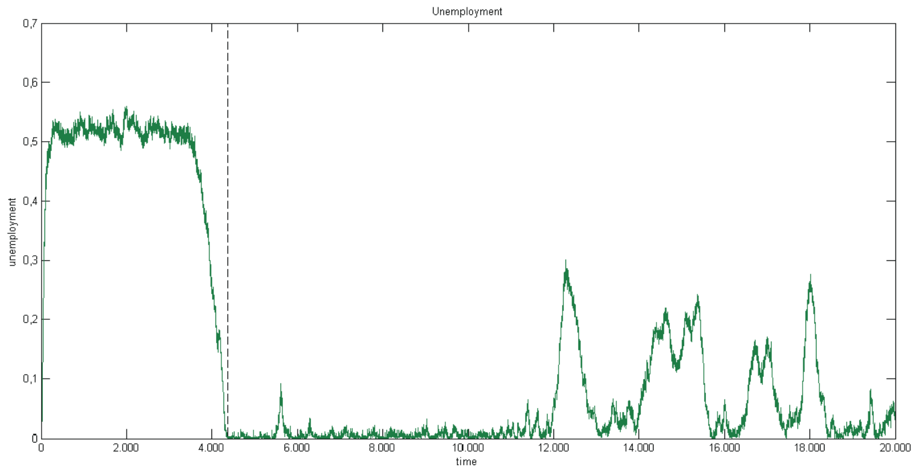


Figure 12 the time series of unemployment rates in mark II of CRISIS. It can be found that there exists a low regime era (the green line before the dashed line. High unemployment rate is corresponding to low total production; thus, the authors define it as low regime era), a high regime-low volatility era and a high regime-high volatility era (Grazzini, J., and D. Delli Gatti, 2008).

1.3.3 Stylized ABM on macroeconomy

While the full-scale ABMs are able to recover various economic processes and to provide a platform to test policies for decision-makers, large amounts of behavior rules, initial conditions and other parameter settings in the model also bring about so many degrees of freedom that the verification of the robustness of results becomes very hard. Therefore, researchers are making efforts to build the minimal ABM by keeping only the least number of types of agents and employing highly abstract models of the interactions (Bouchaud 2017; Gualdi 2015; Tesfatsion 2002). Although the full range of phenomena occurring in a real economy can hardly be reproduced with the minimal ABMs, the link between microscopic mechanisms and some specific macroscopic phenomena can be elucidated more easily. In this sense, the minimal ABMs work like Ising models (McCoy 2014; Yang 1952) do in statistical physics which were used to find basic conditions and control parameters for a spectrum of phenomena, such as criticality, phase transitions, relaxation behaviors, etc. (Goldenfeld 2018; Bak 2013). Indeed, the development of minimal ABMs for financial markets, such as Minority Game (Challet 1997, 2003), Cont-Bouchaud model (Cont 2000), and V. Alfi's model (Alfi 2009a, 2009b), etc., is also one of the hot topics in econophysics, a new research field advocated by E.G. Stanley et al (Mantegna and Stanley1999) since the late 90s.

A typical minimal-ABM, the Mark 0, was then proposed by Gualti, et al. to serve as the skeleton of a macroeconomic ABM where several different statuses of economy can emerge. The concision of this minimal model allows the authors to unveil the key factors and the mathematical principles underlying the model through the tools from statistical mechanics. As is shown below, Mark0 has become a benchmark framework upon which further extended versions tailored for specific economic questions are more easily understood.

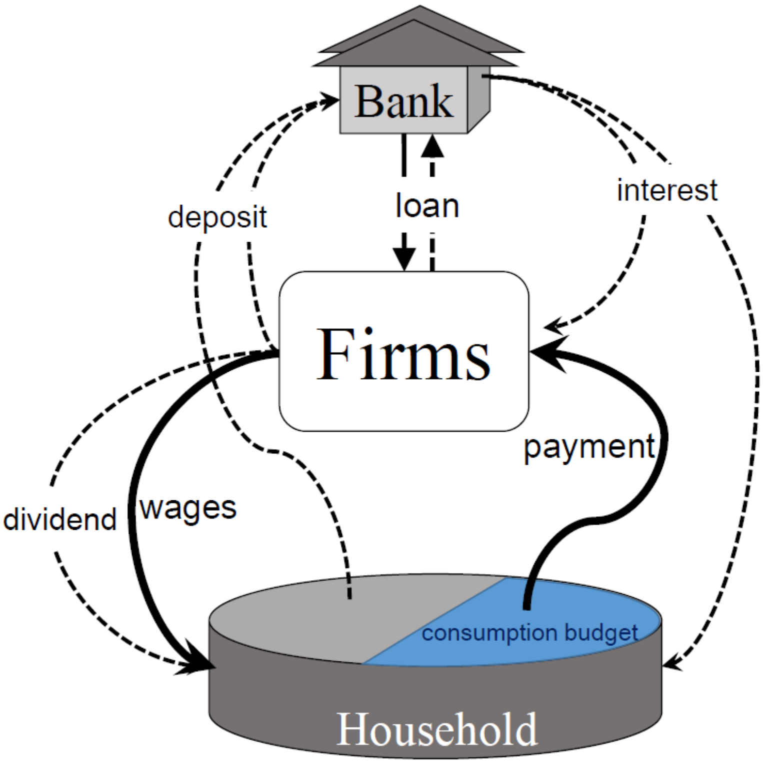


Figure 13 Money flows among three sectors in Mark-0

In the study of Mark0, the phase diagram of the economic status is found to be controlled by a couple of key parameters. The simplicity of Mark0 renders it into a basic framework like the demand-supply curves in analytical economics, rather than a one-to-one mapping of the real economy. Nevertheless, even with only the supply-side played by interacting agents with basic heuristic behavioral rules, it is enough for such a model to give unexpected but understandable pictures of economic circulations. The most interesting phenomena observed in Mark0 is the emergence of endogenous crises as well as the first order phase transitions, governed by a liquidity threshold, among three distinct phases, namely the endogenous crisis (EC) phase, the residual unemployment (RE) phase and the full employment (FE) phase. In another study on Mark0, the authors further simplified the model and found that the occurrence of EC phase could be explained by the synchronization of interacting oscillators (Gualdi, 2015b). From this finding, the phase diagram of Mark0 is proved to be robust against various types of noise or modifications of the model.

1.4 Research motivations and objectives

In Section 1.1 Economic problems for a policy maker and Methodology, I give a brief introduction to the major economic problems for policy makers and their choices of economic models.

The DSGE models are undoubtedly the mainstream tool and are widely used by central banks and national institutes of economic studies to deal with the policy problems about growth and stability. The analytical form and representative agent structure make it possible to perform calibrations and give predictions on dozens of macroeconomic variables. However, the DSGE models are able to provide satisfactory outcomes only when the economic fluctuations are small. The poor performances of the models during periods of economic instability suggest that it is necessary to consider different assumptions to understand the economic crises in reality.

On the other hand, agent-based computational modelling is considered as a promising approach because of its flexibility to incorporate new interactions and behavioral assumptions. Thus, quite a few large projects were funded and gave the development of the models which could incorporate lots of details in a real economy. The validation of these models is usually based on the match of a series of empirical stylized facts. However, as John von Neumann said, “With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.”, the high dimensional spaces and a variety of the adopted behavioral rules also make these model unreliable and arbitrary, even if someone could make a perfect match of the stylized facts.

Therefore, now I can clarify the objective of this thesis. Instead of building another “black box” model for a complex real economy, I will explore the possible and robust scenarios and study the key underlying mechanisms (corresponding to policy combinations) which lead to these scenarios through a simplified and understandable agent-based framework.

The rationality of this methodology can be seen from the following three aspects.

First, from the classical economic thought, we could get a lot of meaningful and understandable analyses from very simple frameworks, for example, the supply and demand curve in microeconomics, or the quantity theory of money by Irving Fisher in macroeconomics. In the latter, $MV = PQ$, which suggests that both the increase of money velocity (M) and money supply (V) could induce the inflation. The deficiency of these frameworks is their ignorance of interactions among economic agents and the possible emergence effects.

Second, from the concept in statistical physics, the properties of a large system consisting of numerous interacting agents could be described in a simple phase diagram. Within each phase, the macroscopic properties could be qualitatively similar and be robust against many changes of microscopic behaviors. Therefore, it is possible for researchers to find very few effective parameters that dominate the system in the macroscopic levels.

Third, from nature of polices, although there seems to be a wide variety of policy choices, what policy makers actually do is just to influence the distribution and redistribution of money and credit (broadly speaking, any resources). It is enough to analyze and understand effects of many polices in a simplified model with traceable and conservative cash flows.

1.5 About the empirical evidence in the appendices

The study on a macroeconomic system is very different from studies on complex systems in the field of natural science. The impossibility of controlled experiment makes it unreliable to say that someone's model can be verified because certain evidence has been found. Traditionally, authors in the field of macroeconomic agent-based modelling may argue that their models make sense because some stylized facts in reality can be reproduced by the models; on the other hand, authors in the field of mainstream macroeconomic modelling (DSGE currently) usually calibrate their models through econometric techniques. However, in order to reproduce various stylized facts or do calibration, many parameters must be introduced and complicated correlations must be considered. Such attempts in modelling may cause more troubles than benefit in understanding some basic mechanisms.

The inclusions of the so-called empirical evidence in the appendices of Chapter 3, 4 and 5 in this thesis do not mean to verify the modeling or the conclusions of the studies. The purposes of these appendices are: (1) providing some clues in a real economy for further investigations, based on the economic implications given by the studies in the corresponding chapters; (2) providing some backgrounds in reality for the readers to better understand the meaning of the conclusions.

1.6 Outline

The main contents of this thesis are organized as follows: Chapter 2 introduces the structure and results of the baseline model; Chapter 3 studies the relations between monetary policy and economic crisis (stability; heterogeneity in firms' profitability) ; in Chapter 4, I discuss how different policy combinations will influence the productivity change of an economy (growth; heterogeneity in firms' productivity); in Chapter 5, a different behavioral assumption of households is considered to explore the possible effects on economic stability and firm dynamics (stability and welfare; heterogeneity in firms' profitability); in Chapter 6, I will study an economic system coupled with a financial engine, and discuss the implications to the economic crisis (stability and competitiveness; firms' financing capacity); Chapter 7 concludes the whole thesis.

Chapter 2
Baseline Models

This chapter will give a brief review on the baseline model, Mark0. This minimal agent-based model is kept simple to study the basic economic circulation between the demand and the supply of products (Gualdi et al. 2015a, 2017). Hence only two kinds of agents, household and firm, are involved. The basic framework of Mark0 can be described as three flows of money (Figure 13): 1) From the households to the firms, i.e. the households pay for the goods produced by the firms; 2) From the firms to the households, i.e. the firms pay wage and dividend to households; 3) From the household and firms with positive cash balance to the other firms, i.e. the household and healthy firms pay the funds for offsetting the bad debts of bankrupt firms and the funds for starting new firms. The total amount of money, which is the sum of firms' net equity and households' wealth, remain constant in the circulation:

$$\text{Total firm assets+Households wealth+Money in bank} = \mathit{const}. \tag{4}$$

2.1 Agent profile

There are three types of agents: firm, household and bank. The total number of firms is N_f and the number of households is μN_f. Although $\mu \gg 1$ is more representative of reality, the value of μ is not relevant to the model behavior, so we just set μ =1 for simplicity. Table 1 Agent profileis a summary of all variables and parameters involved in the basic model (the three bold arrows).

One firm agent produces only one product, and the firms interact with others and household through price competition. At each iteration time t, a firm decides the production $Y_i(t)$, product price $p_i(t)$, relative size of employee $L_i(t)$, according to the demand $D_i(t)$ from the households. All adjustments adopt a heuristic approach which will involve several fractional parameters ηs and γ_p that characterize the speed of heuristic search. After a round of sales, the firm's account will be updated in terms of profit $\rho_i(t)$ and cash balance $\varepsilon_i(t)$. When $\varepsilon_i(t)$, it can be interpreted as net positive deposits $\varepsilon_i^+(t)$ in the bank, and when $\varepsilon_i(t)<0$, it can be interpreted as outstanding debts. $\varepsilon_{-i}(t)$ is the outstanding debts which would be covered by the household and other rich firms if firms i goes bankrupt at this round; in default, $\varepsilon_{-i}(t)$ is set as zero.

Firms have some intrinsic features such as the wage offered to the employee $w_i(t)$, the productivity α per worker, and these two parameters define the core competence of the firm in the labor market and the product market. To note, they represent only the aggregate statuses of the employees.

The agent profile of households encompasses its total wealth $H(t)$, which is just the savings here because no deposits in bank is considered. A fraction c of the savings becomes the consumption $C(t)$, which will be spent on the goods produced by the firms. Household distributed their consumption budget among the products through a choice model involving a parameter β characterizing their sensitivity to the product price. The rate of unemployment $u(t)$ is updated after the firms fire or hire employee.

The function of the bank in the model is rather simplified so that it only records a total deposit $\varepsilon^+(t)$ and a total outstanding debt $\varepsilon^-(t)$ the firms owe to bank. It also controls a level of monetary easing through parameter Θ, which defines an upper limit of financial fragility of firms that can get loans.

Table 1 Agent profile

Type	**Denotation**	**Description**
Firm *i*	$Y_i(t)$	production
	$D_i(t)$	demand
	$p_i(t)$	price
	$L_i(t)$	relative size of employee $\in[0,1]$
	$\rho_i(t)$	profit
	$\varepsilon_i(t)$	cash balance
	$\varepsilon_{-,i}(t)$	outstanding debts to be covered
	$\tilde{u}_i(t)$	employee candidate $\in[0,1]$
	η_+	propensity to hire workers
	η_-	propensity to fire workers
	γ_p	sensitivity of price adjustment
	$w_i(t)$	wage
	α	productivity
	φ	revival rate
Household	$H(t)$	savings(total wealth)
	$C(t)$	consumption
	$C_B(t)$	consumption budget
	$u(t)$	unemployment rate
	c	fraction of consumption
	β	dependence of households' demand on
Bank	Θ	bankruptcy threshold
	$\varepsilon^-(t)$	total loans to firms
	$\varepsilon^+(t)$	total deposits of firms

2.2 Agent behaviors

2.2.1 Firm

A firm and its product are tagged with an index $i = 1,2, \ldots N_f$. The state of firm i is described by price $p_i(t)$ and production $Y_i(t)$ of its product, wage $w_i(t)$ for a unit of labor force and cash balance $\varepsilon_i(t)$. A firm needs to decide how many products to be produced and how much the price of each product to be sold, considering with both the firm's internal status (costs, liabilities, capacity, etc.) and the market conditions (demand for its products, supply of the materials, competition, etc.). The firm in Mark0 is postulated to adopt a set of heuristic rules to adapt with the constantly changing competitive environment. Firm i would adjust the production $Y_i(t)$ to match the market demand $D_i(t)$ for its product and adjust the product price $p_i(t)$ based on the average price $\bar{p}(t)$ in order to compete with the other firms. Updating rules for the two variables are listed as follows:

If $Y_i(t) < D_i(t)$:

$Y_i(t+1) = Y_i(t) + \min\left(\eta_+[D_i(t) - Y_i(t)], \mu\widetilde{u_i}(t)\right)$;

if $p_i(t) < \bar{p}(t)$: $p_i(t+1) = p_i(t)[1 + \gamma_p \xi_i(t)]$;

if $p_i(t) \geq \bar{p}(t)$: $p_i(t+1) = p_i(t)$;

If $Y_i(t) \geq D_i(t)$:

$Y_i(t+1) = \max\left(Y_i(t) - \eta_-[Y_i(t) - D_i(t)], 0\right)$, (5)

if $p_i(t) \leq \bar{p}(t)$: $p_i(t+1) = p_i(t)$;

if $p_i(t) > \bar{p}(t)$: $p_i(t+1) = p_i(t)[1 - \gamma_p \xi_i(t)]$;

where

$$\bar{p}(t) = \frac{\sum_i p_i(t) Y_i(t)(t)}{\sum_i Y_i(t)} \tag{6}$$

is the production-weighted price of firm i at time t; $\xi_i(t)$ are random numbers from a uniform distribution U(0,1) (which are independent across firms and across time steps); γ_p, η_- and η_+ are parameters to control the magnitudes of price and production adjustments. The upward adjustment of production is limited by the available labor force, $\mu\tilde{u}(t)$, which is defined as

$$\mu\tilde{u}(t-1) = \frac{e^{\beta w_i/\bar{w}(t-1)}}{\sum_i e^{\beta w_i/\bar{w}(t-1)}} \mu N_f u(t-1) \tag{7}$$

where

$$\bar{w}(t-1) = \sum_{i\in A} w_i Y_i(t-1) \Big/ \sum_{i\in A} Y_i(t-1)$$

is the output-weighted average wage. Note that β characterizes the households' dependence of intensity of choice on wage (also see the explanation of β for Eq. (15)). For the basic conclusions to be shown, wage dynamics are muted and thus $\mu\tilde{u}(t) = \mu u(t) / N_{of}$, where N_{of} is the number of operating firms in the market.

After adjusting price and production in one round, each firm would update its cash balance. The only cost of production is the wage paid by the firm. Mark0 adopts a simple linear production function, $Y_i(t) = \alpha L_i(t)$, where $L_i(t)$ is the amount of labor employed by firm i and α is the technological parameter. For simplicity, both α and the wage w_i are set to 1 in the simulation. Therefore, the cost of production equals to $L_i(t)w_i(t)$ and the currently realized profit

$$\rho_i(t) := p_i(t)\min[Y_i(t), D_i(t)] - L_i(t)w_i(\mathrm{t}). \tag{8}$$

If both $\rho_i(t)$ and $\varepsilon_i(t)$ is positive, firm i will pay dividend, $\delta\rho_i(t)$ to the household. The cash balance will be updated as:

$$\varepsilon_i(t+1) = \varepsilon_i(t) + \rho_i(t) - \delta\rho_i(t)\theta(\delta\rho_i(t)), \tag{9}$$

where $\theta(x)$ is the Heaviside step function, $\theta(x \geq 0) = 1$ and $\theta(x < 0) = 0$. If the cash $\varepsilon_i(t)$ is not enough for the cost of production $L_i(t)w_i(t)$, the firm can get loan from the bank and $\varepsilon_i(t)$ could be a negative value when firm i is in debt. The financial fragility is measured as the negative of the ratio of the cash balance over the payroll,

$$\Phi_i(t) = -\frac{\varepsilon_i(t)}{Y_i(t)w_i(t)}. \tag{10}$$

By its definition Φ_i could also be interpreted as the leverage of an individual firm.

The indebtment level of a firm would be limited by a default threshold Θ. Firm i would be allowed to continue operating as long as $\Phi_i(t)$ is less than Θ. When $\Phi_i(t) \geq \Theta$, the overindebted firm will go bankrupt. Thus, the parameter Θ is similar to a money multiplier and controls the credit creation in the system. A larger Θ means that the firms can obtain more liquidity with the same scale of operation.

The bad debt of the firms would be accumulated into ε_- which will be borne by the operating firms and the household, that is, $\varepsilon_-(t) \to \varepsilon_-(t) - \sum_i \min\big(0, \varepsilon_i(t)\big)$, $i \in$Bankrupted firms The bankrupt firm would become inactive temporarily and its debt would be cleared, $\varepsilon_i(t) \to 0$.

In each of the following simulation rounds, an inactive firm has a probability φ to get revived. The necessary fund for revived firms, is another portion of ε_-, which would be covered by the operating firms and the household as well, $\varepsilon_-(t) \to \varepsilon_-(t) + \sum_j Y_j(t)w_j(t)$, $j \in$Revived firms. The production $Y_j(t)$ and price $p_i(t)$ of the revived firms would be set to the available labor force $\mu u(t)$ and the production-weighted average price $\bar{p}(t)$, respectively.

After all the firms have the operating status and the cash balances updated, $\varepsilon_-(t)$ would be deducted with priority from the households' wealth, if $H(t) \geq -\varepsilon_-(t)$:

$$H(t+1) = H(t) - \varepsilon_-(t), \varepsilon_-(t) \to 0 \tag{11}$$

and also from the accounts of the active firms with positive cash balance, if $H(t) < -\varepsilon_-(t)$:

$$H(t+1) = 0,\ \varepsilon_-(t) \to \varepsilon_-(t) - H(t),$$

$$\varepsilon_i(t+1) = \varepsilon_i(t) - [\varepsilon_i(t)/\textstyle\sum_{i=1}^{N_f}\max\big(0, \varepsilon_i(t)\big)]\varepsilon_-(t). \tag{12}$$

The cash flow consistency is kept so that the total money

$$H(t)+\sum_{i=1}^{N_f}\varepsilon_i(t)$$

is conserved in the simulation, which evidences Mark0 as a stock-flow consistency model, as described in Equation (4).

2.2.2 Household

The state of the household sector is described by aggregate variables, namely the total saving $H(t)$, the total consumption budget $C_B(t)$ and the unemployment rate $u(t)$. In each round, the total saving is updated after the deduction of ε_- as following:

$$H(t+1) \to H(t+1) + \sum_{i=1}^{N_f} Y_i(t)w_i(t) + \sum_i \delta\rho_i(t) - C(t), \tag{13}$$

where $\sum_{i=1}^{N_f} Y_i(t)w_i(t)$ is the total wage, $\sum_i \delta\rho_i(t)$ is the dividend received, $C(t)$ is the consumption expenditure. The total consumption budget $C_B(t)$ is a portion of the total wealth of household:

$$C_B(t) = c[H(t) + \sum_{i=1}^{N_f} Y_i(t)w_i(t)], \tag{14}$$

where c is the propensity to consume. The demand of product is then distributed among firms based on a choice model (Anderson,1992):

$$D_i(t) = \frac{C_B(t)\, e^{-\beta p_i(t)/\bar{p}(t)}}{p_i(t)Z(t)}, \text{ with } Z(t) = \sum_i e^{-\beta p_i(t)/\bar{p}(t)}. \tag{15}$$

Parameter $\beta \geq 0$ determines the sensitivity of the households, similarly to the role in Equation (7). When $\beta = 0$, it means that the household agent would evenly distribute the consumption budget to all the products without any considerations of price. As β increases, the households become more sensitive so that the demand of product i will be strengthened if the price $p_i(t)$ is more competitive comparing with the average price $\bar{p}(t)$. The demand $D_i(t)$ for the products of firm i would be limited by the realized production $Y_i(t)$, therefore the actual consumption expenditure can be calculated as

$$C(t) = \sum_{i=1}^{N_f} p_i(t)\min[Y_i(t), D_i(t)]. \tag{16}$$

Remember the total number of labor force provided by the household sector is μN_f. The firms would hire labor force evenly from the household sector based on the firms' production plan. Finally, the unemployment rate is calculated as

$$u(t) = 1 - \sum_{i=1}^{N_f} L_i(t)/\mu N_f. \tag{17}$$

2.2.3 Bank

The bank records the total amount of firm deposits

$\varepsilon^{+}(t)= \sum_i \max \ 0, \varepsilon_i(t)$

and the total amount of firms outstanding debts

$\varepsilon^{-}(t)= \sum_i \min \ 0, \varepsilon_i(t)$.

Then the cash flow consistency (Eq. (4) could be represented by the following equation:

$$\varepsilon^{+}(t) + \varepsilon^{-}(t) + H(t) \equiv const. \tag{18}$$

2.3 Results and general conclusions of Mark0

Here we would only give a short introduction of the simulation results of Mark0. The parameters or initial conditions are listed in Table 2.

The detailed analysis and discussion on the phase diagram of Mark0 can be found in (Gualdi, 2015a). Although there exist 8 parameters in Mark0, it is found that the status of the model economy is controlled by the liquidity parameter Θ and hiring/firing propensity $R = \eta_{+}/\eta_{-}$ which measures the relative amplitude of hiring and firing labor force. Note that R could simply be behavioral tendencies of firms, or more sophisticatedly, could be induced by other mechanisms. According to a previous study, the asymmetry could result from the firms' reactions to the changing of interest rates. The rest parameters could only have minor effects on the locations of the phase boundaries. The existence of the four phases, FU, RU, EC and FE, is quite robust against various modifications of the model (Gualdi, 2015a). The full phase space is split, by a critical hiring/firing propensity $R_c = 1$, into the region of FU and the regions of RU, EC and FE (Figure 14a). When $R \geq R_c$, the status of model economy is controlled by the liquidity parameter Θ.

Table 2 Parameter settings in the baseline model.

Parameter/ Initial condition	Value	Remarks
N_f	500	Firm number
$S(0)$	$\mu N_f/2$	$\mu = 1$
c	0.5	
β	1	
w_i	1	
α_i	1	
$p_i(0)$	$1+\zeta_{ip}(t)$	$\zeta_{ip}(t) \in U(-0.1,0.1)$
$l_i(0)$	$1+\zeta_{il}(t)$	$\zeta_{il}(t) \in U(-0.1,0.1)$

$A_i(0)$	0.5	
η_+	0.3	
$\eta-$	0.1	
γ_p	0.05	
φ	0.1	

Note: $\zeta_i(t)$ are random numbers obeying a uniform distribution from -0.1 to 0.1.

In Figure 15b, we give the four typical time series of the unemployment rate in each of the four phases. When Θ is very small, the economy would operate in RU phase and a medium value of unemployment rate persists; when Θ is very large, the economy would operate in FE phase that almost all labor force in the model is employed, indicated by the nearly zero unemployment rates; when Θ is set to an intermediate value, the EC phase emerges. When the model economy is operating in EC phase, the unemployment rate could be nearly zero most of the time as in the FE phase. However, the economic crises occur (quasi-)periodically, indicated by the sharp spikes of the unemployment. Although the other parameters could alter the amplitude and frequency of the crises, the occurrence of crises appear inevitable.

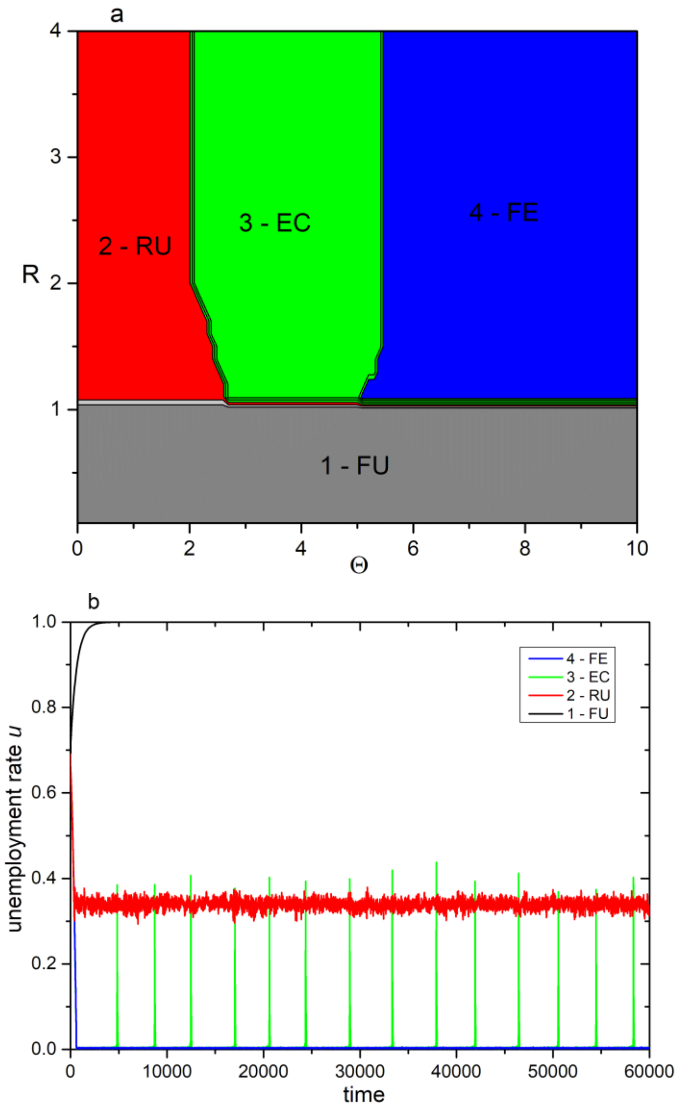


Figure 14 The four phases in Mark0, FU: full unemployment; RU: residual unemployment; EC: endogenous crises; FE: full employment. (a) The phase diagram of Mark0 in the $\Theta - R$ plane, with the parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$. (b) Typical time series of the unemployment rates $u(t)$ in the four phases.

The global leverage ratio k can be used to help understand how the endogenous crises happen in the model economy:

$$k(t) = \frac{\varepsilon_-(t)}{H(t)+\varepsilon_+(t)}. \tag{19}$$

In a good state of the economy (Figure 15), the global leverage k gradually increases and stabilizes around a high level, reflecting the firms' demand for liquidity due to the expansion of production; on the other hand, in the case of a bad economy, k increases quickly at first but stabilizes around a relatively lower level, which is achieved by the balance between the surviving firms and the bankrupt firms.

However, in the EC phase, the dynamics of the global leverage is characterized by recurring cycles of fast increase and sudden collapse corresponding to the occurrence of endogenous crises.

This intermittent behavior is caused by the clustering of the indebted firms. Figure 16 gives the distributions of the individual firms' fragility Φ for 3000 time steps in EC and FE phase of Mark0. Remind that a firm agent's fragility $\Phi_i(t)$, defined as the ratio of its cash balance $\varepsilon_i(t)$ to its scale of production $Y_i(t)w_i(t)$(Eq.(10)), would decide the firm's fate (bankrupt or not). Firms with positive values of $\Phi_\mathrm{i}(\mathrm{t})$ are in debt and firms with negative values of $\Phi_\mathrm{i}(\mathrm{t})$ are holding cash and have no debt. When $\Phi_\mathrm{i}(\mathrm{t})$ hits the threshold, the corresponding firm i would go bankrupt and its bad debt would be assumed by other agents in the system, leading to a jump of $\Phi_\mathrm{i}(\mathrm{t})$ to zero. The bad debt of a bankrupt firm would cause a shock to the households' wealth (thus cut demand in the next round), and to the financial fragilities of the firms with net cash.

In FE phase of Mark0, as long as sufficient liquidity is provided, $\Theta = 15$ here, all the underlying Φ would safely fluctuate below the boundary Θ, thus no firm would go bankrupt and the unemployment rates is stable and near zero. The distribution of Φ is nearly symmetric and gaussian-like (Figure 16a. As the provided liquidity is decreased to $\Theta = 5$, a cluster of indebted firms appears (Figure 16b, which can be identified by the distribution peak in the positive axis of Φ. While the distribution of Φ in FE phase is stationary, the distribution peak in EC would move towards the threshold Θ (the vertical dashed line) as the shade area in the subfigure (indicating the time window of the data samples) get closer to the collapse point of the global leverage k. In fact, the endogenous crises occur when the peak bumps into the thresholds Θ.

Based on the phase diagram of Mark0, we can imagine that for a regulator or a central bank who wants to keep stable and low unemployment in the model economy with $R \geq R_c$, she/he just needs to implement a very loose monetary policy. In the meantime, the regulator should be very cautious to tighten the liquidity because the difficulty of detecting the phase transition from FE to EC in the early stages.

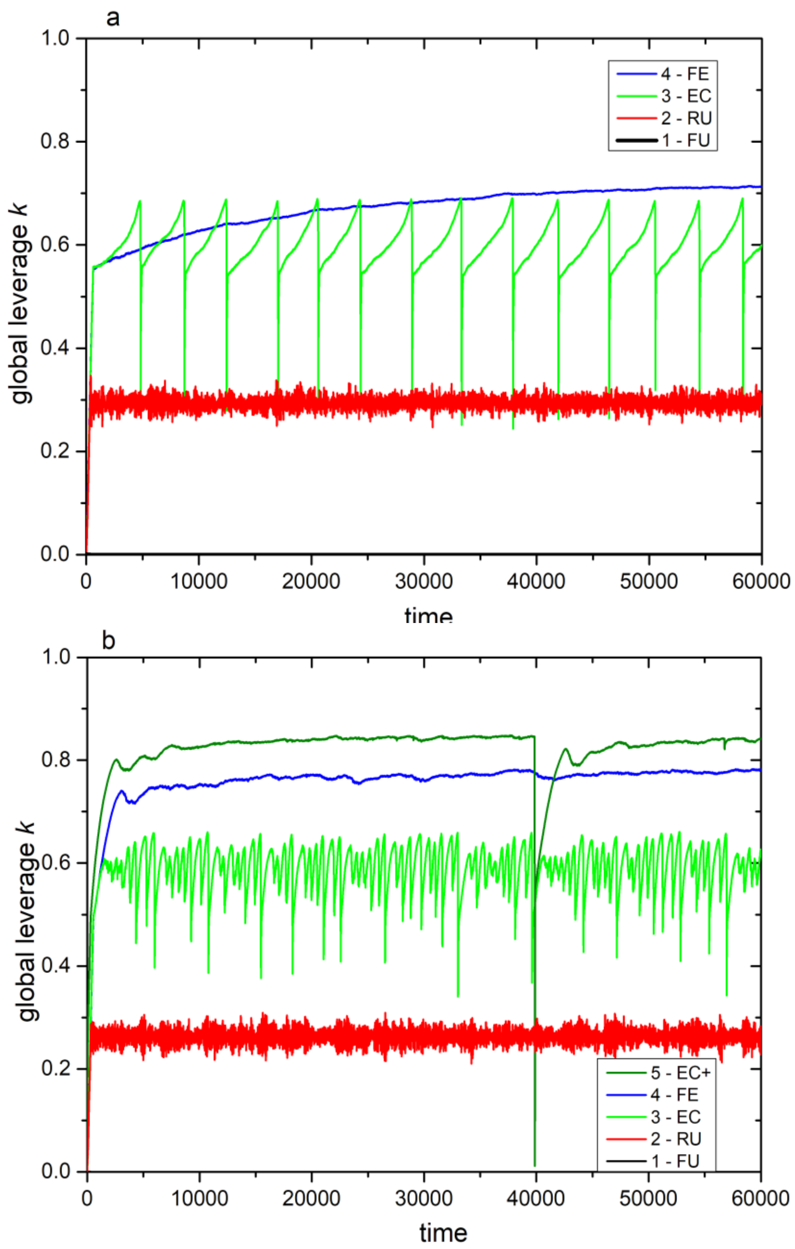


Figure 15 (a) Typical time series of the global leverage $k(t)$ in the four phases in Mark0. (b) Typical time series of the global leverage $k(t)$ in the five phases in HoP-Mark0.

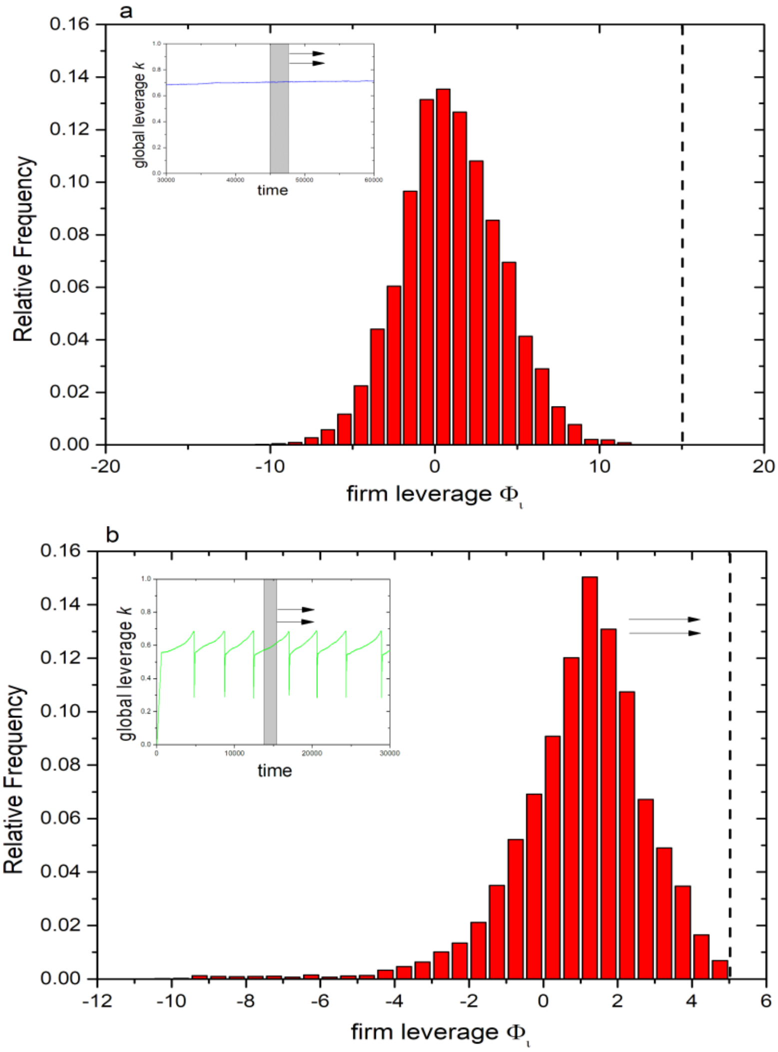


Figure 16 The distributions of firms' leverage Φ in FE and EC phase in Mark0, with $N_f = 2000, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$. (a) FE: the distribution is calculated from the data sample during a period of 3000 time steps, indicated by the shaded region in the subfigure. The dashed line indicates the default threshold $\Theta = 15$; (b) EC: the distribution is calculated from the data sample during a period of 3000 time steps before the occurrence of a crisis, indicated by the shaded region in the subfigure. The dashed line indicates the default threshold $\Theta = 5$.

Chapter 3
Excessive liquidity and endogenous crises

This part studies how the heterogeneity of firms' profitability can lead to economic crises in a stylized macroeconomic agent-based model (ABM). Previous studies showed the relevance of the income distribution to the economic crises, whereas we find, in a well-studied macroeconomic ABM endowed with diverse economic performance of firms, while providing liquidity is an effective tool to stabilize the economy, an excessive liquidity may cause enhanced endogenous crises. The mechanism for such large-scale crises is found in the model as the increasing gap of financial status between the advantageous and disadvantageous groups of firms. Two factors, diverse production cycles and variable wages, are used to test the robustness of the occurrence of crises. Moreover, our study shows that the leverage ratio based on aggregate values may underestimate the systemic risk. Hence, a proposal for the new design of the risk measurement in the macro-economy is given.

3.1 Background

Firms can be very heterogeneous in terms of economic performance. For firms operating in different sectors, the profit margins could be quite different because of sector-specific properties and different stage of development. In fact, even in the same industry, the gap of profitability could be huge between firms, due to a variety of complex causes, such as the ability of cost control and brand premium. For example, the net margins of Japan airlines and ANA group are 11.1% and 2.3% in 2014, respectively, although they were both large Japanese airlines.

Other factors which can cause profitability gaps among firms include market monopoly, difference in competitiveness (see Porter's Five Forces Framework for analyzing firm's competitiveness (Porter, M. E.， 1989), different costs of capital, etc.

The simplicity of the well-studied Mark0 make it an ideal framework for us to extend the model and study links between firm heterogeneity at the individual level and economic crises at the aggregated level. However, one deficiency of Mark0 is that the firm agents are built in a homogeneous way. Except for some randomness, the agents own the same behavioral rules and have no individual characteristics. As a result, it can be shown that the distribution of the firms' accumulating profits is symmetrical and Gaussian-like. In the contrast, if measured by capitalization, a large ratio of the total market value is actually contributed only by a small number of "winner" companies in the real economy (The market capitalization of FAANG is roughly 14% of the value of S&P500, and the S&P500 market capitalization is 70% to 80% of the total U.S. stock market capitalization). In this research, the firm heterogeneity is modeled by introducing the diverse discount rates for products of the firms. We find that, without the consideration of firm heterogeneity, the high liquidity levels could be the "panacea" to maintain the stable and low unemployment status of an economy. However, if the heterogeneity presents, the excessive liquidity can lead to the emergence of a new phase, in which economic crises become less frequent but more severe. This newly found phase is named as "EC+" and its robustness is verified by investigating the influences from factors weakening the heterogeneity, typically the production cycles of firms and the variable wage system. Interestingly, we also find that the global leverage ratio proposed in Mark0 (Gualdi, 2015b) cannot be used to measure the risk of crises in EC+ phase. To fix this deficiency, we further propose an adjusted global leverage ratio which take the firm heterogeneity into account so as to effectively measure the risk in the model economy.

3.2 The model

The only difference of the extended model from the baseline lies in the demand function. Each firm agent would be endowed with a constant discount rate $\sigma_i > 0$, which reflects the competitive advantage of the firm. Then the price p_i in Equation (15) would be substituted by the modified price, $\widetilde{p_i} = p_i/\sigma_i$.

With the modified price, consider that two firms i and j with $\sigma_i > \sigma_j$, coincidentaly set their product prices the same, $p_i(t)$=$p_j(t)$. The demands for the products of firm i and firm j would be actually decided by $\widetilde{p_i} = p_i(t)/\sigma_i$ and $\widetilde{p_j} = p_j(t)/\sigma_j$, which results in $D_i(t) > D_j(t)$. Hence firm i would have a higher probability than firm j to sell out its products. However, $p_i(t)$ and $p_j(t)$ would still be used in the transaction and accounting process. Thus, firm i would have a higher profitability than firm j. From the perspective of the households, σ_i can also be regarded as a measure of the consumer preference to the product of firm i.

3.3 Simulation results

In the following text, we will call the Mark0 model with the extension of heterogeneity of profitability as HoP-Mark0.

3.3.1 Dynamics and phase diagram

Figure 18 gives the new phase diagram and the five typical time series of the unemployment rate $u(t)$ through the simulation of HoP-Mark0. In the phase diagrams of Mark0 (Figure 3a), FE phase persists for any increase of the default threshold Θ, as long as Θ is larger than the critical $\Theta_{EC\rightarrow FE}$ that separates EC phase. However, in HoP-Mark0 simulation, an additional phase, named endogenous crises plus (EC$^+$), would emerge when Θ is larger than a new critical $\Theta_{FE\rightarrow EC^+}$. The crises in EC$^+$ phase is characterized by lower incidence but significantly larger amplitude of the burst. Moreover, the dynamics of unemployment rates in EC phase also becomes chaotic.

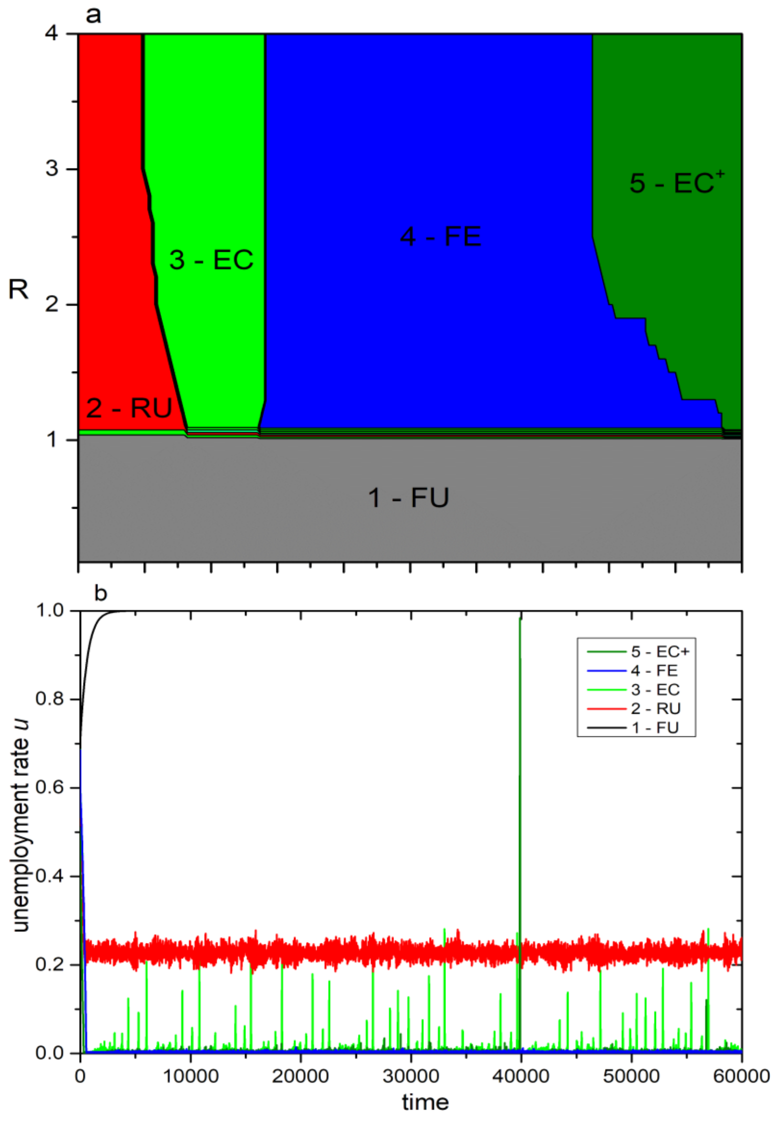


Figure 17 The five phases in HoP-Mark0, FU: full unemployment; RU: residual unemployment; EC: endogenous crises; FE: full employment; EC$^+$: endogenous crises plus. (a) The phase diagram of HoP-Mark0 in the $\Theta - R$ plane with the parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$. (b) Typical time series of the unemployment rates $u(t)$ in the five phases. π_i of the firms are random numbers from a uniform distribution U(1, 3/2). A larger upper limit of the distribution would increase the region of EC^+.

Hence, if considering the heterogeneity in firms' economic performance, easy credit is no longer a panacea for the modeled economy. To achieve a low and stable unemployment, the available credit, controlled by Θ, must be carefully set between the lower limit $\Theta_{EC \to FE}$ and the upper limit $\Theta_{FE \to EC^+}$. Otherwise, the modeled economy would suffer from frequently occurring crises when $\Theta_{RU \to EC} < \Theta < \Theta_{EC \to FE}$,or be in danger of extremely strong crises, when $\Theta > \Theta_{FE \to EC^+}$.

3.3.2 The origins of endogenous crises

The variation of phase diagram motivates us to investigate the influence of the heterogeneity in firms' economic performance on the occurrence of endogenous crisis at the micro-level. We have known in mark0 that for sufficiently large Θ, the distribution of Φ can keep a Gaussian symmetric shape (Figure 16) but this no longer holds in HoP-Mark0. Figure 18 gives the distributions of the individual firms' fragility Φ for 3000 time steps in FE and EC^+ phase of HoP-Mark0. Although the unemployment rates in FE phases (the blue lines in Figure 14b and Figure 17b) of Mark0 and of HoP-Mark0 are similar, from the perspective of Φ distribution (Figure 18a and Figure 16a), one can notice that the low and stable unemployment have different underlying dynamics in the two models. In FE phase of HoP-Mark0, the bankruptcies of the firms with poor economic performance are quite frequent. Because the impact of the bankruptcies is not strong so that it can be absorbed by the firms with good financial conditions, no macroscopic crisis would be observed. The shape of the distributions of firms' Φ would not change in FE phase of HoP-Mark0 as well. As the liquidity is increased to $\Theta = 20$, the higher liquidity would not cause any change in Mark0 and the Φ distribution would be the same as the one when $\Theta = 15$. However, in HoP-Mark0, the cluster of the indebted firms would appear again due to the prolonged survival time of the disadvantageous firms. The existence of the few advantageous firms becomes sort of "liquidity black hole" - the liquidity would not be used to prevent the endogenous crises but be absorbed by the advantageous firms. Moreover, the indebted firms would be allowed to accumulate higher leverages, due to the excess liquidity so that an enhanced endogenous crisis would occur when the cluster bump into the threshold. In the appendix, the time evolutions of the firms' leverage Φ are provided to help understand the underlying dynamics.

Interestingly, it is notable that the global leverage k is quite stable before the occurrence of the collapse in this situation and thus it can no longer be used as a measure of crisis risk in this phase. In Section 3.5 Implication on the measurement of risk for endogenous crises, we would propose an adjusted global leverage which can be used as a risk indicator when heterogeneity of firms' economic performance is considered and excessive liquidity is injected.

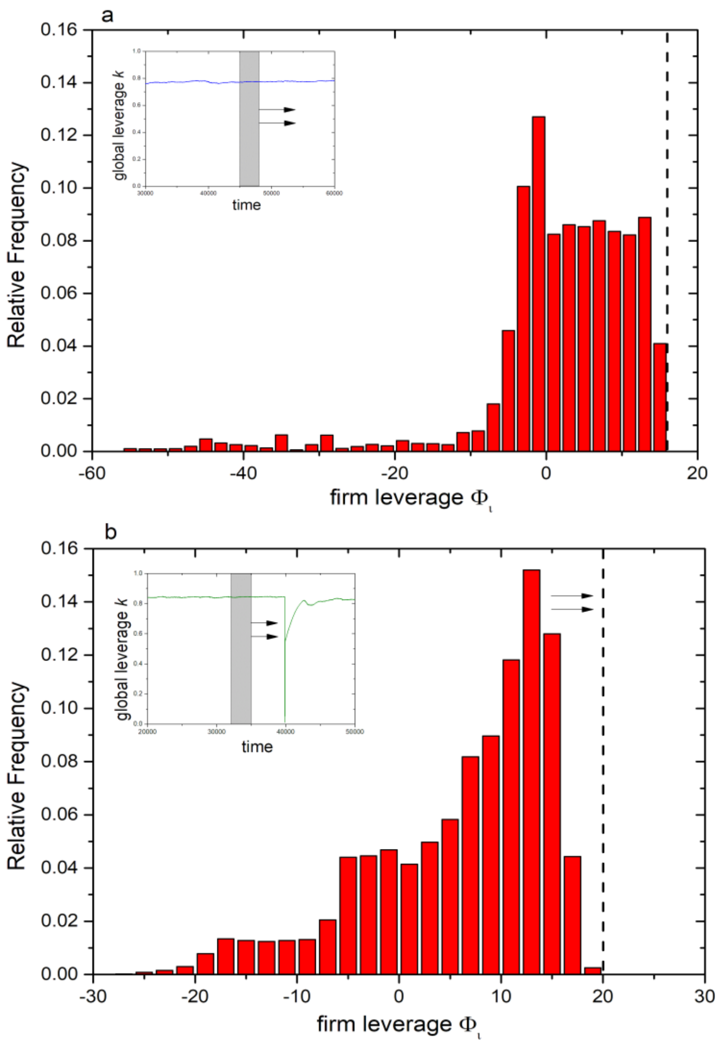


Figure 18 The distributions of firms' leverage Φ in FE and EC$^+$ phase in HoP-Mark0, with $N_f = 2000, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$. (a) FE: the distribution is calculated from the data sample during a period of 3000 time steps, indicated by the shaded region in the subfigure. The dashed line indicates the default threshold $\Theta = 15$; (b) EC$^+$: the distribution is calculated from the data sample during a period of 3000 time steps before the occurrence of a crisis, indicated by the shaded region in the subfigure. The dashed line indicates the default threshold $\Theta = 20$.

3.4 Other factors and the robustness of crises

In reality, there can be factors that would reduce the heterogeneity of firms' economic performance. For instance, firms with good economic performance may pay higher wages and bonuses, thus reduce the net profits; besides, even if a firm has high profit margin, production cycle may lead to mismatch between supply and demand and cause losses. In this section, production cycles and variable wages would be incorporated in the model to examine robustness of the phase diagram, particularly for EC and

EC^+ phase.

3.4.1 Production cycles

In Mark0, the firms can make plans to increase or decrease their production, then fulfil the production and launch the products to the market immediately after they detect the imbalance between demand and supply in the market. However, in reality, the rebalance could be time consuming process, which usually cause a time lag. Note that this time lag was believed to be the mechanism accounting for the inventory cycles, also known as the Kitchin cycle (Kitchin 1923). The time lag itself may be induced by different kinds of factors: 1) the time-costing manufactory process, e.g., the manufactory of an airplane can take years; 2) the complex decision-making process for the managers, e.g., managers from different departments need to have meetings to reach an agreement; 3) the natural limitation of growth cycle, e.g., the production adjustment for agricultural commodities cannot be implemented until the next planting season. Regardless of different origins, we may use the term "production cycles" to represent the synthetic effects of the time lag discussed above.

Because of the existence of the time lag between the production and sale process, the current market supply S_i available to the households is actually the production of firm i before τ_i time steps:

$$S_i(t) = Y_i(t - \tau_i). \tag{20}$$

Clearly, a smaller τ_i indicates a shorter product cycle so that firm i can react to the market imbalance more promptly. When the time lag vanishes, $\tau_i = 0$, the firm launches its products to the market without delay, just the same as the firms do in Mark0. The adjustment rules for price and production, the households' behaviour and the bankruptcy and revival rules are the same as in Mark0. The firm's accounting will be changed to:

$$\rho_i(t) = P_i(t)\min[S_i(t), D_i(t)] - Y_i(t).$$

Thus, besides the challenge of predicting the market demand in a longer time horizon, the production cycles also cause cash flow problems because the current realized revenue $P_i(t)\min[S_i(t), D_i(t)]$ may not match the current production cost $Y_i(t)$ which can only be turned into revenue after τ_i time steps. The other change is that the average price will be calculated according to the price of the products on the market but not the products still in production,

$$\bar{p}(t) = \frac{\sum_i p_i(t) S_i(t)(t)}{\sum_i S_i(t)}.$$

Lastly, we assume that the product price can be adjusted without time delay, though firms in real situations may have some sluggishness in price adjustments.

The effect of the production cycles is quite counter intuitive. In traditional economic theory, the existence of production cycles reduces operational efficiency of firms and is deemed to have negative effect on the market efficiency. However, in Mark0, production cycles can bring positive effects on the macroscopic performance of the system. Under the same parameter setting, while the FE, RU and FU phases are kept unchanged and the phase boundaries are similar to the phase diagram of Mark0, however, EC phase would be replaced by a new phase, cyclical fluctuation (CF) phase. In contrast with the large spikes caused by synchronized collective behaviors of firms in the EC phase, we can observe that in the CF phase only small quasi-periodical fluctuations in the unemployment rates (Figure 19a). In HoP-Mark0, the production cycles also have a stabilizing effect – the original EC phase is found to be transferred to FE phase. In fact, according to the discussion about the heterogeneous economic performance of firms and the endogenous crisis, it can be expected that the production cycles would mitigate the robust endogenous crisis - converting EC phase to CF phase in Mark0 and converting EC phase to FE phase in HoP-Mark0. The validity of the simple heuristic strategy for production implemented by the firm agents in the model is very dependent on the prompt adjustments based on the most recent market imbalance. Thus, the introduction of production cycles would increase the prediction error of firm agents and thus largely weaken the heterogeneity of firms' economic performance – a lucky firm can only maintain its economic advantage for very few time steps, meanwhile the indebted firms will go bankrupt quickly. The result of the very frequent bankruptcies is that total debt risk will not be accumulated.

However, we find that EC^+ phase is robust against the introduction of the production cycles (Figure 19b). In HoP-Mark0, even if the production cycles would reduce the profitability of all the firms, the advantageous firms can still outperform the disadvantageous in the environment with excess liquidity and eventually the large financial gap between the advantageous and the disadvantageous have to be relieve through the occurrence of crisis.

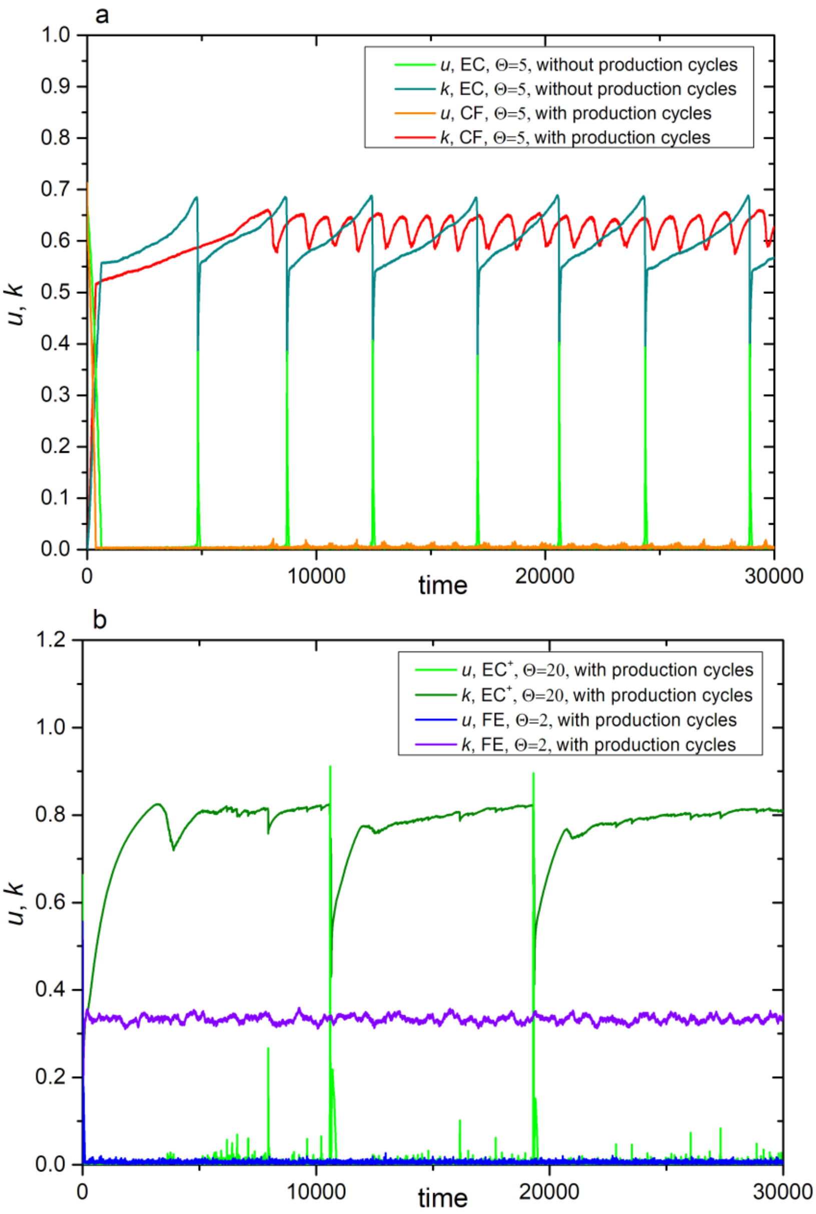


Figure 19 (a) Typical time series of the unemployment rates $u(t)$ and the global leverage $k(t)$ in Mark0. (b) Typical time series of the unemployment rates $u(t)$ and the global leverage $k(t)$ in HoP-Mark0. The parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$. τ_i are random numbers from a uniform distribution U(1,10).

3.4.2 Variable wages

A set of simple wage updating rules are as follows (Gualdi, 2015):

If $Y_i(t) < D_i(t)$ and $\rho_i(t) > 0$:
$$w_i^t(t+1) = w_i(t)[1 + \gamma_w(1 - u(t))\xi_i'(t)];$$
If $Y_i(t) > D_i(t)$ and $\rho_i(t) < 0$:
$$w_i(t+1) = w_i(t)[1 - \gamma_w u(t)\xi_i'(t)];$$
In the other cases: $w_i(t+1) = w_i(t)$. (15)

where γ_w is a parameter controlling the magnitude of wage adjusting and $\xi_i(t)$ an independent random variable from a uniform distribution U(0,1). When a firm raises its wage, $w_i(t+1)$ would also be capped by the "break-even" point $\rho_i(t) = 0$, thus,
$$w_i(t+1) = \min\,(w_i^t(t+1),$$
$$p_i(t)\min[Y_i(t), D_i(t)]\,/Y_i(t)).$$

The logic behind the rule is quite simple: when a firm makes profit and its products is in short supply, the firm will raise wages based on how tight the labour market is (i.e. depending on the employment rate, $1 - u(t)$); when a firm makes losses and its supply exceeds demand, the firm will reduce its wage to make an attempt to return to profit.

The main effects brought by the wage dynamics in Mark0 are the appearance of inflation and the shrinking of EC region (Gualdi, 2017). In HoP-Mark0, we employed the same wage updating rules and found it has similar effects. If using the ratio γ_w/γ_p as a magnitude measure of the relative wage flexibility, higher γ_w/γ_p would have a stronger stabilizing effect. In the phase diagram, EC region would be smaller as γ_w/γ_p is increased. Furthermore, as long as $\gamma_w/\gamma_p > 0.01$, EC^+ phase would disappear (Figure 20a). The disappearance of EC^+ phase can be expected: EC^+ phase relates to the increasing wealth gap between the advantageous firms and the disadvantageous firms in the environment with excess liquidity. The proposed wage updating rules will make the advantageous firms increase the wages until the wages are capped by the "break-even" point. Thus, the excess profits of the advantageous firms would be quickly redistributed through wages and the wealth gap would be eliminated, as long as the relative wage flexibility is high enough.

Inflation and deflation can also be observed in HoP-Mark0 when the wage updating rules are incorporated (Figure 20b). In the "bad" economy (FU phase, $R < R_c$), deflation and high unemployment rate persist. When $R \geq R_c$, the liquidity parameter Θ takes over the status of the modelled economy. For $\Theta < \Theta_{RU \to EC}$, there is zero inflation in the price index $\bar{p}(t)$ and the unemployment rates stay high but remain stable; for $\Theta_{RU \to EC} < \Theta < \Theta_{EC \to FE}$, inflation and deflation will appear alternately; for $\Theta > \Theta_{EC \to FE}$, inflation and full employment persist. As was mentioned above, when the firms adopt the wage updating rules but the relative wage flexibility is relatively low in an environment with excess liquidity, EC^+ phase would appear. Interestingly, in EC^+ phase, the price index is characterized by long-term inflation but occasionally price collapses induced by the endogenous crises (Figure 21).

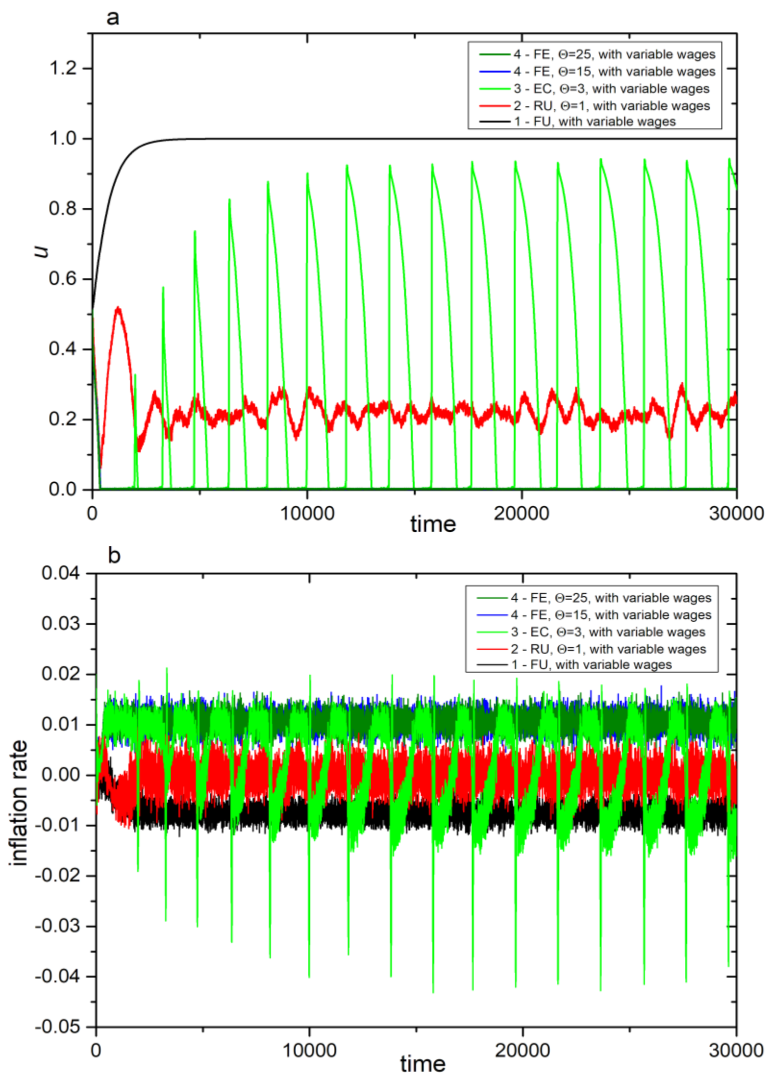


Figure 20 (a) Typical time series of the unemployment rates $u(t)$ with the extension of variable wages in HoP-Mark0. When the wage flexibility $\gamma_w/\gamma_p > 0.01$, EC^+ phase would be converted to FE phase. The parameters: $N_f = 1000, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1$, $\gamma_w/\gamma_p = 0.1$. (b) The corresponding inflation rates in HoP-Mark0. FU, RU, EC and FE phase are featured with deflation, zero inflation, alternations of deflation and inflation and inflation, respectively. The inflation rates are calculated from the 50-step moving average of the average price $\bar{p}(t)$.

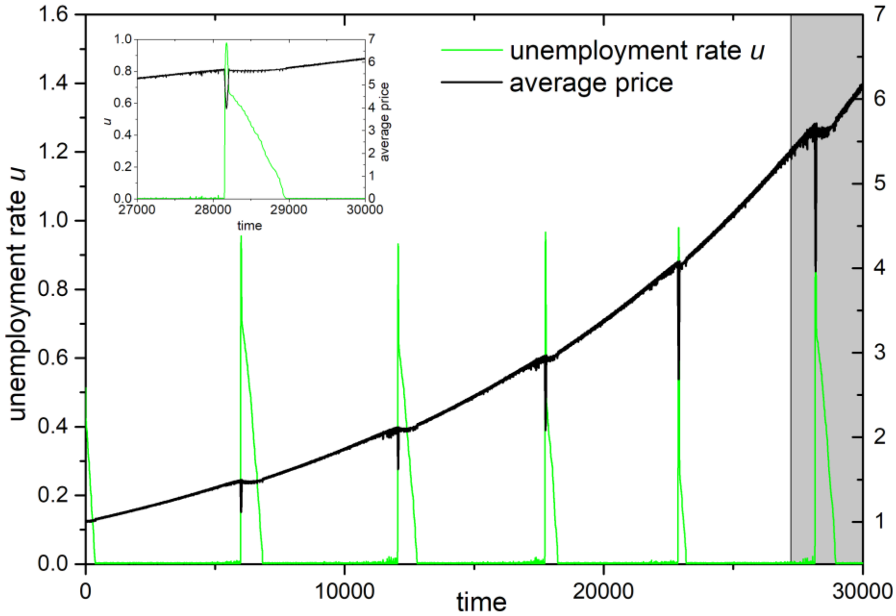


Figure 21 The unemployment rates $u(t)$ and the average price in EC$^+$ phase of HoP-Mark0 with the extension of variable wages. When the wage flexibility $\gamma_w/\gamma_p < 0.01$, EC$^+$ phase would exist. The parameters: $N_f = 1000, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1, \gamma_w/\gamma_p = 0.01, \Theta = 25$.

3.5 Implication on the measurement of risk for endogenous crises

In Mark0, the global leverage k can be used as a measure of risk in EC phase. In the no-crisis phases (FE and RU), k would stabilize at certain levels. But in EC phase, it keeps increasing until the occurrence of crisis, which would lead to a quick deleveraging process. However, when the firms present heterogeneity of economic performance (EC^{+} phase of HoP-Mark0), the global leverage k does not show clear increase before crises (Figure 15b and Figure 19b). Thus, one can hardly detect the increasing risk in the system through the global leverage. This is due to the fact that only the aggregate debt and equity are used in the calculation of the global leverage. But in HoP-Mark0, the liquidity distribution also have an important effect on the systemic risk. When the liquidity is just enough, i.e., $\Theta_{EC\rightarrow FE} < \Theta < \Theta_{FE\rightarrow \mathrm{EC}^{+}}$, the excessive liquidity of the advantageous firms would be used to cover the bad debt of the disadvantageous firms. Thus, the advantageous firms would not increasingly occupy the liquidity and the risk is defused continually. However, when the liquidity is excessive, i.e. $\Theta > \Theta_{FE\rightarrow \mathrm{EC}^{+}}$, the advantageous firms would absorb the liquidity and grow larger and larger, meanwhile the disadvantageous firms would survive for prolonged time and accumulate higher leverages. Therefore, the global leverage k would underestimate the risk in HoP-Mark0 because it does not take the liquidity distribution into account.

To correctly measure the risk accumulation in the HoP-Mark0, we propose a new variable, the adjusted global leverage $k_{x\%}^{adj}$ which mitigate the underestimating effect brought by the advantageous firms:

$$k_{x\%}^{adj}(t) = \frac{\varepsilon_{-}(t)}{H(t)+\varepsilon_{+}(t)-\varepsilon_{x\%}(t)} \tag{21}$$

where $\varepsilon_{x\%}(t)$ is the summation of the cash occupied by the most advantageous x% firms in all the firm agents. Figure 10 gives the original global leverage k and the adjusted global leverage $k_{15\%}^{adj}(t)$ in the moderate liquidity case ($\Theta = 15$) and the excessive liquidity case ($\Theta = 20$), corresponding to FE and EC^{+} phase in HoP-Mark0. In FE phase ($\Theta = 10$), the adjusted global leverages would fluctuate around an equilibrium level, suggesting a stable distribution of liquidity is reached (Figure 22a). The adjusted global leverage $k_{15\%}^{adj}(t)$ clearly indicates the increasing leverage risk before the occurrence of crises in EC^{+} phase, while the global leverage k is stable before crisis (Figure 22b).

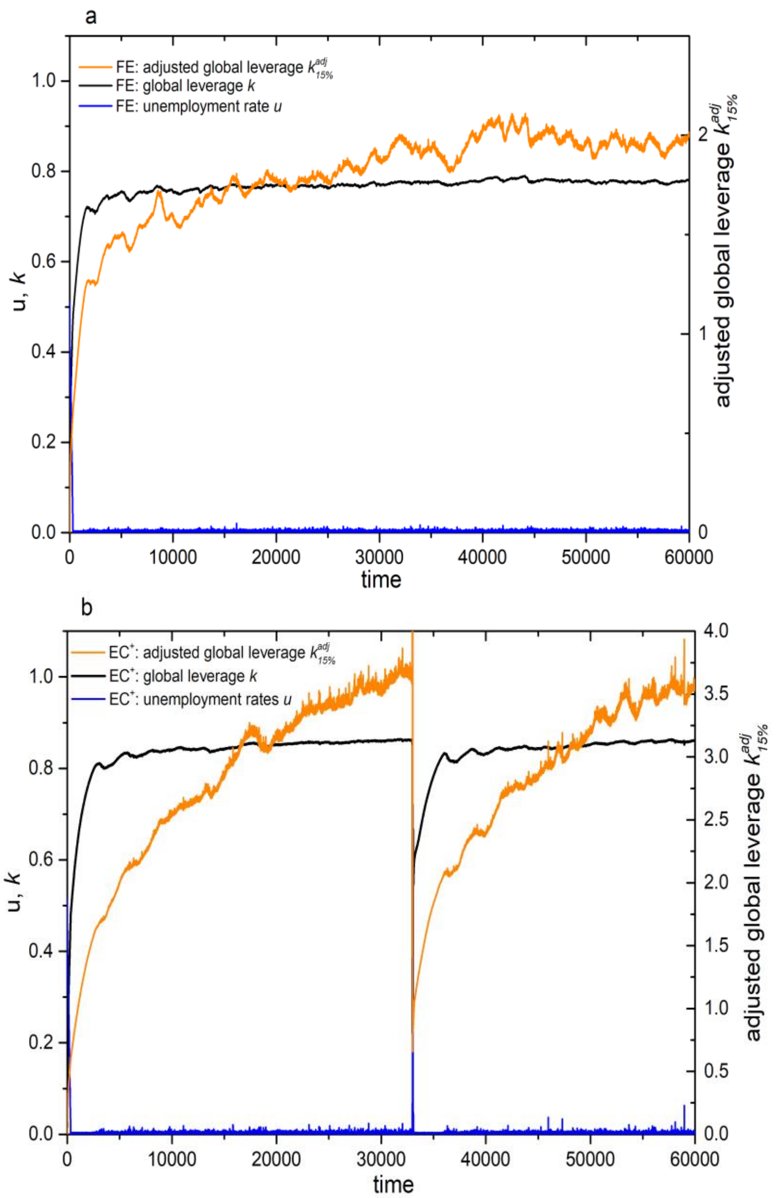


Figure 22(a) The global leverage k, the adjusted global leverage $k_{15\%}^{adj}$ and the corresponding unemployment rates u in FE phase in HoP-Mark0. (b) The global leverage k, the adjusted global leverage $k_{15\%}^{adj}$ and the corresponding unemployment rates u in EC^+ phase in HoP-Mark0.

For a better comparison of the firm dynamics between Mark0 and HoP-Mark0, Figure 23 ~ Figure 26 give the time evolutions of the firms' leverage in EC and FE phase in Mark0, and in FE and EC^+ phase in HoP-Mark0, respectively. The firms with positive values of Φ are in debt while the firms with negative values of Φ are holding cash and have no debt. When $\Phi_\mathrm{i}(\mathrm{t})$ hits the default threshold, the corresponding firm i would go bankrupt and its bad debt would be assumed by other agents in the system, leading to a jump of $\Phi_\mathrm{i}(\mathrm{t})$ to zero. The collective bankruptcies of the firms indicate the occurrence of the endogenous crises in EC or the enhanced endogenous crises in EC^+.

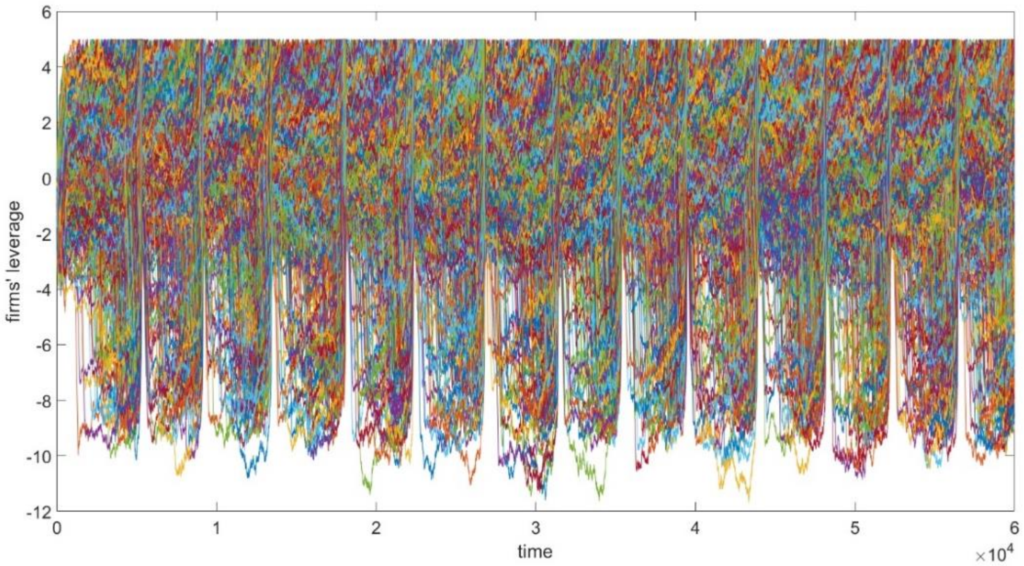


Figure 23 The time evolutions of the firms' leverage in EC phase of Mark0. Each line represents one of the 500 firm agents. The parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1, \Theta = 5$.

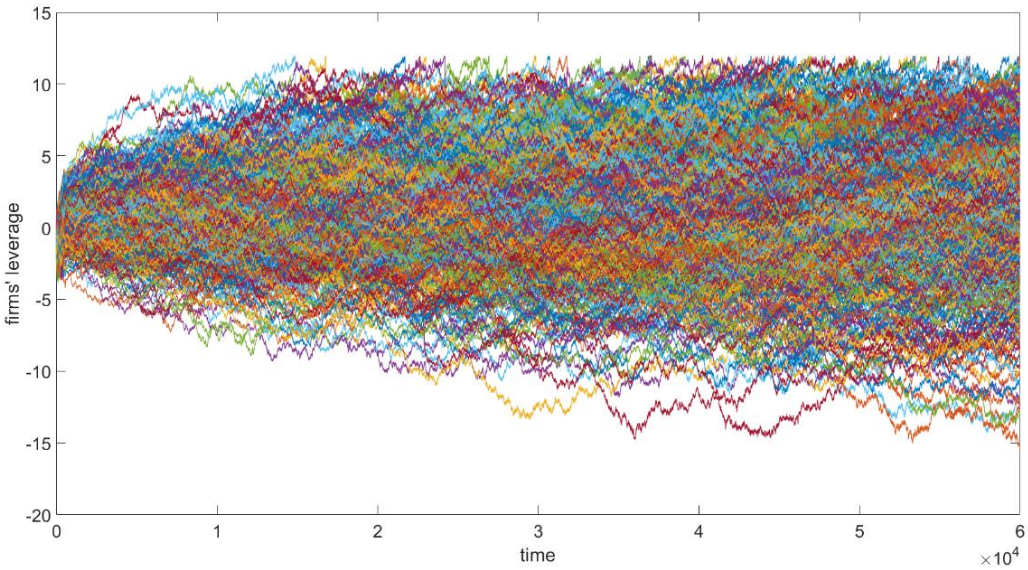


Figure 24 The time evolutions of the firms' leverage in FE phase of Mark0. Each line represents one of the 500 firm agents. The parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1, \Theta = 12$.

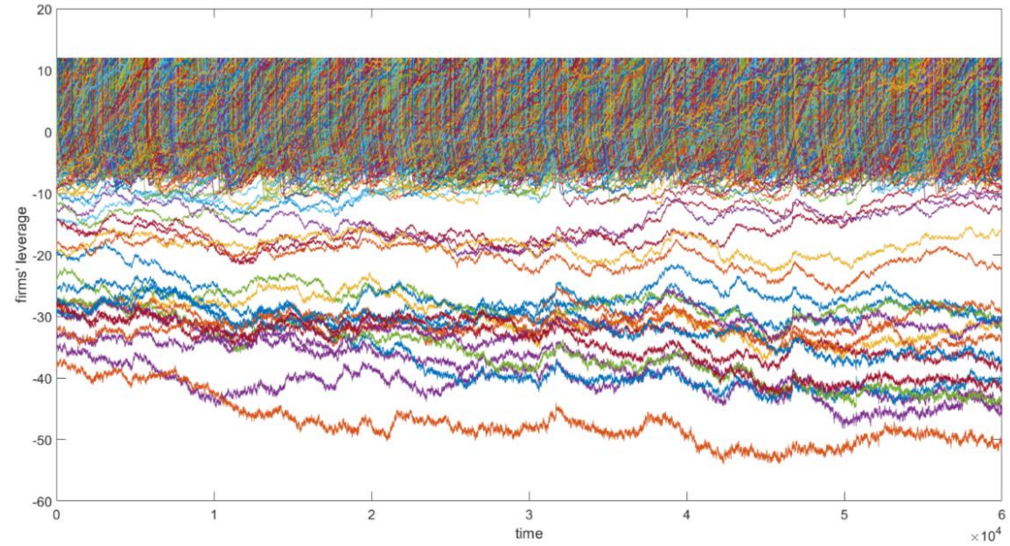


Figure 25 The time evolutions of the firms' leverage in FE phase of HoP-Mark0. Each line represents one of the 500 firm agents. The parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1,$ $\Theta = 12$.

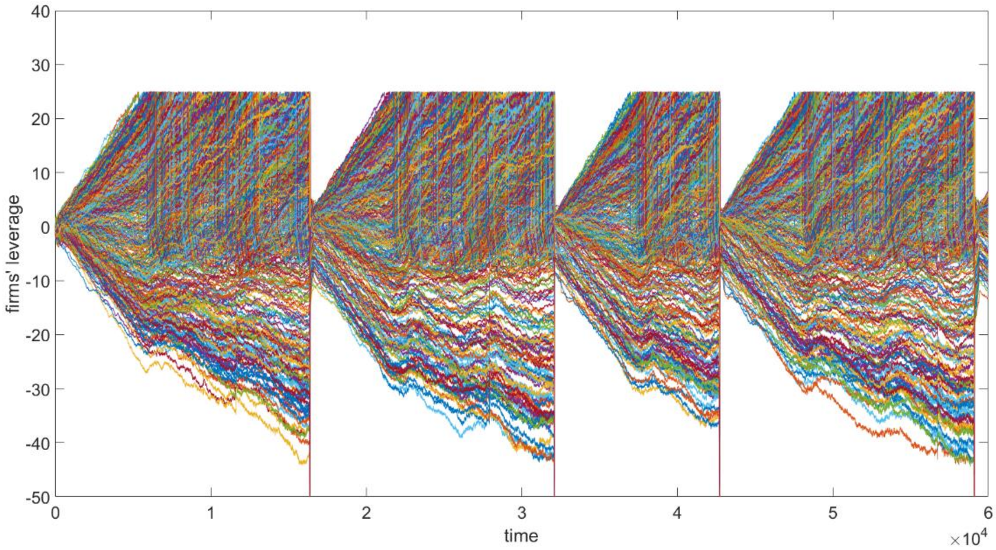


Figure 26. The time evolutions of the firms' leverage in EC^{+} phase of HoP-Mark0. Each line represents one of the 500 firm agents. The parameters: $N_f = 500, c = 0.5, \gamma_p = 0.05, \delta = 0.02, \beta = 1, \varphi = 0.1,$ $\Theta = 25$.

3.6 Conclusion

In different stages of the economic development, there were always some firms outperforming others. If these firms can maintain their competitive advantage in the long term, they may become giant companies. In general, regulators and economists may worry that the existence of giants in an economy would hinder the fair competition as well as the technological innovation. Our study further shows that enhanced endogenous crises can also arise from the increasing gap of profitability between advantageous firms and disadvantageous firms in an environment with excessive liquidity. Nowadays, governments and central banks are accustomed to adopt expansionary monetary policy, which will flood the economy with liquidity, to spur the recovery after economic recessions or crashes. Our study suggests that the negative effects of excessive liquidity should be seriously taken care of. Without the consideration of firms' heterogeneity, excessive liquidity can be the panacea for low unemployment and even zero bankruptcies in the modelled economy. However, when the firms exhibit strong heterogeneity of economic performance, the excessive liquidity can no longer stabilize the economy but lead to severe crises. Moreover, we find that in this situation, the leverage ratio based on aggregate values may underestimate the systemic risk. To correctly measure the risk, the leverage ratio should be adjusted to filter the influence brought by those "liquidity-absorbing entities".

In a real economy, it will be not easy to identify the "abnormal" divergence in the economic performance of firms. Some indicators, such as Lerner Index (LI) (Lerner 1995) and Herfindahl-Hirschman index (HHI) (Rhoades 1993), which are commonly used to evaluate the degree of market concentration, may be relevant ones. Nevertheless, the calculations of these indicators do not reflect the firms' cash flows. The divergence of firms' abilities in earning cash flows is the key reason to lead the model economy to enhanced endogeneous crises. The implication of this study may also be relvent to economic systems in different scales. For example, the effect of heavy subsidies (corresponding to the excessive liquidity) in a sector within which the firms have quite different profitabilities，the global influence of a loose monetary environment in a certain country who has large scale trade imbalances with other countries, can be analyzed in a similar manner.

3.7 Appendix: Emperical evidence

Nowadays, easing monetary policies, including both conventional ones and unconventional ones, have been the common practices to stabilize an economy from recessions. However, the simulation study in Chapter 3 suggests that an excessive liquidity may cause enhanced endogenous economic crises, when the diverse economic performance of firms is taken into consideration.

Empirically, few studies have linked economic crisis with the so-called "heterogeneous profitability of firms" in this chapter. The heterogeneity of firms is considered to be a quite natural phenomenon in the mainstream economics. This is because it is assumed that firms may have some competitive advantage in the short-term, but in the long-term, the outstanding firms would be eliminated by market competition and technological changes so that the relevant issues should not be a major concern.

As shown in the simulation results, the relevance between economic crisis and heterogeneity of firms should be studied through the distribution changes of certain indicators measuring firms' fragilities, which can be calculated from the firms' financial statement, for example, interest coverage ratio or current ratio. However, because the data of the small and middle firms, of which the financial fragilities are very crucial to macro risk of an economy as shown in this study, is usually unavailable, it is difficult to do such verification directly. The firm size distributions have been widely studied by economists and econophysicists. The studies on the changes of firm size distributions may be a potential approach to find empirical evidence of this study.

In Kang, Sang Hoon, et al (2011), the authors calculate the Pareto index from several measures of the firm sizes in South Korea before the 1997 economic crisis. In Figure A1, it can be found that the firm inequality increased rapidly before the 1997 economic crisis, indicated by an increasing Pareto index. In the meantime, the foreign direct investment in South Korea, which could be regarded as the excessive liquidity from external source, also rise rapidly before the 1997 economic crisis. Therefore, the rapid increases of firm inequality and foreign direct investment before the 1997 economic crisis in South Korea could be an illustration of the proposed mechanism in this chapter.

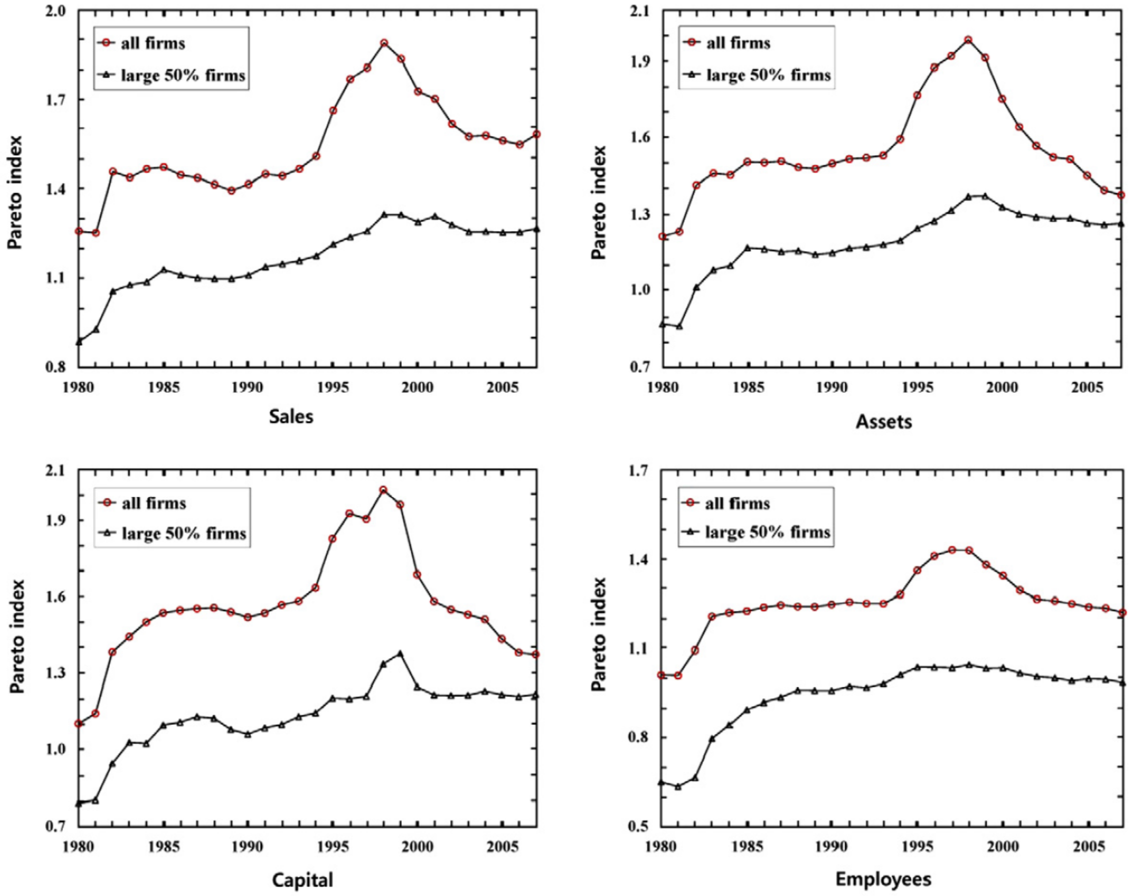


Figure A1. Changes of Pareto index of different measures of the firm sizes in Korea before 1997 economic crisis. (Kang, S. H., Jiang, Z., Cheong, C., & Yoon, S. M., 2011)

Regarding to the application of the adjusted global leverage proposed in this chapter, it is still very difficult to calculate it in the real world currently due to the availability of data. In an IMF report (Kumhof M, Rancière R, Winant P., 2015), the authors use the similar idea to study the households' financial fragility before the 2007~2008 financial crisis in United States. In Figure A2, one can find that the debt-to-net-worth ratios and unsecured debt-to-income ratios for the households of the aggregate economy were stable even before the occurrence of financial crisis. However, if one only considers the two indicators of the bottom 95 percent of the income distribution (the black line), a clear rising trend can be identified. Therefore, just like the study showed in this chapter, the existence of the rich or the firms with outstanding economic performance can distort the aggregate economic indicators and thus, make people underestimate the economic risk of the system which are brought by "hidden fat tail" (the poor households or the weak firms with dangerous balance sheet.

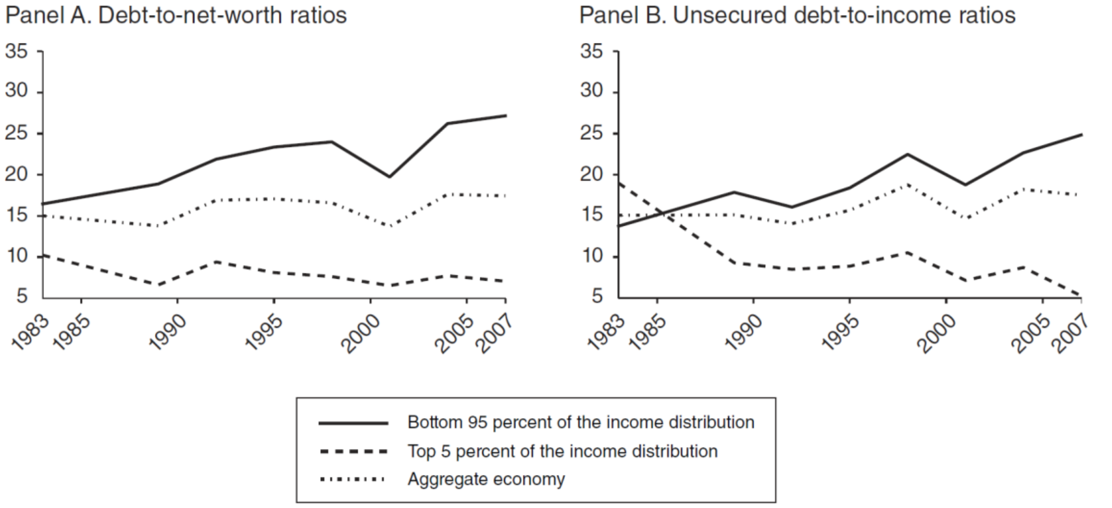


Figure A2 Debt-to-net-worth ratios and unsecured debt-income ratios in United States before 2007~2008 financial crisis. (Kumhof, M., Rancière, R., & Winant, P., 2015)

Chapter 4

Productivity Growth

4.1 Background

In the previous chapter, the base model was extended to incorporate the heterogeneity of economic performance of firms, which corresponds to the different profitability of companies in the real world. Short-term (less than 1 year) factors that influence the profitability of a company could be the demand and supply of its product, fluctuations in prices of the raw materials and energy, etc. A recent example is that most of the companies in pig breeding industry in China have reported more 100% profit growth in 2019 because the significant reduction of live pig supply in 2018 which was caused by the spread of the African Swine Fever and the new environmental policies related to this industry. Mid-term (from 1 to 5 years) factors could be the company’s market position in the industry, the loyalty of its customers, etc. For example, while Apple had about 20% of the global smartphone market share, it captured more than 50% of the industry profit in the last few years (Figure 27, Figure 28).

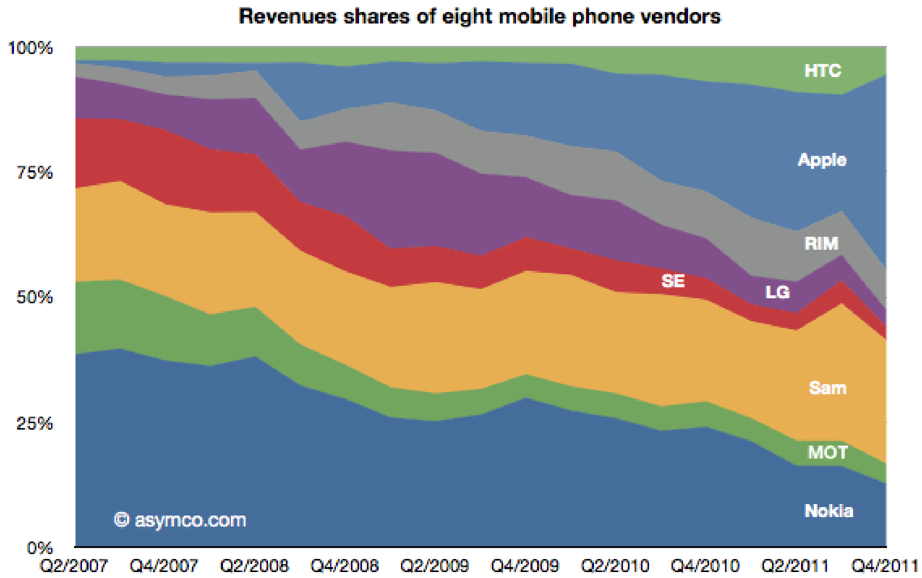


Figure 27 After the release of the first iPhone in Q1/2007, Apple took about 20% revenue shares among the major smart phone producers. *http://www.asymco.com/*

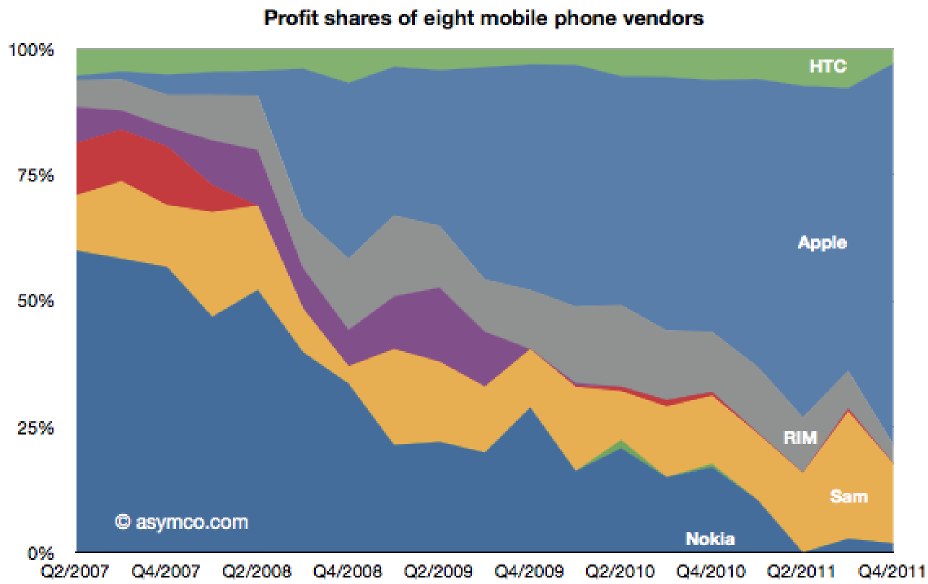


Figure 28 While Apple took about 20% revenues shares among the major smart phone producers, its profit share was more than 50%. *http://www.asymco.com/*

However, companies usually cannot sustainably benefit from those short-term and mid-term factors due to the increase of supply or the change of consumers' preference. In the long-term (over 5 years), a company that wants to remain its competitive usually needs to keep evolving and adapt with changing demand, innovative technology and new competitors. As the competitiveness of a nation described in Chapter 1, a firm's competitiveness also depends on if it can get advantage over its competitors through superior productivity. In fact, TFP of an economy can be strongly influenced by the productivity of the firms operating in it. Therefore, the policy makers who want a sustainable TFP growth of the economy, should provide favorable conditions for the firms to improve productivity.

The firms in an economy can improve their productivities in generally two ways. The first one is through market competition and the survival of the fittest. This is just like the concept "Creative destruction" which is related to the Austrian economist Joseph Schumpeter's theory on the evolution of capitalism and business cycles, he wrote in his book *Capitalism, Socialism and Democracy*," (Schumpeter, J. A., 2010). process of industrial mutation that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one". This kind of mechanism was particularly true in the early and middle stages of industrialization because the firms during that period were usually capital intensive. When a technological change occurs, it would be very difficult for the capital-intensive firms to follow up with the new technology because the replacement of its current capital (for example, factories and machines) would be very costly. It would be more viable and efficient for a new firm to start its production with the new technology. Therefore, the new firm would get productivity advantage over the old firm and would be the survival of the competition with a high probability. Along with the technology advancement, this process would continue to occur so that the aggregate productivity of the economy would increase.

The second one for a firm to improve its productivity is through its internal R&D procedure. After 1980s, with the emergence of the biological medicine, software and (mobile) Internet industries, R&D is becoming an increasingly approach for the firms to improve its productivity and thus, for a nation to improve its competitiveness. This is because, the business of the firms in these industries usually do not rely on much physical capital but rely on their intangible assets. Therefore, the firms can be more flexible and can have better cash flows so that they can benefit from a virtuous cycle of successful R&D, higher profitability and the funds for new R&D.

In this model, both the mechanisms, "Creative destruction" and active R&D would be introduced into the baseline model. Based on this model, we will conduct a series of policy tests. The rest of the chapter is organized as follows. Section 4.2 describes the model. In section 4.3, we give the simulation results and the policy implications.

4.2 Model

4.2.1 Agent profile

Some new variables are added into the firm agent for the unit of technological research and development (R&D) and others are the same as in Table 1 Agent profile

The effect of technological research and development is the enhancement of its productivity. Therefore, the productivity in this extended version is now a variable instead of a constant. The technology of a firm is represented by a vector $M_i(t)$ with m binary bits and at each time it flip some bits with a probability $\lambda_i(t)$, which is updated by reinforcement learning involving its memory on the past experiences of success $l_i(t)$ and failure $l_{i,F}(t)$ in technological research, with a discounting rate κ to characterizing the strength of memory. The productivity $\alpha_i(t)$ is thence linearly related with the difference of its tech meme $M_i(t)$ from a predefined optimal tech meme M_O.

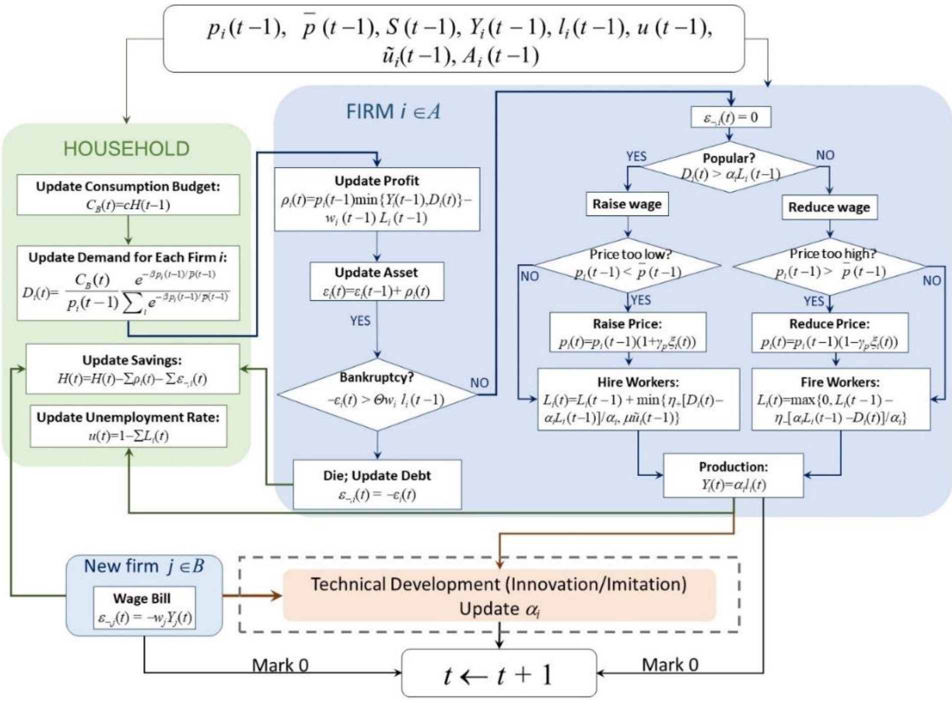


Figure 29 The flow chart of agent behaviors at each iteration t. $\xi_i(t)$ is a random number obeying a standard uniform distribution. Dividend to households, wage dynamics, "bailout" resolution for bankrupted firms, mechanisms of deposits and interest regulation are muted.

4.2.2 Decision making of the agents

To save room for our own version, we have summarized all the details in Figure 29 and here we mainly explain the unit related to the R&D. For clarification, the functioning firms belong to a set A, and the bankrupted firms to another set B.

- Household & Bank

  The households and bank behave the same as in Section.2.2.2 Household.

- Firm

The behaviors of the firms are divided into two steps. First, it will be judged by the bank whether it can continue the production or not, based on a criterion about its "debt-to-sales" ratio; if it can survive, it then sets the price, labor size and production at this round. These behaviors are the same as in Section 2.2.1 Firm.

- What does a revived (new) firm do?

When a firm $j \in B$ revives, it randomly adopts a tech meme $M_j(t)$ and updates its productivity $\alpha_j(t)$. Then it sets a goal of production

$$Y_j(t) = \sum_{i \in A} Y_i(t-1) / |A|$$

and hires some workers $l_j(t) = Y_j(t) / \alpha_j(t)$. Therefore, it borrows some seed money from the households to cover the wage bill $w_i L_i(t-1)$ and so this amount of money become the outstanding debt $\varepsilon_{-j}(t)$ to be subtracted from households' savings $H(t)$.

- How to adjust price, production, and employee size?

Price adjustment depends on whether the new output capacity can meet the current demand. This is different from the baseline Mark 0. If the current demand $D_i(t)$ is larger than the production capacity $\alpha_i(t)L_i(t\text{-}1)$, meaning that the product is more popular than expected, then the firm could raise the price and hire more people. In detail, if its price at last round is below the average, i.e., $p_i(t-1) < \bar{p}(t-1)$ ($\bar{p}$ is the production weighted price defined in Equation (6), the price could be increased by a random portion $\gamma_p \xi_i(t)$, where $\xi_i(t)$ is a random number obeying to a standard uniform distribution.

The amount of labor it recruits is proportional to the excess demand $D_i(t)-\alpha_i(t)L_i(t-1)$ with a coefficient η_+/α_i, where η_+ is the propensity to hiring people and α_i is the productivity per worker; yet the upper limit of new employees is constrained by the amount of unemployed labor willing to work at firm (Eq.(7))

On the opposite, if the product is not popular enough, i.e., $D_i(t) \le \alpha_i(t)L_i(t-1)$, the firm can reduce the price and fire some workers. If its price $p_i(t-1) > \bar{p}(t-1)$, it reduces the price by a random portion $\gamma_p \xi_i(t)$. The amount of employee to be fired is proportional to the excess supply $\alpha_i(t)L_i(t-1)-D_i(t)$ with coefficient η_-/α_i, where η_- is the firm's propensity to fire employee, and also the reduced size of employee is constrained to be non-negative. Finally, the new production is updated as $Y_i(t)= \alpha_i(t)L_i(t)$.

- How to develop a firm's productivity?

The nature of technology is the combination of effective methods (Chang, 2015). Technological development could be interpreted as a "better combination" which levels up the productivity. Therefore, to model technology development in such a model with coarse-grained descriptions of economic sectors and their activities, we also need a sub-model of technology with appropriate abstractness, yet showing the feature a "combination" that can be numerically evaluated and mapped to the productivity α_i.

We assign a new variable, a "tech meme" M_i to any firm i, which is a binary code with m bits where each bit represents an existing method. We call it a "tech meme" because we want to draw an analogy between it and a gene in a biological body. Genes encode sequenced combinations of nucleotides which controls the phenotypes (behaviors) of the bio-entity and finally determines the fitness of the species (under the selection of environment). Just as the genetic information could be replicated and it mutates from now and then, our tech meme can also be copied among firms and innovated on bits sometimes. Most importantly, the tech meme can also determine the "fitness" of the firm, i.e., its productivity, under the selection of socioeconomic environment.

To evaluate whether a combination of methods is good for productivity, the simplest way is to model the best choice of combination under this environment as an optimal tech meme M_O. Then the Hamming distance between M_i and M_O, which is denoted as $|M_i - M_O|_H$, is used to evaluate the additional cost if adopting M_i. The larger distance from the M_O is, the larger the cost. Particularly, the productivity α_i is linearly related to $|M_i - M_O|_H$ as:

$$\alpha_i(t) = 1 - 2\alpha_{\mathrm{r}}\left(\frac{|M_i(t) - M_O|_H}{m} - 0.5\right). \tag{22}$$

Hence, α ranges from $1-\alpha_r$ to $1+\alpha_r$.

Next, let's consider how a firm should develop its technology. Inspired by the R&D model proposed by Chang (2015), we use reinforcement learning procedures to model the firms' decision making on whether to do technological research. At each time t, firm i has a probability $\lambda_i(t)$ to invest in R&D to get a better $M_i(t)$; otherwise it has a $1-\lambda_i(t)$ to keep the current technology. When the firm chooses to research, it can develop by innovation if it has a positive asset, i.e., $\varepsilon_i(t) > 0$ and by imitation of another firm's tech meme if it is indebted, i.e., holds a negative asset. The research expenditures which should be subtracted from the current asset for innovation and imitation are, at this stage, set as some portions of its gross profit, which is $\tilde{\rho}_i(t) = p_i \min\{Y_i(t-1), D_i(t)\}$. Then the investments into R&D are $E_{IN}\tilde{\rho}_i(t)$ and $E_{IM}\tilde{\rho}_i(t)$, respectively. The expenditure of innovation or imitation would be deducted from the firms' account and be added to the savings of the households, which can be interpreted as the salaries to the researchers. Thus, the money flow is kept consistent. The firm has multiple times to try innovation (or imitation), and the number of chances $\pi_i(t)$ is proportional to the amount of expenditure of innovation (or imitation) as:

$$\begin{aligned}\pi_{i,IN}(t) &= \left\lceil mE_{IN}\tilde{\rho}_i(t) / \overline{p}(t)\right\rceil \\ \pi_{i,IM}(t) &= \left\lceil mE_{IM}\tilde{\rho}_i(t) / \overline{p}(t)\right\rceil,\end{aligned} \tag{23}$$

where m is the total number of bits in the tech meme and $\overline{p}$ is the output-weighted average price (Eq.(6)). Note that $\pi_i(t)$ is at least 1 so that the firm has at least one chance of trial once it decides to do the technological research.

If the firm chooses to innovate, it randomly selects one bit of the tech meme to flip; if the firm chooses to imitate, it selects one from the top ten firms j and copy one bit of $M_j(t-1)$ from the top profitable firm.

If the mutated tech meme has a lower Hamming distance to the optimal combination M_O, i.e., $|M_i(t)-M_O|_H < |M_i(t-1)-M_O|_H$, the firm then adopts the new tech meme; otherwise, it must discard it. Finally, the probabilities are updated based on the respective success rates. For example, $\lambda_i(t)$ will be updated as

$$\lambda_i(t) = \frac{l_i(t)}{l_i(t) + l_{i,F}(t)}, \tag{24}$$

where $l_i(t)$ is the discounted times of successful technology research both innovation and imitation) and $l_{i,F}(t)$ is the discounted times of failures. In particular, when the research succeeds, $l_i(t)$ and $l_{i,F}(t)$ are updated as

$$\begin{aligned} l_i(t) &= \kappa l_i(t-1) + 1 \\ l_{i,F}(t) &= \kappa l_i(t-1) \end{aligned}, \tag{25}$$

where $\kappa \in [0,1]$ characterizes the strength of memory. When the research fails, $l_i(t)$ and $l_{i,F}(t)$ are updated as

$$\begin{aligned} l_i(t) &= \kappa l_i(t-1) \\ l_{i,F}(t) &= \kappa l_{i,F}(t-1) + 1 \end{aligned}. \tag{26}$$

If $\kappa \to 1$, the firm can remember all the previous results, i.e., the firm is more conservative and relies on its historical experience; by contrast, if $\kappa \to 0$, the firm can make more radical changes in its strategy because it acts on only the performance of last round.

One can refer to Figure 30 for the summary of detailed updating rules.

Here is the end of flow chart for the extended model of technological development, where many elements of economic significance are still missing. Nevertheless, the minimal framework without the technological development suffices to give conclusions qualitatively robust against many extensions regarding dividend, flexible consumption budget, wage dynamics, floating interest rate, households' heterogeneous preference, and so forth. Moreover, the effect of those modifications is thus easily detected and understood, from the subtle changes in the dynamics of macro-indicators and phase diagrams. The following results also will show the effect of technological development on the stability of macroeconomic and the dynamics.

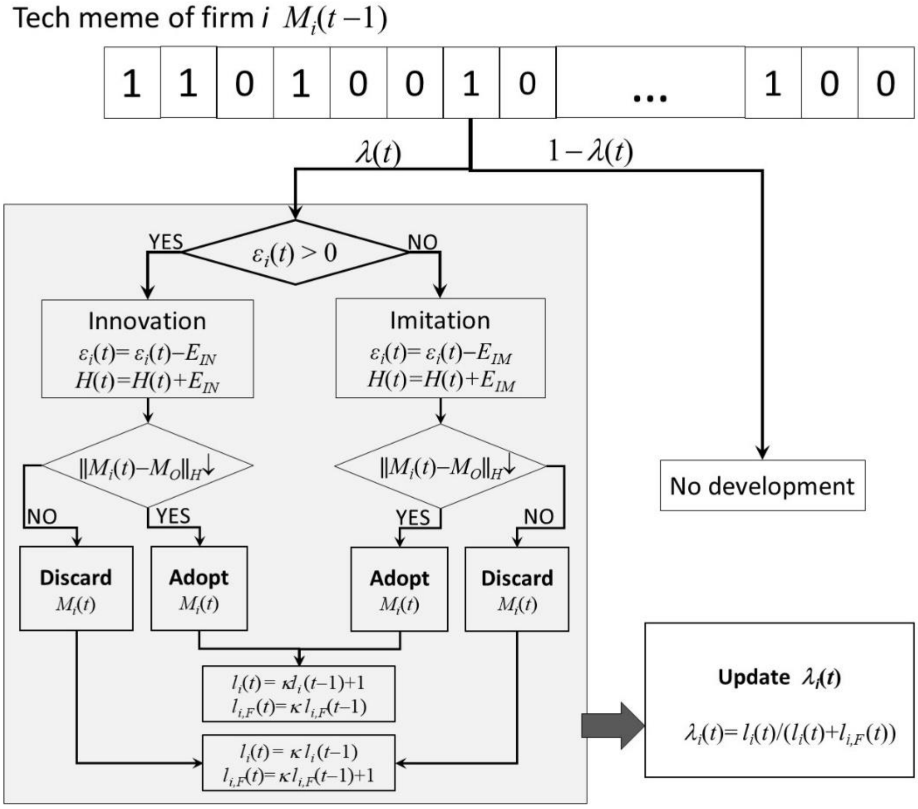


Figure 30 The flow chart of firm doing technological research. The initial condition is $l(0) = l_F(0) = 1$, so that $\lambda(1) = 50\%$.

4.3 Simulation results and policy discussions

In this section, we will show the effects of technological development on the stability of macroeconomy under various scenarios. Before that, we first present the general conclusions from the basic model without the sub model of technological research, which is a foundation for a better interpretation of the results of our extended version. The initial condition for variables and parameters is the same as the baseline simulations (Table 2). There are N_f = 500 firms in the simulation. Households' initial savings and firms' initial assets are all set as $N_f/2$, so that the total money in circulation is always N_f. The price and labor size of each firm are set as uniformly distributed random numbers around the means which is 1 and 0.5, respectively. Therefore, the initial unemployment rate is 50%. Wage w_i and productivity α_i in this basic model are set as a homogeneous value 1. Time step of the simulation is iterated from t =1. Through exhaustive analysis, the control parameters are identified as $R=\eta_+/\eta_-$ and Θ, and the revival rate φ, and other parameters give trivial impact on the dynamics and phase diagram. The following results about the role of R and Θ are thoroughly discussed in (Gualdi, Stanislao, et al, 2015), and those of φ are discussed in (Gualdi, Stanislao, et al. 2015b).

4.3.1 A recap on the baseline results

A typical result of the basic model after reaching equilibrium is as such: there exists a critical value of R, separating a phase of a dead economy $u(t\to\infty)=1$ from that of a living economy $u(t\to\infty)<1$. For a living economy, the bankruptcy threshold Θ, which is also a measure of liquidity, there exist two critical values Θ_{EC} and Θ_{FE}, separating the parameter space into three phases:

(i) For $\Theta<\Theta_{EC}$ a miserable economy with high residue unemployment rate $u(t\to\infty)>>0$ (2-RU in Figure 31);

(ii) For $\Theta_{EC}<\Theta<\Theta_{FE}$, an active economy with low unemployment rate but occasionally assaulted by endogenous crises (3-EC in Figure 31);

(iii) For $\Theta>\Theta_{FE}$, a perfect economy with very low unemployment rate $u(t\to\infty)\sim 0$ (4-FE in Figure 31).

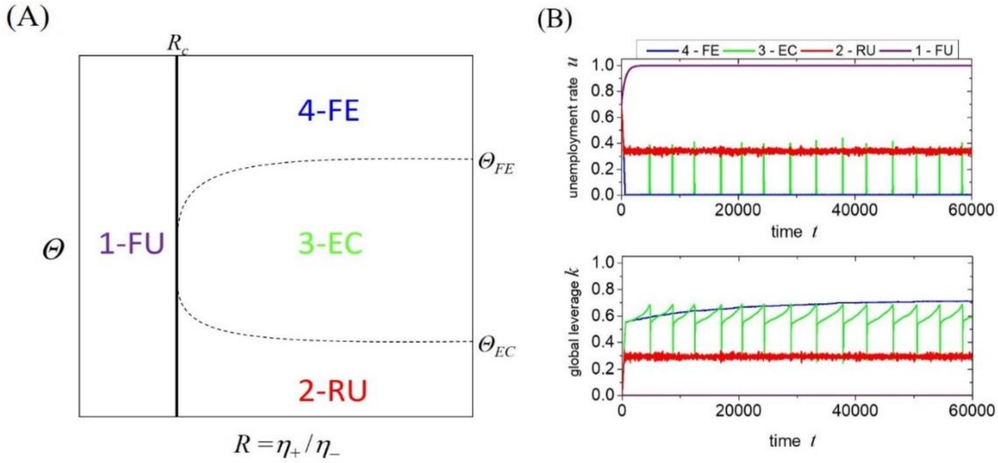


Figure 31 General conclusions of the basic model. (A) Four phases are separated by a combination of the control parameter R=η_+/η_- and Θ: 1-FU is full unemployment, 2-RU is residual unemployment, 3-EC is endogenous crisis, 4-FE is full employment. (B) Typical dynamics of the unemployment rate $u(t)$ and the global leverage $k(t)$.

The boundary of phases may move due to the change of other parameters like β and γ_p, but the qualitative feature of the phase diagram is rather robust. In extended models, other control parameters of policy significance would give diagrams in parameter spaces of higher dimensions, where the four basic phases are still prominent and yet some new phases of interest may appear (as shown in our extended model).

Figure 31b shows the time evolution of unemployment $u(t)$ and global leverage $k(t)$ with respect to four phases. Global leverage $k(t)$ is the ratio of total outstanding debts of firms $\varepsilon(t)$ over total positive assets of firms (Eq.(19)).

4.3.2 The "Creative destruction" (C-D) scenario

In the first scenario, firms change their tech meme only through the natural selection and the mechanism of technical research is off, i.e., $\lambda \equiv 0$. Therefore, a firm would be able to get a new technology $M_i(t)$ only if it goes bankrupt and revives as a start-up. In this way, the aggregate productivity growth of the economic system is realized by market competition and the survival of the fittest. In this scenario, the firms cannot do R&D initiatively so that we can check the pure "Creative destruction" effect on the macroeconomic performance in the model.

First of all, we point out that the conclusions from the basic model are generally kept in the C-D scenario: a low Θ renders a macroeconomy with residual unemployment rate with deflation (RU phase); a mild Θ renders endogenous crises (EC phase); when Θ is high enough, the macroeconomy eventually becomes stable with persisting inflation (FE phase). However, besides the level and stability of unemployment rate, the growth of the average productivity should also be an important concern.

In the C-D scenario, since the elimination of firms with disadvantageous tech memes (i.e., those with larger Hamming distances to the optimal technology M_O) is realized by their bankruptcies, while the unemployment rate can reach a lower level and be more stable with a larger Θ (Figure 32a), after the relaxation period), the average productivity $\overline{\alpha}$ climbs more quickly with a smaller Θ (Figure 32d). Remember that Θ measures the level of available credit to the firms in the system.

The improvement of productivity in C-D scenarios occurs only at when the bottom firms with low productivity revive. This is why the stepwise enhancement of average productivity $\overline{\alpha}$ could be discovered during period of endogenous crises (blue and orange curves).

Similarly, the stepwise increase in $\overline{\alpha}$ in Baseline II also seems to correlate with endogenous crises yet with some difference. Figure 32 exhibits the dynamics of total number of successful trials of living firms for innovation and imitation per iteration. One can generally see that the successful trials of innovation become prominently frequent when unemployment rate is higher. This phenomenon is associated with the reset of memory when a firm gets revived. It has a blank of history, $l_i = 1$ and $l_{i,F} = 1$, and a higher research curiosity $\lambda_i(t)$ than those matured firms.

In the second scenario, the natural selection is switched off and firms update their tech memes by technological research. The range of productivity α_r is set as 0.5, the expenditure budget for innovation E_{IN} is 50% and that for imitation if E_{IM} is 10%. The length of tech meme m is 10. The memory strength κ for the reinforcement learning on research propensity $\lambda_i(t)$ (Eqs.(25-(26) is 0.1, which means the firms have short memories and can radically change strategies.

Wage should also adapt to the fluctuating productivity. At each time t, if the firm i has positive net profit (definition in Eq.(8)), $\rho_i(t)>0$, it will raise the wage by a random portion $\gamma_w\xi_i(t)$ is a random number obeying a standard uniform distribution. By contrast, if $\rho_i(t)<0$, it will reduce the wage by a random portion. In the baseline simulations, γ_w is set as $0.8\gamma_p$, where γ_p is the sensitivity of price adjustment (see Table 1 Agent profile and Table 2).

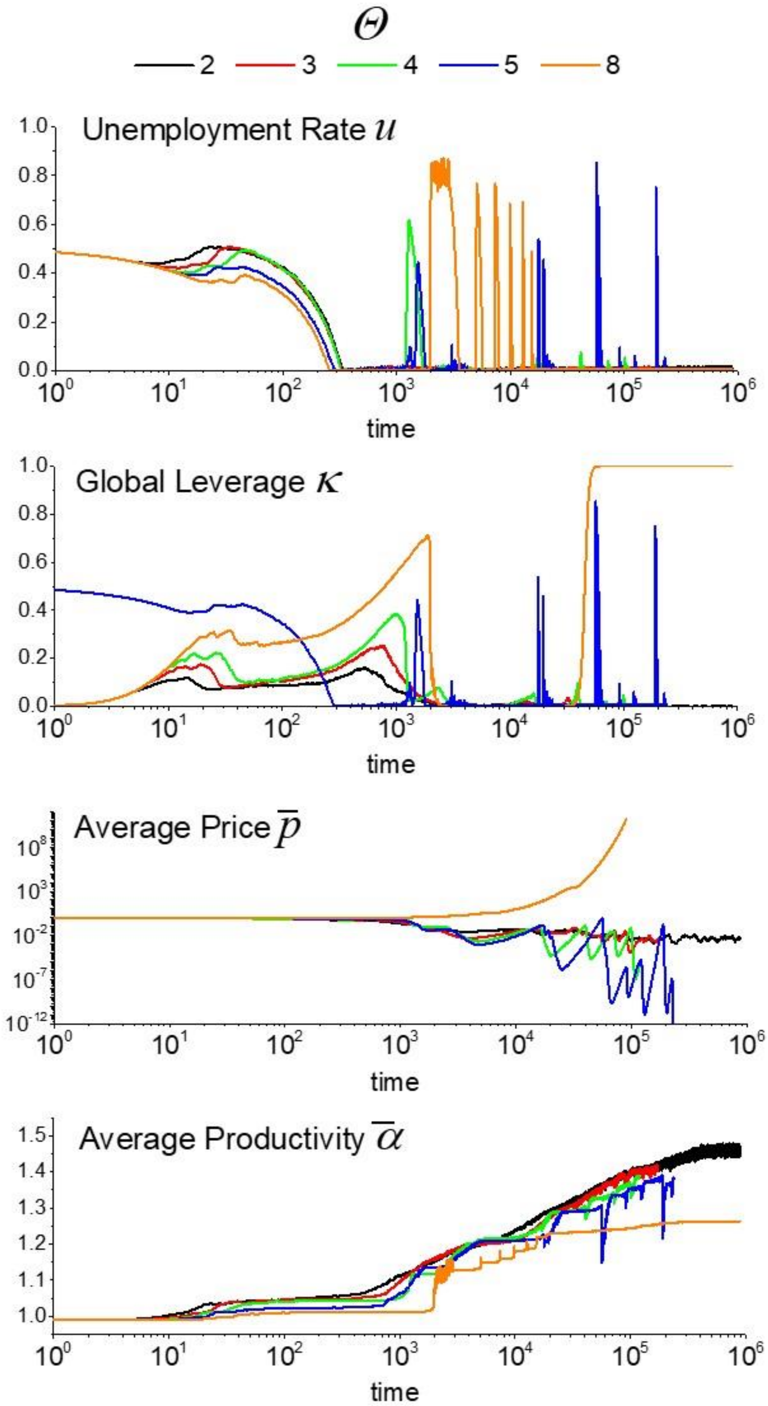


Figure 32 Simulation results in the C-D scenario: Tech memes of firms are updated randomly when bankruptcies occur.

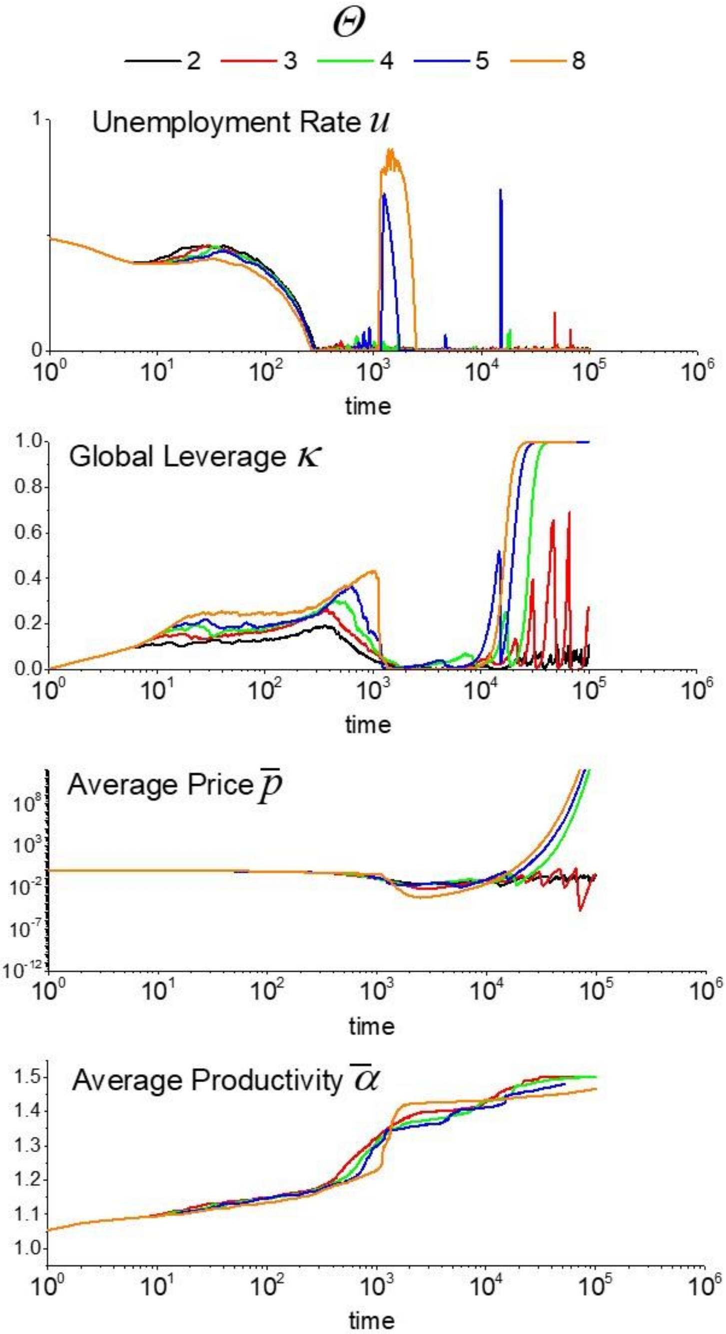


Figure 33 Simulation results in the ARD scenario: Tech memes of firms are updated by research (innovation or imitation).

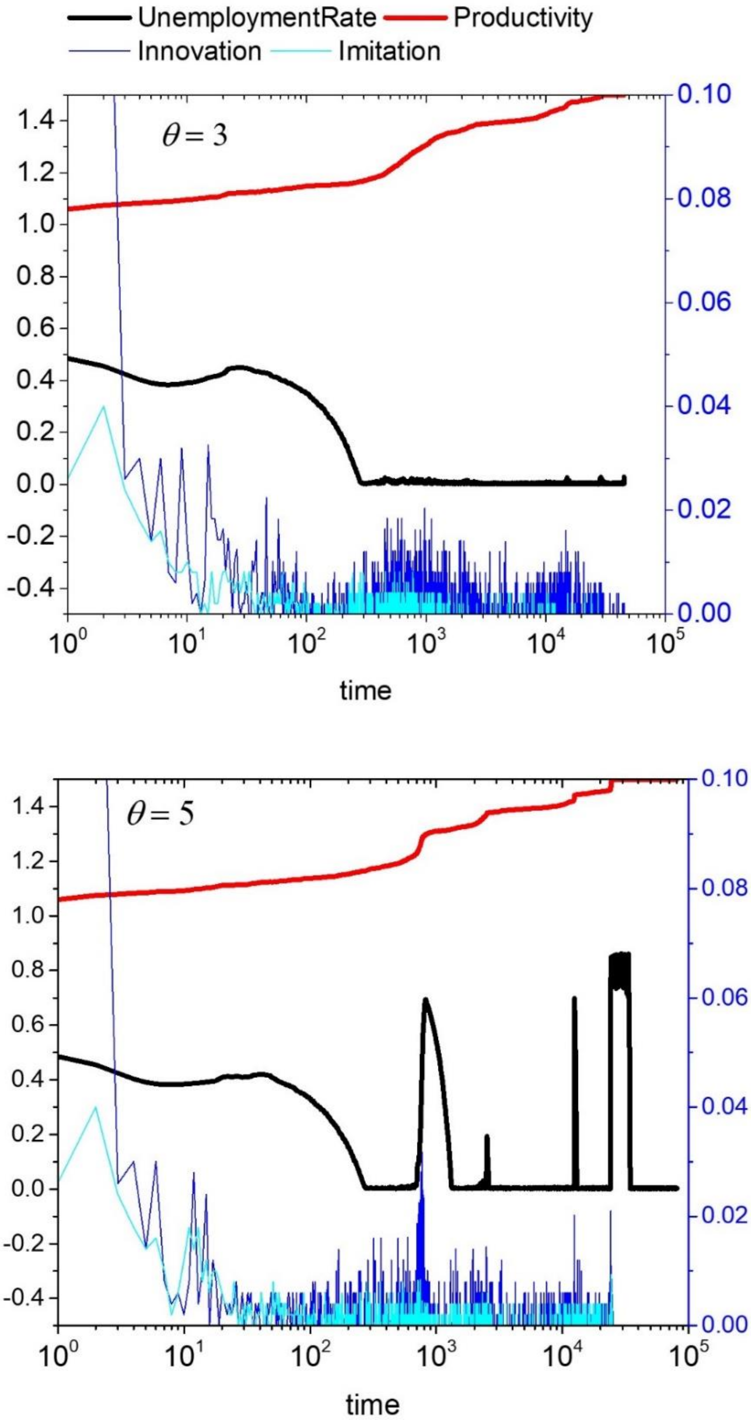


Figure 34 Time evolution of total number of successful trials for innovation and imitation by living firms in the ARD scenario.

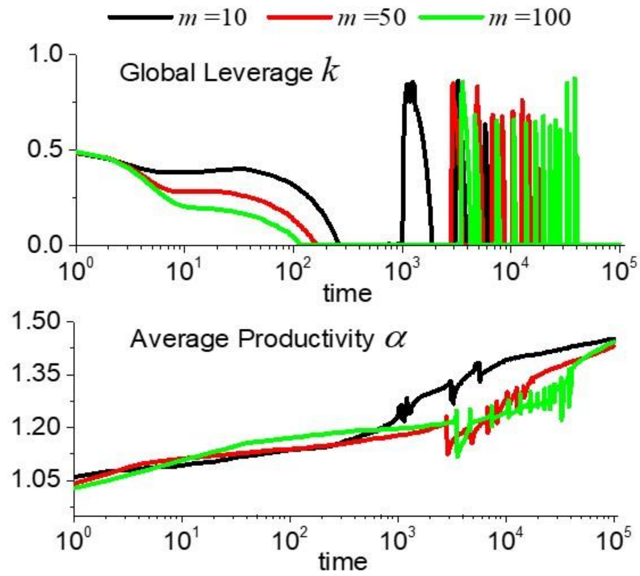


Figure 35 Simulation results in the C-D+ARD scenario with varying length *m* of tech memes for *Θ* = 8.

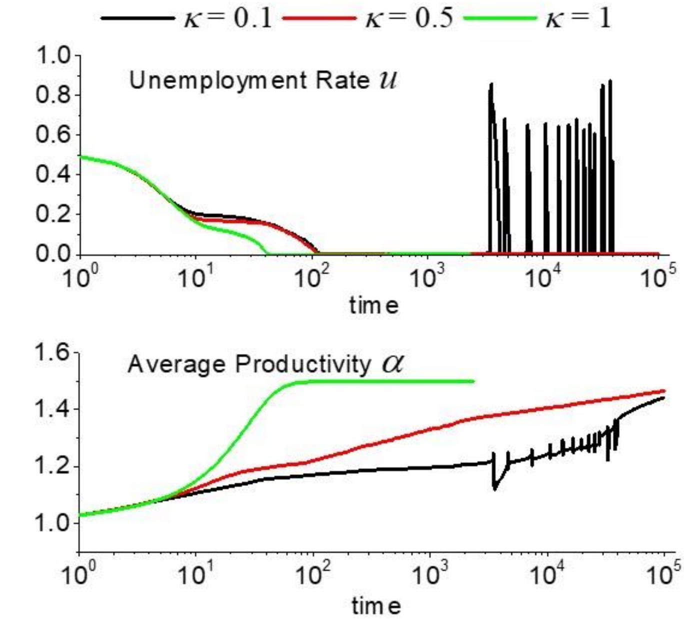


Figure 36 Simulation results in the C-D+ARD scenario with *Θ* = 8, *m*=100.

4.3.2 Adaptive R&D

First of all, we point out that the conclusions from the basic model are generally kept in the two baseline scenarios: a low Θ renders a macroeconomy with residual unemployment rate with deflation (RU phase); a mild Θ renders endogenous crises (EC phase); when Θ is high enough, the macroeconomy eventually becomes stable with persisting inflation (FE phase). In C-D scenarios (Figure 32), since the elimination of disadvantageous tech memes (i.e., those with larger Hamming distances to the optimal technology M_O) is realized by bankruptcies of firms, the average productivity $\overline{\alpha}$ climbs more quickly with a lower Θ. By contrast, in ARD scenarios (Figure 33), Θ does not affect the improvement rate of $\overline{\alpha}$ so significantly.

The improvement of productivity in Baseline I occurs only at when the bottom firms with low productivity revive. This is why the stepwise enhancement of average productivity $\overline{\alpha}$ could be discovered during period of endogenous crises (blue and orange curves). Similarly, the stepwise increase in $\overline{\alpha}$ in ARD scenarios also seems to correlate with endogenous crises yet with some difference. Figure 34 exhibits the dynamics of total number of successful trials of living firms for innovation and imitation per iteration. One can generally see that the successful trials of innovation become prominently frequent when unemployment rate is higher. This phenomenon is associated with the reset of memory when a firm gets revived. It has a blank of history, l_i = 1 and $l_{i,F}$ = 1, and a higher research curiosity $\lambda_i(t)$ than those matured firms.

We also show the effect of tech meme length m and the memory strength κ in a scenario where both natural selection and technological research are switched on. Basically, if the tech meme has more bits, it is more difficult for the firms to find the optimal solution and the improvement of the average productivity $\overline{\alpha}$ is slower. Figure 35 shows a comparison of unemployment rate $u(t)$ under various values of m for Θ =8, and it is evident that with a slowdown of improvement on the productivity, the process to the final FE phase becomes more struggled with longer temporal phase of EC.

Figure 36 shows the effect of κ which is also salient. With $\kappa \to 1$, firms learn the optimal solution more quickly and the process to final FE phase is faster without a temporal phase of EC. However, other factors such as the investment amount (E_{IN} and E_{IM}) and a slowly evolving environment (the optimal tech meme M_O changes slowly with time) have much complex impacts on the system.

4.3.2.1 The effect of research expenditure

Figure 37 shows a comparison among four sets of E_{IN} and E_{IM} for Θ = 8, m = 100 and κ = 0.1. In baseline scenarios (red curves), this parameter setting eventually yields a good macroeconomy (FE phase) preceded by several waves of economic crises. The reason why economic crises disappear is that most of the firms learn a tech meme very close to M_O and the variance between them become small. One can clearly see the evolution of productivity variance α_{max}-α_{min} in the bottom subfigure that when the variance is large, the system is inclined to have crises. Therefore, if the investment rate E_{IN} is large enough, rich firms will invest more into innovation and approach the optimal solution very quickly; if

E_{IM} is then low(green curves), the heavily-indebted firms catch up with the top firms with low speed, thus the variance of productivity enlarged and finally inducing endogenous crises. If E_{IN} is also low (black curves), the variance among firms still gets enlarged but the overall macroeconomy will fall into a bad state with very high unemployment rate and incessant bankruptcies. However, if the E_{IN} is very little amount (blue curves), the firms can hardly learn the optimal tech meme so that the average productivity climbs very slowly so that the variance among them is also small; in this case, the macroeconomy is stable and in a FE phase.

Because of this nonlinear effect of research investment, the phase diagram in the basic conclusions (Figure 31) conditionally holds in our model. For very large or very small amount of investment, the economy will be stable with full employment as long as the productivity variance among firms is sufficiently small. For a medium extent of investment, the system bears a risk of crises and even bad economy if the bottom firms could not catch up with the top firms.

4.3.2.2 The effect of evolving environment

So far, the optimal tech meme M_O is constant. Now let us investigate scenarios with evolving environment. The optimal tech meme will randomly flip one bit at every $t=n\tau$ time step, where $n\in\mathbb{N}$ is a natural integer. Therefore $1/\tau$ infers the speed of environmental evolution. Figure 38 shows the results with varying τ. When τ is small (black curves), the environment changes so fast that the top firms cannot establish the leading status and the average productivity $\overline{\alpha}$ converges to 1, with relatively small productivity variance; The macroeconomy in this case is stable (FE phase). For a medium range of τ (red, green, blue), the top firms can accumulate the advantage through time whereas the bottom firms cannot catch up and get bankrupted; hence the macroeconomy always encounters crises or even consistent high unemployment rate. By contrast, if τ is rather large (orange), most firms can learn well ($\overline{\alpha}$ above 1.3) the new tech meme, with a shrinking variance of productivity; thence, the system is also in a very stable state with full employment.

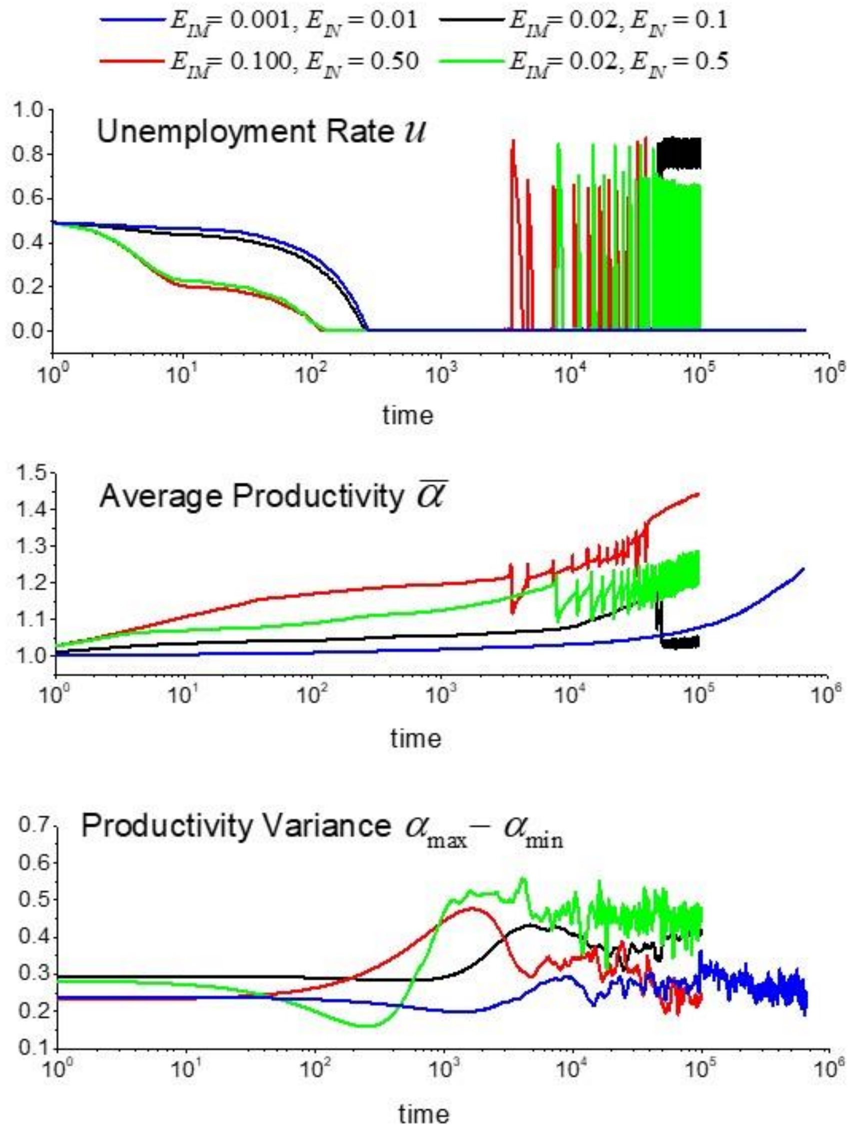


Figure 37 Results with different sets of expenditures on innovation and imitation, Θ = 8, m=100, and κ = 0.1.

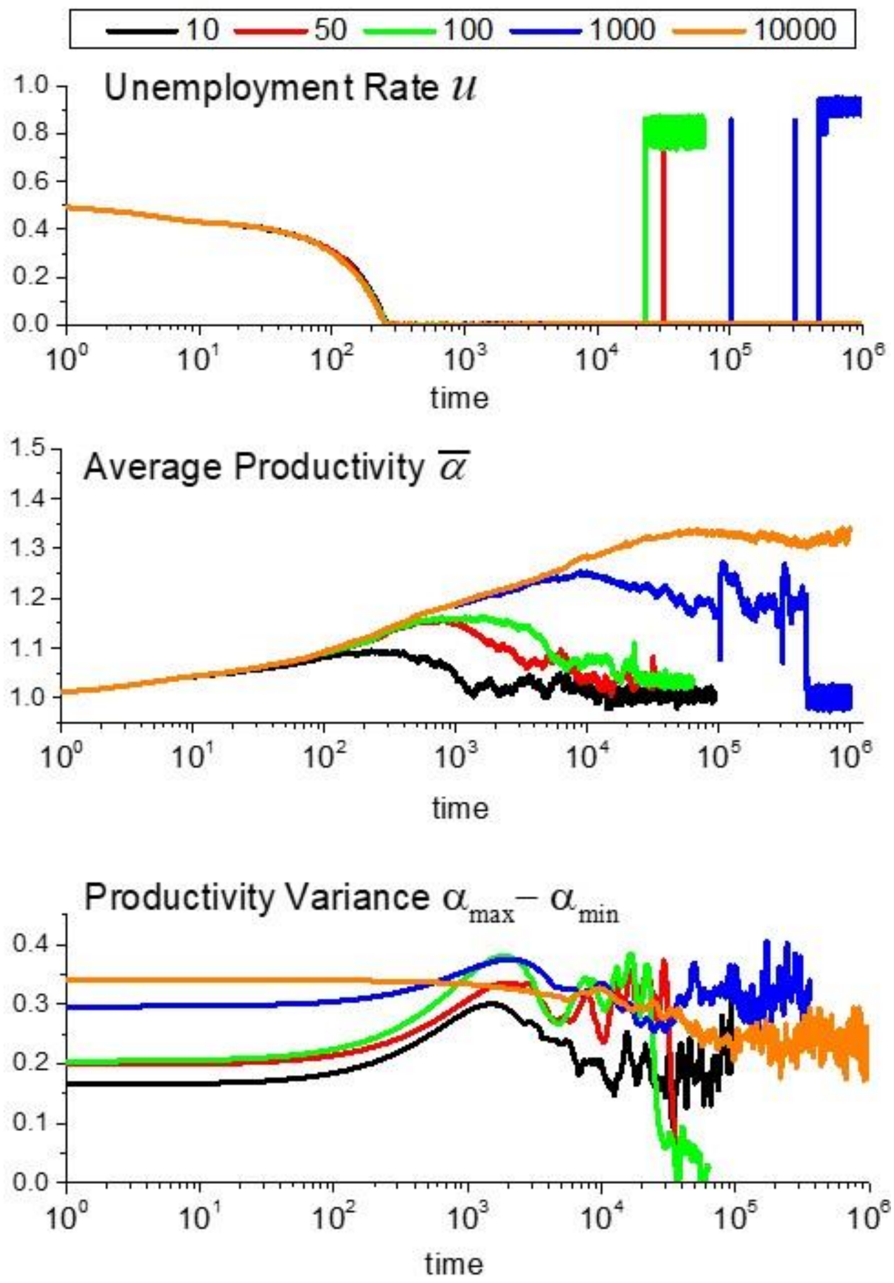


Figure 38 Results under evolving environment with $\Theta = 8$, $m = 100$, $\kappa = 0.1$, $E_{IM} = 0.1$, and $E_{IN} = 0.5$.

4.4 Policy discussions and conclusion

Although proactive fiscal and loose monetary policies were implemented to stimulate the economy, the potential negative effects which are usually concerned about would be serious inflations and/or speculative bubbles. From our simulation studies, it is found that excessive credit (a high Θ) can also slow down the productivity growth. This is because that the excessive credit would prolong the lifetime of the firms with low productivity and thus weaken the effect of "Creative destruction". Moreover, the productivity gap between the high productivity firms and the low productivity firms would not be reduced for a long time and lead to serious economic crises because of the polarization of firms' financial states (the mechanism of such economic crises is similar to the one in *EC+* phase, which has been elaborated in Chapter 3).

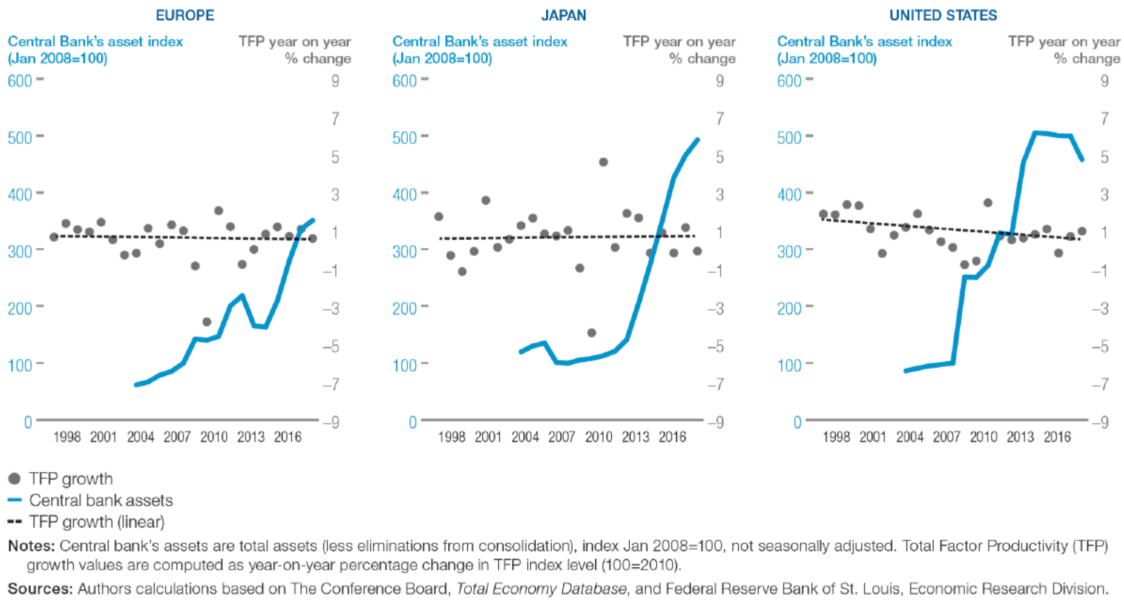


Figure 39 Monetary policy and TFP growth (The Global Competitiveness Report 2019, by Klaus Schwab, *https://www.weforum.org/)*

In the recent decades, however, it has been quite popular for the central banks and governments all over the world to implement loose monetary policy for prolonged periods to achieve the inflation targets. Many European countries and Japan have got their interest rates at zero or even negative for years. Meanwhile, unconventional monetary policies, such as Quantitative Easing, have been seen as effective solutions to recover economies from recessions or crises. This study has shown that proactive fiscal and loose monetary policies could not only slow down the productivity growth, but also have stabilization effect only in the short-term.

In the Global Competitiveness Report 2019 published by World economic forum, negative correlations between the central banks' asset index and the changes of total factor productivity (TFP) in Europe, Japan and United States (Figure 39). Although the causality of the negative correlations has not been mentioned in the report, this ABM simulation study may provide a potential methodology for understanding such phenomena.

This study also shows that the slowdown effect on productivity growth would differ by the industrial structure of an economy. From the simulations, while a loose monetary policy would slow down the productivity growth in CD scenario, it only has a minor effect on the productivity growth in ARD scenario. It is easy to understand because the productivity growth would depend on the shakeouts of the disadvantageous firms in CD scenario. When excessive liquidity is injected into the economy, a disadvantageous firm will be able to operate for a longer time before its inevitable bankruptcy and thus the economy will evolve at a slower rate. However, in the ARD scenario, although the shakeouts of disadvantageous firms can still contribute to the productivity growth, the firms are able to improve their productivities through R&D activities. Therefore, longer lifetime of the disadvantageous firms may not impede the evolution of the economy as much as they do in CD scenario.

In fact, CD scenario is a good description of an economy that consists of industries with intensive capital, mainly manufacturing companies, would be similar to the industry structure in Europe during Schumpeter's era, Japan during 1950 to 1990 and China since 2000. This is because if the operation of a firm relies a lot on the fixed assets (usually the machinery and equipment), it would be very costly for the firm to upgrade the fixed assets. Then the firm might choose to manufacture products as its machinery and equipment depreciates even if the next generation technology was available. Therefore, it would be more likely for new firms to adopt new technologies and improve the productivities. This is why the shakeouts of firms is important for an economy which consists of industries with intensive capital to increase its productivity.

On the other hand, ARD scenario describes economies that consist of industries with light asset, which are different from the industry structure in Schumpeter's era but are similar to the one in U.S. and some European countries since 1990. The firms in these industries usually provide products and/or services of technology, information, biological pharmacy, etc. It is found in this study that loose monetary policy has a minor effect on slowing down the productivity growth. This is because the feature of light asset makes the firms in these industries more likely to evolve and adopt to technological changes through their R&D investment.

Therefore, the implementation of policies should take into consideration the industry structure of the economy. For an ARD-type economy, a loose monetary policy would only slightly slow down the TFP growth of the economy. Thus, it would be advisable to adopt it if consider its positive effects on sustaining a moderate inflation and a low unemployment rate. However, for a CD-type economy, it should be extremely prudent to implement policies which could weaken the shakeouts of firms, including but not limited to a loose monetary policy and industrial policies. In a CD-type economy, if polices benefit advantageous firms (for example, a strong patent protection impedes the imitation of disadvantageous firms), the productivity gap would increase and the economy would be led into crisis regime. On other end, if polices benefit disadvantageous firms (for example, excessive subsidy to the whole industry), the gap between innovation firms and imitation firms would be tiny and the productivity growth would be slow. In general, a moderate level of the productivity gap between firms facilitates creative destruction and technology cycles, which are necessary to promote productivity growth.

4.5 Appendix: Empirical evidence

In the Global Competitiveness Report 2019 released on the World economic forum, the author finds a negative correlation between the rise of central bank's asset and the growth of Total Factor

Productivity (TFP) in three main economies, Europe, Japan and United States (Figure 39 Monetary policy and TFP growth (The Global Competitiveness Report 2019, by Klaus Schwab, *https://www.weforum.org/)*). A rise of central bank's assets means a releasing of liquidity into the economy, caused by the central bank's purchasing of asset from the markets. While the author of the report did not mention possible mechanisms behind the negative correlation, the study in Chapter 4 suggests that an increasing liquidity would slow down the elimination process of firms with low productivity and therefore, lead to a lower growth rate of TFP.

It should be noticed that the calculation of TFP of an economy could be very complicated due to the method how to decompose the GDP of the economy. The trend of TFP growth in the short-term may not be so clear. The unconventional monetary policy is a new tool for the central banks and become popular until recent years. Therefore, the impact of the excessive liquidity on TFP growth should be further investigated when rich data is available.

In the long-term of TFP growth trend (Figure 2 Trend of TFP (total productivity factor) growth in the United States, the Euro Area, United Kingdom and Japan, 1890~2015 (average annual growth rate), the two peaks of TFP growth in 1930s and 1960s seem to correspond to "The New Deal" since 1933 implemented by the Franklin D. Roosevelt, which was expected to stimulate the U.S. economy from the Great Depression, and the end of Bretton Woods on 1973, which allowed a higher flexibility of central banks to adopt monetary policies. Both events had significant influences on the liquidity levels. The study in this chapter suggests that polices which intend to stabilize an economy, could have a negative impact on the productivity growth of the economy. Therefore, these two events might be relevant to the trend reversal of TFP growth trend. However, many factors were involved in the development of an economy. It is difficult to confirm a causality in such a complex system unless it was a dominant factor.

Regarding to the effect of easing monetary policy on economies with different industrial structure, the study in this chapter may provide a possible explanation for the growth of TFP in China and United States after the 2007~2008 global financial crisis.

Before 2007, nearly half of the economic output in China was contributed by manufacturing industry. This means that the economy of China was similar to the "Creative destruction" one in the simulation. Meanwhile, the economic growth in United States relied more on the technology, information services and biological pharmacy industry, which meant that the economy of United States was similar to the "Adaptive R&D" one in the simulation. After the global financial crisis, both of the countries implemented very easing monetary policies (Q.E. in United States and "4 trillion yuan" in China) to stimulate the economies from recessions. However, in Figure A3, one can find that China suffered a much more significant loss of TFP growth than United States. According to the study in this chapter, this was because that the productivity growth in China relied more on the elimination process of the low productivity firms. The excessive liquidity largely slowed down this elimination process and thus, led to a larger loss of TFP growth than the loss of TFP growth of United States. Not until 2015, China strengthened the "supply-side structural reform" to eliminate the low productivity firms mandatorily, which would fuel TFP growth effectively in the future.

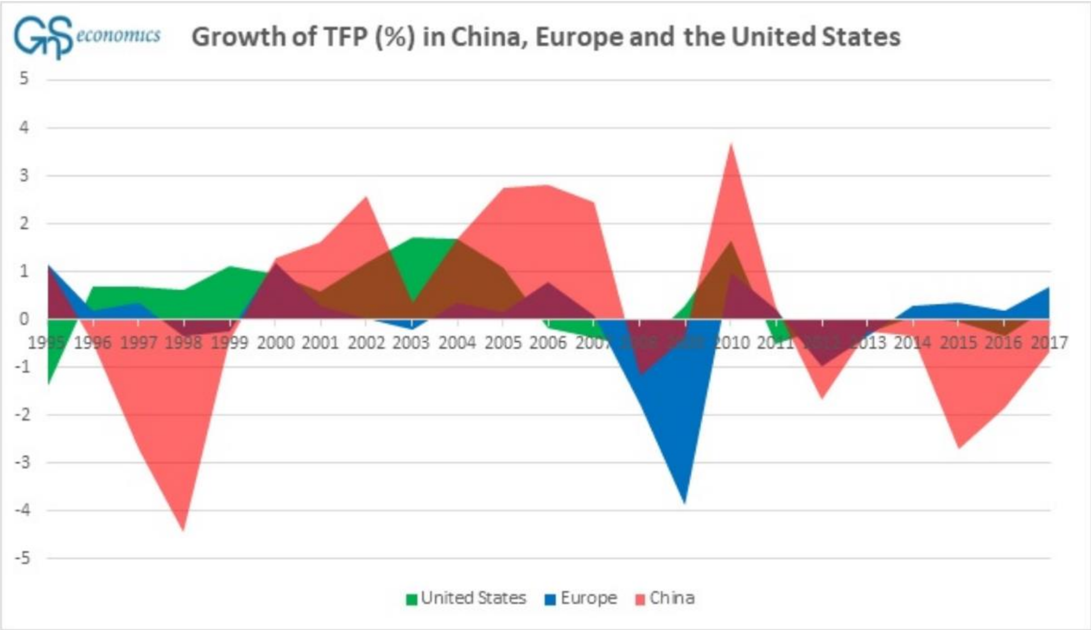
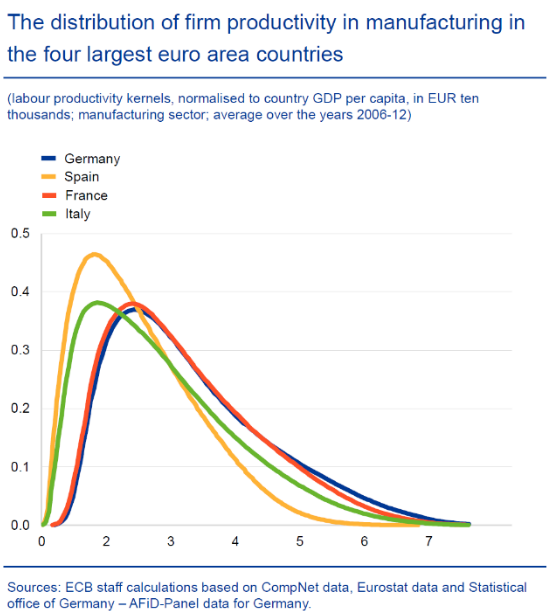


Figure A3 Changes of TFP growth in China, Europe and United States. see *http://freeworldeconomicreport.com/the-failing-engines-of-global-growth/*

Regarding to the relationship between the productivity gap between firms and the productivity growth of an economy, Figure A4 show that Germany and France which had a moderate level of the productivity gap during years 2006~2012 (Figure A4 left), exhibited stronger productivity growth than Spain and Italy (Figure A4 right), which had a more skewed distributions of firm productivity.



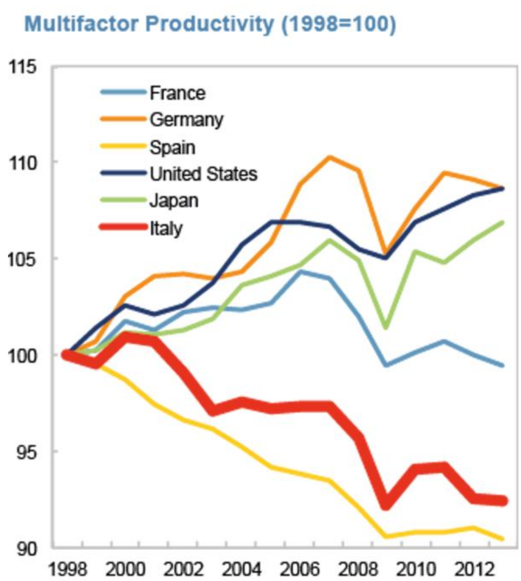


Figure A4 Left: the distribution of firm productivity in manufacturing in Germany, Spain, France and Italy. *Page 85*, Firm heterogeneity and competitiveness in the European Union ECB Economic Bulletin, Issue 2 / 2017 *https://www.ecb.europa.eu/pub/pdf/other/eb201702_article02.en.pdf;* Right: Evolution of aggregate productivity for selected countries. Source: *https://voxeu.org/article/public-sector-inefficiency-and-firm-productivity-italy*

Chapter 5

Nonlinear Demand Function

In this part, I will investigate the macroeconomy with irrational households' behaviors, particularly, the trend following behaviors. Trend following in this context means that the households' preference on the products depends on not only the price information, but also on the popularity of the products. Some synonym terms could be the herding behaviors and bandwagon effect. This dependence of preference on popularity in this minimal ABM could be modeled via a specific potential function added to the original demand function (Eq. (15)). Various types of functions have been studied to model different types of trend following behaviors. Generally, the modeled macroeconomy will become less stable with rational households, sometimes it undergoes multiple regimes of macroeconomics stages (e.g., perfect competition, monopoly, and oligopoly, crises) under different levels of monetary easement (Θ in this model).

5.1 Background

In the basic and Hop-mark 0, households select their products in reference to the price (or the discounted price) of the product. Figure 40 shows the relationship between a firm's demand and price at several time steps. One can easily find that households demand for a product monotonically decreases with its price in a quasi-linear way. This is a rational behavior of households' demand for a perfect market in the classic economic textbooks.

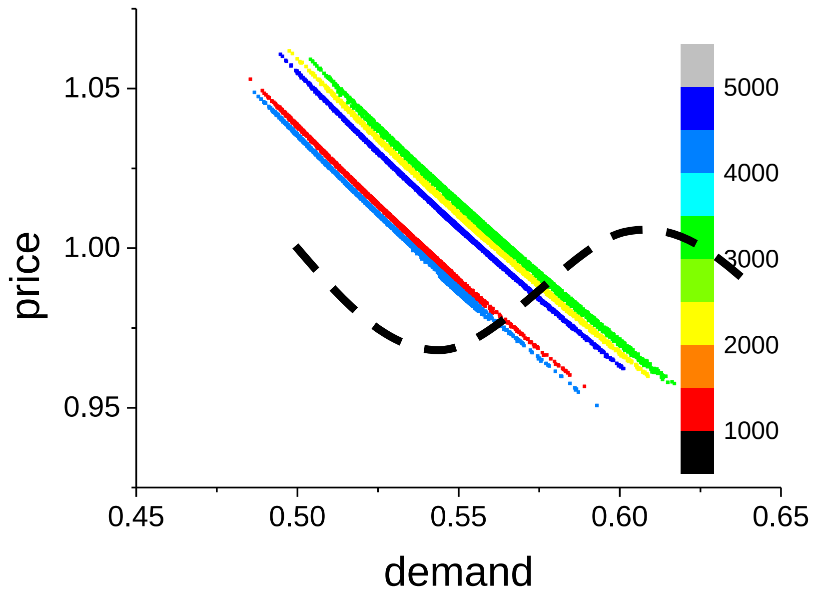


Figure 40 The relationship between the price p and demand D as a scatter plot for all pairs of (D_i, p_i) at different times remarked with different colours. Two control parameters are $\Theta = 3$, $R = 3$. The black dashed curve is the s-curve proposed by Becker.

Nevertheless, households may often concern other aspects when deciding whether or not to buy the product for some social reasons. Among which, the trend-following behaviors of the households are commonly observed in our daily life. A trend-following consumer may be willing to purchase a product regardless of its price and very probably pay much higher than his price-based choice.

Back to 1991, Gary S. Becker from the University of Chicago wrote in a note about the irrational pricing strategies of popular restaurants, plays, sporting events, etc. (Becker, 1991) and pointed out that their prices will deviate from the classic theoretical prediction (as the colored curves in Figure 40) under social influences. In particular, the firms with excess demand did not raise prices or larger profits to avoid losing popularity. In this note, a new S-curved price-demand relationship was proposed to explain the existence of two stable amount of demand under one price (black dashed curve in Figure 40).

5.2 Model

A trend in this model is defined as that a product is bought by the households because it has excess demand in the last round. Thus, it could emerge spontaneously due to the randomness or be conducted by firms' propaganda of lowering price. Hence, trend following behaviors of households could be modeled as an excess-demand-dependent potential in the demand function

$$D_i(t) = \frac{C_B(t)}{p_i(t-1)} \frac{e^{-\beta p_i(t-1)/\bar{p}(t-1) + \Omega\ \tilde{D}_i(t-1)}}{Z(t)}, \quad (27)$$

where $Z(t) = \sum_i e^{-\beta p_i(t-1)/\bar{p}(t-1) + \Omega\ \tilde{D}_i(t-1)}$.

This demand function differs from the original one (Eq.(15)) only in that a new term $\Omega\ \tilde{D}_i(t-1)$ is added to compete with the influence from the price, where $\tilde{D}_i(t-1)$ is the excess demand at last round, i.e., $D_i(t-1) - Y(t-2)$ and Ω is a predefined function of the excess demand. We can interpret Ω as a potential of trend following for the household. Several choices for Ω have been considered in the following simulation, such as linear, parabolic, cubic, and tangent hyperbolic functions. Other parts in the model is the same as the basic model.

Other parts are kept the same with the baseline model in Section.2.2 Agent behaviors.

5.3 Result

The following results all has parameters the same as in the baseline model (Table 2) except that a new trend-following potential is considered. Since there are many choices for the function of excess demand Ω, let's first categorize the functions into two kinds: diverging and converging. A converging function of Ω means that the households has limited craziness about products out of stock. By contrast, a diverging function of Ω infers that households behave like speculators and they will prefer products with more excess demand.

Let's take a vivid example to show the different between the two types. Households would like to buy a popular new cell phone and they are told to wait for some months for the available stock because there are other people queueing to buy this cell phone. For the case of a converging potential, it is assumed that the people evaluate the time for waiting and the willingness to wait decays with the time. In the end, the time length for queuing would converge to, for instance, 2 months. By contrast, for the case of a diverging potential, more people would like to wait if the queue is longer, because they fear to lose the final chance to buy this phone and then the length for queuing would diverge until reaching some physical boundary (e.g., policy, production capacity).

Also, we assume the function of centrosymmetric to the origin point (0, 0) because it is reasonable that trend-following attitudes could occur to both popular products ($\tilde{D} > 0$) and unpopular products ($\tilde{D}$ <0). In fact, this assumption of symmetry is trivial to the result but we use it here for the simplicity of demonstration. Figure 41 exhibits two schematic curves for the converging and diverging functions of excess demand.

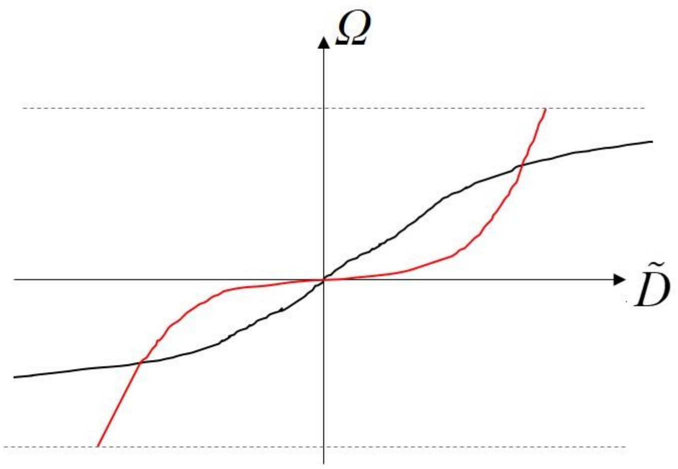


Figure 41. Two schematic functions for the excess demand. One is converging to the dashed line (black curve) and the other diverging to the infinity (red).

5.3.1 A converging potential: weak trend following

We first consider the case of a converging curve (black). Without a loss of generality, the function of excess demand is set as $\Omega(\tilde{D}) = a\tanh(b\tilde{D})$ for all firms at each time. Note that two new parameters are involved:

- *a* gives the upper and bottom limit of the potential, i.e., $\Omega\in(-a,a)$;
- *ab* describes how sensitive the potential of trend-following depends on the excess demand $\tilde{D}$.

Figure 42 shows the dynamics of the system under three sets of *a* and *b*. The two control parameters in the basic model is set as $\Theta = 15$, $R = 3$. As is introduced before, this set of control parameters should yield a system with stable macroeconomy with full employment. Yet with a potential of trend-following added to the demand function, the results may significantly change.

Figure 42(A) shows the case with a=1, b=1, where the range of the potential of trend-following is from -1 to 1, thus comparable with the scale of the price term in Table 1 Agent profile. One can see in this case, the overall dynamics do not change very much and the macroeconomy is in the FE phase as in the baseline model. The price is slightly above the equilibrium value 1 and the economy has a slight shortage of supply (5%). This means that factor of trend-following does not play an important role, and the households still seem to be very rational.

Figure 42(B) shows the case with $a = 3$, $b = 1$. The enhancement of *a* not only enlarges the range of the potential and but also strengthens the sensitivity to the excess demand, which means the households' demands are more dependent on the popularity of the products and this dependence could be strong enough to make households' concern on the price negligible. In this case, the macroeconomy falls into a RU phase, with the price far beyond the equilibrium value (which is 1) and the total demand radically fluctuating. The economy meets a serious shortage of supply (60%) and firms are frequently bankrupted. The reason behind is that the effect of price almost gets muted in this case so the firms could hardly adapt well by price adjustment only so that the disadvantaged firms cannot catch up with the top ones.

Figure 42(C) shows the case with $a = 10$, $b = 0.1$. This setting of parameter has the same sensitivity to the excess demand with $a = 1$, $b = 1$ yet has a larger range of strength of potential. The macroeconomy under this setting is assaulted by endogenous crises now and then. This means that the effect of trend following will sometimes enlarge the variance among top firms and disadvantaged ones and lead to crises.

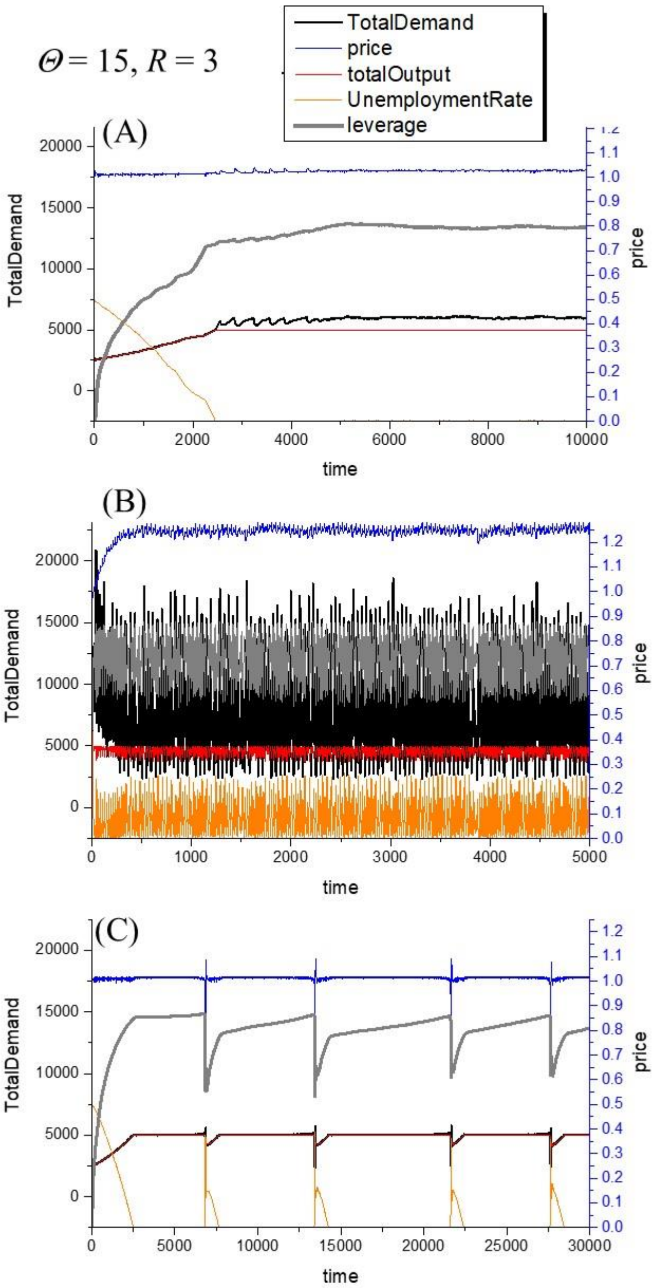


Figure 42 Simulated time evolutions of total demand $\sum_i D(t)$ (black), total output $\sum_i Y_i(t)$ (red), average price (blue), unemployment rate (orange) and global leverage (grey) with the potential of trend following predefined as $\Omega = a\tanh(b\tilde{D})$. (A) a = 1, b = 1. (B) a = 3, b = 1, (C) a = 10, b = 0.1.

5.3.2 A diverging potential: strong trend following

Next, let's consider the diverging potential of trend-following. Without a loss of generality, we choose a function $\Omega(\tilde{D}) = \tilde{D}^3$ with a physical constraint of $\Omega \in [-a,a]$. As is demonstrated before, the constraint could be interpreted as a ceiling imposed by external factors irrelevant to households' preference. Hence, a decides the maximal strength of the potential. Figure 43 shows the dynamics under three different values of a for Θ =15, R = 3. Overall, the economy encounters crises, yet the situations are more complicated than the EC phase in the basic model. In all the simulation results shown in this section, there are N_f = 5000 firms in the simulation, hence the maximal total output is $\alpha\mu N_f$ = 5000.

Figure 43(A) shows the case of a = 3. There are several economic cycles which ends with a large economic crisis. Within each cycle, three regimes can be identified. The first regime features an economic recovery, where the unemployment rate is continuously decreasing, and the total output perfectly meets total demand. The second regime is featured by an exponential growth in total demand and the economy in this period is in a full employment state. The third regime is a short crisis period, with a soaring price, shrinking demand and a volatile unemployment rate.

Figure 43(B) shows the system evolution in the case of a =5. Generally the three regimes exist, and the last regime of crises persist longer than the one in the case of a = 3. By contrast, Figure 43(C) shows the results in the case of a = 10 where the second full employment regime is substituted by a residue employment (RU) regime. In this new regime, the total output struggles to remain its level but the total demand is gradually shrinking. Moreover, the RU regime could be repeated more than once before the advent of the regime of crisis. The disappearance of the regime of exponentially growing demand indicates that in this case, a trend occurs abruptly and the households' desire for some products suddenly could become crazy, bringing partial instability to the system.

Figure 44 exhibits the dynamics of system with a = 8 for varying Θ. For a lower Θ (=3), the macroeconomy tends to fall into residual employment phases; however, with an increased Θ (=7), the system shifts into an endogenous crisis (EC) phase with a residual unemployment rate, unlike those in the typical EC phase in the basic model and also in Figure 43(C). In these two cases, the total output meets the total demand well therefore the effect of trend-following in the demand function is still mild and comparable with the effect of price adjustment, although the unemployment rate is much higher than that without the modeling of trend following. If Θ is still higher as 12 and 20, the economics within one cycle ended with crises should experience multiple regimes. In the case of Θ =12, a cycle is much shorter and the second RU regime (mentioned in the last paragraph) featured by a slow shrinkage of demand and persistent output factures and splits into several sub-periods while the unemployment rate has a stepwise elevation once a sub-period ends. For a very large Θ = 20, the second RU regime occurs less frequently, preceded by a rather long FE regime and most importantly, the RU regime and the final regime of crises persist in a relatively shorter time period, manifesting the stabilizing and resuming effect of the sufficient liquidity in the market.

In a more extreme case, we could predefine a diverging potential of trend-following in an exponential function, i.e., $\Omega(\tilde{D}) = \mathrm{sgn}(\tilde{D})(e^{\tilde{D}} - 1)$ with a range of $\Omega \in (-a,a)$. Figure 45 shows the results for a =3 and Θ=15. The macroeconomy experience three regimes within one cycle: the first regime of recovering regime, yet the final regime is a long period of residual employment phase with a high volatile price.

All these examples indicate that with a diverging potential of trend following, the modeled macroeconomy is more likely to be unstable and multiple regimes may appear within one economic cycle. The mechanisms behind the appearance of these regimes are related both to the strength of trend following and the liquidity Θ.

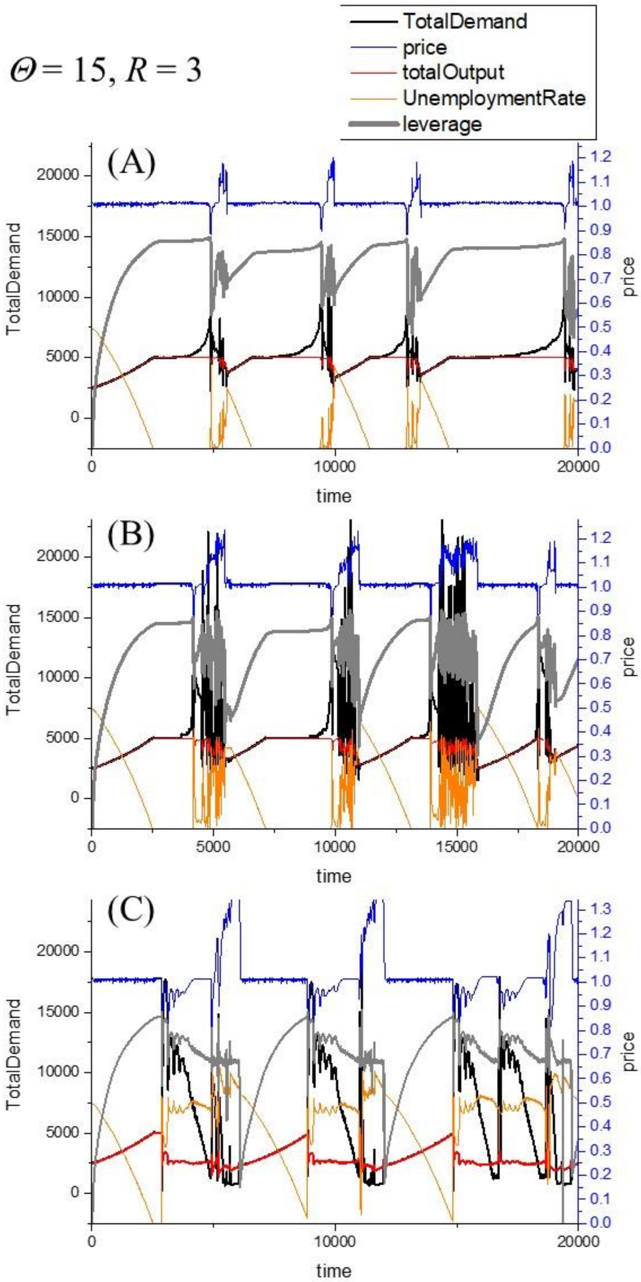


Figure 43 Simulated time evolutions of total demand $\sum_i D(t)$ (black), total output $\sum_i Y_i(t)$ (red), average price (blue), unemployment rate (orange) and global leverage (grey) with the potential of trend following predefined as $\Omega = \tilde{D}^3$. (A) *a* = 3. (B) *a* =5. (C) *a* = 10.

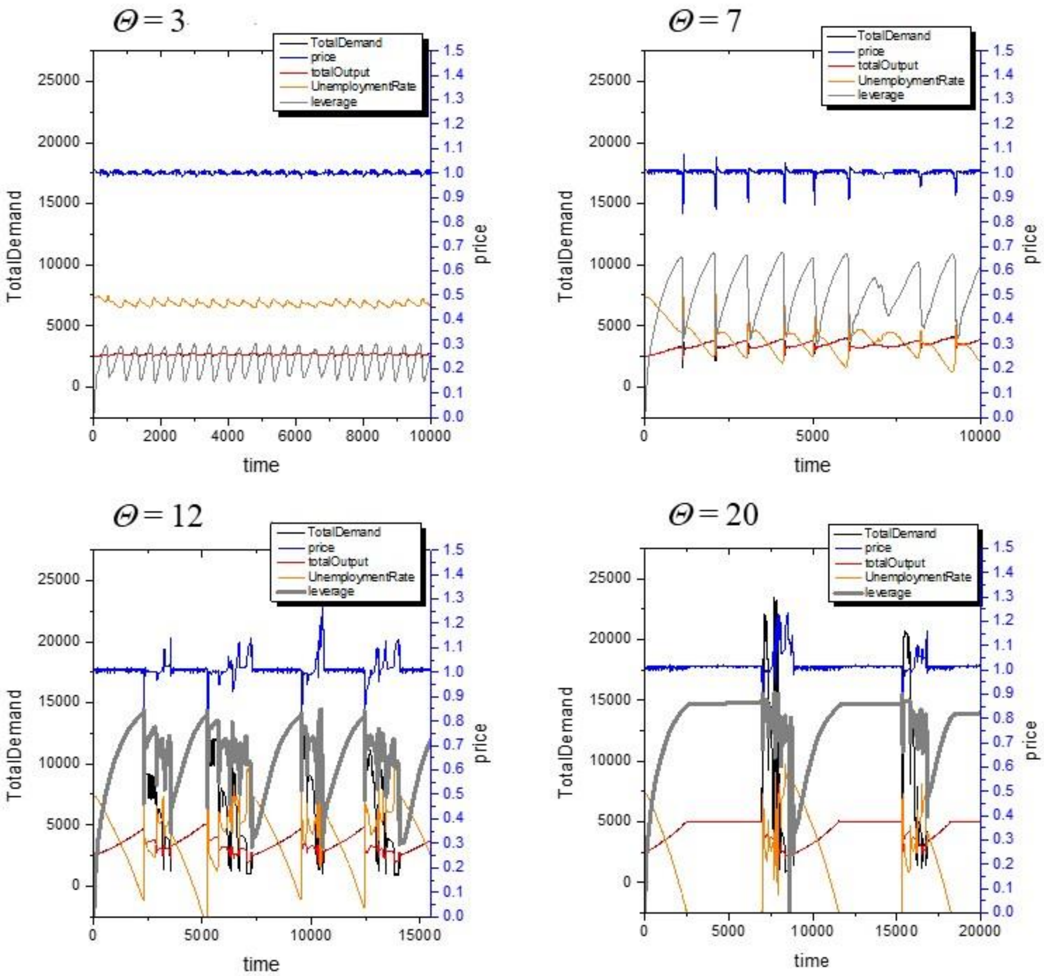


Figure 44 Simulated results with a diverging potential of trend following $\Omega(\tilde{D}) = \tilde{D}^3$, a = 8.

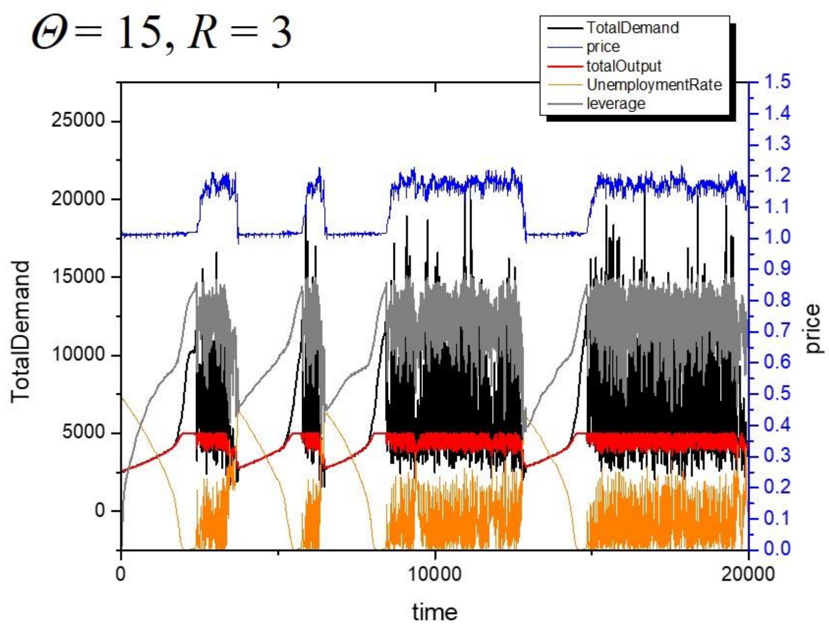


Figure 45 Simulated dynamics with a diverging potential of trend-following with $\Omega(\tilde{D}) = \mathrm{sgn}(\tilde{D})(e^{\tilde{D}} - 1)$, a = 3.

5.3.3 Firm dynamics

In order for a better understanding of the mechanisms behind the complicated phenomena shown in the last section, we need to look into the dynamics of individual firms. In all the simulation results shown in this section, there are N_f = 500 firms in the simulation, hence the maximal total output is $\alpha\mu N_f$ = 500. (In fact, the number of firms has almost no affect in the results).

Figure 46 shows the simulated dynamics of the macroeconomic indices with correspondent dynamics of effective asset $\tilde{A}_i$ of individual firms. The effect asset $\tilde{\varepsilon}_i$ is defined as

$$\tilde{\varepsilon}_i = \mathrm{sgn}(\varepsilon_i)\log(1 + \varepsilon_i) \quad . \tag{28}$$

This definition in fact is to map the original firm asset A_i to a logarithmic scale, and we use $\tilde{\varepsilon}_i$ here just for demonstration purpose.

In Figure 46, the potential is chosen as $\Omega(\tilde{D}) = 3\tanh 0.6\tilde{D}$. One can easily find that within one economic cycle there are two basic regimes I and II. In regime I with decreasing unemployment rate, increasing output and demand, the firm assets are relatively more "equal" than in the regime II, where an overshoot of demand and global leverage precedes a series of crises. By examining the asset dynamics, one could know that the overshoot of the demand and global leverage is a result of the rising of giant firms and the radically diverging status among good and bad firms. Those giant firms are those benefited from households' trend-following behaviors and but they undergo over-heated competitions so that the waves of bankruptcy occur after the overshoot of demand during regime II. In this case, although the potential of trend-following is defined as converging, the strength of this term is still so strong that the weak firms can hardly survive with the rising giants and thence the market becomes so volatile that no giant firm can survive for long time, either. Regime II will finally end with the last giant firm die.

Let's investigate another case with a diverging potential $\Omega(\tilde{D}) = \tilde{D}$ with $\Omega \in (-8,8)$. This potential of trend-following is even stronger than that in Figure 46. Figure 47 shows the results and the correspondent dynamics of firm effective assets (Eq.(28)). In this case, although the shift from regime I to regime II involves a harsh increase in the unemployment, the second regime (regime II) is rather stable, featured by an increasing total output and decreasing unemployment rate and a reasonable price. Nevertheless, by digging into the firm dynamics, one could find the economy of regime II is predominantly contributed by one super giant firm, and this superstar employs more and more labors to suppress the persisting excess demand. This regime of monopoly thus seems to be a rather promising stage. Nevertheless, once the excess demand disappears, the superstar will face a large pool of employees which cost him too much to sustain. Then regime III comes with several other strong firms with excess demand rising quickly and the price soars. This period of oligopoly also terminates quickly because the unemployment rate is too high and total demand falls into shortage. One could also note that during regime II and III, weak firms have no room for growth at all.

Figure 48 shows the results with a high liquidity Θ =20 under the same diverging potential. Compared with that in Figure 47, regime II is largely expanded and regime III becomes transient. With a higher liquidity, the regime of monopoly even has a period with increasing total demand, indicating that the total market is still very healthy despite that the variance between the top 1 and other firms is still increasing. The dominating firm in the top notch may even be replaced and another era of monopoly may start until the variance among firms are too large to sustain. In short period of regime III, new firms replenish the markets to eliminate all the old ones with bad asset/debt structures and then a new cycle begins with economic recovery.

The prosperity in regime II could also occur when a group of super giant firms share one top notch. Figure 49 shows the results under a weaker potential of trend following compared with those in last paragraphs. Regime II here is always dominated by more than one firms. As in the last case, the leading firms in regime II can be replaced others with a redistribution of labor forces but regime II with a good economy continues until a wave of bankruptcy happens and the system enters a short period of regime

III.

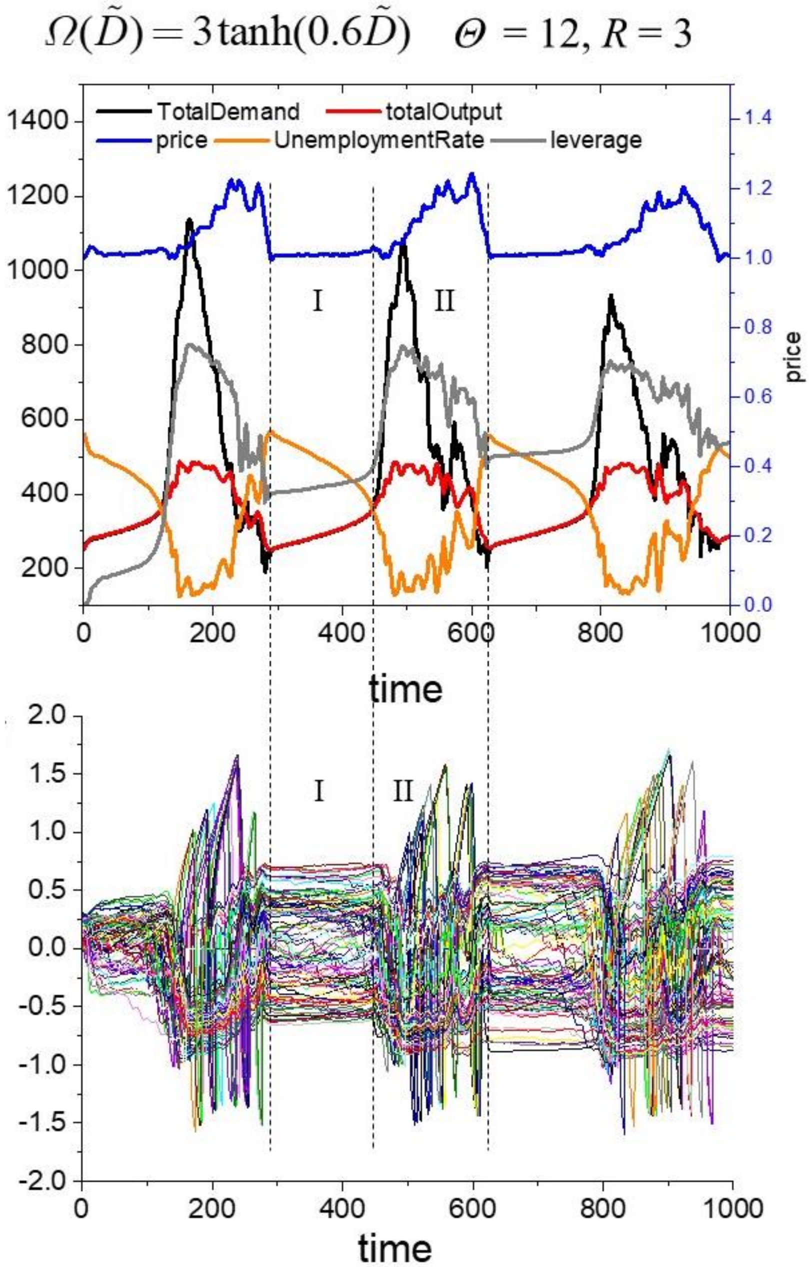


Figure 46 Simulated time evolutions with correspondent firms' dynamics of their effective asset $\tilde{\varepsilon}_i = \mathrm{sgn}(\varepsilon_i)\log(1+|\varepsilon_i|)$, where ε_i is the asset of firms. The potential of trend following Ω is predefined as $\Omega(\tilde{D}) = 3\tanh(0.6\tilde{D})$, with $\Theta = 12$, $R = 3$.

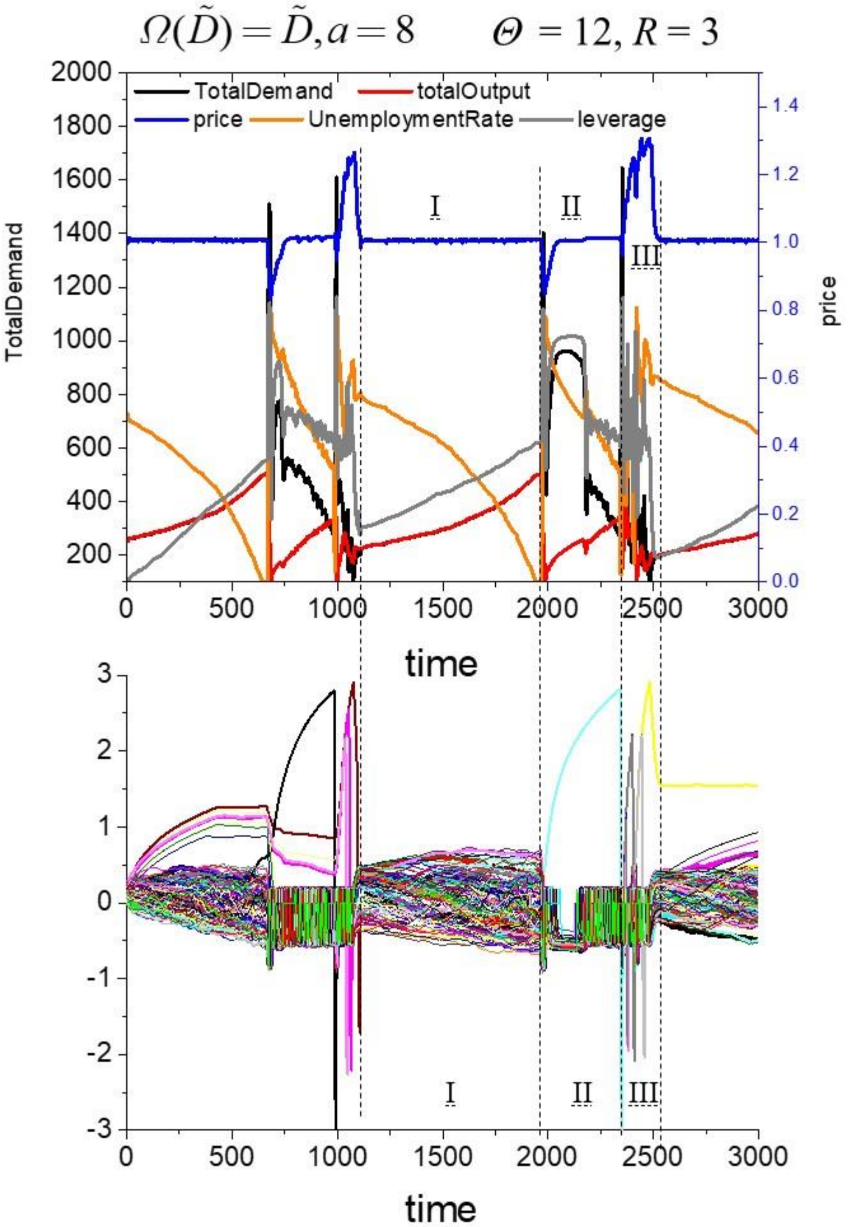


Figure 47 Simulated time evolutions with correspondent firms' dynamics of their effective asset $\tilde{\varepsilon}_i = \mathrm{sgn}(\varepsilon_i)\log(1+|\varepsilon_i|)$, where ε_i is the asset of firms. The potential of trend following Ω is predefined as $\Omega(\tilde{D}) = \tilde{D}, a = 8$, with Θ = 12, R = 3.

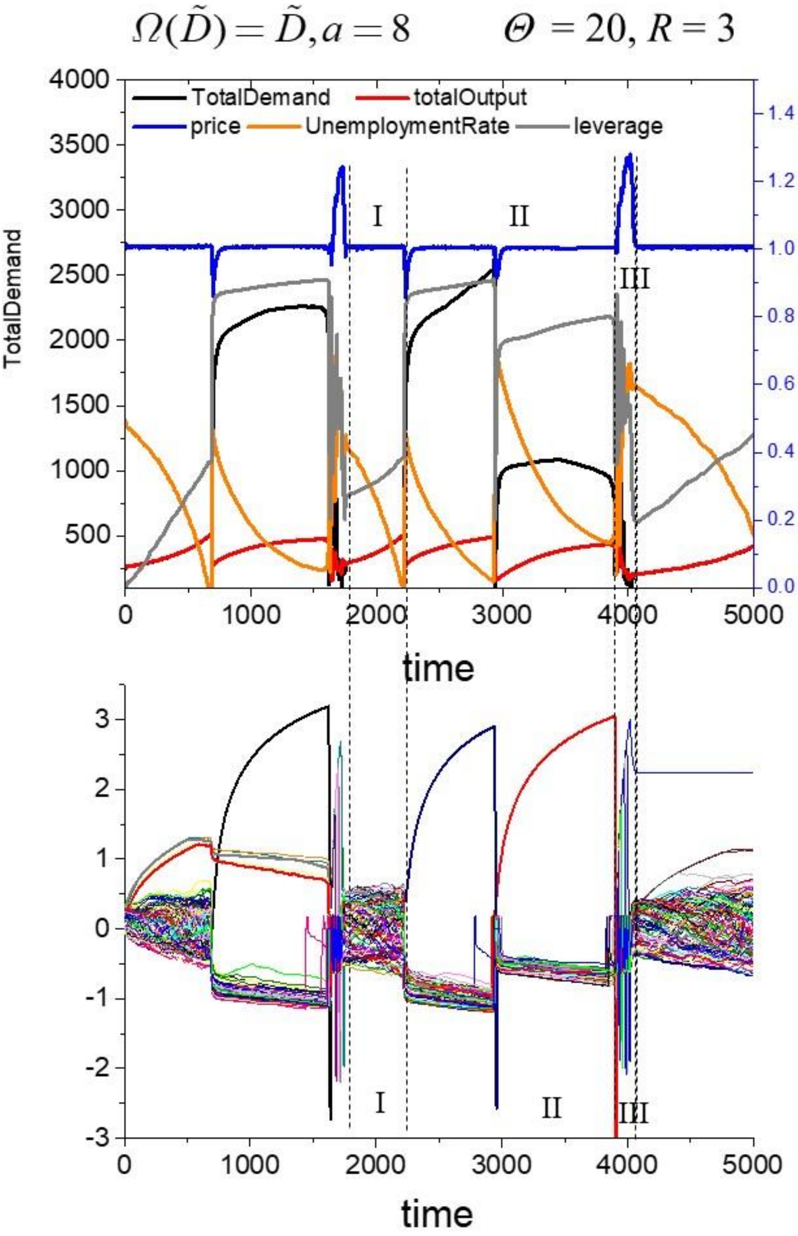


Figure 48 Simulated time evolutions with correspondent firms' dynamics of their effective asset $\tilde{\varepsilon}_i = \mathrm{sgn}(\varepsilon_i)\log(1+|\varepsilon_i|)$, where ε_i is the asset of firms. The potential of trend following Ω is predefined as $\Omega(\tilde{D}) = \tilde{D}, a = 8$, with $\Theta = 20$, $R = 3$.

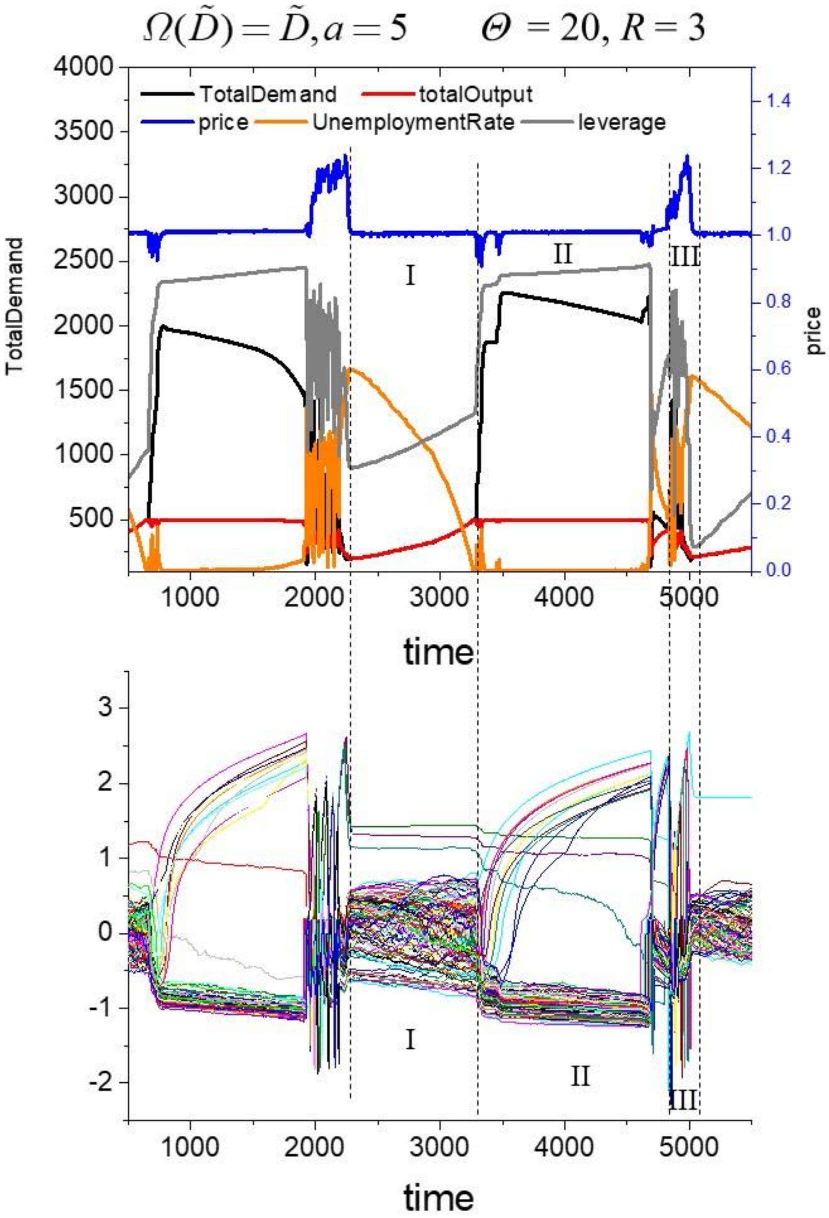


Figure 49 Simulated time evolutions with correspondent firms' dynamics of their effective asset $\tilde{\varepsilon}_i = \mathrm{sgn}(\varepsilon_i)\log(1+|\varepsilon_i|)$, where ε_i is the asset of firms. The potential of trend following Ω is predefined as $\Omega(\tilde{D}) = \tilde{D}, a = 5$, with Θ = 20, R = 3.

5.4 Discussion

With a potential of trend-following, the classical demand-price relationship collapses. Figure 50 exhibits two kinds of demand-price relationship under a converging potential $\Omega(\tilde{D}) = 3\tanh\tilde{D}$ and a diverging potential $\Omega(\tilde{D}) = \tilde{D}^3, \Omega \in [-10,10]$.

In the former case (top), a weak trend-following atmosphere cultivate many firms with higher demand and one can see the cluster of products with greater demand is generally priced higher, as opposed to the classic theory; yet for firms with similar level of demand, demand-price relationship still obeys a typical inverse proportional one.

In the latter case (bottom), only few products become extremely popular because of a strong trend-following and these hot products are more expensive than those unexpected ones despite that an inverse proportional relationship between demand and price still holds. It seems that the Becker's demand-price curve could be somehow reproduced in our model without the existence of stable range with positive slopes. This result indicates that the classic negative sloped price-demand relationship *Price* ~slope×log(*Demand*) +χ (where χ is a parameter controls the imaginary intercept of the curve, i.e., the marginal valuation) still holds as an equilibrium state but the system could run with a large number of equilibriums states in sub-phases with varying χ. The dispersion of χ as a process occurs at a larger time scale and may have some steady distribution of χ with a slight strength of trend following (Figure 50 top) and may undergo a lasting divergence of few clusters until the large-scale crises happen (Figure 50 bottom) when the trend following is extremely strong. Here comes the question: could we find any evidence in real economic data in order for our reference?

Before touching the reality, let's first have a retrospect in the theories. In fact, the idea about consumer's demand which increases with other consumers' demand was first proposed rather early in history by Harvey Leibenstein, who defined this self-dependent fashion of demand function on as a bandwagon effect (Leibenstein 1950). Yet then, Leibenstein claimed that the demand would also be constrained by the consumers' salaries so that a demand curve with positive slopes to the price could never be found in reality. Then as pointed by Gisser et, al., there was a lack of evidence for Becker's "S-curved" demand function and they explained the reason with a general equilibrium formalism for a demand-dependent function for demand quantity as *D*~ *F*(*p*, *D*) and showed that with the assumption of bandwagon effect with a positive slope in the demand function, i.e, $\partial_{\text{Demand}}F > 0$ and $dp/dD > 0$ could give only nonsensical solution with $D < 0$ (Gisser et al. 2009). These theoretical deductions accord with our results here that a trend following effect (or the bandwagon effect termed by Leibenstein) does not give a positively sloped price-demand curve as an equilibrium state. However, my new findings here are that a positive relationship between price and demand could be found as a dynamical process through which firms could climb from a sub phase with low marginal values (χ) to a high one. Hence, it is possible to observe a positive correlation between the time evolutions of price and demand during a specific period during which big firms emerge whereas small firms still survive (Figure 46-Figure 49).

Another implication regarding the empirical evidence is that the data should be evaluated by sector as the motives of trend following would largely differ from sectors to sectors. For instances, in the real estate sectors, sometimes people tend to follow the “trend” for strong speculative purposes, while in the sector of fashion products, people follow the “trend” for social purposes. And these different motives of trend following could correspond to distinctive potential terms Ω and lead to different features of statistics, e.g. of distributions of firm quantities, time evolutions of macro-indices, etc.

5.5 Conclusion

The demand function with a diverging potential characterizes the products or services with the network effect, which facilitates the global expanding of the Internet Giants. The positive feedback loop of demand creating demand and “more users, better services/products” makes it possible for the Internet Giants to keep their monopoly positions for a longer period. On the other hand, the demand function with a converging potential characterizes the products or services which are popular because of the customers’ herding behaviors, which can be further accelerated by the rapid spread of information. In this case, the firm that provides the products or services can achieve an unexpected rapid growth but cannot stay ahead for long. With the existence of either of those demand functions, excessive liquidity will no longer stabilize the economy but aggravate crisis.

Beyond that, the introduction of the non-linear demand functions in the agent-based modelling also provides a new approach to understand the industry dynamics and the different outcomes of firm size distributions in different sectors.

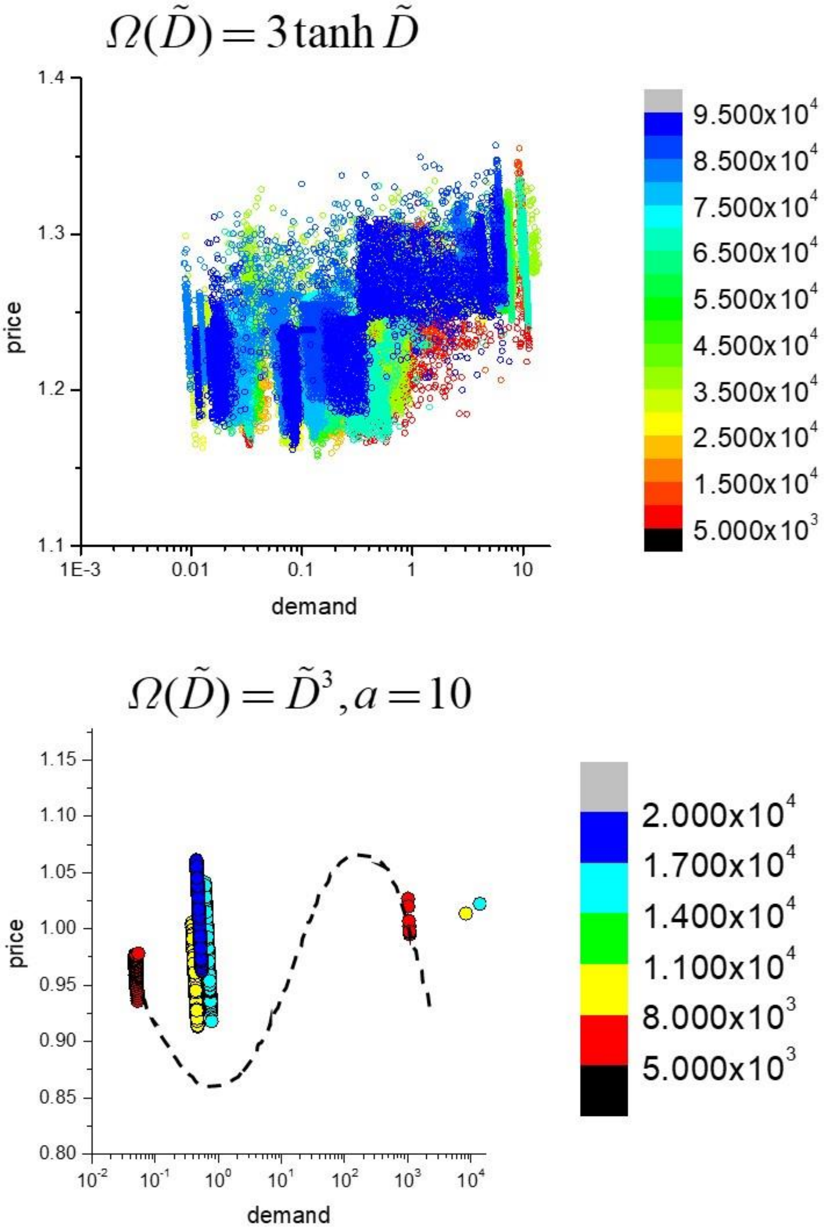


Figure 50 Relationship between price $p_i(t)$ and demand $D_i(t)$ at a specific time step under two different trend-following potentials Ω, with Θ=15, R = 3. Different colours for different times. The dashed curve is a schematic relationship in Becker's theory.

5.6 Appendix: Empirical evidence

The proposed model in Chapter 5 provides some possible explanations for the differences of firm size distributions in different sectors or one sector in different developing stages. For example, the firm size distributions in information and communication technology (ICT) sectors tend to be more skewed (a pareto distribution) than the ones in the manufacturing sectors (near a lognormal distribution) (see *Segarra, A., & Teruel, M., 2012* for a survey on the firm size distributions in different countries and different sectors). The study in this chapter suggests that the ICT firms might be more likely to get a diverging herding potential in the demand functions, while for a firm in manufacturing sector, even if it could get a herding potential in its demand function, it was more likely to be a converging one.

Chapter 6 Coupling with a financial engine

In this chapter, I established an agent-based model (ABM) to simulate the coupling of an economic system with a financial market. In the model, I find the economy can operate in two status – stable status and cyclical status. In both statuses, the endogenous business cycles indicated by short-term imbalance of the demand and supply exist. The long-term credit cycles only emerge in the cyclical economy. The credit cycles are caused by speculative bubbles in the model. They can accelerate the economy. However, it is just an illusion of prosperities. Because after the collapse of the bubble, the economy will be trapped in recession for long time.

6.1 Introduction

Business cycles is a series of up-down deviations from the long-term trend of gross domestic product (GDP). Although being termed "cycle", unlike similar concepts in natural science and engineering, it is hard to observe or detect any clear periodic phenomenon in GDP. In fact, the business cycles act more like fluctuations. However, people can feel them. Basically, one typical business cycle includes the expansion and recession phases of the economy (Figure 51).

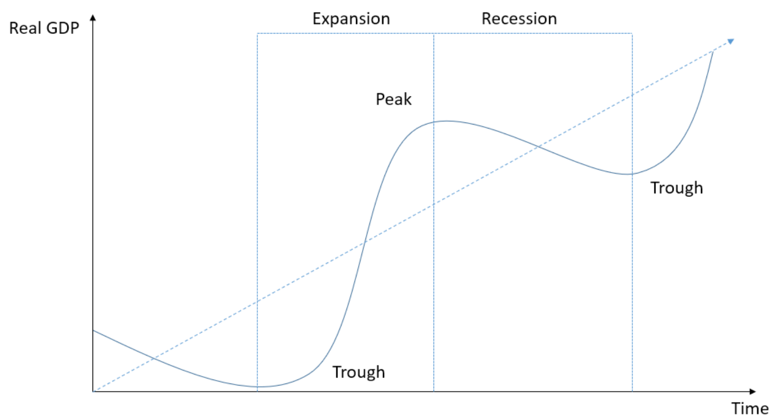


Figure 51 an illustration of the business cycles

In the beginning of an expansion phase, the demand for durable goods picks up because the loose credit usually favors them. Thus, the liquidations of inventories slow down and the manufacturers start to increase their production and rebuild the inventory. In the same time, the economic growth speeds up and the increase of employment rate follows. In the mid-term of the expansion, as the profitability of businesses becomes higher and higher, the firms start to expand their capacity, which will lead to strong demand for credit. Then the interest rates start to increase. In the late of the expansion, because the consumption demand is still surging and the release of production capacity needs time, the inflation rates will also increase. This situation indicates an overheating economy so that the central bank will start to tighten the liquidity. As the credit supply becomes tighter, the expansion phase reaches its peak.

As the economic growth slows down, the recession phase starts. The consumption demand starts to fall and the firms' investments in the expansion phase may become excess capacity. However, the cost of funds and the maintenance expenses cannot be reduced easily. Thus, the firms may choose to cut bonus for the employees or even fire some of them, depends on the amounts of cost needed to be trimmed. This will further reduce demand and hurt the confidence on the economy. The recession phase usually ends when the central bank turns to a loose monetary policy and the loose monetary policy is effective. One business cycle can last from several years to several decades.

There is also lots of debate when economists try to give explanations to business cycles (Morgan, M. S. 1990). One of the major divergences is exogenous cause versus endogenous cause of the cycles. While Keynesian economics believe that business cycles reflect the nature of economy to run above or below equilibrium levels so that government should implement monetary and fiscal policy to smooth these fluctuations, Austrian School argues that the exogenous government involvement aggravates the regular fluctuations and should be blamed for causing economic instabilities. Alternative theory argued that business cycles are essentially credit cycles (Mankiw, N. G. 1989; Dalio, R. 2014). Credit expansions and contractions cause the economic prosperities and recessions. As the gap of real economic growth and credit expansion enlarges, the collapse of speculative bubble will be the turning point of upward trend. On the other end, deleverage of the heavy debt loads and effective monetary stimulation by the central bank usually become the turning point of downward trend.

Besides the above explanations, we can find more theories and frameworks about business cycles, which are beyond the scope of this work. In general, we see there are lots of ingredients and interactions being involved in the economy. However, traditional macroeconomic theory usually explains phenomenon from one or two aspects of its concern. This leads to our first motivation to establish an ABM to investigate macroeconomics problems: ABM is able to treat the economy as a complex system in a bottom-up approach and take into account many important ingredients and interactions which may have to be neglected in traditional macroeconomic models for the sake of analysis.

On the other hand, the operation of market-based economy today is strongly fueled by financial systems. A financial system, for example, a stock market or a bond market, facilitates the transactions between fund demanders and providers, who have different preferences of returns, risks, time horizons and etc. Ideally, funds are supposed to be allocated in a more efficient way when the market for a financial asset exists.

Theoretically, the pricing of a financial asset is based on the present value of its expected cash flows in the future (Graham, B., Dodd, D. L. F., & Cottle, S. ,1934). In the long-term (for a stock market, longer than 5 years), the price trend of a financial asset usually reflects the economic performance or the intrinsic value of the asset. Figure 52 provides a comparison between real GDP per capita in U.S. and Dow Jones Industrial Average, which is one of main stock market indexes, during the similar periods.

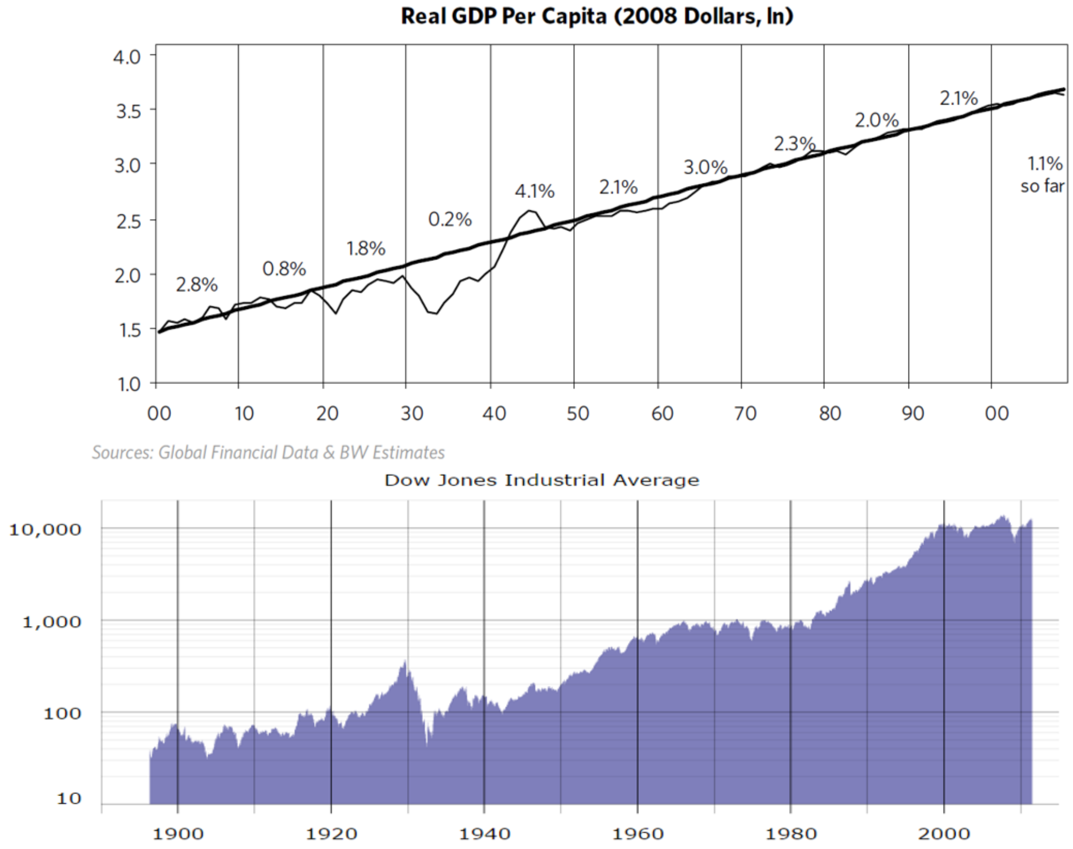


Figure 52 a comparison between real GDP per capita in U.S. and Dow Jones Industrial Average in more than 100 years. (Dalio, R., 2014).

However, the calculation of "expected cash flows in the future" involves not only objective facts but also subjective opinions and believes. Therefore, the fluctuations of the asset price may deviate much from the intrinsic value of the underlying asset. When the asset price is thought to be much higher than the intrinsic value of the asset, some may argue that it is a bubble, although in most cases, an asset bubble can only be confirmed when it crashes. One example of the asset bubble is the dot-com bubble from 1994 to 2000 in United States. During the doc-com bubble, most (if not all) firms related to Internet service were valued at a price as if they would all become Internet giants, even if scarcely any firm at the time found a profitable business model. The over-optimism of the investors clearly played an important role in the formation of the bubble. After the collapse of the dot-com bubble, United States entered into a recession.

The existence of business cycles, and furthermore the irregularities of the durations and the amplitude of the expansion and recession phases make it more difficult for the market participants to estimate the future cash flows and predict the economic changes. On the other hand, the mispricing of the financial market may sustain an expansion phase or a recession phases, but at the cost of over-accumulation of debt, or a late recovery of an economy, which is similar to the mechanism proposed as the Theory of Reflexivity in Soros, G., 2015.

The interactions between a real economy and a financial system have been rarely investigated in traditional macroeconomic studies. The commonly adopted rational behavioral assumptions also neglect the characteristics of human nature, which can amplify economic fluctuations through financial activities. So, the second motivation of this study is to introduce heuristic and adaptive behavioral rules into an ABM to study the interactions between a real economy and a financial system.

In this work, we will establish an agent-based economy in which the financial system plays a significant role. We will see, the financial system not only accelerates the growth of economy, it also induces short-term and long-term cycles. By examining the cross-sectional data, we find that in our model, the short-term cycles are similar to the endogenous caused business cycles, meanwhile the long-term cycles are credit cycles caused by speculative bubbles.

6.2 Description of the Model

In this model, we have four groups of agents: firms, households, funds and bank. Each firm agent has independent balance sheet and updates his operation strategy in an adaptive way. The households behave as a representative agent, so that they set an aggregate consumption budget and wealth allocation. The funds invest the equity allocation of total wealth on behalf of the households. The bank offers loans to the firms and set the loan rate according to the firm's financial status.

6.2.1 Firms

The major role of firm is producing consumption goods for the households. Each firm $i = 1 \ldots N_f$ updates its production $Y_i(t+1)$ and product price $p_i(t+1)$ in a heuristic way (Gualdi, S., et al, 2015):

$$
\begin{aligned}
&\text{If } I_i(t) - I_i(t-1) > 0 \text{ and } p_i(t) > p'(t), \\
&\qquad p_i(t) = p_i(t-1) * (1 - \xi_i(t)); \\
&\text{If } I_i(t) - I_i(t-1) > 0 \text{ and } p_i(t) < p'(t), \\
&\qquad Y_i(t) = Y_i(t-1) * (1 - \varepsilon_i(t)); \\
&\text{If } I_i(t) - I_i(t-1) < 0 \text{ and } p_i(t) > p'(t), \\
&\qquad Y_i(t) = Y_i(t-1) * (1 + \varepsilon_i(t)); \\
&\text{If } I_i(t) - I_i(t-1) < 0 \text{ and } p_i(t) < p'(t), \\
&\qquad p_i(t) = p_i(t-1) * (1 + \xi_i(t)). \qquad (29)
\end{aligned}
$$

Where $I_i(t)$ is firm i's inventory at time t, and $p'(t)$ is the production weighted price for all firms, $\xi_i(t)$ and $\varepsilon_i(t)$ are two random numbers giving the quantities of the adjustment to price and quantity.

Clearly, the inventory change $I_i(t) - I_i(t-1)$ measures whether the products of firm *i* are in over supply or over demand.

For simplicity, we use production function $Y_i(t) = W_i(t)$, $W_i(t)$ is the amount of required workforce. Wage for unit workforce is set to one. Therefore, it costs $W_i(t)$ of firm *i's* cash to finish production. When firm *i* do not have enough cash, he would ask for loan from the bank. Financing rules will be described in 6.2.4 Bank.

6.2.2 Households

The households buy products from firms, work for the firms and receive wage. In the current version of the model, we use an aggregate account for all the households. Therefore, in each round *t*, the total amount of wage $\sum W_i(t)$ flows in the aggregate account. Then the consumption budget $C(t)$ for this round can be set:

$$C(t) = \rho * (S(t) + \chi(t) + \sum W_i(t)) \quad (30)$$

Where ρ is the propensity to consume, $S(t)$ is the value of the households' savings, $\chi(t)$ is the value of the households' equity portfolio.

The consumption budget will be distributed among the firms using a choice model (Anderson, S. P., De Palma, A., & Thisse, J. F., 1992), which is the same as equation (15).

If firm *i* cannot satisfied the demand, the corresponding amount of cash will be returned to the household account. Then a fixed proportion of the surplus wealth will be allocated to the investment fund (6.2.3 Funds) and the remains will be put into bank as deposits.

6.2.3 Funds

There are *M* funds making investment decisions on behalf of the households. In this version, all funds trade the market portfolio *index (t)* based on an adaptive method. The opinion of fund *j* on the market is:

$$O_j(t) = C_1 * u(t-1) * f(t) + C_2 * \upsilon_j(t); \quad (31)$$

Where C_1 and C_2 are parameters, $f(t)$ is the total profit of the firms (equals to revenue minus wage cost $f(t) = \sum p_i(t)Y_i(t) - \sum W_i(t)$, this term can be understood as the fundamental information of the firms), and $\upsilon_j(t)$ is the private expectation of an individual fund, which is simulated as random numbers drawn from the standard normal distribution. When $O_j(t)$ is positive, fund *j* would submit a buy order; when $O_j(t)$ is negative, fund *j* would submit a sell order. After all the funds have made the decisions, the relative power $\tau(t)$ between the buy side and the sell side can be calculated as the difference between the total number of the buy orders and the total number of the sell orders. The price return of the equity index $\Omega(t)$ would be:

$$r(t) = ln(\Omega(t)/ \Omega (t-1))= \tau(t)/M.$$

$$\Omega(1)=1 \quad (32)$$

The weight on the fundamental information $u(t)$ updates as:

$$u(t) = \lambda * u(t-1) + (1 - \lambda) * f(t-1) * r(t)/\sigma(t); \quad (33)$$

Where $0<\lambda<1$ is a parameter measuing the length of memory of the funds, $\sigma(t)$ is the standard deviation of $\Omega(t)$. A larger λ means that the funds have a longer memory. Therefore, $u(t)$ increases when $f(t-1)$ gives right predication to the price change $r(t)$ and decreases when it makes mistake, this also makes the relative importance of the private expectation move toward the opposite direction.

The value of the equity index $\Omega(t)$ would influence both the households and the firms. For the households, the value of the households' equity portfolio $\chi(t)$ would change at the same rate as the change of $\Omega(t)$. Therefore, when $\Omega(t)$ increases, the households would feel richer and consume more. For the firms, $\Omega(t)$ would influence the leverage ratio $L_i(t)$ of each firm, which would influence the willingness of the firms to expand their business. The details would be discussed in the next section.

6.2.4 Bank

If one firm is short of cash for its planned production, it asks bank for financing:

$$F_i(t) = W_i(t) - \eta_i(t); \quad (34)$$

Where $\eta_i(t)$ is the current cash of firm i, thus $F_i(t)$ is the firm's financial deficit.

Then the bank will quote an interest rate for the loan based on the current leverage of this firm:

$$i_i(t) = R * (1 + \ln L_i(t)); \quad (35)$$

where R is the risk-free interest rate. The leverage $L_i(t)$ is calculated as the ratio of the firm's asset and equity $L_i(t) = [d_i(t) + \eta_i(t) + e_i(t)] / [\eta_i(t) + e_i(t)]$, where $d_i(t)$ is the debt of the firm and $e_i(t)$ is the equity value of the firm. In each round, $d_i(t)$ would increase by $F_i(t)$ if the firm successfully gets loan from the bank and would decrease by a ratio b of $\eta_i(t)$ if the firm's cash $\eta_i(t)$ increases in this round. Therefore, when a firm's leverage $L_i(t)$ increases, the bank would quote a higher interest rate for the firm.

As we mentioned in 6.2.3 Funds, funds only trade the market portfolio. Therefore, the price of equity $e_i(t)$ moves as the following function (Black, F., Jensen, M. C., & Scholes, M. 1972) of the price change of the market index $\Omega(t)$:

$$\Delta e_i(t) = R + \beta_i(\Delta \Omega(t) - R); \quad (36)$$

Where β_i is a risk measure of the return of e_i to the market return, in this work, we just set $\beta_i = 1$ for $i = 1 \ldots N_f$. and Δx means the change of x from $t-1$ to t.

Received the quotation, the firm has a simple rule to decide if it fully accept it:

(1) If the marginal profit of the production supported by financing is larger than the marginal cost of financing, that is,

$$F_i(t) * p_i(t) - F_i(t) * W_i(t) > F_i(t) * i_i(t); \quad (37)$$

The firm will accept all the loan to financing its production, and $F_i(t)$ will be added to firm's debt.

Parameter table	
Total round T	10000
Number of firms N	100
Number of funds M	10
length of memory of the funds λ	0.95
Debt Shrink ratio γ	0.8
Risk free interest rate R	0.01
Wage	1
Propensity to consume ρ	0.8
C_1	1
C_2	1
Price adjustment ξ_i	Randomly picked from Uniform distribution (0,0.1)
Production adjustment ε_i	Randomly picked from Uniform distribution (0,0.1)

(2) If the marginal profit of the production supported by financing cannot cover the marginal cost of financing, that is,

$$F_i(t) * p_i(t) - F_i(t) * W_i(t) < F_i(t) * i_i(t); \quad (38)$$

The firm will shrink its financing need by a ratio γ:

$$F_i'(t) = \gamma * F_i(t); \quad (39)$$

So here even if the marginal profit cannot cover the marginal cost, firm *i* still keep operating, and expect to a recovery of the marginal profit in the future.

6.3 Result and Discussion

6.3.1 Results

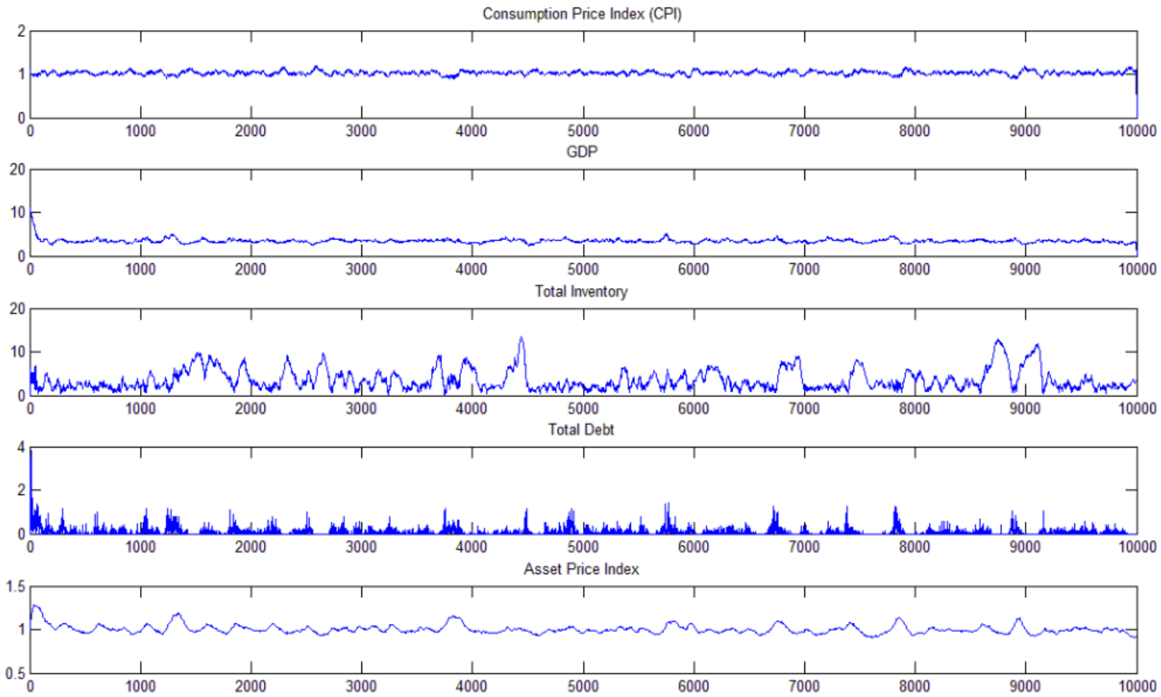


Figure 53 CPI, total production, total inventory, total debt and asset price index in the stable economy

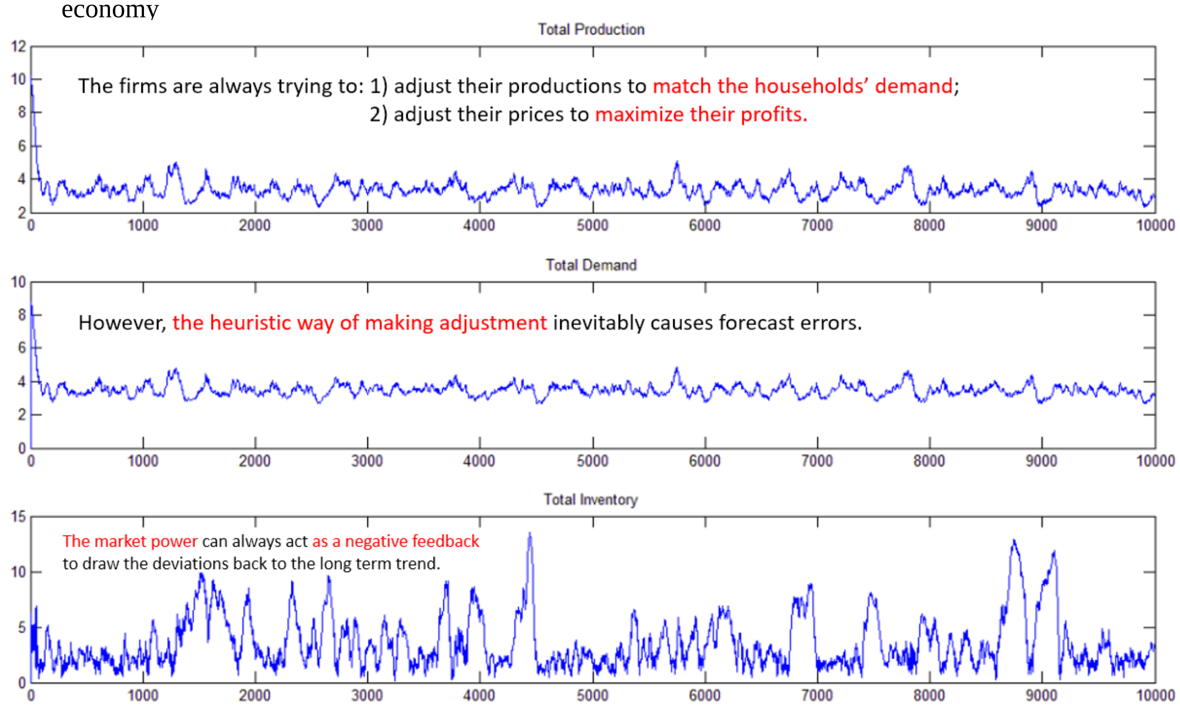


Figure 54 Short-term cycles indicated by the changes of production, demand and inventory in the stable economy.

In our simulation, we find two categories of outputs from the model. We call one as the stable economy and the other as the cyclical economy. Two samples of the main macroeconomic indicators are given in Figure 53 (stable) and Figure 55 (cyclical). We use the production weighed price as the indicator of consumption price index (CPI), and we use the summation of the quantities of the firms as the other macroeconomic indicators.

In the stable economy (Figure 53 and Figure 54), CPI and total production is quite stable in the long term (during the whole simulation here). However, we find mild fluctuations in the data “total inventory”. This means although the total demand and total production are stable, because of the heuristic way of the firms to plan future production, it is inevitable to have forecast error. Therefore, in the short-term, there always exists over supply and over demand, this is just like the endogenous business cycles described in the macroeconomic theory. This is at the opposite of what a fully rational firm agent who can always set the production and demand at equilibrium may face. However, these short-term cycles are harmless, the market power can always act as a negative feedback to draw the deviations back to the long-term trend.

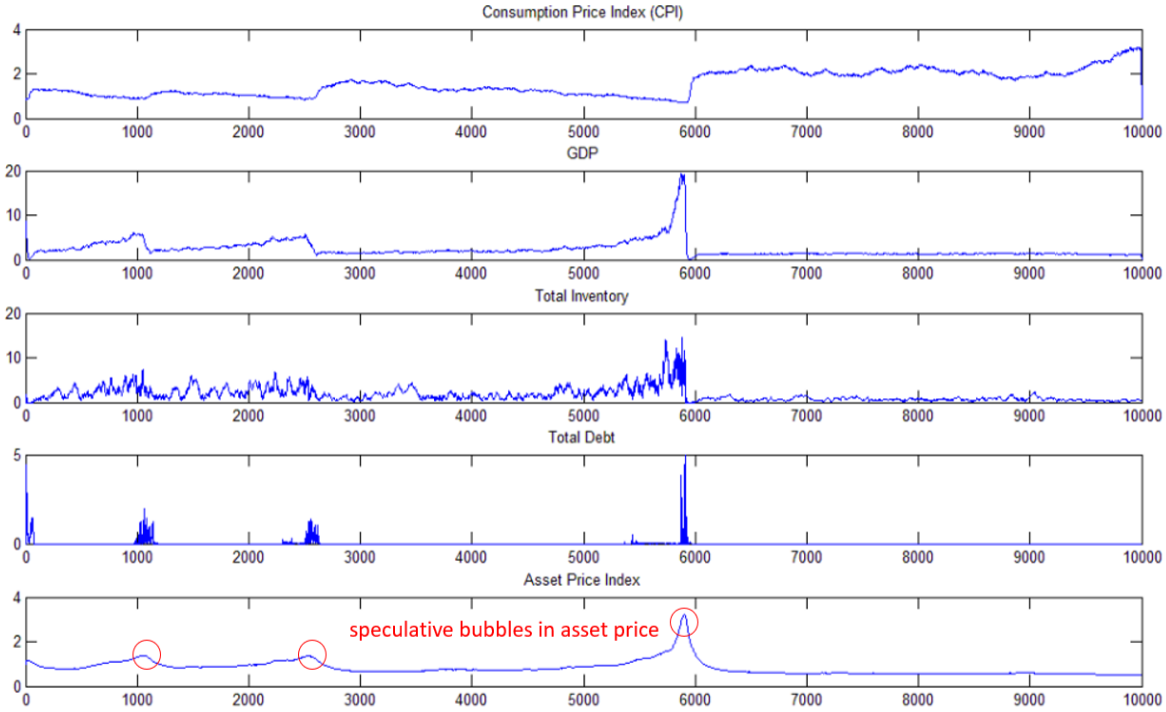


Figure 55 CPI, total production, total inventory, total debt and asset price index in the cyclical economy, fuelled by the financial "engine".

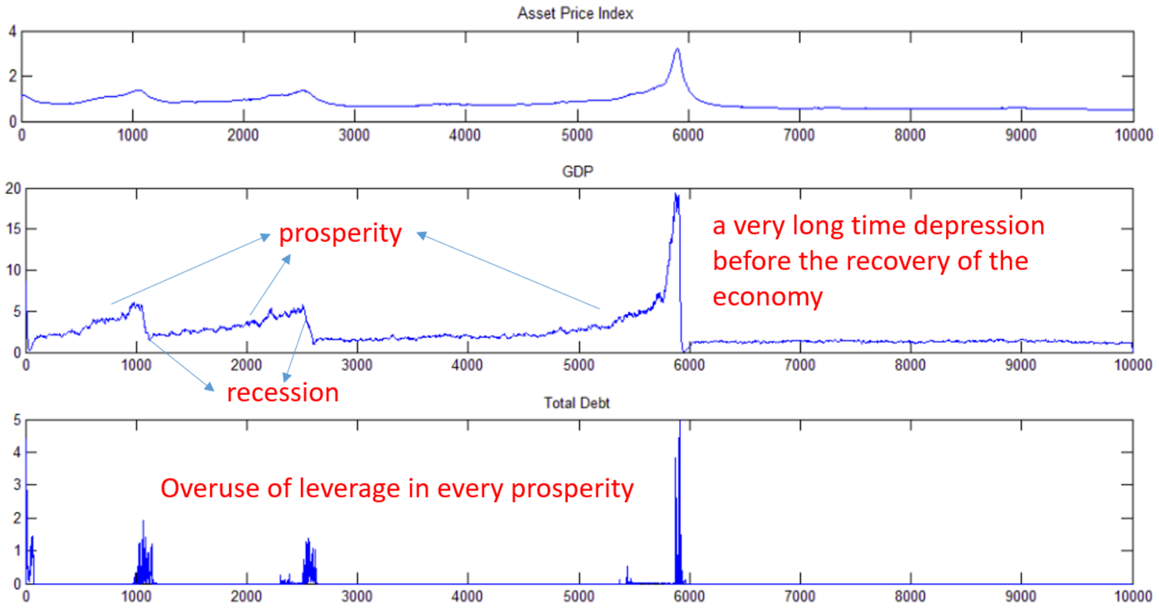


Figure 56 Prosperity, recession and depression in the cyclical economy

In the cyclical economy (Figure 55 and Figure 56), things are quite different. We have not only the short-term cycles indicated by the total inventory, but also wild fluctuations in the total production. Although the production grows to a very high level which cannot be found in the stable economy, it in fact produce too much thing that cannot consumed in a very long time. Therefore, we can regard the high-level production as an illusion of prosperity. Because at last, most of wealth is locked in the inventory, and this makes the firms stop producing so that the households cannot receive wage. Then the consumption becomes very weak, keep the inventory stay high. Without any exogenous involvement, the economy will be trapped. How can this happen? Let us check the equity index. We find larger fluctuations in the index. And in the period of uptrend (bull market), we can always see significant increases in the total debt in the economy. This is exactly the credit cycles caused by the speculative bubbles. When the equity market booms, the operation leverage of the firms may seem low so that the firms is able to expand their production at very low financing cost. However, when the bubble finally crashes, the loan loads will suddenly become very heavy. So, the end is, heavy loan, high inventory and weak consumption trap the economy into recession.

6.3.2 Discussion

In both the stable economy and the cyclical economy, the short-term cycles can be identified by fluctuations in the total inventory (Figure 54). Indeed, the origin of the short-term cycles in this model are caused by the firms' heuristic way of decision making. The firms are always using the trial and error approach to adjust their productions to match the households' demand and adjust their prices to maximize their profits. Such way of making adjustment inevitably causes forecast errors. Fortunately, the competition among the firms can always work as a negative feedback to push the deviations back to the long-term trend.

Therefore, the short-term cycles in the model are close to the "endogenous" business cycles in Keynesian economics – it's the nature of an economy to operate above or below the equilibrium status. While Keynesian economics would usually suggest that there should be some government interventions when the economy was above or below the equilibrium status, it is not necessary to implement policies to react to the short-term cycles alone in this model – the "invisible hand" itself is able to fix any deviations.

However, when the economic growth is fueled by the financial engine, long-term cycles, which can be identified by the wild fluctuations of the asset price in the financial market, would emerge (Figure 56). The cause of the long-term cycles is a positive feedback loop between the real economy and the financial system (Figure 57). As the real economy has unexpected good performance sometimes, the capital investors may pay more attention to the financial market and increase the funds invested in the market so that the asset price would be pushed up. In turn, the higher asset price would support significant expansion of the credit in the real economy which would further accelerates the economy. The growth of the economy would then support the believes of the capital investors. This process would lead to fast growth of production and demand and creates an illusion of prosperity. However, if the asset price collapsed, the loan loads would suddenly become very heavy and crunch the economy. Without external involvement, the economy will be trapped for a long time.

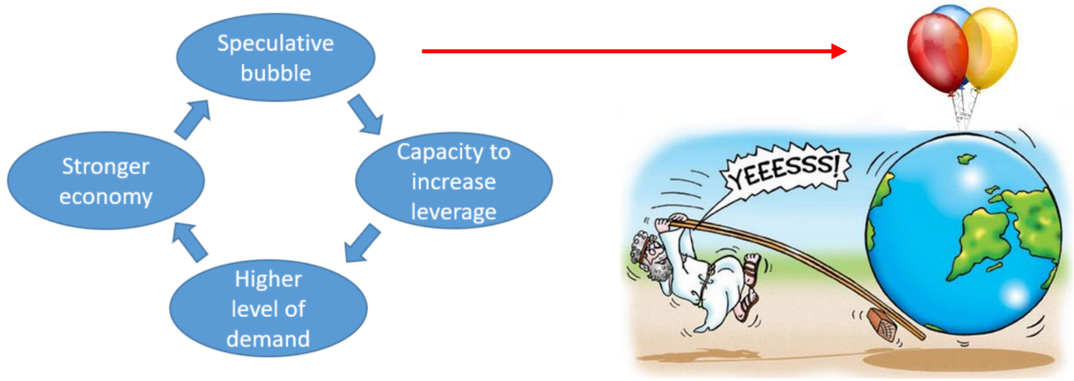


Figure 57 an illustration of the positive feedback loop

6.4 Conclusion

The real economy is very complex. Policy, culture, technology, human nature, etc. may all involved. In this work, we tried to integrate the very basic parts of the modern economy to establish an agent-based macroeconomic system. In this model, we find two types of business cycles. One is the endogenous short-term cycles, caused by heuristic behavior of firms, and do no harm to the long-term trend of the economy. The other is the long-term credit cycles caused by speculative bubbles. These credit cycles are much more dangerous. They may create illusion of prosperities but will finally trap the economy into long time recession.

In fact, some countries have successfully utilized the financial engine to drive the economic growth so far. For United States, the financial engine is a strong stock market. By means of the advantage in Internet services, biological pharmacy and other high-tech sectors, the firms listed in the U.S. stock market are able to sustain a high valuation. The high valuation would in turn facilitate the financing process of the new companies and motivate entrepreneurs to start new business in U.S. Moreover, as an average U.S. household can also benefit a lot from the growth of the stock market, if consider the contributions of the pensions, a high valuation of the stock market can also support a strong consumption demand and in turn, drive the growth of U.S. economy. This process forms a positive feedback loop

(Figure 58 top), as described in the model of this study.

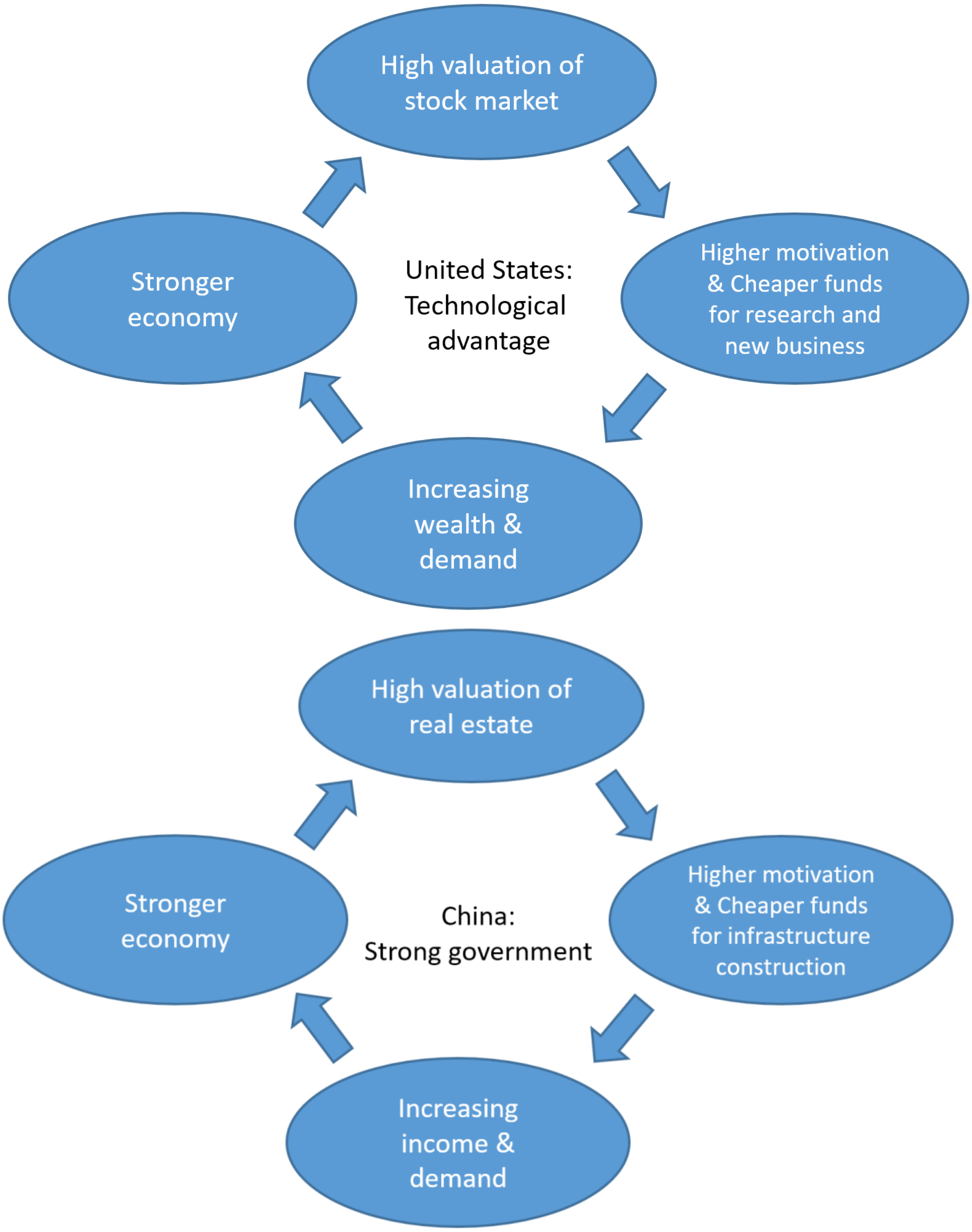


Figure 58 illustrations of the financial engines for United States (Top) and for China (Bottom)

On the other hand, the financial engine is not necessarily a stock market. In China, the real estate market plays as the role of the financial engine. Because of the heavy investment in the infrastructure construction by the governments and decades of urbanization, the valuation of Chinese real estate market is on a high level. The high valuation of the real estate also makes it possible to the governments to receive large amounts of funds from the land-transferring fees, which in turn can be used to finance the infrastructure investment and thus, sustain the high valuation of real estate. Moreover, the high valuation of real estate also contributes a lot to the growth of households' wealth. The wealth share of real estate for an average Chinese household is more than 70% today. Therefore, a high valuation of real estate can also make the households feel rich and increase their propensity to consume. This process also forms a positive feedback loop (Figure 58 bottom).

Although the positive feedback loops of the stock market and the real estate market have promoted the economic growth in U.S. and China, respectively, the leverage ratios of the households and corporations also reach historical high levels. Therefore, the sustainability of the high valuations of the stock market in U.S. and of the real estate market in China become a crucial factor. Moreover, if the high valuations cannot sustain and finally collapse, what kinds of policy tools can be used? This topic is far beyond the scope of the current study.

In the future work, we will first investigate control parameters that turn stable economy to cyclical economy in the established model. Based on this result, we may find useable policies to adjust the economy, and keep it developing in a sustainable track. In fact, we have tried some popular monetary and fiscal policies to implement on our model. But most of such policies do little help in saving the economy from recessions. And some of them seem effective at first, but finally they are just creating a larger illusion of prosperity.

Chapter 7 Conclusion

With the consideration of firm heterogeneity, the macroeconomic agent-based models present very rich phenomena of the complex economic systems. Through further investigation and analysis, I find that this series of computational studies can indeed provide some unique insights into understanding the macroeconomic implications of the firm heterogeneity, which were usually neglected by the mainstream economic studies.

The heterogeneity in firms' profitability can frustrate the loose monetary policy, which is popular in many countries since the 2008 financial crisis and is intended to re-stimulate the economy. When the firms in an economy present strong heterogeneity in profitability, the excessive liquidity injected into the economy would help the advantageous firms grow larger in their market value, and make it possible for the disadvantageous firms to accumulate more debts. Therefore, the popular loose monetary policies today, such as quantitative easing, may increase global financial fragility and lead to severe economic crisis.

A moderate level of heterogeneity in firms' productivity will lead to technology cycles, during which both "creative destruction" and active R&D can play the roles so that the economy will reach its full potential to achieve TFP growth. However, the overuse of monetary policy would impede the effect of "creative destruction" and thus would result in low productivity growth. Moreover, the choices of industrial policies and patent laws should also consider the structure of industries in an economy.

With the heterogeneity in the demand functions of products or services, multi-equilibrium will emerge in the system. The demand function with a diverging potential characterizes the products or services with the network effect, which facilitates the global expanding of the Internet Giants. The positive feedback loop of demand creating demand and "more users, better services/products" makes it possible for the Internet Giants to keep their monopoly positions for a longer period. On the other hand, the demand function with a converging potential characterizes the products or services which are popular because of the customers' herding behaviors, which can be further accelerated by the rapid spread of information. In this case, the firm that provides the products or services can achieve an unexpected rapid growth but cannot stay ahead for long. With the existence of either of those demand functions, excessive liquidity will no longer stabilize the economy but aggravate crisis. Beyond that, the introduction of the non-linear demand functions in the agent-based modelling also provides a new approach to understand the industry dynamics and the different outcomes of firm size distributions in different sectors.

A financial engine can improve the economic growth in a country when the real economy and the financial system can form a positive feedback loop. However, because the pricing of financial assets is based on the present value of the future expected cash flows, the asset price may deviate from the economic performance of the underlying asset. If the expectation of market participants becomes overly optimistic and the economic performance fails to meet the expectation eventually, a collapse of the asset price would happen and would significantly harm the economic growth. This is because the households who benefit from the wealth effect of the increasing asset price have to cut their demand and at the same time, the users of capital, who get financing from the asset, will find themselves threatened by high leverage ratio and heavy debt burden. Nevertheless, even if we know the financial engine is a double-edged sword, we can hardly find any better solution.

Reference

1. Alfi, V., Cristelli, M., Pietronero, L., & Zaccaria, A. (2009). Minimal agent based model for financial markets I. *The European Physical Journal B*, *67*(3), 385-397.
2. Alfi, V., Cristelli, M., Pietronero, L., & Zaccaria, A. (2009). Minimal agent based model for financial markets I. *The European Physical Journal B*, *67*(3), 385-397.
3. Alvaredo, F., Atkinson, A. B., Piketty, T., & Saez, E. (2013). The top 1 percent in international and historical perspective. *Journal of Economic perspectives*, *27*(3), 3-20.
4. Anand, S., & Sen, A. (2000). Human development and economic sustainability. *World development*, *28*(12), 2029-2049.
5. Anderson, S. P., De Palma, A., & Thisse, J. F. (1992). *Discrete choice theory of product differentiation*. MIT press.
6. Aoki, M., & Yoshikawa, H. (2011). *Reconstructing macroeconomics: a perspective from statistical physics and combinatorial stochastic processes*. Cambridge University Press.
7. Atkinson, A. B., & Bourguignon, F. (Eds.). (2014). *Handbook of income distribution* (Vol. 2). Elsevier.
8. Bak, P. (2013). *How nature works: the science of self-organized criticality*. Springer Science & Business Media.
9. Banerjee, A. V., Banerjee, A., & Duflo, E. (2011). *Poor economics: A radical rethinking of the way to fight global poverty*. Public Affairs.
10. Bank of England (2018). Quarterly Bulletin retrieved on 13th September 2018
11. Batty, M. (2007). *Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals*. The MIT press.
12. Bazillier, R., & Hericourt, J. (2017). The circular relationship between inequality, leverage, and financial crises. Journal of Economic Surveys, 31(2), 463-496
13. Becker, G. S. (1991). A note on restaurant pricing and other examples of social influences on price. *Journal of political economy*, *99*(5), 1109-1116.
14. Bergeaud, A., Cette, G., & Lecat, R. (2015). Long-run per-capita gross domestic product in France and the advanced countries: the role of productivity and labour. *Economie & Statistique*.
15. Bilbiie, F. O. (2017). *The New Keynesian cross: Understanding monetary policy with hand-to-mouth households*. Centre for Economic Policy Research.
16. Black, F., Jensen, M. C., & Scholes, M. (1972). The capital asset pricing model: Some empirical tests. Studies in the theory of capital markets, 81(3), 79-121.
17. Blanchard, O. (2016). Do DSGE models have a future?. *Revista de Economía Institucional*, *18*(35),

39-46.

18. Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the national academy of sciences*, *99*(suppl 3), 7280-7287.
19. Bookstaber, R. (2019). *The end of theory: Financial crises, the failure of economics, and the sweep of human interaction*. Princeton University Press.
20. Bouchaud, J. P., Gualdi, S., Tarzia, M., & Zamponi, F. (2017). Optimal inflation target: insights from an agent-based model. *Available at SSRN 3037397*.
21. Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., & Stiglitz, J. E. (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control*, *69*, 375-408.
22. Challet, D., & Zhang, Y. C. (1997). Emergence of cooperation and organization in an evolutionary game. *Physica A: Statistical Mechanics and its Applications*, *246*(3-4), 407-418.
23. Challet, D., Marsili, M., & Zhang, Y. C. (2013). Minority games: interacting agents in financial markets. *OUP Catalogue*.
24. Chang, Myong-Hun. A computational model of industry dynamics. Routledge, 2015.
25. Christiano, L. J., Motto, R., & Rostagno, M. (2014). Risk shocks. *American Economic Review*, *104*(1), 27-65.
26. Cincotti, S., Raberto, M., & Teglio, A. (2010). Credit money and macroeconomic instability in the agent-based model and simulator Eurace. *Economics: The Open-Access, Open-Assessment E-Journal*, *4*
27. Cincotti, S., Raberto, M., & Teglio, A. (2012). Macroprudential policies in an agent-based artificial economy. *Revue de l'OFCE*, (5), 205-234.
28. Colander, D., Howitt, P., Kirman, A., Leijonhufvud, A., & Mehrling, P. (2008). Beyond DSGE models: toward an empirically based macroeconomics. *American Economic Review*, *98*(2), 236-40.
29. Cont, R., & Bouchaud, J. P. (2000). Herd behavior and aggregate fluctuations in financial markets. *Macroeconomic dynamics*, *4*(2), 170-196.
30. Dalio, R. (2014). *How the Economic Machine Works – Leveragings and Deleveragings*. Economic Principles, Draft Version. Ray Dalio, Copyright.
31. Dalio, R. (2018). *Principles for Navigating Big Debt Crises: German Debt Crisis and Hyperinflation (1918-1924); US Debt Crisis and Adjustment (1928-1937); US Debt Crisis and Adjustment (2007-2011). Detailed Case Studies*. Bridgewater.
32. Dawid, H., Gemkow, S., Harting, P., Van der Hoog, S., & Neugart, M. (2012). The eurace@ unibi model: An agent-based macroeconomic model for economic policy analysis.
33. Deissenberg, C., Van Der Hoog, S., & Dawid, H. (2008). EURACE: A massively parallel agent-based model of the European economy. *Applied Mathematics and Computation*, *204*(2), 541-552.
34. Dosi, G., Fagiolo, G., & Roventini, A. (2006). An evolutionary model of endogenous business cycles. *Computational Economics*, *27*(1), 3-34.
35. Dosi, G., Fagiolo, G., & Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, *34*(9), 1748-1767.

36. Dosi, G., Fagiolo, G., Napoletano, M., & Roventini, A. (2013). Income distribution, credit and fiscal policies in an agent-based Keynesian model. *Journal of Economic Dynamics and Control*, *37*(8), 1598-1625.

37. Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., & Treibich, T. (2015). Fiscal and monetary policies in complex evolving economies. *Journal of Economic Dynamics and Control*, *52*, 166-189.

38. Fagiolo, G., & Roventini, A. (2012). Macroeconomic policy in DSGE and agent-based models. *Revue de l'OFCE*, (5), 67-116.

39. Gaffeo, E., Gallegati, M., & Palestrini, A. (2003). On the size distribution of firms: additional evidence from the G7 countries. *Physica A: Statistical Mechanics and its Applications*, *324*(1-2), 117-123.

40. Galbraith, J. K. (2012). *Inequality and instability: A study of the world economy just before the great crisis*. Oxford University Press.

41. Galí, J. (2008). Monetary policy, inflation, and the business cycle: an introduction to the new Keynesian framework.

42. Galí, J. (2015). *Monetary policy, inflation, and the business cycle: an introduction to the new Keynesian framework and its applications*. Princeton University Press.

43. Gao, B., Chan, W. K. V., & Li, H. (2015). On the increasing inequality in size distribution of China's listed companies. *China Economic Review*, *36*, 25-41.

44. Gatti, D. D., Desiderio, S., Gaffeo, E., Cirillo, P., & Gallegati, M. (2011). *Macroeconomics from the Bottom-up* (Vol. 1). Springer Science & Business Media.

45. Gatti, D. D., Palestrini, A., Gaffeo, E., Giulioni, G., & Gallegati, M. (2008). *Emergent macroeconomics: an agent-based approach to business fluctuations*. Springer.

46. Geels, F. W. (2013). The impact of the financial–economic crisis on sustainability transitions: Financial investment, governance and public discourse. *Environmental Innovation and Societal Transitions*, *6*, 67-95.

47. Gisser, M., McClure, J., Ökten, G., & Santoni, G. (2009). Some anomalies arising from bandwagons that impart upward sloping segments to market demand. Econ Journal Watch, 6(1), 21-34.

48. Goldenfeld, N. (2018). *Lectures on phase transitions and the renormalization group*. CRC Press.

49. Graham, B., Dodd, D. L. F., & Cottle, S. (1934). *Security analysis*. New York: McGraw-Hill.

50. Grazzini, J., & Delli Gatti, D. (2008). A paper on development of MABM mark I. CRISIS Project Deliverable D3.2.

51. Grazzini, J., and D. Delli Gatti. (2013) "Paper on the development of MABM Mark II: The input-output network in the CRISIS Macro Agent-Based Model." CRISIS Project Deliverable D 3.

52. Gualdi, S., & Mandel, A. (2019). Endogenous growth in production networks. *Journal of Evolutionary Economics*, *29*(1), 91-117.

53. Gualdi, S., Tarzia, M., Zamponi, F., & Bouchaud, J. P. (2015). Tipping points in macroeconomic agent-based models. *Journal of Economic Dynamics and Control*, *50*, 29-61.

54. Gualdi, S., Bouchaud, J. P., Cencetti, G., Tarzia, M., & Zamponi, F. (2015). Endogenous crisis waves: stochastic model with synchronized collective behavior. *Physical review letters*, *114*(8), 088701.

55. Gualdi, S., Tarzia, M., Zamponi, F., & Bouchaud, J. P. (2017). Monetary policy and dark corners in a stylized agent-based model. *Journal of Economic Interaction and Coordination*, *12*(3), 507-537.
56. Goda, T. (2013). The role of income inequality in crisis theories and in the subprime crisis. Post Keynesian Economics Study Group Working Paper, 1305.
57. Gu, X., & Huang, B. (2014). Does inequality lead to a financial crisis? Revisited. Review of Development Economics, 18(3), 502-516.
58. Janssen, M. A., & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and society*, *11*(2).
59. Kang, S. H., Jiang, Z., Cheong, C., & Yoon, S. M. (2011). Changes of firm size distribution: The case of Korea. *Physica A: Statistical Mechanics and its Applications*, *390*(2), 319-327.
60. Kirman, A. P. (1992). Whom or what does the representative individual represent?. *Journal of economic perspectives*, *6*(2), 117-136.
61. Kitchin, J. (1923). Cycles and trends in economic factors. *The Review of economic statistics*, 10-16.
62. Korinek, A., & Simsek, A. (2016). Liquidity trap and excessive leverage. *American Economic Review*, *106*(3), 699-738.
63. Kumhof, M., Rancière, R., & Winant, P. (2015). Inequality, leverage, and crises. *American Economic Review*, *105*(3), 1217-45.
64. Leibenstein, H. (1950). Bandwagon, snob, and Veblen effects in the theory of consumers' demand. *The quarterly journal of economics*, *64*(2), 183-207.
65. Lerner, A. (1995). The concept of monopoly and the measurement of monopoly power. In *Essential Readings in Economics* (pp. 55-76). Palgrave, London.
66. Mankiw, N. G. (1989). Real business cycles: A new Keynesian perspective. Journal of economic perspectives, 3(3), 79-90.
67. Mantegna, R. N., & Stanley, H. E. (1999). *Introduction to econophysics: correlations and complexity in finance*. Cambridge university press.
68. Marx, K. (1867). Kapital [Capital]. Volume I.
69. Mary S. Morgan, *The History of Econometric Ideas*, Cambridge University Press, 1991.
70. McCoy, B. M., & Wu, T. T. (2014). *The two-dimensional Ising model*. Courier Corporation.
71. Novo-Corti, I., Țîrcă, D. M., Ziolo, M., & Picatoste, X. (2019). Social Effects of Economic Crisis: Risk of Exclusion. An Overview of the European Context. *Sustainability*, *11*(2), 336.
72. Ormerod, P. (2004). Information cascades and the distribution of economic recessions in capitalist economies. *Physica A: Statistical Mechanics and its Applications*, *341*, 556-568.
73. Ormerod, P. (2010). Risk, recessions and the resilience of the capitalist economies. *Risk Management*, *12*(1), 83-99.
74. Ozel, B., Nathanael, R. C., Raberto, M., Teglio, A., & Cincotti, S. (2019). Macroeconomic implications of mortgage loan requirements: an agent-based approach. *Journal of Economic Interaction and Coordination*, *14*(1), 7-46.
75. Perugini, C., Hölscher, J., & Collie, S. (2015). Inequality, credit and financial crises. *Cambridge Journal of Economics*, *40*(1), 227-257.
76. Phillips, M. (2015). The DuPont invention that changed how things work in the corporate

world. Quartz (publication). Retrieved 9 December 2015.

77. Piketty, T., Saez, E., & Atkinson, A. B. (2011). Top incomes in the long run of history. Journal of Economic Literature, 49(1), 3-71
78. Pogson, M., Smallwood, R., Qwarnstrom, E., & Holcombe, M. (2006). Formal agent-based modelling of intracellular chemical interactions. *Biosystems*, *85*(1), 37-45.
79. Porter, M. E. (1989). How competitive forces shape strategy. In *Readings in strategic management* (pp. 133-143). Palgrave, London.
80. Raberto, M., Ozel, B., Ponta, L., Teglio, A., & Cincotti, S. (2016). *From financial instability to green finance: the role of banking and monetary policies in the Eurace model* (No. 2016/07).
81. Raberto, M., Ozel, B., Ponta, L., Teglio, A., & Cincotti, S. (2019). From financial instability to green finance: the role of banking and credit market regulation in the Eurace model. *Journal of Evolutionary Economics*, *29*(1), 429-465.
82. Ranciere, R., Throckmorton, M. N. A., Kumhof, M. M., Lebarz, M. C., & Richter, M. A. W. (2012). Income inequality and current account imbalances (No. 12-18). International Monetary Fund.
83. Rhoades, S. A. (1993). The herfindahl-hirschman index. *Fed. Res. Bull.*, *79*, 188.
84. Schneider, F., Kallis, G., & Martinez-Alier, J. (2010). Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue. *Journal of cleaner production*, *18*(6), 511-518.
85. Schumpeter, J. A. (2010). Capitalism, socialism and democracy. routledge.
86. Scott, B. R., & Lodge, G. C. (1985). US competitiveness in the world economy. *The International Executive*, *27*(1), 26-26.
87. Segarra, A., & Teruel, M. (2012). An appraisal of firm size distribution: Does sample size matter?. Journal of Economic Behavior & Organization, 82(1), 314-328.
88. Sornette, D. (2014). Physics and financial economics (1776–2014): puzzles, Ising and agent-based models. *Reports on progress in physics*, *77*(6), 062001.
89. Soros, G. (2015). *The alchemy of finance.* John Wiley & Sons.
90. Spangenberg, J. H. (2005). Economic sustainability of the economy: concepts and indicators. *International journal of sustainable development*, *8*(1-2), 47-64.
91. Stiglitz, J. E. (2012). Macroeconomic fluctuations, inequality, and human development. Journal of Human Development and Capabilities, 13(1), 31-58.
92. Stiglitz, J. E. (2015). *Towards a general theory of deep downturns* (No. w21444). National Bureau of Economic Research.
93. Stockhammer, E. (2015). Rising inequality as a cause of the present crisis. *Cambridge Journal of Economics*, *39*(3), 935-958.
94. Tacchella, A., Cristelli, M., Caldarelli, G., Gabrielli, A., & Pietronero, L. (2012). A new metrics for countries' fitness and products' complexity. *Scientific reports*, *2*, 723.
95. Tacchella, A., Cristelli, M., Caldarelli, G., Gabrielli, A., & Pietronero, L. (2012). A new metrics for countries' fitness and products' complexity. *Scientific reports*, *2*, 723.
96. Teglio, A., Raberto, M., & Cincotti, S. (2012). THE IMPACT OF BANKS'CAPITAL ADEQUACY

REGULATION ON THE ECONOMIC SYSTEM: AN AGENT-BASED APPROACH. *Advances in Complex Systems*, *15*(supp02), 1250040.

97. Tesfatsion, L. (2002). Agent-based computational economics: Growing economies from the bottom up. *Artificial life*, *8*(1), 55-82.
98. Thornton, D. L. (2010). The downside of quantitative easing. *Economic Synopses*.
99. Tonelli, F., Fadiran, G., Raberto, M., & Cincotti, S. (2016). Approaching industrial sustainability investments in resource efficiency through agent-based simulation. In *Service Orientation in Holonic and Multi-Agent Manufacturing* (pp. 145-155). Springer, Cham.
100. Wisman, J. D. (2013). Wage stagnation, rising inequality and the financial crisis of 2008. Cambridge Journal of Economics, 37(4), 921-945.
101. Wu, X., Xu, Y., Lou, Y., & Chen, Y. (2018). Low carbon transition in a distributed energy system regulated by localized energy markets. *Energy policy*, *122*, 474-485.
102. Yang, Chen Ning. "The spontaneous magnetization of a two-dimensional Ising model." *Physical Review* 85.5 (1952): 808.