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A Study on Crises in an Agent-Based Socioeconomic System
（エージェントベースの社会経済システムの危機に関する研究）

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A Study on Crises in an Agent-Based Socioeconomic System

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List of Abbreviations

DSGE	Dynamic Stochastic General Equilibrium
ABM	Agent-Based Model
FU	Full Unemployment
RU	Residual Unemployment
EC	Endogenous Crisis
FE	Full Employment

List of Symbols

t	Time
i	Firm ID
C_B	Consumption Budget
S	Household Savings
Y	Production/Labor
C	Consumption Propensity
W	Wage
D	Demand
p	Price
$\overline{p}$	Average Price
η_+	Hiring Propensity
η_-	Firing Propensity
u	Unemployment Rate
N	Number (of Firms)
ε	Firm Asset
ρ	Profit
δ(delta)	Dividend Ratio (Profit Tax) Rate
Φ	Debt Ratio
Θ(theta)	Default Threshold
R	Employment Propensity
Λ	Group of Firms

Chapter

1. Introduction

1.1 Socioeconomic System and Crisis

Even back to the age of Adam Smith, some primitive ideas of complex economic system have already emerged (Cabannes (2004)). For example, the famous term “invisible hand” proposed by Adam Smith (see Smith (1759,1776)) describes the self-regulation (or self-organization) in the unpredictable economic system. In other words, the “invisible hand” can be regarded as a metaphor of the manifestation of spontaneous order in a complex system as if the order is built and manipulated by an invisible hand. However, regardless of the complexity indicated in the “invisible hand”, the early economists believe in an optimal stable state of the economic system that can be always reached.

The concept of ‘complexity and crisis in a socioeconomic system’ can also be traced back to Malthus’ famous study on population dynamics. He is the first to argue for a crisis in the system level of whole human society (Malthus (1798)). Although his prediction does not come true, however, during the history of human society, we do witness events similar to Malthus’ implications. This also implies the complexity of the socioeconomic system considering the difficulty in crisis predictions.

Another famous prediction on crisis in socioeconomic system made with system dynamics is the model simulation study “Limit to Growth” (Meadows et al. (1972)). In particular, they simulated the impact of economic activities on the environment system. The system eventually collapsed all of a sudden. Fortunately, their prediction has not yet been actualized and the unpredictability of the complex system still holds. In 2004, they revisited the prediction and signed a thirty-year updated version (Meadows et al.(2004)). Nevertheless, the complexity and crisis in our socioeconomic system persist as interests of the research community.

Nowadays, though the extreme collapse predicted by Malthus (1798) or Meadows et al. (1972) has not come into reality yet, the frequent occurrence of economic and financial crises has already reflected the instability rooted in our socioeconomic system. The crises in our socioeconomic system, equivalent to the "disaster" in the natural systems, greatly threaten the economic sustainability. They can result in sudden market crash, economic recession and finally widespread unemployment in a society. From the age of Great Depression, there has been an alarming frequency of economic crises. Here, the references to two existing empirical data set are presented as in Tab. 1.1 and Fig. 1.1. In Tab 1.1, the Caproasia Institute summarized the occurrence of economic crises from 1900 to 2015. The sudden frequent occurrence of economic crises can be observed after the Great Depression in 1930s. The extreme high frequency after 1970s indicates how unstable our economic system has already been. More recently, the default of Greece during 2016-2017 is the warning of future crises. Reid et al. (2017) in Deutsche Bank even discussed the next financial crisis. Their results are shown in Fig.1.1. Two distinct features of the crisis occurrence can be summarized as: high propagation rate to a global scale and high frequency occurrence following an onset of a single crisis. A few recent examples include the 1997 Asia financial crisis and the 2008 Lehman Brothers bankruptcy.

Period	Region	Affected	Crisis
1901	America	United States	Panic of 1901
1907	America	United States	Panic of 1907
1920 – 1921	America	United States	Depression of 1920 – 21
1929 – 1939	America	United States	Great Depression
1939 – 1945	Europe & Asia	Europe & Asia	World War II
1970s	Global	Global	1970s Energy Crisis
1973	Global	Global	OPEC Oil Price Shock (1973)
1973 – 1975	Europe	UK	Secondary Banking Crisis & Property Crash
1979	Global	Global	Iranian Revolution
1980s	Global	Global	Early 1980s Recession
1982	America	Latin America	Latin America Debt Crisis
1982	America	Chile	Crisis of 1982
1983	Middle East	Israel	Bank Stock Crisis
1986 – 2003	Asia	Japan	Japanese Asset Price Bubble
1987	Global	Global	Black Monday
1990s	Global	Global	Early 1990s Recession
1990s	Europe	Finland	Finnish Banking Crisis
1990s	Europe	Sweden	Swedish Banking Crisis
1991	Asia	India	1991 Indian Economic Crisis
1994	America	Mexico	1994 Economic Crisis
1997	America	Asia	1997 Asian Financial Crisis
1998	Europe	Russia	1998 Russian Financial Crisis
1999 – 2002	America	Argentina	Argentine Economic Crisis
2000	Global	Global	Dot-com Bubble
2001	Global	Global	911
2003	Asia	Asia	SARs
2008	Global	Global	Subprime Global Financial Crisis
2009	Europe	Europe	Sovereign Debt Crisis
2014	Europe	Russia	Russian Ruble Crisis
2015	Asia	China	Chinese Stock Market Crisis

Table 1.1 List of economic crises from 1900 to 2015.

Source:https://www.caproasia.com/2016/04/12/economic-crisis-since-1900-2015/, by the Caproasia Institute

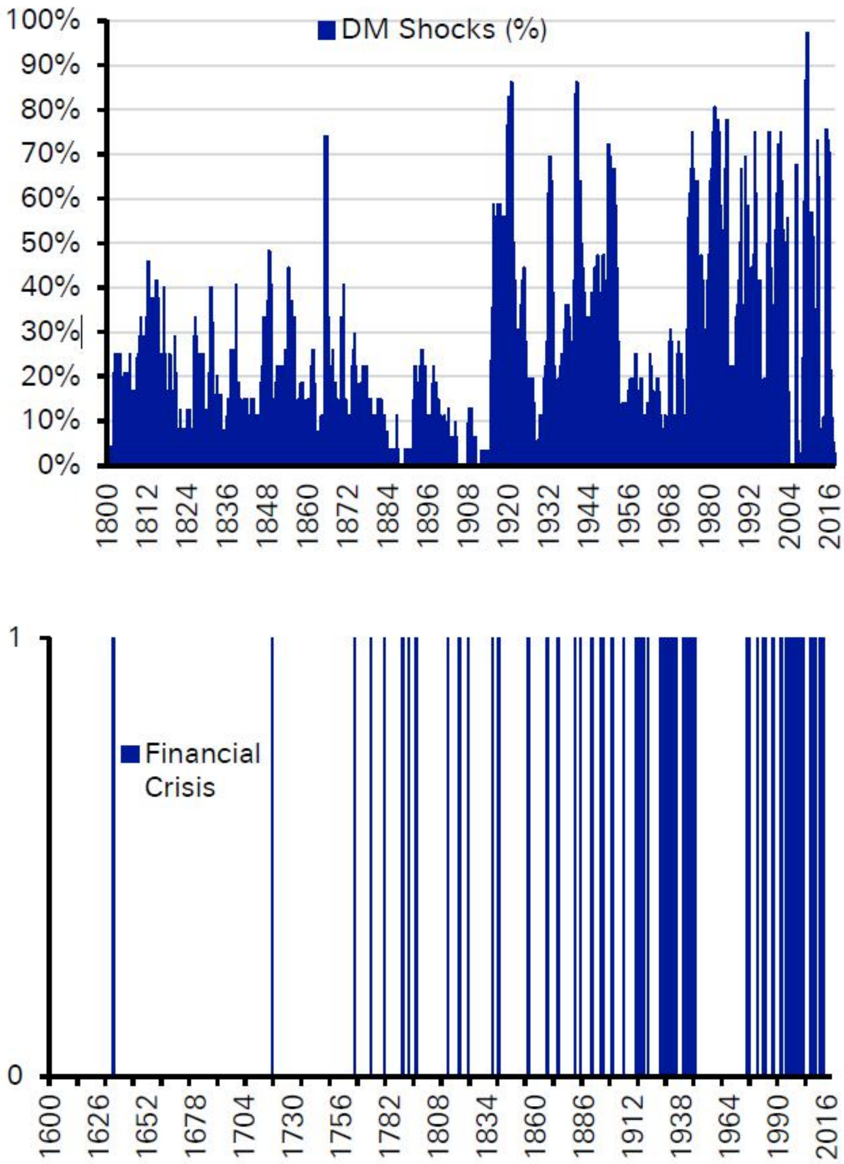


Figure 1.1 (Top) The proportion of developed market (DM) countries which are affected by a single financial crisis. (Bottom) The financial crisis occurrence along the historical timeline. Source: http://www.tramuntalegria.com/wp-content/uploads/2017/09/Long-Term-Asset-Return-Study-The-Next-Financial-Crisis-db.pdf, by Deutsche Bank.

Nevertheless, the socioeconomic crisis has become a prevailing trend in the socioeconomic system in the last three decades, and it brings the research interests together as an integrated study on the crisis phenomena.

1.2 Failure in Macroeconomics

Traditional macroeconomic methods' limitations and failure in comprehending crises of the current economic system have been widely discussed. The focuses of the discussion can be largely divided into two categories: the inappropriate tools in macroeconomics and the simplification on the complexity of the real socioeconomic system.

The mainstream tools of representative agents and general equilibrium model in macroeconomics, though effective in many issues, can not provide insights to the crisis occurrence. It is because a group of identical rational representative agents with optimization behavior simply drives the system to equilibrium but not the non-equilibrium state of crises. Stiglitz (2017) thoroughly sorted the problems and arguments of mostly used DSGE model in macroeconomics. For examples, DSGE models can not incorporate state contingency in a meaningful way (Galati and Moessner (2013)). DSGE is also not competent for modelling financial intermediation and frictions (Bean (2009)). Furthermore, DSGE implicitly assumes that defaults do not take place (Goodhart et al. (2009)). Although DSGE deals with deviations from equilibrium, the financial booms and busts are not modeled (Tovar (2008)).

The second direction of discussion focuses on the way of thinking about the complex system and its origin in Keynes (Keynes, (1936)). Keynes is the pioneer to realize that the economic system is a complex system and try to lay the foundation for this thought (e.g. Citera (2016)). Unluckily, his efforts and awareness of the importance of the complex system on crisis are not well accepted in the economic community. Recently, other researchers started to reconsider the relationship between economics and complex system both theoretically (e.g. Arthur (1999), Foster (2006)) and in a more practical sense with regard to the emergence of crisis (e.g. Sau (2013)).

In Skidelsky (2009), he argues for the Keynes' way of thinking to return to the modern economics . He pointed out the current crisis occurrence was largely due to the "intellectual failure", as both non-market and market players had false assumptions about markets and believed that the market was self-correcting as if the financial risk could never be grown.

In summary, the key issues for the traditional methods are the improper application of identical representative agents and the equilibrium model to crisis studies. The reality is that interactions take place among heterogeneous agents, and crises stem from non-equilibrium processes.

1. 3 Chaos and Catastrophe theory - Rise and Fall

After the failure of the macroeconomics to theorize crises, chaos theory and one of its children－catastrophe theory have taken place in the economic studies in hope of explaining the crisis occurrence (see example as in Seeger (2002)).

The chaos theory has triggered the studies on the asset prices in financial markets and possible causes of nonlinear deterministic variables of financial markets (Săvoiu and Iorga-Simăn (2008)). Fractals are also investigated in the chaotic systems in this trend (Rosser (2000)).

The catastrophe theory has been applied to many topics of economics in history. For examples, Zeeman (1974) modeled bubbles and crashes in stock markets with catastrophe theory. Debreu (1970) and Balasko (1978) combined catastrophe theory with general equilibrium to study discontinuous structural transformation in a critical economy. Moreover, Bonanno (1987) studied market segmentation with catastrophe theory, and Varian (1979) applied the theory to the business cycle. Fischer and Jammernegg (1986) studied the shift of Phillips Curve empirically with catastrophe theory. Ho and Saunders (1980) modeled the bank failure with the catastrophe theory.

However, such application of catastrophe theory has been criticized by later scholars (Sussmann and Zahler (1978), Weintraub (1983)). According to the review of Rosser (2007), the mathematical conditions of a potential function and gradient dynamics have made the application invalid in theory and thus limited the use of catastrophe theory.

The main reason in critics of Sussmann and Zahler (1977,1978) is that the application of catastrophe theory only models the crashes in a trivial way concerning the discontinuity embedded in the theory. Therefore the catastrophe theory can not explain why the crash happens but simply describe it as a phenomenon of discontinuity.

Rosser (2007) contended that the catastrophe theory was good enough for "sufficiently low dimensional systems with gradient dynamics derived from a potential function". Rosser (2007) also suggested other alternatives for modeling dynamic discontinuities within economic processes. For instance, one suggestion is the "phase transitions or dynamic discontinuities in models with heterogeneous interacting agents" (Föllmer (1974)) from the complexity studies. Brock (1993) used the mean field approach to generate phase transitions between different forms of system organizations. Lorenz (1992) employed the basin of attraction to model the multiple equilibria. Bak et al. (1993)

exercised the self-organizing criticality with which the small exogenous shocks could trigger large endogenous reactions. Weidlich and Braun (1992) utilized synergetics (Haken (1978,1983)) to model the sudden change, and Lung(1988) introduced the self-organization concept.

To put it briefly, the catastrophe theory, though important in the course of modeling crisis, has been challenged by the strict requirement to satisfy the mathematical conditions and its trivial explanations for the mechanism. As Rosser (2007) pointed out, the phase transition with self-organization has become a significant and powerful toolkit to interpret the crisis phenomenon, whereupon the main focus of this thesis is to bridge this research gap.

1.4 Econophysics - a New Hope?

Surprisingly, physics actually has a long history to influence economics and social science. Galam et al.(1982) coined the term 'catastrophe theory' in social sciences as 'sociophysics'. Mirowski (1989) named this trend as the 'physical attraction'. In this aspect we can consider econophysics as the deviant of catastrophe theory in social science, but with more powerful tools.

Econophysics, though still an emerging field only for 20 years, has developed into an active domain to address the unsolved challenges in traditional macroeconomics. Reviews on development and achievements of econophysics can be found in Chakraborti et al (2011a,b), Ray (2011), Gingras and Schinckus(2011, 2012), Schinckus (2013), Schinckus and Jovanovic (2013), Drakopoulos and Katselidis(2015). Especially in Chakraborti et al (2011a,b), they provided in-depth reviews on the recent development of econophysics, with two parts of the statistical empirical facts and agent-based models. Later in an commentary paper on Chakraborti et al (2011a,b), Schinckus (2012) clarified the difference between the statistical econophysics and agent-based econophysics, since the former assumed 'zero-intelligence' of agents with random behavior whereas the latter postulated objective-oriented adaptive behavior of agents.

In traditional macroeconomics, the assumption about the extreme intelligent cognitive state that all agents are rational to achieve utility maximization is unrealistic. In contrast, the empirical studies in statistical econophysics present the results from a stand closer to 'zero-intelligence' models, which are opposite to the previous assumption (Gode and Sunder (1993)). Modeling examples of this kind constitute the main literature of econophysics (refer to Stigler (1964), Garman (1976), Chakraborti et al. (2011a), Bouchaud et al. (2002), Potters and Bouchaud (2003), LeBaron (2006), Wyart and Bouchaud (2007)). While the traditional macroeconomics tackles with the possible roots in the exogenous intelligence or rational behavior of agents in the economy or the market, the econophysics tends to identify another type of potential roots in physical structure by abandoning the perfect rational assumption. Here is an example. The econophysics approach reproduces the stylized facts solely by the properties of the order flows and the structure of the order book itself (Chakraborti et al.(2011b)).

Methodologically, according to Chakraborti et al. (2011b), one observable feature of models in econophysics is that they are simpler models in structure, yet with a clearer focus only on well-identified and presumably realistic rules of behaviors. This feature contributes to building the linkage between empirical phenomena, models and theoretical explanation. The "herding phenomenon" of the traders in financial market (Cont and Bouchaud (2000), Raberto et al. (2001)) can be a representative case. Lux and Marchesi (2000) first built an interactive ABM to reproduce the volatility cluster without order book, and the model was steadily improved by many other researchers (see examples as Bak et al. (1997), Chiarella and Iori (2002)). Maslov (2000) was the one who completed the whole order book integration. Thanks to the simple model, Slanina (2001) and Cont et al. (2008) could analytically solve the model and shed light on the mechanism of it, finally bringing in the stylized facts that were comprehensive and reproducible. Totally different from the giant and incomprehensible macroeconomic model, the new trend in econophysics is to reproduce non-trivial phenomena with simple models and mechanisms. The important methodological divergence between mainstream economics and econophysics can also be found in Ball(2006) and Burda et al. (2003).

The main scopes of the current literature in econophysics can be divided into three categories: 1. stylized facts and order books in financial market (see examples in Challet and Stinchcombe(2001), Lux and Sornette(2002), Smith et al.(2003), Dremin and Leonidov(2005), Hasbrouck(2007), Preis et al.(2007), Mike and Farmer(2008), Slanina(2008), Bouchaud et al.(2009), Gu and Zhou(2009), Muni Toke(2010)); 2. wealth distribution in an economy (see examples in Dragulescu and Yakovenko(2001), Lux(2005), Chatterjee and Chakrabarti(2007), Patriarca et al.(2007), Chakrabarti and Chakrabarti(2009), Yakovenko and Rosser(2009)); 3. minority game (see examples in Challet and Zhang (1997,1998), Johnson et al.(1999a,b), Savit et al.(1999), Li et al.(2000a,b), Hart et al.(2001), Sysi-Aho et al.(2004), Coolen(2005), Chakrabarti et al.(2009))

The primary reason for econophysics to stand against traditional macroeconomics is the crisis occurrence as many econophysics literature indicate in the 2008 financial crisis (Bouchaud (2008), Farmer and Foley (2009), Lux and Westerhoff (2009)). Unexpectedly, even though many econophysics literature such as Chakraborti et al. (2011b) listed the crisis as a main factor for the emergence of econophysics, the literature list in Chakraborti et al. (2011b) regarded crisis in their review as literally zero. This huge research gap becomes the key motivation of this thesis.

1. 5 Complex System - What is More

A system is composed by elements and the relations among the elements. When the elements are connected and organized in a specific way, the system realizes its function to fulfill the tasks or exhibits patterns at different order levels. A system can be either an artificial system (e.g. the power system to provide electricity) or a natural system (e.g. the ecological system with a food chain for life balance).

In the studies of different systems, a general issue is the complexity of a system that determines both the system type and the main research focus on the system. Based on the complexity of the system, the system can be divided in two categories: simple systems and complex systems. A simple system is a system that can be fully understandable and predicable, that is, the behavior of the entirety can be inferred from the behavior of the element. The essential patterns of the system are indicated by the patterns of an individual element. An example of a simple system can be the binary star system in which the two stars are connected by the gravitational force between them. The two stars' orbital motion around the shared centre is fully predictable and understandable given the motion pattern of a single star. Another example might be a simple system composed by many homogeneous independent agents, as the behavior of an individual agent can represent the behavior of the system. To make a simple analogy, the 'diffusion' or 'propagation' of elements is a simple system. Because the simple system is fully predictable and under control, the main focus of research on simple system falls into the control of the simple system to fulfill different function or make different application out of such systems.

On the contrary, a complex system usually consists of heterogeneous agents so that the patterns of the whole system can not be predicted from the patterns of the individual agents. This is to say, the unexpected behavior of the whole system can be generated from the interactions of elements, components or individual agents, which are not foreseen in the individual behaviors. Such systems are usually non-linear and universal in the nature, economy and society. Compared to a binary star system, a three-star system could be deemed as a complex system, for the motion of the three-star system can demonstrate many patterns depending on the initial conditions of each star. One more example could be the system of the stock market. Many heterogeneous traders co-create the dynamics of bubbles and market crash, together with the unpredictability of market behavior. To make a similar analogy, the 'reaction' or 'transformation' of elements creates a complex system.

The formal definition of 'a complex system' is still an open issue. The early studies on simplicity and complexity has posed a question mark on whether the reductionism can be applied to every system. By researching the fractal and comments, even if he was a reductionism believer, Gell-Mann (1988) had to admit that certain system could not be analyzed with reductionism. Later in social science, the term "complex system" emerges as an idea for comprehending socioeconomic system, due to the fact that the formation of the overall social structure or phenomenon cannot be understood when referred to the dynamics of system components. There is a common misunderstanding about the complex system that a complex system should be a complicated system. Notwithstanding, as Ottino (2004) mentioned, a complicated system was not always a complex system, and vice versa. A system of ideal gas is complicated but not complex (Ladyman et al. (2013)). Likewise, a two-pendulum system can be taken as a complex but not complicated system.

As a result, the definition of 'the complexity of a dynamic system' is still under debate, in defiance of the fact that "complexity" or "complex system" have been frequently used. Attempts on this topic can be found in the discussions in Funtowicz and Ravetz (1994), Crutchfield and Wiesner (2010), Ladyman et al. (2013). Ladyman et al. (2013), particularly, proposed a quantitative measure to rigorously define how much complexity is for a complex system. Other studies, such as in Norman and Kuras (2006), argue for other concepts such as "Intricacy" for complex system and its engineering. Another track of research is trying to identify the architecture of a complex system to demonstrate its complexity as in MacCormack et al. (2010) However, we believe the reductionism measurement of complexity is not to be emerged based on the discussion in Gell-Mann (1988), Gell-Mann (1955), Ziemelis (2001), Gell-Mann (2002). Because if the complexity can be reduced to the combination of several elements, then the needs to treat it as a whole inseparable system would no longer exist. Therefore, up to certain level, the system must not be reducible so that the idea of complex system holds. Therefore, it is logically impossible to quantify "complexity" by referring to the parts which a system is composed of. In other words, we can conclude, by deduction, there exist parts to be complex subsystems with its own complexity which is not reducible. Perhaps, the relationship only lies on the famous interpretation by Aristotle as "The whole is greater than the sum of its parts." (Upton et al. (2014)).

In Manson (2001), it discussed three kinds of complexity: Algorithmic complexity in mathematical information theory; Deterministic complexity in chaos theory and catastrophe theory; and Aggregate complexity in network and complex system.

The deterministic complexity, though seemingly attractive as the catastrophe theory, is hard to apply to real system especially to the social system (Manson (2001)). In the meanwhile, because a chaos system is sensitive to the initial condition, the prediction power is very low in this type of complexity which also limits the understanding towards it. Besides, the deterministic complexity requires simple mathematical tractable equations as well as the assumptions, which make it very incapable to deal with system without an explicit mathematical form.

The aggregate complexity deals with the internal structure of a system. Even homogeneous components of a system can have complex behavior when the connections are with different strengths. Holland (1992) stated that through the persistence of internal structure a system can shape certain pattern. Lansing and Kremer (1993), Baas and Emmeche (1997) stated that the emergence can not be decomposed and reduced to the analysis of its components. Manson (2001) stated that without an idea of emergence, the simple intervention to our economic (Youssefmir and Huberman (1997)) or ecological system (Lansing and Kremer (1993)) could bring big side-effects which can be against our initial purpose. As an example, Andreoni and Miller (1995) stated the volatility cluster and investor "herd behavior" can emerge surprisingly from non-linear rational interactions rather than the traditional belief of irrationality or imperfect market.

However, though not rigorous defined, the interests in complex systems at least origin from two hallmarks, as indicated in Ottino (2004), Johnson (2015).

Emergence: Emergent phenomenon is perhaps the most important concept in leading the complex system research. Emergence is usually the distinct macro-level phenomenon that can not be indicated in the micro-level behavior of the agents. As the emergence is the integrated results of interactions among agents, the argument presents a complex system in which the components can not be treated separately in order to understand the collective phenomenon of the whole. Under the current situation without a definition for complex system, the emergence phenomenon becomes an important indicator for a system to be considered as a potential complex system.

Self-organization: Different from the phenomenon indicator emergence, self-organization focuses more on the internal order and structure formation mechanism. Self-organization, also called spontaneous order, is a process among which an overall order arises from the interaction of initially disordered group of elements. The presence of self-organization in a system without center control is a necessary condition to be considered as in a complex system.

The above two key properties of complex system can be reflected in Dr Weisner's summary as a tentative criteria for the qualification of a complex system as follows:

"It boils down to something that consists of many elements that are interacting in a disordered way out of which is generated a robust order. There is nothing that controls centrally how things are supposed to behave." - Dr Karoline Weisner

Furthermore, Manson (2001) listed the features of a complex system as self-organization and self-organized criticality from the studies of complexity. While self-organization is about internal order/structure formation, self-organized criticality is about the balance between randomness and stasis (Manson (2001)). Bak and Chen (1999) described the self-organized criticality as the ability to stay at a critical point at which the system internal order is on the edge to trigger a crisis but still on the safe side. Scheinkman and Woodford (1994) stated the self-organized criticality has a high rate of internal restructuring so that the impact of destruction is quickly fixed.

Arthur (1999) compared the mainstream economics and the complexity studies as the economics studies stability and periodic behavior whereas the complexity studies care more about the uncertainty.

As the summary, Manson (2001) pointed out that the studies on self-organized criticality are still very few in economic systems. The potential method to conduct such research is through "exploratory computer simulation", which is another research gap for this thesis to focus on.

1.6 Agent-based Approach - an Integration

Agent-based models (ABM) have become an active laboratory for social studies in various spheres, several examples include Gilbert (1999), Gilbert and Terna (2000), Lux and Marchesi (2002), Feng and Jo (2003), Sawyer (2005), Batty (2007). Especially, the focus of interests in economics is to re-examine the fundamental assumptions and to create tools capable to compensate the incapability of traditional macroeconomics. The advantages of ABM has been summarized in Lin (2012). Here, we only emphasize the big picture based on Bonabeau (2002), Farmer and Foley (2009) as the following two aspects:

Emergent phenomenon. This is the most important feature that traditional macroeconomics is lack of but the study of crisis requires for. In the same time, the philosophy of ABM is the interaction of agents from bottom-up so that the macro-level phenomenon automatically emerges.

System self-organization. It is easier to understand and describe the behaviors of economic individuals than those abstract principles governing the whole system. ABM sketches the system in a bottom-up manner and through the description of individual behavior rules. The system-level phenomenon is formed by the process of self-organization, which makes it a natural and fundamental modeling approach of a complex system.

Besides these two main advantages, in our opinion and based on Schinckus (2016) as well, we add one more benefit for ABM:

Econophysics-oriented modeling. ABM with computer simulations deals with interaction of agents, while the study of statistical physics also deals with the interaction of molecules in a complex system. Therefore while ABM can be a simple realization of physical systems, the methodological advantages in theoretical physics can also be applied to understand the dynamical behavior in ABM too. Concepts such as non-equilibrium phase transition, irreversibility are very useful in the investigation of agent behavior and even the prediction of the model outcomes.. ABM with econophysics should be a starting point for theoretical investigation on the crisis mechanism in our economy.

Note that although the statistical econophysics is empirical data based without a firm theoretical foundation in economics (Keen (2003), Carbone et al. (2007)), the agent-based econophysics started to build their micro-foundation and shape their own theory.

It is true that financial economics is the main topic of econophysics. For example. Alfi et al.(2009a,b) introduced an ABM approach for construction of a basic financial market. Iori et al. (2006) built an interbank market model to discuss systemic risk. Studies on macroeconomic phenomena started to emerge. For example, Thurner et al. (2009) studied leverage effects. Yakovenko and Rosser (2009) concentrated on the wealth distributions and the resulted phenomenon of inequalities. Still more following-up works are expected along this direction.

The aim of the agent-based econophysics is to model the non-trivial behavior and identify essential mechanisms in order to connect to empirical macroeconomic phenomena. For example, the herding behavior (Cont and Bouchaud,2000), fundamentalists and trend followers (Lux and Marchesi (2000)), threshold behavior (Cont (2007)) can be studied from the non-identical, inter dependent agents through their interactions.

Agent-based econophysics describes socioeconomic systems as complex systems (Schinckus (2002)) in the way Keynes suggested to do with learning and adaptive behavior (Schinckus (2012)). What is more, econophysics does not use arbitrary assumptions but rather build on empirical verifications. (Axtell (1999)) , Holland (1999)).

The complexity theory is the strong threatical foundation upon which econophysics is built (see in Rickles (2007, 2008), Rosser (2009)). In doing so, econophysics can contribute significantly to economics even without an economic translation (Stanley (2003), Schinckus (2011,2013)).

However, this way of processing has been pointed out that the relevant studies has no reference to macroeconomic theory. It is true that the macroeconomic system is usually conceived as a large complex system similar to physical systems, such as in Alfarano et al. (2005) it is stated that mathematical convenience is more concerned than economic meaning. However, this trend can be fixed in future by considering remedies for econophysics. One way to connect macroeconomic theory is to try to demonstrate core mechanisms with a small set of parameters, which could result in analytically tractable models (this approach will be demonstrated in the main part of this thesis). Another way is to seek for the universal laws that govern the behaviour of the complex system. Burda et al. (2003) commented that the macroeconomic systems are more likely to make theoretical attempts in this direction.

In the meanwhile, if the model became too simple, such as in Cont (2007), it might have calibration problems with empirical data, but the key point is that the main mechanism studied in such simple theoretical models could be applied to a more elaborate agent-based model to reproduce the empirical reality. Therefore, the purpose of a simple agent-based model is more about the theoretical part and the mechanisms governing the agents to form the macro-level phenomena rather than the pure empirical validation. This point will also be demonstrated through the whole thesis of this crisis study with a minimal ABM for the socioeconomic system.

The study of economic crises and cycles is an increasingly popular topic for econophysicists, especially since 2008 (Schinckus (2011)). Black (1986) and the constantly presence of bubbles and crashes, started the research interests of agent-based model for crisis. The standard Gaussian framework used by economists is the key issue to to addressed. Non-Gaussian distributions and scaling laws which are commonly observed in phase transitions are applied to this issue. The key future of a phase transition is the sudden and abrupt variation in order parameters of the system (Gingras and Schinckus(2012)). Yalamova & McKelvey (2011) demonstrated that a non-Gaussian framework is more capable to deal with big fluctuations under extreme conditions.

Another issue the econophysics lists is that the atomistic reductionism is not a proper description of economic reality especially the economic crises. For econophysicists, the economic crisis is generated through the interactions between different sectors in the economic system such as firms, banks and households which enables the crisis analysis (Stanley et al. (2007)). As mentioned before, Agent-based econophysics focuses on interactions of the heterogeneous components of the economy that induce complex phenomena (Schinckus (2011)), which will be followed by this crisis study as well.

1.7 Research Objectives

In this study, two main objectives are set: to implement the agent-based econophysics framework to unveil the crisis mechanisms behind complex socioeconomic phenomena to understand crisis occurrence theoretically, and to utilize the mechanisms for investigation of key factors of crisis for the future empirical implementation and policy recommend in a more practical sense. The theoretical analysis mainly focuses on the phase transition mechanisms with self-organized criticality, while the key factor analysis focuses on various players in the socioeconomic system such as household, firm, bank, government, and population factor to gain the insight of the future direction in applications of the main crisis mechanism to regulate in various heterogeneous factors in the socioeconomic system.

The first objective on mechanism of crisis occurrence comprises three sub objectives as follows:

1. Reproduction of crises in a macro-economic ABM.
2. Development of a theory for the occurrence of crises.
3. Numerical validation of the theory in the ABM.

A model which can reproduce the crisis occurrence non-trivially is the crucial precondition to build this research. To this end, we adopt an existing macroeconomic agent-based model Mark0 for the basic investigations on the mechanisms of crisis emergence and instability issues in a complex economic system. The details of Mark0 (Gualdi et al. (2015a)) will be introduced in the chapter 2. As far as we know, Mark0 is the few model in which a non-trivial crisis occurrence can be observed. The theoretical analyses will be the core of this study, for the crisis mechanism is the basis to understand the phenomenon in a more elaborated model. The theoretical analysis is through non-equilibrium phase transitions which have been mentioned in Gingras and Schinckus (2012), Brock (1993). Both the dynamical transition processes in the time space and the phase diagrams in the parameter space are studied. The last part of the first objective is to show the numerical validation of proposed theory in the form of numerical test against the predication from the model. The numerical validation will test against a non-trivial predication from the theory to proof the validity of the theorizing process.

The second objective on the key factor analysis for crisis alert and regulation is comprised of three sub objectives as follows:

4. Investigate on the influence of various socioeconomic factors.
5. Recommend on the directions for policy making.

6. Alerts on new types of crises.

Roles of key factors of firms and household, modifications of policy rules and population dynamics are investigated as extensions of Mark0 in a systematic way with both simulations and theoretical insights relating to the crisis emergence. The simulations focus on identification of the long term instability which is theoretically analyzed and referred as the endogenous crisis phenomena in the first objective. Applying the general insights from the model, several key factors of crisis emergence in the economy are further analyzed and elaborated. In particular, market pricing strategy, labor wage incentives, demand-supply balance, firm debt, household debt, bank policy, government control, population interaction are studied case by case to demonstrate the applications of systematical factor analysis on crisis occurrence with extensions to a general basic model. The ultimate goal for these factor analyses is two-fold: firstly, we would like to examine the necessity and the important role of government of intervention in the spirit of original idea of Keynes (Keynes, (1936)). As in Krugman (2009), who received his Nobel Prize in Economics one year before in 2008, he observed that:

"New Keynesians, unlike the original Keynesians, didn't think fiscal policy — changes in government spending or taxes — was needed to fight recessions. They believed that monetary policy, administered by the technocrats at the Fed, could provide whatever remedies the economy needed." - Dr. Paul Krugman

It is not only the necessity of government intervention that matters. Through this study, we also want to recommend the proper actions taken by the government during the crisis. To this end, the hypothesis is improper policy from the Fed and the government would only do nothing to the economy rather than recovery from the crisis. The proof of this point and the consequent more proper action recommendation are the focuses of this sub-objective.

The other sub-objective is along the heritage of the pioneer simulation study by Meadows et al. (1972) which aims to issue alert for the future potential global crisis. This part is more focused on examination on the limits of the current system to activate the broad discussion on the related future crisis issues which hopefully can bring enough attention of the future researchers to provide solutions to the issues properly and timely in avoiding the worst scenarios and maintain the sustainability of human society through a reliable socioeconomic system configuration.

1.8 Contribution of this Study

This study contributes to the understanding of emergence of crisis in a direct way and from multidimensional aspects.

Firstly, the current literature under the topic of crisis is more concentrated on the prediction or impact of the crisis. For example, a review on the prediction of crisis as an early warning system could be found in Demyanyk and Hasan (2010). Felix Raj and Roy (2014) provided an example of the studies of post-impact of crisis. The studies on the causes of the crisis are in general following a statistical approach with empirical data (see an example as in Tonkiss (2009)), or a theoretical behavior analysis such as the "animal spirit" and trust discussed in Corsetti et al. (1999). As pointed out by Chakraborti et al. (2011b), the mechanism of crisis occurrence through simulation with agent-based econophysics will become one of the significant contribution to the crisis studies. Given this starting point with few research has addressed in this direction, this study contributes to the direct mechanism investigation on emergence of crisis in a multi-agents socioeconomic system which could be considered as the basis for more sophisticate agent-based simulation study.

Second, the study adopts the complex system thinking to understand the crisis occurrence. In particular, this study deals with a simple minimal model to investigate the root of crisis inside the base of socioeconomic system. This study is built upon reproduction of crises in a modeled economy, which is usually lacking in the empirical data-driving economic research focusing only on the explanation of crisis through the statistics of data. In particular, this study contributes to the theoretical analysis of crisis by deriving the system dynamics. We developed a self-organization theoretical analysis to theoretically demonstrate the hidden condition for crisis occurrence through the development of internal order within specific subgroups of firms inside the economy. We have found this link is especially lacking in the current literature in ABM. The current ABM studies regarding to macroeconomics are mostly done at two ends. On one hand, the baseline models for a basic economic system are under construction as a social laboratory, such as in Lengnick (2013). On the other hand, models purely for phenomenon-specified investigations are also constructed for interpretation of the limited problems in concerns, such as the cases to investigate the relationship between the leverage and system risk (see examples in Bookstaber (2017), Thurner (2011), Kuzubaş et al. (2016)). However, the two lines of research in ABM are not merged into each other to provide more general insights of crisis occurrence, which is the investigation of common mechanism of crisis phenomenon in a basic economic model. This study bridges the two ends of research and intends to provide theory connecting the basic structure and the phenomenon occurrence in an ABM, so that we can further use the theory and make predication on some undiscovered process, with possible validation by the numerical experiments.

Third, this study conducts a systematic investigation on different key factors and their relationship to crisis, which are under one common framework of an agent-based socioeconomic configuration. Different from the previous studies on crisis factors which are more case-specific, this study provides a unified modeling approach and a common ground for comparison, integration and validation among results which previously can only be discussed either purely conceptually or purely empirically. In doing so, the crisis occurrence can be conceived in a multidimensional factor space with more accountability and reliability in the case that the potential effective policy intervention and early warning schemes are considered.

1.9 Outline of the Dissertation

Agent-based model is naturally connected to the emergence of complex system. Given our extreme complex socioeconomic reality, a minimal agent-based model for basic socioeconomic system and various investigations on the fundamental roots of crisis is the main perspective of this study. This dissertation contains two approaches; 1) the theoretical analysis on the model; 2) the key factor analysis on various aspects of applications to the practical scenarios. The five chapters are structured as follows:

After the introduction in Chapter 1, where we discuss the previous efforts on comprehension of crisis occurrence and the philosophy of complex system approach on investigation of crisis emergence with agent-based model, we introduce the minimal model Mark0 for this task in Chapter 2. Apart from the structure and the discovered phase diagram of the model from the previous studies, we will also provide a philosophical discussion on the open issue of validation of an agent-based model, together with some evidence on comparison with stylized facts of empirical economic studies. In particular, we argue for a new angle of system complexity comparison through stylized facts as an indirect way to provide some hints on the validity of model.

In Chapter 3, our main focus is on the theoretical analysis of the phase transition mechanism and the explanation of the emergence of crisis in the modeled economy. We will focus on the two control parameters of the phase diagram and derive the dynamics theoretically to understand the role of two control parameters, namely, employment propensity of the firm and the default threshold set by the bank. In particular, we will demonstrate the self-organization that occurs in some parts of the seemingly random economy, which maintains the development of structure of some subgroup of firms in certain irreversible direction, until the boundary of phases has been hit.

In Chapter 4, we will discuss several key sectors and their relation with the crisis occurrence. In particular, we will investigate on the household debt behavior and the crisis control policy of the government, the impact of future change in the labor market in an aging shrinking population scenario and the adaptation of firms in an economy.

In Chapter 5, we will summarize the key findings.

Chapter

2. Model

This chapter is composed by two part: From section 2.1 to 2.2, we will introduce the previous work which is the Mark0 model (Gualdi et al.(2015a)) we build our more detailed crisis analysis on. This two parts serve only as the introduction of previous work without any modification from our side.

In section 2.3 to 2.4, we provide an original complexity validation to test the complexity of the model to reproduce the stylized facts in the real economy world. We first discuss the philosophy of validation in ABMs, which is a very important issue and a huge research gap in the newly developed ABM community. Though currently there exists no common way or standard on how to validate an ABM, we discuss the possible directions from the characteristics of ABM. Then we introduce an indirect way to validate the complexity of an ABM against the real system it modeled. The focus of this approach is not on the strict data fitting to reproduce the exactly same historical empirical data, but rather close to the verification of the order of complexity of the model based on which the main mechanism emerge the aggregate pattern. Note that this validation does not aim at perfectly reproduce the empirical results, but rather it is an examination on whether the model is a complex system and whether it is similar to the real economic system in certain degree such as the macro-behavior. By demonstrations of the complex patterns of stylized facts which the model can produce, we argue that the model itself represents a complex system which can be used to understand the core mechanism of crisis. We demonstrate that the macro-level statistics can not falsify the model configurations.

2. 1 A Minimal ABM of a Socioeconomic System

Developed in the European CRISIS project, the macroeconomic ABM Mark0 focuses on solving the complexity for systemic instabilities (Gualdi et al.(2015a)). As shown in Fig 2.1, Mark0 has three sectors, agent firms, aggregate state variable household and parametric bank and government sector. Therefore, it is not unnatural that Mark0 can be considered as a minimal agent-based model to the modern complex economic system.

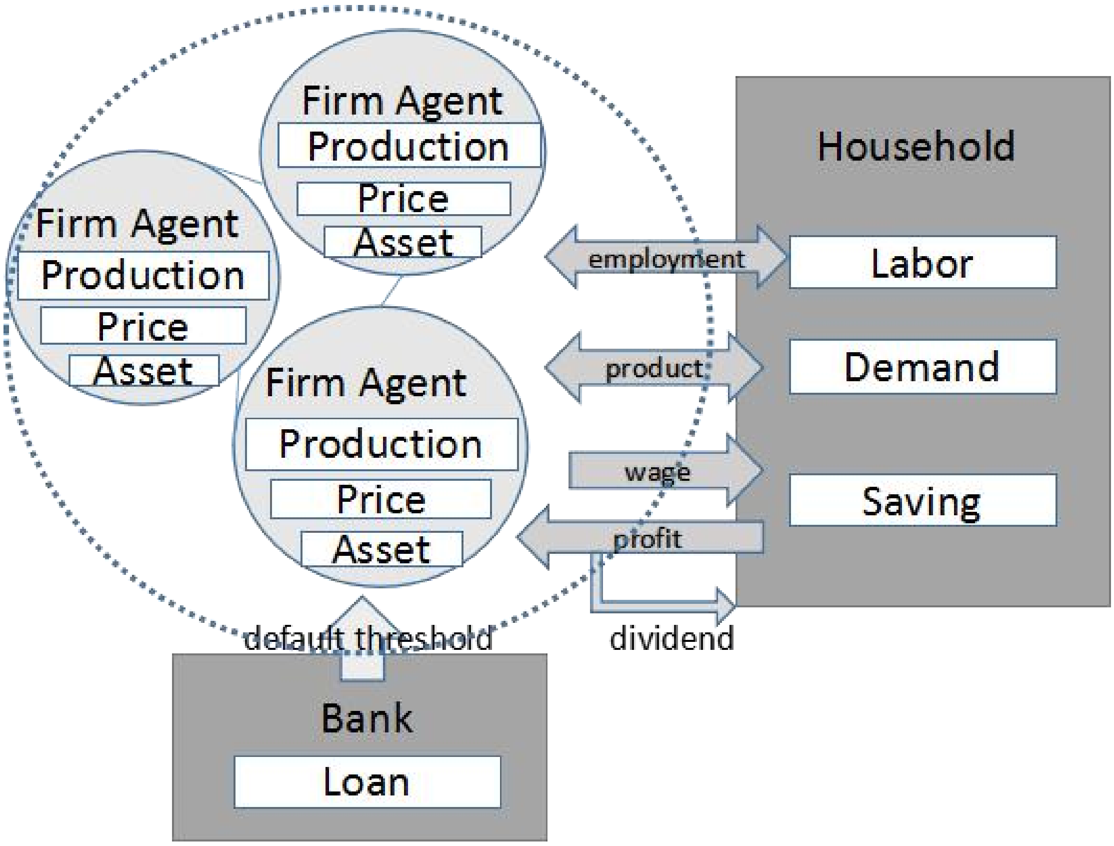


Figure 2.1 The basic structure of Mark0

2. 1. 1 Household Budget and Demand

In an economy, a household forms the demand side for the products from the firms. In general, a household can manage their budget from two sources. The first one is the accumulate savings during the period before the current time step. The second source is the income in the form of wage at the current time step. In practice, the household budget is certainly a more complicated composition from other sources such as dividends or loans. These forms of sources can actually be included in the above two sources conceptually. For example, the loans can be the case that simply the budget to spend larger than the available savings and incomes. For the dividends, it can be included in the savings which will be introduced in the accounting in section 2.1.3. Therefore, to maintain the simplicity and minimal condition of the model, the consumption capacity of households is then defined with two terms of savings and wages, as the maximum amount of available money which households can spend on the consumption of products during a single time step. The budget is a proportion of the consumption capacity of the consumption capacity. In summary, the consumption budget $C_B(t)$ is determined with the household savings $S(t)$, the total wage (equivalent to the sum of production $Y_i(t)$), and a constant coefficient *c,* as shown in Eq. (1).

$$C_B(t) = c\left[S(t) + \sum_i Y_i(t)\right] \tag{1}$$

Note that for the baseline model we have a constant unit wage rate, thus the total wage paid in a single time step to the household is the same numerical value as the total employment in the economy, which is also the same numerical value as the total production in the economy by assuming a constant productivity rate. In summary, $W_i(t)=1\times L_i(t)=1\times Y_i(t)$, where $W_i(t)$ is the wage paid in firm *i*, $L_i(t)$ is the labor or employment in firm *i*, and $Y_i(t)$ is the production in firm *i.* The constant *c* is a positive number. When *c* is not greater than 1, the household can be seen as consuming without loans. When *c* is greater than 1, the scenarios of loans can be included equivalently in a compact and conceptual way of modelling, which greatly reduces the structure of household to a simple level, still matching the reality to certain complex level.

After the household decided their budget to purchase the products of different firms, the demand for each firm is decided. The rule of demand determination is two-fold. First, based on the price competition, the cheaper the products are, the higher the demand is for a firm who produces the products. Second, the household preference, i.e their price sensitivity also determines the distribution of the total budget among the all firms. The higher the price sensitivity is, the more the demand is for the products with a lower price. A high price sensitivity represents the strong preference of products with low price in the household, which skews the uniform distribution of budget among firms in terms of price. In an extreme high price sensitivity household, almost all the budget is allocated to buy the products of the firms who offer the cheapest price. In summary, the household consumption budget is distributed based on the sensitivity of price preference of the household, while the demand for products of a firm is determined by competing the price $p_i(t)$ offered by firm i in the economy as shown in Eq.(2). And to capture the price sensitivity of household in its demands, a Boltzmann distribution $Z(t)$ is applied as defined in Eq.(2). Together the demand $D_i(t)$ for firm i is determined.

$$D_i(t) = \frac{C_B(t)}{p_i(t)} \frac{e^{-\beta p_i(t)/\overline{p}(t)}}{Z(t)}, \quad \text{with} \quad Z(t) = \sum_i e^{-\beta p_i(t)/\overline{p}(t)}, \tag{2}$$

In the Boltzmann distribution, β is a parameter called the price sensitivity coefficient. The larger β is, the more budget is flowing to the products of the low price. In the simplest case where β=0, the budget is equally distributed among all the firms. Note that the normalization of Boltzmann distribution ensures the sum of budgets for the total demands for all the firms is conservative.

$\overline{p}(t)$ is the production-weighted average prices defined as the following

$$\overline{p}(t) = \frac{\sum_i p_i(t) Y_i(t)}{\sum_i Y_i(t)} \, . \tag{3}$$

Note that the Boltzmann distribution measures the distance between the offered price of each firm and the production-weighted average price of the whole economy. It ensures the relative advantages/disadvantages from the market average price. This settings of the system create profound influence in the market behavior of the firm agents . Later we will see, especially in the case of perfect inflation control, the production-weighted average price is actually the target price for all the firms dynamically adjusted its price to achieve the dynamically varying maximum utility, and as a result, statistically all of them converge to the average price during the relatively stable period of the economy.

2.1.2 Firm Employment and Production

In an economy, firms have two functions: production and employment. The main purpose of a firm is to make profit through production and supply the products to the household. In order to doing so, firms need to employ labor from the household. Firms need to hire more labor to expand their production if a higher demand from the household is presented. On the contrary, firms also fire their current labor to adjust their production to a optimal level if a low demand is imposed. Therefore, give a short period within which productivity improvement is not very likely to happen, a strong correlation has existed between the production and employment in a firm. This is why, in the simplest case as mentioned in the previous section 2.1.1, by normalize the productivity to a unit number, the production and employment can be treated the same in a numerical fashion. As in the model, each firm has to adjusts its production/employment to try to narrow down the demand-supply gap in every time step. Besides the number of production, another variable that a firm can adjust is the price of the products. The price adjustment has two kinds of effects to a firm. First, price adjustment can affect demand. As a lower price can stimulate demand, a firm probably decreases their price if their price is higher than the market price when they are in the oversupplying situation. Consequently, the demand will increase as the price goes down. Second price adjustment can affect profit. For firms in a position with lower prices than the average, and still with a higher demand than their production, an increase in the price aims at more profit to the firm, though at a cost of potential decrease in the demand from household.

Accordingly, the model specifies the following firm behavior rules based on the general principle above. In an oversupplying state, the firm will fire a number of labor to reduce its production and try to meet the demand, as shown in Eq. (4). Normally, firm i will fire the labor proportional to the gap between its production $Y_i(t)$ and the demand $D_i(t)$. The proportion coefficient is called a firing propensity coefficient η_- , which represents how likely a firm would fire their labor. Note that η_- is usually much smaller than 1, which represents a relatively slow adjusting process by firms compared with the market volatility since the labor and production cannot be reduced instantly. After the production adjustment, firm i would also adjust its price as we have already discussed. As a general principle, firm i would lower its price if it is higher than the market average price $\overline{p}(t)$. In particular, the price adjustment is modeled in a random way by a ratio of a constant γ_p times a uniform random factor $\xi_i(t)$ between 0 and 1. The constant γ_p represents the average price sensitivity of firms as the maximum ratio for their adjustment. The bigger γ_p is, the volatile the price could vary. However, if the price is already lower than the average price, the firm will lose more profit by lowering its price. As a result, the strategy is the price would remain unchanged if it is already below the market average even under the oversupplying case.

$$Y_i(t) > D_i(t) \Rightarrow \begin{cases} Y_i(t+1) = \max\{Y_i(t) - \eta_-(Y_i(t) - D_i(t)), 0\} \\ p_i(t) > \bar{p}(t) \Rightarrow p_i(t+1) = p_i(t)(1 - \gamma_p \xi_i(t)) \\ p_i(t) \le \bar{p}(t) \Rightarrow p_i(t+1) = p_i(t) \end{cases} \quad (4)$$

Another point need to be mentioned is that, since the production cannot be negative, the firm can at most fire all the existing employees. Therefore, the production adjustment in Eq. (4) is bounded by a predefined minimum value of zero production in a firm.

On the other hand, as in the case of under-supplying, basically symmetric rules of production and price adjustment are applied to a firm, as shown in Eq. (5). The only biased parameter is the hiring propensity η_+, which is different from the previous firing propensity η_-. The reason for this heterogeneity is that the relative strength of firing propensity and hiring propensity is changing over time in real world. As in a good time of economy, most firms are hiring people more likely than firing people. However, in the time of a crisis, this hidden propensity of firms can change as they are more prone to fire their employees than to recruit new people. Therefore, the difference of the firing and hiring propensity can create different scenarios and also might influence the performance of the economy during the period of crisis recovery. In fact, the ratio of hiring propensity over firing propensity can be proved to be a key control parameter which governs the phase transition in the economy (details can be found in Chapter 3). The firms normally hire labor proportional to the demand-supply gap. However, in Eq.(5) as in the case of labor shortage (for example, in an almost full-employment period), a firm can only at most hire the amount of labor smaller than the predefined proportion of demand-supply gap, which is set to the equals to $u(t)$, the current unemployment rate of the economy, as defined in Eq. (6). The reason for this setting is to ensure the firms can still hire some labor equally, and can at least hire some labor to meet their demands. For simplicity in Eq.(6), the numerical value of the total available labor from the household is set to equal to the total number of firms N_F , for the absolute number of labor can be easily normalized anyway. And in terms of firm agent dynamics, actually the size distribution of the firms, which is the important stylized statistical property of an economy, is independent of the absolute value of the available labor. The unemployment rate defined in Eq.(6) is also an important indicator for status of the whole economy, which will be used in the phase classification later in this chapter.

$$Y_i(t) < D_i(t) \Rightarrow \begin{cases} Y_i(t+1) = Y_i(t) + \min\{\eta_+ (D_i(t) - Y_i(t)), u(t)\} \\ p_i(t) < \overline{p}(t) \Rightarrow p_i(t+1) = p_i(t)(1 + \gamma_p \xi_i(t)) \\ p_i(t) \geq \overline{p}(t) \Rightarrow p_i(t+1) = p_i(t) \end{cases} \quad (5)$$

$$u(t) = 1 - \sum_i Y_i(t) / N_F \quad (6)$$

2. 1. 3 Accounting

As we already introduced the household and the firms, besides their short-term planing for budget, production and price in an economy, both sides dynamically accumulate their resources in a long run which include the calculations of firm asset $\varepsilon_i(t)$ and household savings $S(t)$. as shown in Eq.(7) and Eq.(8), respectively.

$$\varepsilon_i(t+1) = \varepsilon_i(t) + \rho_i(t) - \delta \rho_i(t) \theta(\rho_i(t)) \quad (7)$$

$$S(t+1) = S(t) - \sum_i \rho_i(t) + \delta \sum_i \rho_i(t) \theta(\rho_i(t)) \quad (8)$$

Different than the previous behavior rules only depending on the current time step, the firm assets and household savings are depending on all the previous events, with a "memory" of the history. In order to update a firm's asset, the first important variable is its profit $\rho_i(t)$ at the current time step. which is calculated as

$$\rho_i(t) = p_i(t) \min\{Y_i(t), D_i(t)\} - Y_i(t) \quad (9)$$

In Eq. (9), the profit of a firm equals to the difference between sales from the products and wages to the labor. The sales is the price times the actual number of sold products, which equals to the production number when the firm is under-supplying, or the demand number when the firm is oversupplying. The wages paid to the labor are the same as the production in number for we assume a constant unit wage rate for the simplest case. The calculated profit can be either positive as in the case of earning money, or negative as in the case of losing money. The negative profit can deepen the debt of a firm which could be temporarily absorbed by the bank before its bankruptcy. Therefore the asset of a firm could be negative as in the case of "operation with loans". On the other hand, when the profit is positive, the firm will give out part of its profit in the form of a dividend, as shown in the last term in Eq.(7). The dividend is calculated as a proportion of the profit. The dividend ratio δ is used to measures the willingness of firms to return profits to the household. To control the dividend term is only effective when the profit is positive, the heavy-side function $\theta(\rho_i(t))$ is engaged, which gives to the value of 0 when the profit is negative, and 1 when the profit is positive. Note that the dividend rate as we discussed here is only conceptual, and other interpretation in the real world can be imposed on δ as well. For example, δ can be interpreted as the profit tax rate which can be adjusted by the government rather than by firms themselves. The important point here is, δ represents such a general feedback in our real socioeconomic system in many kinds of actual forms, and this feedback is universally existing in our real economy.

Household savings are accumulated with the decrease in the total firm asset in the economy, which is designed to ensure the conservation of money in the modeled economy, as shown in Eq.(10). Note that the household savings decrease with the gained total profit by the firms (for the profit must be obtained from the household), and increase with a higher dividend rate.

2.1.4 Bankruptcy and New Entries

In an economy, the firms are in a dynamic process of bankruptcy and birth of new firms. The two processes balance each other and maintain a healthy economy with new blood replacing the old organization in “malfunction”. A firm can reach a state of “malfunction” if it keep incurring debts and ask loans from the bank till a point that the bank decide to reject its request for loans. A firm goes bankrupt if it cannot resolve its debts to keep the payment to the hired labor. To model this process, a measurement of the level of debts is needed. To reflect how deeply the asset of a firm is in deficit, a debt ratio

$$\Phi_i(t) = -\varepsilon_i(t) / Y_i(t), \tag{10}$$

is used to measure how much debt (a negative asset) a firm must incur in each time step as a ratio to its labor cost. Again because the assumption of a constant unit wage rate, the labor cost is equal to the production number. A firm can still operate in the economy as long as $\Phi_i(t)$ does not exceeds a threshold Θ, which is set by the bank. However, if $\Phi_i(t)$ hits the threshold Θ, then the firm i goes bankrupt. Note that the default threshold Θ set by the bank is also conceptual, which leaves space for multiple practical interpretations. For instance, Θ could be interpreted as the maximum credits which the bank can grant for every firm, or even the long term investment on the firm for its growth.

When the bankruptcy of a firm is initialized, all the labor employed by the firm will become unemployed. As a result, a sudden release of the labor into the labor market occurs. Moreover, the debt of the firm will be propagated across the whole economy. It will be covered by other firms with enough assets in the form of a takeover, and by household savings in the form of indirect financial loss of the stock holders. All in all, the money is maintained conservative during the bankruptcy of firms and the influence is on the whole economy

On the other hand, the new entries of firms are modeled in a random event since the entries of new firms in a economy depends on many random factors. Specifically, as in the simplest case, the upper limit of number of firms in the economy is set. As a result, the market vacancy provided by the bankrupt firms can provide space for the new firms to start in the economy. Therefore, for every vacancy the default firms have left, a new firm can be started with a predefined probability φ at each time step after, as shown in Eq.(11). And the initial conditions for a new entry is that the price is made to the market average price, the employment is equal to the current unemployment rate of the whole economy as the initial available labor for a start-up, and the initial asset is equal to the labor so that they are capable to pay the labor their wage in the next time step.

$$prob\{p_i(t)=\overline{p}(t),Y_i(t)=u(t),\varepsilon_i(t)=Y_i(t)\}=\varphi\,. \tag{11}$$

Note that again in order to make the money conservative in the economy, the cost of the new entries is covered by other firms or households in the form of an investment.

2.1.5 Inflation

Inflation is an important issue in real economy. For some situation, an extreme inflation can induce crises and even destroy an economy. In this model, extreme inflation event similar to the events which happened in the history can be also reproduced. However, in some case, we do want to simulate other factors to see their influence other than the overwhelming inflation effect. Thus, in particular, inflation can be chosen to under perfect control in the model. To do so, inflation is controlled in each time step, after the prices are updated in Eqs. (4-5). Specifically, all the prices are normalized by the market average price $\overline{p}(t)$ in each time step. As a result, it indicates that $\overline{p}(t)=1$ always holds when the perfect inflation control is imposed in the simulations.

2.1.6 Overall Flow of the Simulation

Based on the settings of the components of the model above, the overall flow of the simulation is illustrated in Fig. 2.2. The initialization of the model create an economy with uniform distribution of price in [0.8, 1.2] centered in 1, of production in [0.3,0.7] centered in 0.5, of demand in constant 0.5. The wage rate is set in constant 1. The asset is set randomly between 0 and 2 times of the payroll (which is $2\times W_i(t)\times Y_i(t)$). Then the simulation iterates itself in the loop of household budget and demand calculation, firm production and price adjustment, household savings and firm asset accounting, bankruptcy of deeply indebted firms and entries of new firms, and post-processing of inflation and others, as shown in Fig.2.2.

Note that the long term phase of the economy in almost all situation is not depending on the initial conditions (This is entirely true when wage is constant.) Therefore, the results is robust against initial conditions. Actually, the insensitivity to the initial conditions of firm distributions lead to the emergence of the phases of the modeled economy, which will be introduced in the next section.

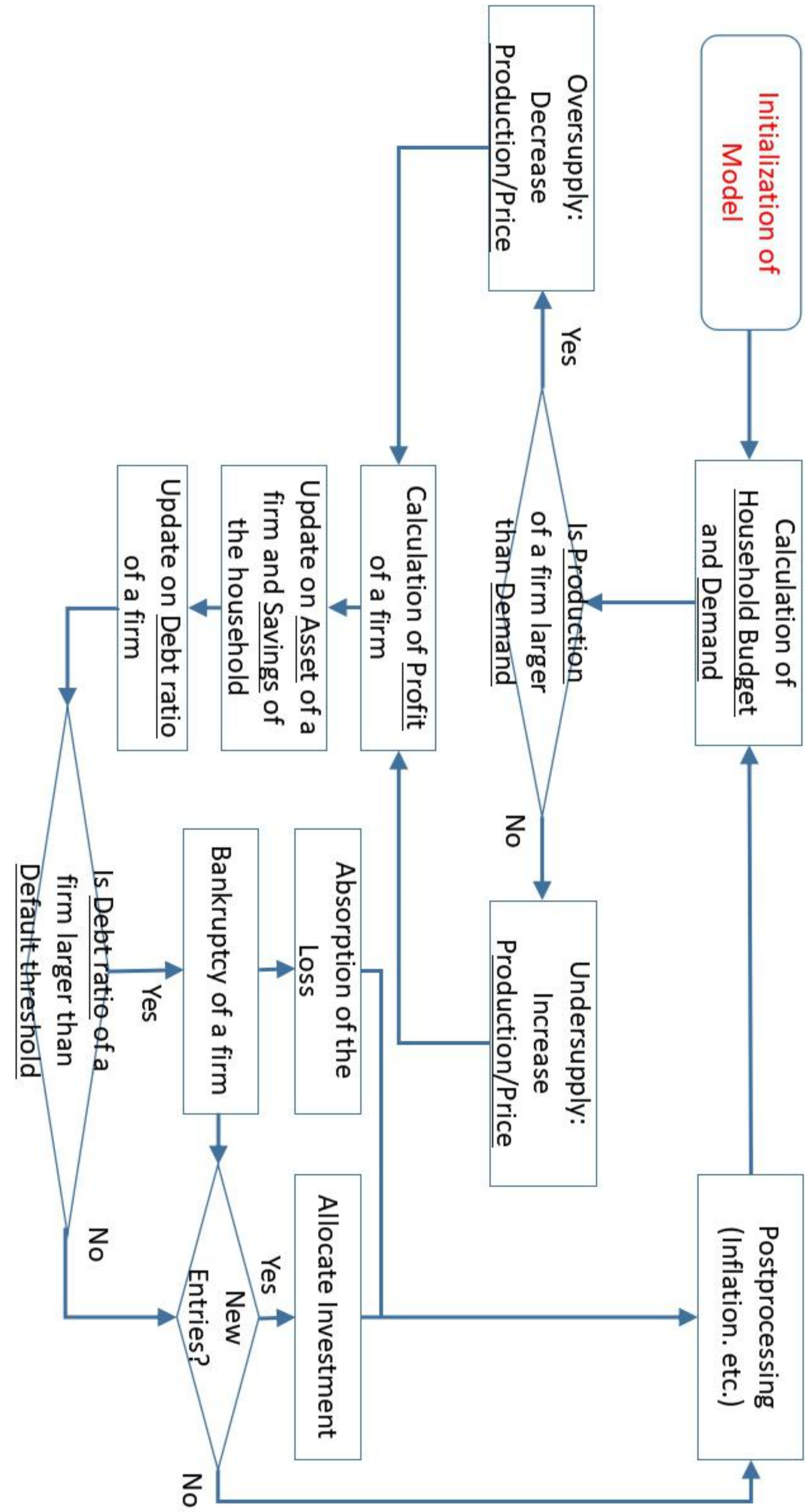


Figure 2.2 The flow of the simulation is illustrated as the household budget and demand, firm production and price update, household savings and firm asset update, bankruptcy and new entries, and post-processing of inflation etc.

2.2 Phases and Phase Transitions

In Gualdi et al.(2015a, 2017), Mark0 can generate four distinct economic phases, namely, full unemployment (FU), residual unemployment (RU), endogenous crisis (EC), and full employment (FE). (see Fig. 2.3) It is further found that the phases are separated by two control parameters. One is the propensity of hiring/firing, defined by

$$R = \eta_+ / \eta_- . \tag{12}$$

The critical value is $R_c \leq 1$, which separates FU from all the other phases. The other control parameter is the default ratio Θ. Given $R > R_c$, as Θ decreases from infinity to 0, the states of system shift from FE to EC and then to RU, see Fig. 2.4.

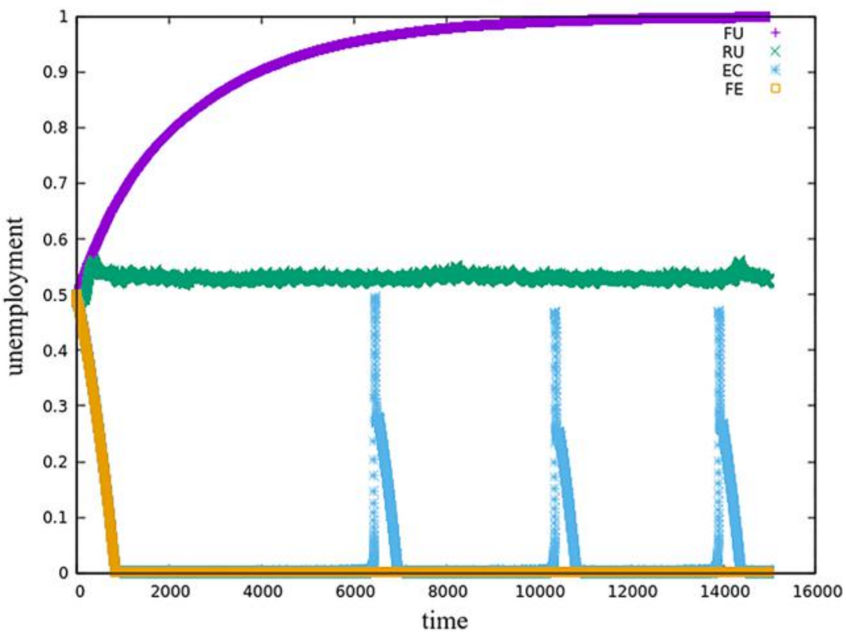


Figure 2.3 The four phases are shown from top to bottom are: full unemployment (FU), residual unemployment (RU), endogenous crisis (EC) which has spikes of large unemployment, and full employment (FE).

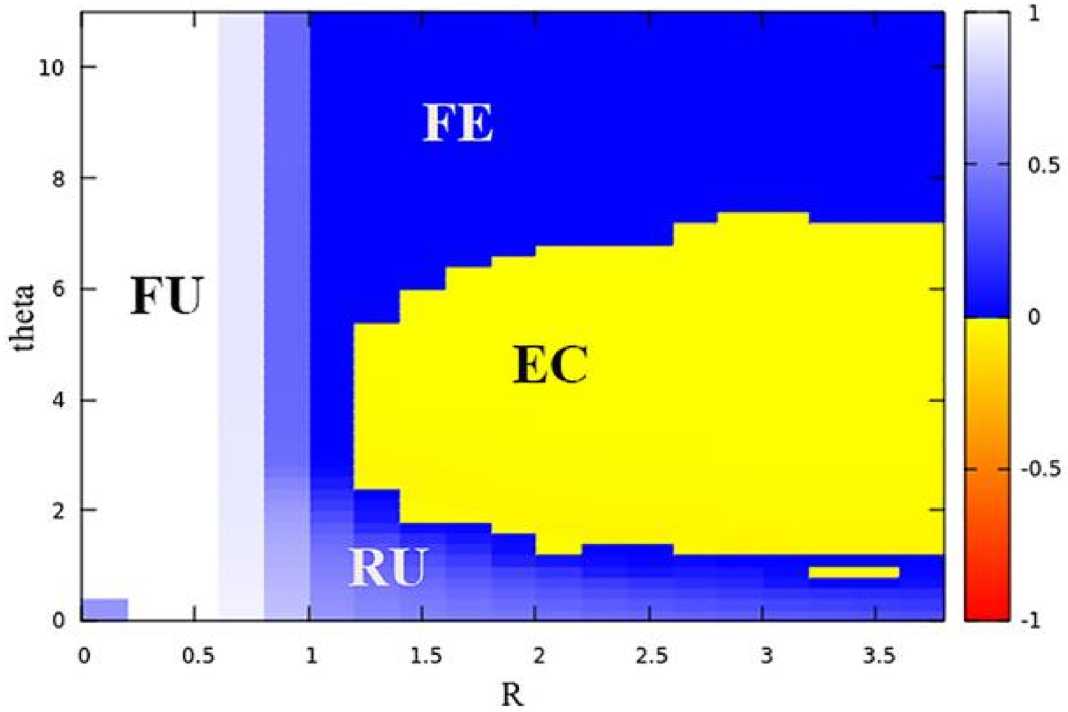


Figure 2.4 Auto-generated phase diagram based on average unemployment rate and its volatility. The phase is judged by the dynamics after the first period of time of settlement. For slow asymptotic equilibria especially close to the phase boundary, a very long relaxation time is expected therefore some artifacts of "transient bands" instead of sudden transitions are presented. Phase FU, RU, EC, FE are represented by the color map. The absolute value of the color bar denotes the average unemployment rate. The sign of the color bar is assigned by the volatility of the unemployment rate. (positive: stable states; negative: unstable states). The criteria for the volatility to identify EC phase are two-fold: the volatility is larger than 0.1 or the average unemployment smaller than 0.01 but with any spike value larger than 0.1.

Combining Fig 2.3 and Fig 2.4, we can observe that the FU phase is separated from other phases by the control parameter R, and another control parameter Θ can classify the FE, EC and RU phase. In fact, the control parameter R regulates two convergent phase as FU and FE, both of which are attractors. On the other hand, the RU is an equilibrium phase which is the competing results of unemployment dynamic component controlled by Θ and the employment attractor of FE. The EC phase, however, is not the same attractor of FE because large deviation from FE can autonomously occurs as a sign of instability. Neither is EC an equilibrium state for it is for sure out of equilibrium during the crisis occurrence. Therefore, EC is a critical non-equilibrium state within what both order (as in FE and FU) and random disorder (as in RU), coexist in the collective behavior of the agents developed from the self-organized criticality process, which we will talk in details in chapter 3. Here the important point is the four phases are not the same type in terms of the detailed mechanism, which implicitly demonstrates the complexity of the model Mark0.

2.3 Complexity of the Model and Real Economy

2.3.1 Overview on Philosophy of Model Validation

According to Bianchi et al. (2007), Tesfatsion and Judd (2006); Tesfatsion (2007), the methodological reflection on empirical validation of an ABM based on a view from a multiple-input-multiple-output system can be divided into three types:

1. Input validation
2. Descriptive output validation
3. Predictive output validation

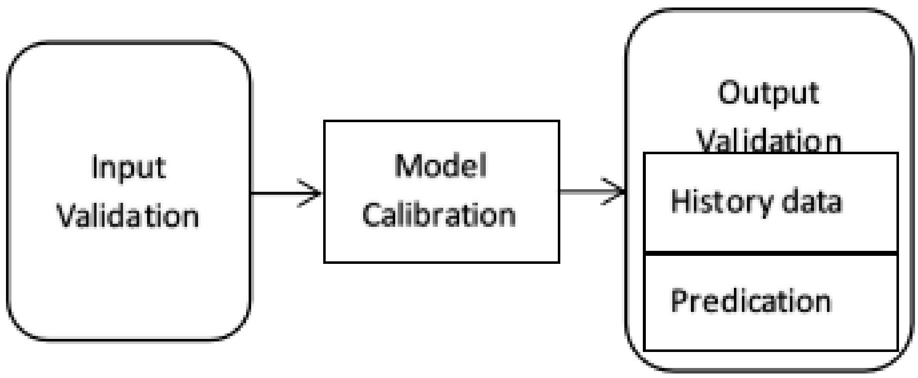


Figure 2.5 The illustration of validation of an ABM based on multiple-input-multiple-output framework.

Generally speaking, the methodological validation framework for an ABM can be illustrated based on a multiple-input-multiple-output system. The validation process of a model can be conducted from the input side or the output side, as shown in Fig. 2.5. To validate an ABM from the input side, the focuses are on the fundamental structure, the basic settings, the behavior rules and institutional conditions in reproducing most of the main aspects of the real system modeled, which is usually before the parameter calibration. On the other hand, after calibration of the model, the output validation can be conducted. The output validation is a comparison between the actual data and the corresponding artificial data from the simulation results of the calibrated model. Based on the availability of the data, the output simulation can be further divided into two categories: the descriptive output validation and the predicative output validation.

The descriptive output validation is a straightforward approach with a comparison between the historical available data and the simulation results. Because the descriptive output validation is limited to the available data, the effective validation highly depends on the quality of the data. If the “noise” of the data (the hidden factors included in the data which cannot be accounted by the model itself) is significant enough, the data cannot be used to validate a basic model since the noise would falsify the model which can be actually true in its basic settings. This is particularly true when the macroeconomic data with a complicated composition of “noises” is involved. Another limitation for descriptive output validation is that the scope is confined to models which has a similar configuration of the current socioeconomic system. Theoretically, it becomes virtually impossible to use current available historical data (also the only type of available data in our socioeconomic system) to verify the generated output of most modeled socioeconomic systems with modification different from the current configuration. Therefore, the descriptive output validation cannot help in the case of an alternative scheme of socioeconomic system or policy recommendations if the settings stay away from the ones in use in the current system.

The predictive output validation is to validate the theoretical predictions with the data yet to be acquired. Theoretically, the predictive output validation can compensate the descriptive output validation, if and only if the future data can be constructed in the same way as the predication required and the corresponding modification in our socioeconomic system can be reflected in the future institutional changes by policy interventions. However, practically, the availability of the future data is highly uncertain which usually results in an extreme long period before the final validation if possible. In addition, a dilemma emerges that the recommendations of institutional change for the purpose of validation of the model predictions can only be accepted after the model results are validated first in almost all the cases for the policy makers. This is because the real socioeconomic system is a huge system and any improper violation in the system could result in huge negative impacts in the system thus no one would like to bear the costs in practical. Therefore, predicative output validation is not widely applicable to the current system either.

On the contrary, the input validation refers to the validation of the specific system characteristics indirectly rather than the target output directly. This is mainly because the problem of data availability which makes the direct output validation impossible at the current time. Therefore, the indirect input validation with the other sources of available data becomes one alternative to extend the scope of validation for socioeconomic ABM. As shown in Fig. 2.5., the input validation happens before the calibration of the model thus it is also considered as the precondition for calibrating a model. The most popular data set for input validation is the so called 'stylized facts' from empirical macroeconomic studies. Typical stylized facts include the statistics such as firm size distribution, firm growth distribution, firm entry and exit distribution, firm debt distribution, profit rate distribution, wage and profit share distribution, income distribution, GDP growth and business cycle (e.g. Lin (2012)). However, it is noted that even among these stylized facts, most of them cannot be recovered universally among data across all the countries. The heterogeneity of stylized facts creates the problem that even if the model can reproduce the facts in some country, it might not hold true for other countries.

In order to solve the validation dilemma mentioned above, one possible approach is to discuss whether the universality exists in the stylized facts as the discussion in the financial market (e.g. Eisler and Kert (2006), Kufenko and Geiger (2017)). Therefore, the validation of a general model with insights on the emergence of crisis from the fundamental socioeconomic system structure highly depends on the existence of universality of stylized facts.

However, even though we do not know the universality of the stylized facts, we can still compare the similarity in terms of complexity of the model and the real economy indirectly. Our argument is that the similar magnitude of complexity is the necessary condition for the modeled system to be close to the real socioeconomic system. By examining the different distributions between the model and the real system, we can argue that in terms of degree of the complexity, the model is statistically comparable to the real system by generating similar distributions in multiple dimensions. In the following section, we will illustrate how complex the statistics can be in the dynamics of the model simulations when compared with the statistics of the empirical data.

2.3.2 A Comparison on Stylized Facts

Following the philosophical discussion on validation, we will demonstrate with concrete examples of how to validate the complexity of Mark0 and how significantly comparable it is regarding to the macroeconomic phenomena to the real economic system. In the real economy, the statistical data in the bankrupt firms follows some forms of laws. These statistical features of the real data provide a way to falsify the model if the model can not reproduce these structures. For example, in Fujiwara (2004), it examined the 10 years period data of bankrupt firms in Japan before the 1997 Asian crisis. In particular, it found that the debt of the bankrupt firms follows a Zipf law which is the cumulative probability distribution and the debts following a power law. Also it examined the lifetime of a firm who showed an exponential region in the whole lifetime distribution, as well as a clustering correlation between the debts and the sales/sizes of firms. All these findings, in our opinion, demonstrate that the structure of the statistical facts can be used as indirect representations of the minimal complexity of the real system. Therefore, successful reproduction of the statistical facts is a proof of the complexity of the model which can be compared with the real system in certain essential scopes.

Hence, we examined the basic statistical structure in Mark0. The results are the log plot cumulative distribution of debts in bankrupt firms in Fig 2.6, semi-log plot cumulative distribution of lifetime in bankrupt firms in Fig 2.7, correlation plot on the power of sales or sizes of bankrupt firms and the power of their debts in Fig 2.8 and Fig. 2.9. Note that this validation is not a numerical fitting. The number in the power is meaningless since the scale of the real economy is very different from the scale of this model. And the model can not be calibrated into one which can fit the real data in. Neither is the purpose of this investigation for this study which aims at the mechanism and pattern generation to understand the main system behavior .

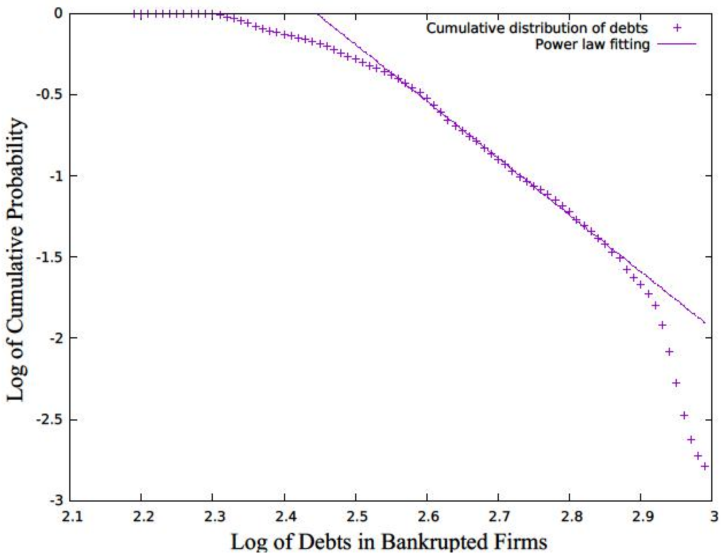


Figure 2.6 R=2, theta=15. The cumulative probability distribution of debts in bankrupt firms follows a power law. The power fitting line is -3.5log2(debt)+8.56.

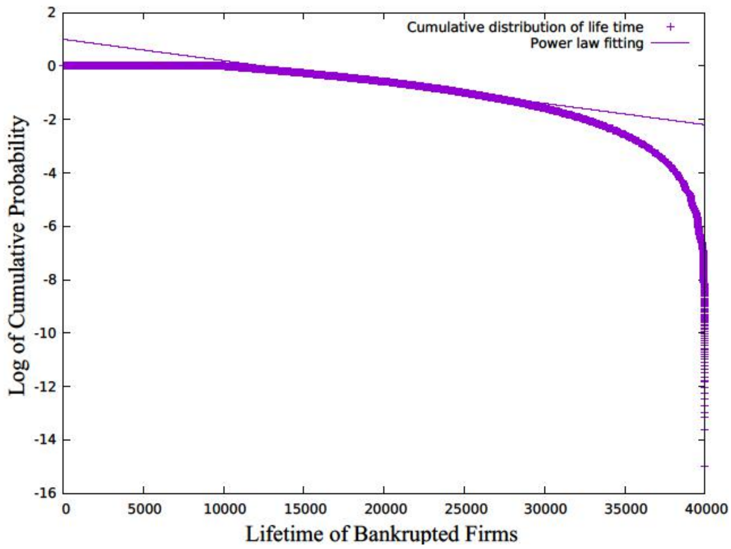


Figure 2.7 R=2.4, theta=2. The log of cumulative probability distribution of lifetime in bankrupt firms also has a linear region. The linear fitting line is -0.0008*lifetime+1.

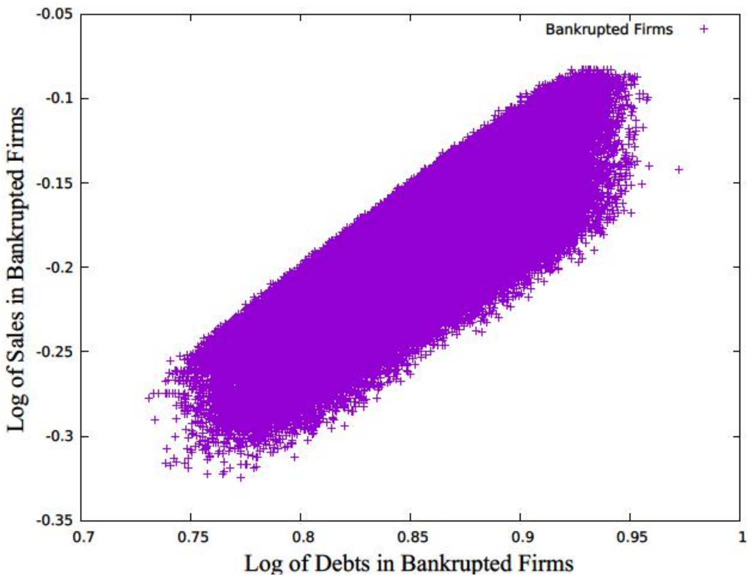


Figure 2.8 R=2.4, theta=2. The correlation plot of the power of sales in bankrupt firms and the power of the debts in bankrupt firms shows a cluster along the diagonal line.

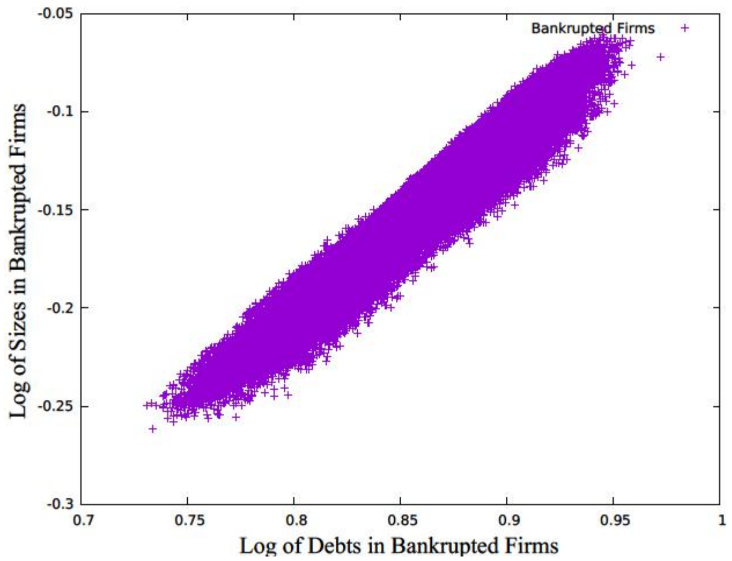


Figure 2.9 R=2.4, theta=2. The correlation plot of the power of sizes in bankrupt firms and the power of the debts in bankrupt firms shows a cluster along the diagonal line.

We find that in some control parameter sets (an example is shown in Fig. 2.6.), the cumulative probability of the debts in the bankrupt firms follows a Zipf law, which means a linear region can be found as in the form of power law. This statistical structure using artificial data generated in Mark0 is the same with the empirical data analysis in Fujiwara (2004), which can be consider as an evidence which implies similarity in complexity between Mark0 and the real economic system.

In Fig 2.7, we again can reproduce a linear region in the cumulative probability of the lifetime in bankrupt firms. However, this time the linearity is weaker. Because the lifetime is not in the log form, this indicates there is one region with exponential decline. Interestingly, in the empirical data in Fujiwara (2004), the linear region is also distorted by a region following an even steeper decline. The pattern of Mark0 in lifetime of firms and the real data still have a lot of similarities which can be considered as the same category with similar patterns.

Similarly, as in Fig. 2.8 and Fig. 2.9, the correlation cluster in bankrupt firm debts and firm sales/sizes can also be reproduced as similar patterns which can be found in Fujiwara (2004). The correlation implies the group structure of bankrupt firms with the herding behavior.

In summary, all the patterns discovered in empirical data fittings as in Fujiwara (2004) can be reproduced in Mark0 to a very similar degree. Therefore, with some confidence, Mark0 can be considered with enough complexity in reproduction of the bankruptcy and crisis occurrence to shed light on the real economic system. Based on this confidence through statistical structure validation, in the next chapter, we will discuss in details the crisis mechanism in Mark0 in hope of a better understanding of the key mechanisms which could also be shared in the real economy.

Chapter

3. Theoretic Analysis on Phase Transitions and Emergence of Crisis

In this chapter, we will build the theoretical foundation to understand the key crisis occurrence mechanism through a detailed analysis of the dynamic transition process and the role of the key variables and parameters in Mark0. We will firstly give an overview on the phase transition concept and its insights on the dynamics of Mark0. Then we will conduct an analysis on the control parameter employment propensity R, to theoretically elaborate the key variables leading to the phase transition controlled by R. We will also conduct numerical validation to test our prediction from the analysis. The analysis on the control parameter default threshold Θ will follow the same procedure as mathematical dynamical derivation first, and numerical validation after the theorizing process. Combining the two parts, we will have a complete understanding of the phase transition and the related crisis occurrence mechanism in this model Mark0. The key conclusion and theoretical insights will also be applied to help the understanding and explanation of simulation results of the roles of key factors in chapter four. This chapter is the core of this thesis without which the extensions and factor analysis can not be possibly done in a systematic way.

3. 1 Overview on Phase Transitions

Phase transition is a general process in physical world. Especially, phase transition in physics is usually associated with the self-organization process of molecules approaching its criticality. However, in the economic world, the possible phase transition has not yet been studied systematically. The multiple phase transitional phenomenon in Mark0 (Gualdi et al.(2015a, 2017)) has revealed the potential similarity of the physical and economic phase transition, by discovery of four economic states in the model, as in Fig.2.3. By further observation, the four phases can be divided into two categories: First, phase FU, FE and RU are all stable phases with small random fluctuations around the average value. Second, EC can be considered as an unstable transient phase between RU and FE. Especially, EC can reach the same full employment state and behave exactly the same as FE phase until a sudden large endogenous unemployment event is triggered in the economy. The key difference between EC and FE is whether the critical condition for bankruptcy induced unemployment event is satisfied or not. In other words, the criticality of a large unemployment event is steadily approached in the economy by a self-organization process which synchronize the random default firms who originally release their labor randomly, into a simultaneous event by the collective behavior of a large number of firms. Nevertheless, the understanding of the phase transition mechanism in the model is crucial to the possible interpretations of crisis occurrence in the real world. In particular, it has the potential to develop a theoretical framework for crisis and its regulation in a systematic way with the help of econophysics and ABM, which is not even possible by previous approaches sole relying on statistical data. In order to theoretical derive the phase transition mechanism and its relationship with crisis occurrence, we decompose the problem into two sub problems:

1. What dynamic processes are involved in the phase transitions with the two control parameters as shown in Fig 2.4?

2. What are the key conditions in triggering these phase transitions, especially the the transition to a crisis phase?

Regarding to the above two questions, a key work by Gualdi et al. (2015b) has to be mentioned as a theoretical interpretation of the emergence of crisis in EC phase. In this work, it is inspired by the idea of synchronization pattern originally from the Kuramoto model (Kuramoto (1975), Rodrigues et al. (2016)). In order to form a general synchronization pattern, a biased random walks is introduced with a drift as the bias to explain the crisis occurrence in EC phase. The random walk is a general insight into the mechanism of crisis. However, the drawback is that it gives no socioeconomic interpretation in the theoretical analysis. Without the socioeconomic content, the understanding of crisis is still incomplete since concrete and useful applications such as indicators for crises cannot be provided by the general random walk model.

Therefore, in this study, the focuses of theoretical analysis on phase transition are on the socioeconomic contents and concrete conditions of non-equilibrium phase transition processes among different phases. In this way, it is clear that each control parameter regulates on what processes, and the conditions can be derived through critical values on the parameters which in turn control the dynamical evolving socioeconomic processes.

3. 2 Theoretical Analysis on Employment Propensity

In this section, we focus on one of the control parameter, the employment propensity *R*. By observation of the phase diagram in Fig. 2.4, *R* separates FU on one side of the critical value, and all other phases on the other side. In order to only consider the processes controlled by *R*, we consider the case Θ→∞, which excludes its control effect on the economy. To see the labor dynamics, we can write the total labor change rate in one time step as follows,

$$\sum_i^N (Y_i(t+\Delta t) - Y_i(t)) / \Delta t = \sum_i^{N_1} \eta_+ (D_i(t) - Y_i(t)) - \sum_i^{N_2} \eta_- (Y_i(t) - D_i(t)) . \quad (13)$$

where *N* denotes the total number of firms, N_1 denotes the number of firms which have demand higher than their production, and N_2 denotes the number of firms which have demand lower than or equal to production, at time step *t*. Obviously, the condition $N = N_1 + N_2$ is satisfied. With this, the equation becomes as

$$\sum_i^N (Y_i(t+\Delta t) - Y_i(t)) / \Delta t$$

$$= \eta_+ \sum_i^N (D_i(t) - Y_i(t)) + (\eta_- - \eta_+) \sum_i^{N_2} (D_i(t) - Y_i(t))$$

$$= \eta_+ (\sum_i^N (D_i(t) - Y_i(t)) + (1/R - 1) \sum_i^{N_2} (D_i(t) - Y_i(t))) . \quad (14)$$

Note that in each time step a firm adjusts both its production and product price as indicated in Eqs. (4-5). Without external shocks, the modeled economic system intrinsically will be pushed to approach the equilibrium condition of maximum efficiency, i.e., $Y_i = D_i$, $\forall i$. This efficient market adjustment indicates the firms fluctuates around its equilibrium line eventually, which gives the situation that the number of oversupplying firms will be approximately equal to that of undersupplying firms. Under this condition, the condition is imposed that the total demand-supply gap should be fluctuating around zero, $\sum_i^N (D_i(t) - Y_i(t)) = \chi(t) \approx 0$. On the other hand, the long term effect because of the settings of the economic system of Mark0 (the update of demand is based on the symmetrical division rules over price but the update of price is based on the symmetrical addition rules indicated in Eqs. (2-5)), the cumulative value of the demand-supply gap in the economy over long time has a slowly increasing tendency, i.e. $\sum_t \sum_i^N (D_i(t) - Y_i(t)) = \sum_t \chi(t) = \kappa(t) > 0$, with $\chi(t) \approx 0$. With this two conditions, we can derive the critical value of *R* which controls the phase transition of FU and FE.

To do so, we derive the second term in Eq. 14, which is a subgroup with N_2 number of firms which is currently oversupplying. Based on the equilibrium state condition above, we have the condition $\sum_i^{N_2}(D_i(t)-Y_i(t)) = -\omega(t) \approx const < 0$. Different than the whole economy, the gap of this subgroup remains a negative value which is undiminished . With Eq. (14), we can derive the condition below:

$$\sum_i^N (Y_i(t)-Y_i(0)) < 0 \Leftrightarrow R < 1/(1+\kappa(t)/\sum_t \omega(t)) \le 1 . \qquad (15)$$

Eq. (15) indicates the direction of long term variation in employment status in the economy solely depends on the value of R.

Note that the following conditions hold true:

$$|\chi(t)| < |\omega(t)|, \kappa(t) < \sum_t \omega(t), \lim_{t\to\infty}\kappa(t) = +\infty, \lim_{t\to\infty}\sum_t \omega(t) = +\infty ,$$

we further derives that,

$$\lim_{t\to\infty}[(\kappa(t+\Delta t)-\kappa(t))/\sum_t^{t+\Delta t}\omega(t)] = \lim_{t\to\infty}\kappa(t)/\sum_t \omega(t) = \Psi \ge 0 .$$

Combining Eq. (15), the following condition is proved,

$$\exists \kappa(t), \omega(t), t_0 > 0, \forall t > t_0 ,$$

$$\sum_i^N (Y_i(t+\Delta t)-Y_i(t))/\Delta t < 0 \Leftrightarrow R < 1/(1+\Psi) . \qquad (16)$$

Now we showed that the critical value of R exists and it satisfies R_c=1/(1+Ψ)≤1. Eq. (16) indicates on either side of the R_c, the production, or the employment, eventually undergoes monotonous processes, with opposite directions. The role of R is to modulate the relative strength of employment variation based on the demand-supply gap in the subgroups N and N_2, which eventually drive the system to either extreme employment state, which is the formation of the two attractors in the economy.

Next we want to confirm that the theoretical insights on the demand-supply gap in the subgroups N and N_2, can be justified by numerical validation. Therefore we will show below, as a common simulation result, the demand-supply gap for the group of total N firms, and for the group of N_2 firms with excess supply, respectively. The results are shown in Fig. 3.1, in which we can see that $\sum_i^N((D_i(t)-Y_i(t))$ is fluctuating around the zero level, while the corresponding gap in the group with N_2 oversupplying firms, is also stable but deviating from the zero level. By validating the difference between the two gaps of different group of firms, the role of parameter R is also justified as the regulation on the eventually irreversible monotonous production variation in Eq. (16). Therefore, we can prove that R controls the transition between FU and FE theoretically.

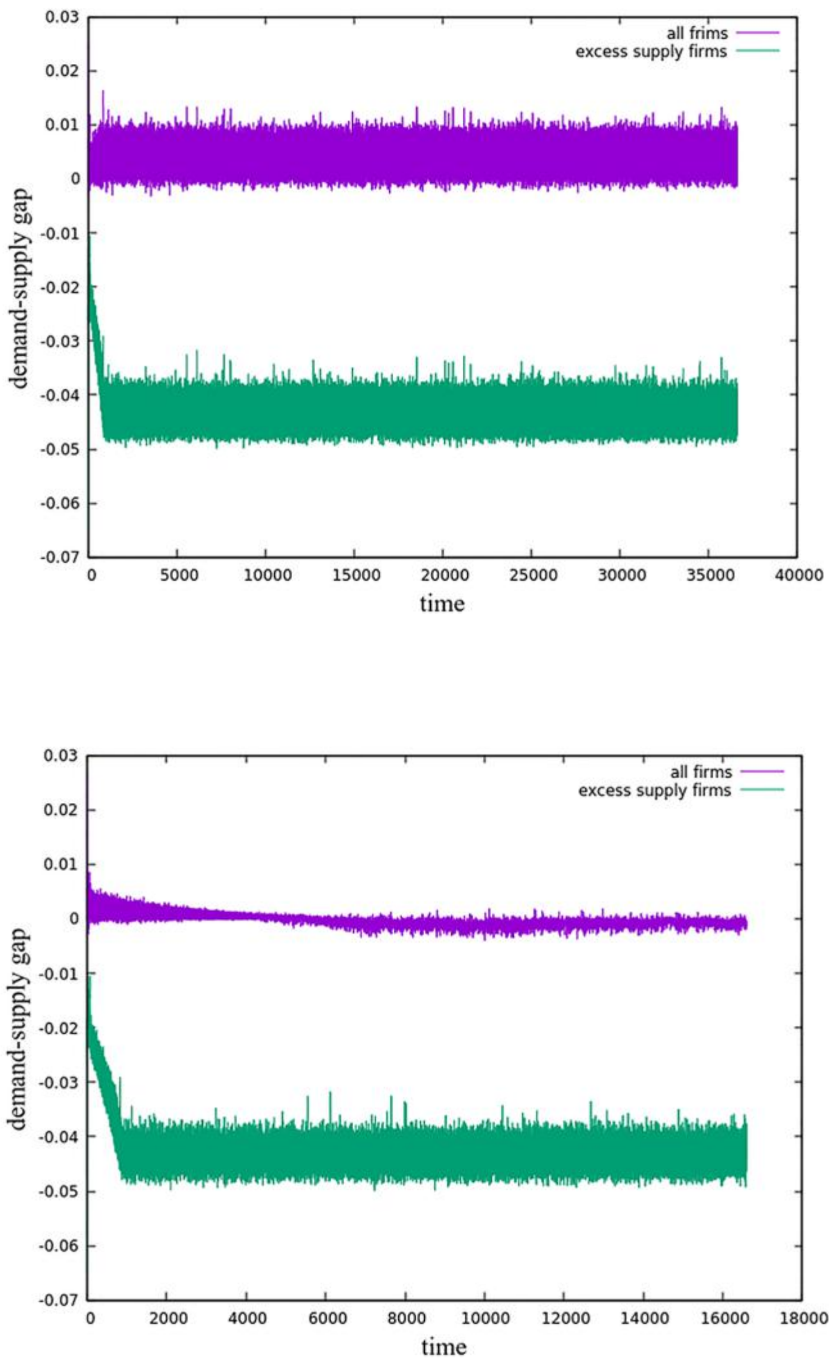


Figure 3.1 The demand-supply gap variation over time for all firms N and for the N_2 firms with excess supply, from top to bottom respectively, (Top) in FE phase, for R=1.7, Θ=20. (Bottom) in FU phase, for R=0.6, Θ=20. In both cases, the demand-supply gap of the subgroup composed of N_2 oversupplying firms is significantly larger in absolute value than the gap in the whole economy.

3. 3 Theoretical Analysis on Default Threshold

In the discussion of control parameter R, we deliberately set Θ to be infinity. In this section, we discuss the phase transition by setting a finite Θ. A finite Θ can bring two consequences, i.e unemployment due to default firms, and debt propagation due to bankruptcy/revival processes. When $R<R_c$, the unemployment is reinforced by the unemployment events controlled by Θ, hence no doubt that the tendency for unemployment is dominating. As a result the FU phase becomes the only phase when $R<R_c$. On the other hand, when $R>R_c$, the unemployment effect by Θ can be balanced by the positive employment tendency controlled by R. Therefore, the relative strength of the processes controlled by R and Θ can lead to different phases transitions so that the phase transitions from FE to EC, and from EC to RU can emerge.

The key to understand phase transition triggered by Θ, lies on the debt dynamics in the EC phase. Especially, when the debts of firms develop into specific pattern of firm collective behavior. Accordingly FE and RU can be treated as two extreme states beyond certain debt conditions which satisfies EC. The debt dynamics can be started with the calculation of the change of debt ratio $\Delta\Phi_i(t)=\Phi_i(t+\Delta t)-\Phi_i(t)$, over a very short time increment Δt, with $\Delta Y_i(t)=Y_i(t+\Delta t)-Y_i(t)$ and $\Delta\varepsilon_i(t)=\varepsilon_i(t+\Delta t)-\varepsilon_i(t)$ defined for firm i, which gives

$$\Delta\Phi_i(t) \approx -\Delta\varepsilon_i(t)/Y_i(t) - \Phi_i(t)(\Delta Y_i(t)/Y_i(t)). \tag{17}$$

In Eq. (17) , at the first stage a firm starts to bear a small debt, which gives a small positive Φ_i far below the threshold Θ, the second term $\Phi_i(\Delta Y_i/Y_i)$ in Eq. (17) can be ignored in determining $\Delta\Phi_i$. Therefore, at the initial stage of debt dynamics in a firm, i $\Delta\varepsilon_i<0$ is a necessary condition for a firm to bear more debt in future through the increment of Φ_i. Otherwise, the firm would never be possible to reach the bankruptcy threshold Θ. In a more realistic situation, we can interpret this as the bankruptcy of a firm is due to the long term loss in assets, whereas the temporary layoffs of labor does not lead to the final bankruptcy. Eq. (17) also tells us when Φ_i is very close to the default threshold, a layoff in labor could trigger the default of a firm regardless of the profit the firm makes. In the early stage of indebtedness, the loss of firm asset can be derived from Eq. (7), which equals to a negative profit ρ_i. Furthermore, the profit can be expressed by the price, production and demand of a firm with Eq. (9), which can be summarized as follows:

$$\Delta\varepsilon_i(t) = \begin{cases} p_i(t)D_i(t) - Y_i(t) & Y_i(t) > D_i(t) \\ (p_i(t) - \bar{p})Y_i(t) & Y_i(t) < D_i(t) \end{cases},$$

which can be transformed into the relationship between price setting and asset loss,

$$p_i(t) < \bar{p} \Rightarrow \Delta\varepsilon_i(t) < 0. \quad (18)$$

By now, we have derived the debt dynamics of a single firm. As the most important feature to the EC phase should be the collective debt behavior of a group of firms, we will deal with the relationship between different firms in the following.

First, we know for two different firms, from Eq. (2), the demand is negatively correlated with the price, which can be proved as follows:

$$\begin{aligned} & D_i(t) > D_j(t) \\ \Leftrightarrow & \frac{C_B(t)}{p_i(t)} \frac{e^{-\beta p_i(t)/\bar{p}(t)}}{Z(t)} > \frac{C_B(t)}{p_j(t)} \frac{e^{-\beta p_j(t)/\bar{p}(t)}}{Z(t)} \\ \Leftrightarrow & \frac{e^{-\beta p_i(t)/\bar{p}(t)}}{p_i(t)} > \frac{e^{-\beta p_j(t)/\bar{p}(t)}}{p_j(t)} \\ \Leftrightarrow & \frac{p_i(t)}{p_j(t)} > e^{\beta(p_j(t) - p_i(t))/\bar{p}(t)} \end{aligned}$$

Because $\beta > 0$, $\bar{p}(t) > 0$,it requires,

$$p_i(t) < p_j(t) \Leftrightarrow \frac{p_i(t)}{p_j(t)} > e^{\beta(p_j(t) - p_i(t))/\bar{p}(t)}.$$

Thus, $p_i(t) < p_j(t) \Leftrightarrow D_i(t) > D_j(t)$ holds.

This gives us a rigorous price-demand relationship among different firms, which gives a reverse ordering of demands to the ordering of prices in this economy,

$$p_i(t) < p_j(t) \Leftrightarrow D_i(t) > D_j(t), \forall i \neq j \;. \quad (19)$$

Eqs. (18-19) give us all the information to reason about the relationship between price and profit in a firm. For firms of positive profit $\Delta\varepsilon_i$>0 they need to set their price as $p_i(t) > \bar{p}$ at a cost of less demand from households than their counterpart with a price advantage by setting $p_i(t) < \bar{p}$. As a result of less demand, they are more likely in the process of firing labors so that they can maximize their assets to take the advantage of higher price settings. In this case, we can infer that for most of the firms with a small Φ_i the change rate of debt ratio is $\Delta\Phi_i$<0. Therefore, these firms actually are moving towards the opposite direction of default threshold and they shall be free of the bankruptcy risk.

For the other group of firms who set their prices as $p_i(t) < \overline{p}$, we know that they are the firms who are losing their asset based on Eqs. (18-19). On the other hand, because the low price will stimulate more demand, this situation usually indicates expansion of their production together with expanding the labor force. As a result, their asset will keep losing for a period until $\Phi_i(t)$ saturates at a maximum level. The reason for the saturation to occur is due to the adjustments in Eqs. (2,5). The firms will adjust their production and price, so that the demand and production can meet each other. The result is a shrinking demand-supply gap in general and it slows down the increase rate of $\Phi_i(t)$, i.e $\Delta(\Delta\Phi_i)<0$. Since firms in this group experience a period of continuous asset loss, they do have a bankrupt risk before they reached their maximum Φ_i.

To summarize the grouping of firms above, the unemployment effect controlled by the default threshold Θ can only be activate by a specific group of firms with bankrupt risks in order to trigger the transition to a crisis phase. To explicitly address the target group of firms, we define a subgroup of firms $\Lambda=\{i \mid \Delta\varepsilon_i<0, \Delta Y_i>0, \Delta\Phi_i>0, \Phi_i>0\}$. This subgroup includes firms satisfying two conditions, $p_i(t) < \overline{p}$ and $D_i(t)>Y_i(t)$. In fact, in the following part of this section, we will focus on the dynamics of collective debt behavior of this subgroup in terms of their emerging pattern of debt ratio cluster. Specifically, we will use a decomposition approach and show that the evolution of this collective behavior of firm debts can be decomposed into two independent process, i.e. a dynamic irreversible clustering process and a randomly fluctuating process. In fact, the interaction between Θ and the growing cluster with similar debt ratios is the key precondition for the system to experience the transition to a crisis phase. In the following, we will show both the physical dynamical process in mathematical derivation and its economic interpretation of this physical evolution.

In order to understand the clustering behavior, firstly, we examine the collective behavior of pricing dynamics of firms with the distribution of prices in the whole economy. In fact, we will see later the root of the clustering in debt ratios is from the pricing mechanism which leads to the clustering in the economy. We will show that, with inflation control, the price distribution of all the firms will converge into cluster around the market average price $\overline{p}$ as follows.

First, from Eq. (3), we know that,

$$\overline{p}(t)=\frac{\sum_i p_i(t)Y_i(t)}{\sum_i Y_i(t)}\geq\frac{\sum_i p_{\min}(t)Y_i(t)}{\sum_i Y_i(t)}=p_{\min}(t).$$

In the symmetrical rules, we can prove that $\overline{p}(t)\leq p_{\max}(t)$.

Furthermore, it is indicated in Eqs. (4-5),

$$p_{\min}(t)\leq\overline{p}(t)\Rightarrow p_{\min}(t+1)\geq p_{\min}(t),$$

$$p_{\max}(t)\geq\overline{p}(t)\Rightarrow p_{\max}(t+1)\leq p_{\max}(t),$$

Combining the above two equations, we have

$$p_{\max}(t+1)-p_{\min}(t+1)\leq p_{\max}(t)-p_{\min}(t).$$

This completes the proof of the price convergence theorem:

$$p_{\max}(t+1)-p_{\min}(t+1)\leq p_{\max}(t)-p_{\min}(t),\text{ with}$$

$$p_{\min}(t)=\min\{p_i(t)\mid\forall i\},p_{\max}(t)=\max\{p_i(t)\mid\forall i\}. \quad (20)$$

Eq. (20) tells that, a cluster of prices will emerge in the economy. Moreover, combining Eqs. (19-20), we can further prove that the demands for firms also converge to a cluster given a good period of the economy without any crisis occurrence, i.e. a temporal full employment before a crisis. With these two clustering behavior, we know that for all the firms in the group Λ who developed their maximum size right before the crisis, the size growth is approaching a saturation level thus the growth rate $\Delta Y_i/Y_i\approx u/Y_i\approx const\geq 0$, for $i\in\Lambda$. In fact, ΔY_i decreases linearly with the size Y_i in the whole economy until the cluster in which ΔY_i fluctuates around 0, which presents in the largest firms, see Fig. 3.2. Especially for the large firms approaching its maximum size in Y_i, we will prove that they are actually experiencing a clustering process given that they are a subgroup of firms with approximately the same value of $\Delta Y_i/Y_i$. From the condition $\Delta Y_i/Y_i\approx const\geq 0$ and Eq. (17), we know that $\Delta\Phi_i(t)$ will decreases as debt $\Phi_i(t)$ increases, and this property leads to the collective behavior which is

$$\Phi_i(t)>\Phi_j(t)\Rightarrow\Delta\Phi_i(t)<\Delta\Phi_j(t)\Rightarrow\Phi_i(t+1)-\Phi_j(t+1)<\Phi_i(t)-\Phi_j(t).$$

Interestingly, this physical property can be interpreted in the economic content as diminishing marginal debt ratio, for an analogy to the economic concept of diminishing marginal returns (Samuelson and Nordhaus (2001)). Consequently, $\Phi_i(t)$ will finally saturate and stop its growth. With the diminishing marginal debt ratio of individual firm, we can further prove that the collective clustering behavior of firms with another concept called diminishing debt ratio gap in a group of firms. To see this, firstly, we define debt ratio gap as the difference between the maximum and minimum $\Phi_i(t)$ in the group Λ, with $\Phi_{\max}(t) = \max\{\Phi_i(t) \mid i \in \Lambda\}$, and $\Phi_{\min}(t) = \min\{\Phi_i(t) \mid i \in \Lambda\}$. Assuming $\Phi_{\max}(t+1)=\Phi_i(t+1)$, $\Phi_{\min}(t+1)=\Phi_j(t+1)$, the gap of debt ratios follows

$$\Phi_{\max}(t+1) - \Phi_{\min}(t+1) < \Phi_i(t) - \Phi_j(t) \le \Phi_{\max}(t) - \Phi_{\min}(t). \tag{21}$$

Eq. (21) shows the diminishing gap of debt ratios in subgroup Λ in general as one type of collective behavior of the firms. Especially, this irreversible diminishing process creates the order in the form of clusters in subgroups inside the "random" economy. The result is the organization of growing cluster of firms within close distance in terms of Φ_i. As the cluster is given space to grow into more ordered group with more firms, this starts to drive the system into the boundary of transition to EC. The criticality of the system is reached in the self-organization process of firm debt cluster. Besides the clustering, because debt ratios in group Λ are increasing based on the definition, the debt dynamics of firms in group Λ can be considered as a superposition of a decelerating motion towards the default threshold before the maximum indebtedness, together with a contraction motion of the firms.

In one extreme picture of the collective motion above, we need to mention that even the cluster reaches its maximum, it does not mean that for every individual firm in Λ, the debt ratio also reaches its maximum and becomes static. In fact, each firm is still doing a random motion ceaselessly which can be described as a fluctuating process around the saturation level of the cluster. The source of the randomness inside the individual debt ratio is from the stochastic factor in the price update in Eqs. (4-5). To illustrate in details, the p_i fluctuating around $\overline{p}$ causes the variation in firm assets $\Delta\varepsilon_i$, which can induce the non-stop random motion of the debt ratio $\Phi_i(t)$. Therefore, the firms in the economy are always doing a Brownian motion because Eq. (17) is transformed into a dynamic equation of Langevin type approximately. Accordingly, the first term in Eq. (17) corresponds to the noise term in Langevin equation and the second terms corresponds to the drag term in the Langevin equation.

As a summary, the debt dynamics of firms can be decomposed into two independent motions: the spontaneous travelling cluster motion and the Brownian motion. In the next step, we will show that the degree of order established in a self-organization process is the necessary condition to drive the system to the phase criticality. The default threshold Θ controls the tolerance for the order to persist. As in the EC phase, the tolerance for the cluster formation is the precondition of crisis occurrence. And the

Brownian motion serves as the trigger of the crisis once if the precondition gets matured as the cluster gains enough order and gets close enough to the threshold. The result is a cascade of bankruptcy of the firms in the cluster as if the cluster of firms is dragged across the default threshold. As a reference, this kind of instability problem is actually very similar to the sudden crash in the stock market (see Gao and Chen (2016) as an example).

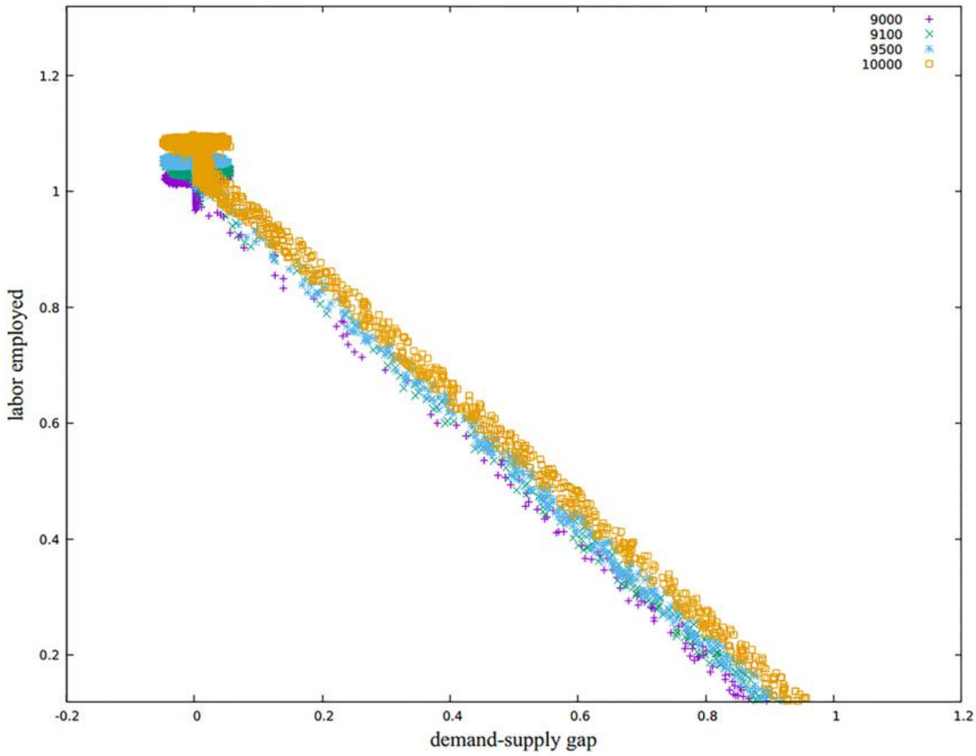


Figure 3.2 The distribution of firms based on the relationship between labor employed by each firm and the demand-supply gap of each firm at time step 9000, 9100, 9500 and 10000 ahead of a crisis (around time step 10020). Each dot represents one firm. The relationship is constant linear until a high level of labor force is reached in a cluster of firms .

As the last step of the theoretical analysis, the question how the default threshold Θ controls the tolerance for the order persistence will be addressed. To understand how much tolerance Θ controls for the order in debt cluster, we first examine the possible range of debt ratio $\Phi_i(t)$ can cover. To find the maximum $\Phi_i(t)$, by setting $\Delta\Phi_i(t)$=0 in Eq. (17) , we have

$$\Phi_i(t) = -\Delta\varepsilon_i(t) / \Delta Y_i(t) = -(p_i(t) - \overline{p})Y_i(t) / \Delta Y_i(t) . \quad (22)$$

The maximum of $\Phi_i(t)$ is bounded by two different cases given different tolerance conditions as;.

1. A lower bound that firms can develop the cluster with their maximum debt ratio value $u(t)>>0$, $\Delta Y_i(t)=\eta_+(D_i(t) - Y_i(t))$.

2. An upper bound that the cluster of firms can asymptotically approach (travel) as the limit of maximum debt ratio, $u(t)\approx 0$, $\Delta Y_i(t)=u(t)$.

The lower bound is ,

$$\tilde{\Phi}_i(t) = -(p_i(t) - \bar{p})Y_i(t)/(\eta_+(D_i(t) - Y_i(t))) \,. \tag{23}$$

The upper bound is,

$$\hat{\Phi}_i(t) = -(p_i(t) - \bar{p})Y_i(t)/u(t) \tag{24}$$

With $\tilde{\Phi}_i(t) < \hat{\Phi}_i(t)$, it can be inferred that for $\Phi_i(t)$ between the lower and upper bound, a firm has the potential to develop its maximum debt ratio. Basically, Θ represents the degree of tolerance for $\Phi_i(t)$ to asymptotically develop to its possible maximum value so that the individual firms in group Λ can form and maintain certain order. Depending on the tolerance for the order to emerge and last, Θ can be divided into three regions as: $\left[0, \min_{i,t}(\tilde{\Phi}_i(t))\right)$, $\left(\min_{i,t}(\tilde{\Phi}_i(t)), \max_{i,t}(\hat{\Phi}_i(t))\right)$, $\left(\max_{i,t}(\hat{\Phi}_i(t)), +\infty\right)$, which correspond to region of tolerance for partially developed order, tolerance for fully developed order temporarily, and tolerance for fully developed order permanently, respectively.

1. $\Theta \in \left(\max_{i,t}(\hat{\Phi}_i(t)), +\infty\right)$

In this scope, Θ is set that almost every firm can reach their possible maximum debt ratio without risk in bankruptcy. The maximum order of cluster can be developed and maintain permanently in whatever production variation. Because the maximum order is maintained, it is no difference with FE phase in the extreme $\Theta\to\infty$, $R>1$ situation.

2. $\Theta \in \left(\min_{i,t}(\tilde{\Phi}_i(t)), \max_{i,t}(\hat{\Phi}_i(t))\right)$

In this scope, Θ gives certain space for the firms to develop to their maximum debt ratio under certain asymptotic conditions of production variation. The temporary order is established in the economy by a subgroup of deeply indebted firms as more and more firms develop their maximum debt ratio and form a cluster together. The formed order by the subgroup of firms would be still evolving and growing as long as the cluster does not hit the default threshold. In this situation, the random default events by firms beyond the organization of cluster are absorbed by the full employment equilibrium determined by $R>R_c$. However, while the cluster of the indebted firms moves close to the default threshold, the order of the cluster organization can be destroyed by sudden chain reaction of the defaults of every firm in the cluster. Specifically, the default of one firm in the cluster will spread the influence and deepen the debts of other firms in the cluster, which triggers the defaults of more firms in the same cluster. This process will repeat itself, which is the cascade of defaults events occurs in the whole cluster. The appearing sudden crisis is the result of this sudden destruction of the hidden order in a cluster of a subgroup of firms in the economy. The established order in the cluster is only allowed to exist temporarily with restriction to certain asymptotic evolving process within the default threshold. After the order is destroyed, the economy is reset to the randomness without order and attracted by the attractor controlled by $R>R_c$ again. At the same time, new cluster of firms emerges and new order is slowly evolving in the economy again, until enough order is reestablished and thus the condition for next endogenous crisis occurrence is satisfied.

3. $\Theta \in \left[0, \min_{i,t}(\widetilde{\Phi}_i(t))\right)$

In this scope, Θ limits the cluster size before it is fully developed, thus the default events are constantly and uniformly without much order can be established in any any group of firms. For an individual firm, it can not reach his maximum debt ratio before it hits the line of default threshold. As a result, the constant unemployment ensures that the condition of $u(t)\approx 0$ will never be satisfied. From Eqs. (10,17), a small $\Phi_i(t)$ controlled by Θ, will result a non-diminishing $\Delta\Phi_i(t)$, which indicates firms are not able to be close enough in their debt ratios and no ordered cluster can be formed before their bankruptcy. For $\sum_i (Y_i(t)-Y_i(0)) \propto \Theta$ (because of $\sum_t \Delta Y_i(t) \propto \Theta, \forall i \in \Lambda$), RU phase presents as a relaxation process to one of the infinite equilibrium states smoothly controlled by Θ.

We conduct numerical validation to the theoretical analysis based on the self-organization and ordered cluster above. To show the establishment of order in a group of firms to form the cluster, it is equivalent to the observation of irreversible diminishing process of the debt ratio gap among a subgroup of indebted firms as defined in Λ. In our the numerical validation, the target group of firms are selected and observed based on the conditions in Λ. The theoretical expectation is from Eq. (21), where the debt ratio gap $\Phi_{max}(t)$-$\Phi_{min}(t)$ of this selected group of firms should diminish to zero to establish enough order in the group. And a cluster of firms with similar debt ratios would emerge ahead of the crisis. Fig. 3.3 shows the simulation result. As we can see, the diminishing gap represents the order in the cluster. The established order right before the crisis can be observed, which justifies ordered cluster formation as the precondition for crisis occurrences.

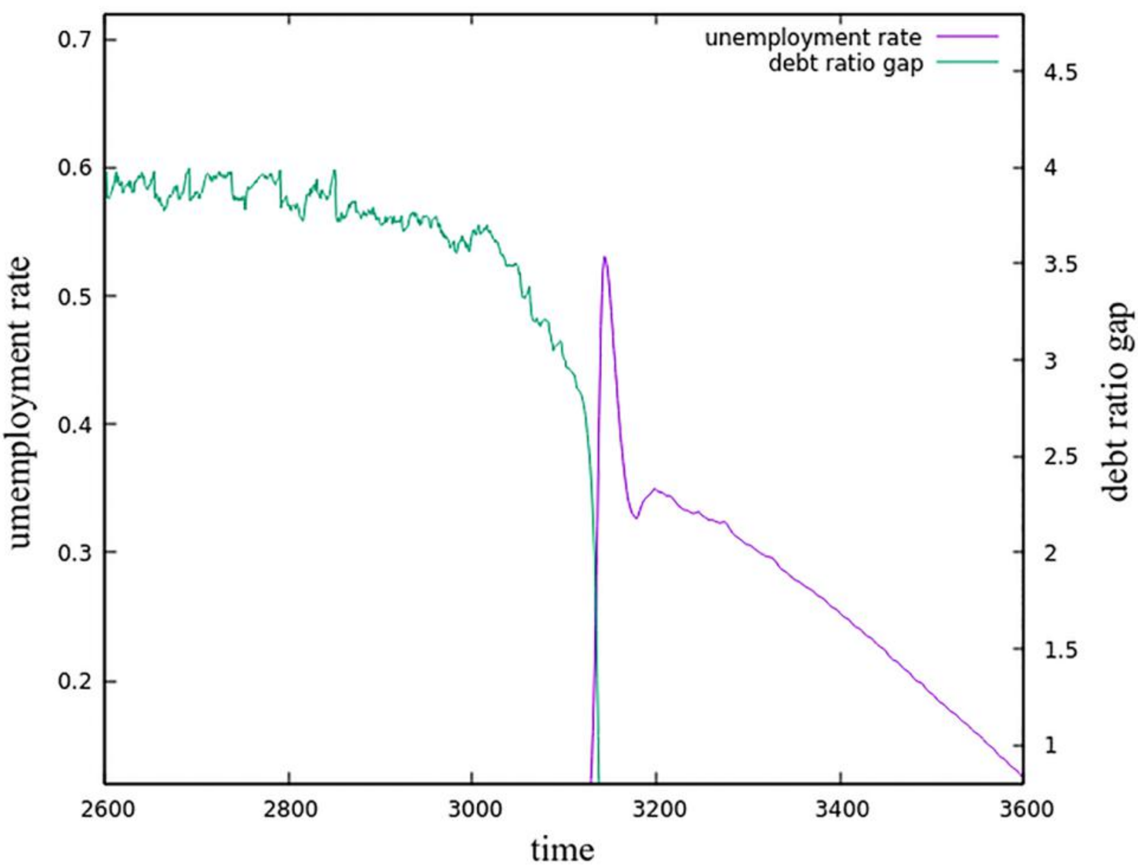


Figure 3.3 The evolution of debt ratio gap (right axis) in a subgroup of firms with positive debt ratios in phase EC for R=1.7, Θ=5. The debt ratio gap is diminishing ahead of an occurrence of a crisis as a spike in unemployment rate (left axis) is triggered.

3.4 Summary

In this chapter, we focus on the theoretical analysis of crisis occurrence in the basic model. In our analysis with self-organization and order formation among a group of agents to push the system to the criticality, we refers to those physics approaches in non-linear deterministic systems (V.G. Ivancevic and T.T. Ivancevic (2008)) and non-equilibrium phase transitions (Henkel and Pleimling, 2008). Regarding to the clustering of agents, some similar ideas are available such as in synergetics (Haken (1978,1983)), or in microscopic simulation study of collective behavior and/or crisis in the socioeconomic systems (Bouchaud (2013), Cheung (2011)). In particular, the theoretical analysis in this work confirms that the effectiveness of using the drift and random walk (Gualdi et al. (2015b)) of the physical models to explain the crisis mechanism. What's more, our method realized the economic contents of those physical processes. For example, the drift in biased random walk, has its economic meaning in the collective cluster indebtedness which is an irreversible process equivalent to a drift in a random walk.

The minimal ABM, and the phase transition mechanism illustrated in this chapter, only serves as a basic model for the following more complicated factor analysis. Nevertheless, this minimal model can still offer the insights on "endogenous nature of economic slumps and recessions" (Lux and Westerhoff (2009)) without losing the tractability of the economic world.

The clustering effect of the firms in crisis occurrence and the boundary conditions for the phase arrangement are the most important insights in this chapter, which will also help to understand the mechanisms or roles of the key factors in the next chapters.

Chapter

4. Key Socioeconomic Factors of Crisis

In this chapter, we will address the crisis-related issues in an economy in a series of key factor analyses. The key factors will cover every components of this artificial economy. In details, we will discuss the firm strategy and adaptation, the household debt and saving behavior, the bank credit supply and government tax policy, and the labor market in a depopulation scenario. Each of these factor analyses is conducted with an extension/modification of the original model Mark0. And in each extension of the model, we further investigate the relationship between the key factor and the crisis occurrence with multiple scenarios. In this way, our intention is to build a systematic approach to integrate the previous discussions of of crises in the literature of different spheres into a common platform, so that we can compare and elaborate the previous unsolved debates and arguments with the same criteria and the same basic configurations of one model.

The objective for this chapter is to utilized the simulation of various versions of extended models built on Mark0, and to utilize the theoretical clustering mechanism of crisis occurrence in the basic model of Mark0 as in chapter three to discuss the key factors which are mostly relating to the potential crisis occurrence and the system instability risk. Our final goal is to provide key variable for monitoring the risk of crises during their development, alert the possible new crisis occurrence, recommend the remedy for crises, develop crisis control policy, and even prepare beforehand for potential new type of crises through simulation and application of the basic phase transition and crisis occurrence mechanism. By applying the basic model and its mechanism in several more practical scenarios of the real world, we will add more evidence from both the theoretical and simulation perspective in hope to build a sustainable socioeconomic system in future.

4. 1 Household Debt and Crisis

4. 1. 1 Background

Household debt has increased substantially in developed countries, in terms of a ratio to household incomes (Settlements (2004)). It has also been pointed out the explosive increase in household debt has caused a sustainable recovery problem as in Moseley(2013). This increase in household debt has been considered as a potential risk in the stability of an economy. For example, the relationship between increase in debts and a subsequent fall in consumption during the 1980s has been pointed out as a reason for a deeper and longer recession (King (1994)). Furthermore, debt can be a reason of ‘a disruptive financial cycle’ which causes the economy undergoes a path ‘between credit-fulled booms and default-driven busts’ (Cecchetti et al. (2011)). However, household debt also has good side. For example, there is common belief that, a rise in household debt can boost aggregate demand as long as debts are incurred at a higher rate than they are repaid (Insel (2017)). The household debt can also increase the consumption of the low wages for the increment in the system’s actual output (Barba and Pivett (2009)). Therefore, the relationship between household indebtedness and consumption volatility has been proposed as an important topic for the macroeconomics (Hunt (2015)). For the policy implications, Andersen et al. (2016) and Abildgren (2018) discussed the household leverage in Denmark during the financial crisis and the Great Depression. In Andersen et al. (2016), their recommendation are to pay special attention on the rapid increase in household borrowing which issues the signal of future relapse in consumption. And in Abildgren (2018), it argues the household debt level is not only related to financial instability but also important to the macroeconomic instability, and the macroprudential policy is needed to regulate it.

This study aims at study the effect of consumption variation and indebtedness on the stability of an economy. We apply an existing agent-based macroeconomic model to study the potential crisis induced by consumption propensity and indebtedness of the household. In particular, we simulate the the effect of the precautionary savings on the firm default rate, which is usually taken by the household to repay the debts, as the similar spirit in Lindquist (2012) states that “households’ debt servicing income may cause a ‘below steady state’ fall in consumption that threatens financial stability through firms’ debt servicing capacity”.

4.1.2 Model Modification

To understand the influence of the dynamic household consumption behavior on the economic stability relating to debts, we study the dynamic relationship of consumption level and the shocks to the employment in an economy. For the consumption variation, we adjust the consumption rate c in Eq. (1), for $c < 1$ represents a saving action and $c > 1$ represents a borrowing action. We use a sinusoidal function to simulate the variation of c, as shown in Fig. 4.1. The reason of a sinusoidal function for this task is because, first, we want a slow smooth variation to exclude unwanted shocks induced by the function itself other than by the debt accumulation process in concerns. In addition, a periodic sinusoidal function can represents the cyclic pattern of debt observed in empirical investigations (Barba and Pivett (2009), Covas and Den Haan (2011)). For the states of the economy, we choose two typical cases, of which one represents a stable economy and another represents an unstable economy. In this way, we can investigate the complicated relationship between consumption behavior and economic shocks with a simple agent-based model. In simulation, we have 5000 firms as heterogeneous agents interacting with each other and also hire labor from the household.

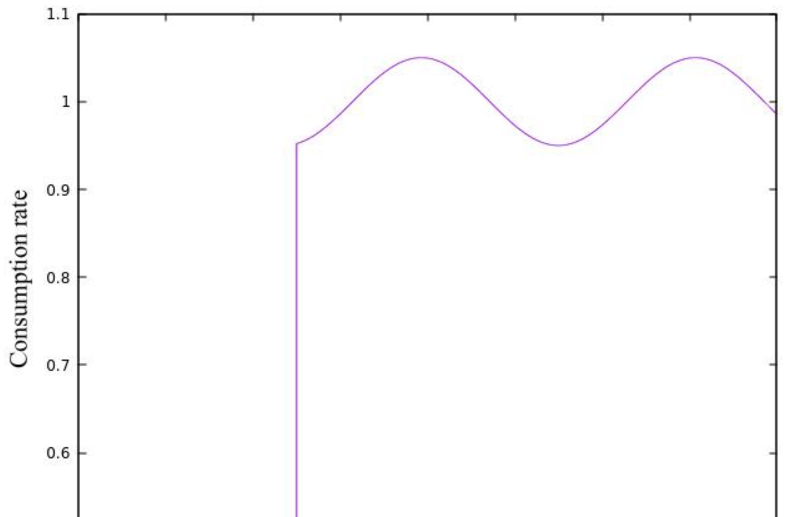


Figure 4.1 Sinusoidal variation in consumption rate *c*. For the first 25000 time steps, *c* is set as 0.5 for the model to settle in different economic states. Then *c* is set as a sinusoidal function in the form of $c=a+0.05*\sin(2\pi t/30000)$. *a* starts from 0.94 (no borrowing) to 1.06 (fully borrowing) so that between the two extreme cases the variation in *c* represents different borrowing propensities of the household.

According to the average consumption level comparing with the current income and savings of the households, which is determined in the consumption propensity variation in the form of $c=a+0.05*\sin(2\pi t/30000)$, the influence of household debt is investigated under different consumption scenarios.

Scenario	**Parameter Setting**
No borrowing	$a<0.95$
Minor borrowing	$0.95<a<1$
Equal borrowing and saving	$a=1$
Major borrowing	$1<a<1.05$
Fully borrowing	$a>1.05$

Table 4.1 Household debt scenarios and the corresponding parameter settings given that the consumption propensity $c=a+0.05*\sin(2\pi t/30000)$.

In Table 4.1, the scenarios of household debt based on the borrowing period are specified with the corresponding range in the parameter *a*. In particular, the borrowing behavior of household is measured by the proportion of the borrowing period in the household. The borrowing behavior becomes dominant as the period is prolonged. To a very extreme situation, the household might count on borrowing and debt to maintain their living standard and the debt will be accumulated to a very high level. These scenario settings can help to understand the different borrowing behavior and status of household debts and their relationship with the economic instability and crisis occurrence. One of the strength of this model in this issue is that it can simulate the same borrowing behavior or the status of household debt in different phase of the economy and provide investigations correlating with the phase of the economy which could be considered as the control of the basic economic states. In this way, the impacts of the household debts could be investigated case by case so that the lines of the positive and negative impacts could possibly be drawn.

4.1.3 Results

4.1.3.1 No Borrowing

This case represents an extremely conservative economy. Also, this case serves as the the baseline scenario of an economy for later comparison of the impact of household debts. Two phases, one stable phase in RU and one unstable phase in EC are set for investigations of the relationship between the household debts and the economic stability. The results shown in Fig. 4.2 represent the two phases in the economy where the negative household debts represents a long term saving custom in the economy. An interesting finding is that, when the household only consumes with what they earned and keeps savings for future, without borrowing from the bank, their increase in consumption rate, actually has little influence in a stable economy whereas it can increase the volatility of an unstable economy. This baseline scenario demonstrates the boost in consumption within the savings of the household brings no improvement in the stability of the economy. Instead, contrary to the common belief that the boost in demand could stabilize the economy, especially during a period of frequent crisis occurrence as in an endogenous phase, the boost in household consumption actually trades the stability of the economy with a higher production level in average from a higher demand of the household. This result indicates that the stable recovery from the crisis with high employment rate can not be achieved simultaneously by directing of the current available household savings into the market in the form of stimulus for a higher household consumption as well as higher demands. Other policies than consumption stimulus and demand elevation are also necessary to recover from a crisis phase. In this sense, to stabilize the economy, the effects of the different degrees of household debt become the interests of the following scenarios. In fact, as later we will see, the household debt indeed can stabilize an economy in a simulation, but with certain cost of future risks.

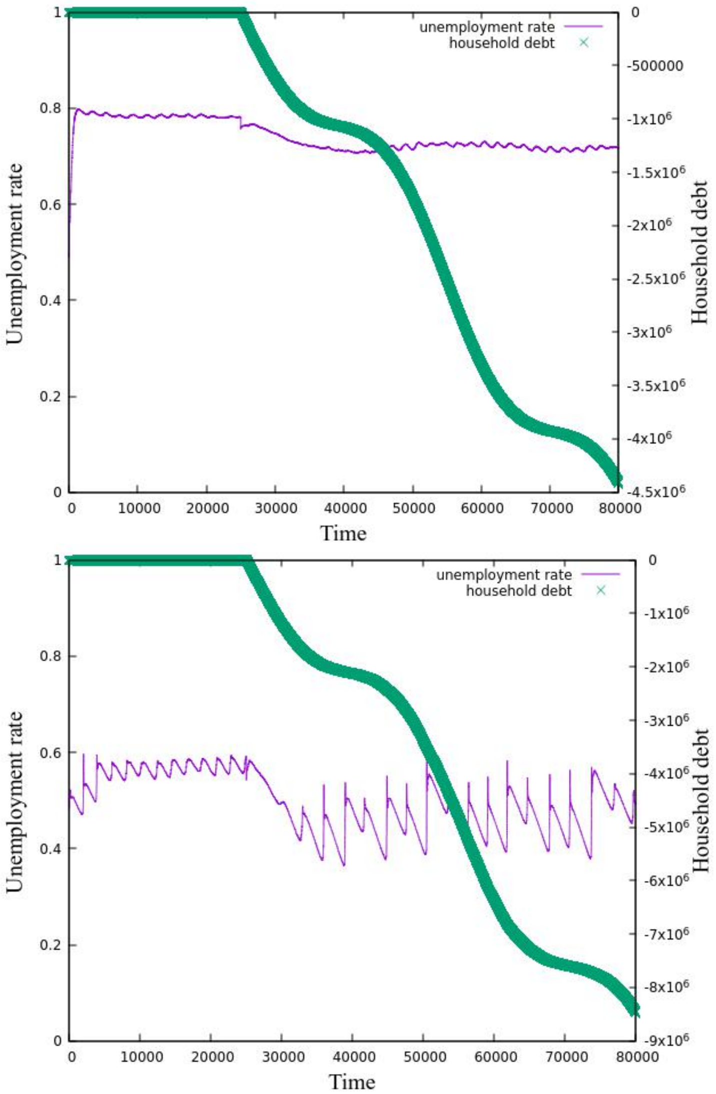


Figure 4.2 Consumption without borrowing by adjusting the consumption rate of the household always below 1. a=0.94, β=0, η_+=0.02, η_-=0.01, φ=0.1. (Top) In a stable economy Θ=3, the variation of c has basically no influence on the output of the economy. (Bottom) In an unstable economy Θ=8, the variation in c injects more volatility to the economy. The negative household debt implies a positive household savings.

4.1.3.2 Minor Borrowing

In setting a short period of household consumption to rely on borrowing in order to further increase the consumption, the household incurs the debts occasionally. In this scenario, the household shows a minor borrowing tendency in average as only a short period of the household consumption are depended on borrowing and debts. The impact of a minor borrowing on an economy is shown in Fig. 4.3**.** In this case, we can see that overall the the savings can compensate the debts in time on the household side though the household borrows during a short period. The minor borrowing represents a consumption behavior exceeding the maximum capacity only within a small fraction of whole lifetime. Contrary to the intuition that the small amount of borrowing would not bring shocks to the system , the results shows that in both stable and unstable phase of the economy, the minor borrowing behavior can only deteriorate the stability of the economy with crisis occurrence in a larger magnitude. However, the borrowing behavior seems to improve the employment by boosting the demand with the extra money from the borrowing temporarily, but at a cost that the subsequent fall in the consumption and the demand will trigger a large crisis occurrence as the improvement of employment is following by a bigger unemployment shock.

In particular, the minor borrowing behavior in an unstable phase of the economy seems to do more harms than in a stable economy. The reason is that the bigger crisis of the economy will be followed by a series of smaller crisis occurrence afterward. Equivalently, the minor borrowing behavior only magnifies certain crisis occurrence without stabilize the other crises comparing with the no borrowing scenario. As a result, the minor borrowing behavior is in generally not preferred if the system stability is the first priority in the policy making process.

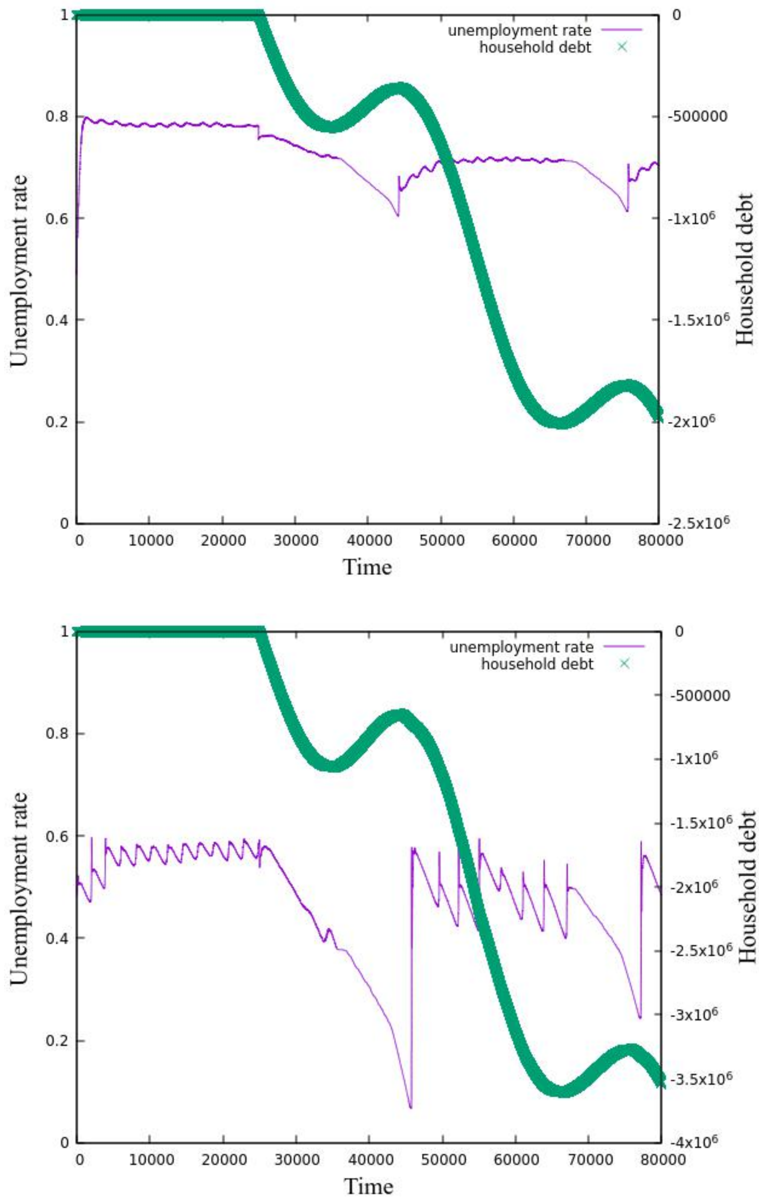


Figure 4.3 Consumption with a minor borrowing behavior by setting *a*=0.97, *β*=0*,* η_+=0.02, η_-=0.01, *φ*=0.1. (Top) With a minor borrowing, the variation in consumption rate induces small shocks to the previously stable economy for Θ=3. (Bottom) In a previously unstable economy Θ=8, the minor borrowing can increase employment temporarily as the good side, with a cost of large unemployment shocks following. The negative household debt implies an positive household savings.

4.1.3.3 Equal Borrowing and Saving

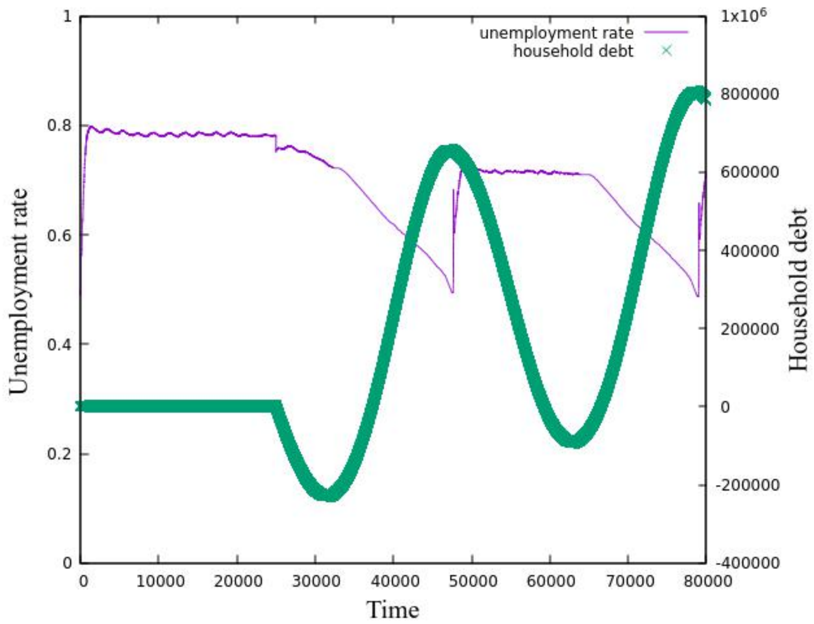
The impact of the borrowing behavior becomes complicated when the borrowing period is same as the saving period of the economy as shown in Fig. 4.4. In both of the stable and unstable economy, the pattern of an improved employment period followed by a big crisis occurrence can be observed. In details, the impacts are on three aspects.

First, the variation in consumption rate in equal saving and borrowing behavior actually improves the employment rate and prevents the small crisis occurrence, though only temporarily. In both phase of the economy, a period of decreasing unemployment can be observed. Therefore, the borrowing behavior can constantly boost demand and increase employment in the economy.

Second, the crisis occurrence in the form of the unemployment shock becomes larger in magnitude but less in frequency. As the high demand is only temporarily, the change in the behavior of the household from borrowing to saving can cause a big shock to the economy in the form of a big crisis of unemployment. However, different from the minor borrowing, the equal borrowing and saving scenario can prevent the smaller crises from occurrence in the whole period. Therefore, the frequency of crisis occurrence is largely reduced but both the previously stable and unstable economy are transformed into a similar phase as EC, with a cost of the risk of bigger scale crises to be triggered occasionally. In this scenario, the RU phase can also look the same as EC, and the crisis like behavior is induced by the significant borrowing behavior.

Third, in an unstable economy, enough borrowing can stabilize the economy. As in the unstable economy in Fig. 4.4, except the occurrence of a big crisis, the economy is steadily recovered after the crisis until a temporary full employment state is reached. Therefore, though the occurrence of crisis can not be eliminated, the previously unstable economy is now resilient to crisis occurrence, as even after the big unemployment shock (see the bottom figure after 60000 time steps in Fig. 4.4), the economy turns out to recover itself steadily.

To sum it up, the significant borrowing behavior of household is a double-edge sword to the economy. On one hand, it eliminates the small crises, reduces the frequency of crises and significant improves employment temporarily. On the other hand, it increases the risk of big crisis occurrence and transforms the stable RU economy into an unstable economy much similar to the EC phase.



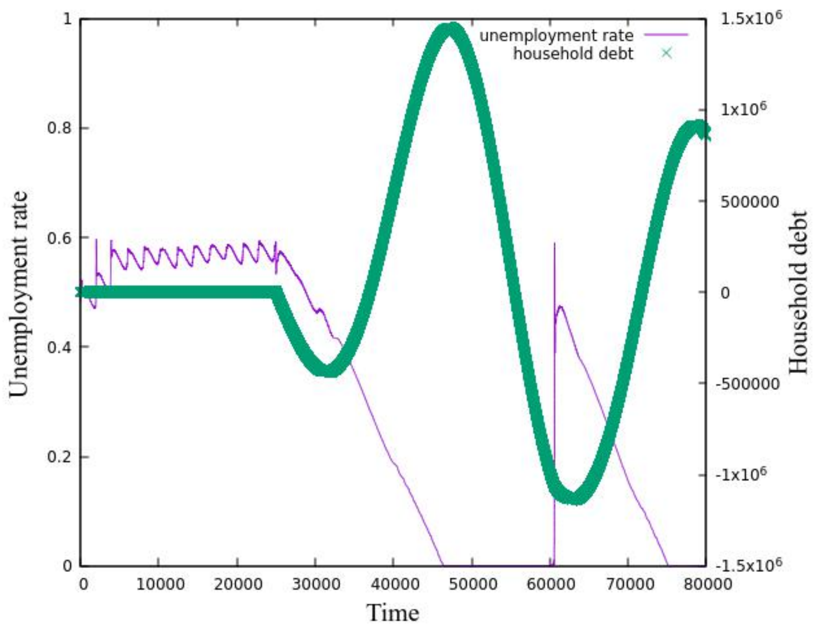


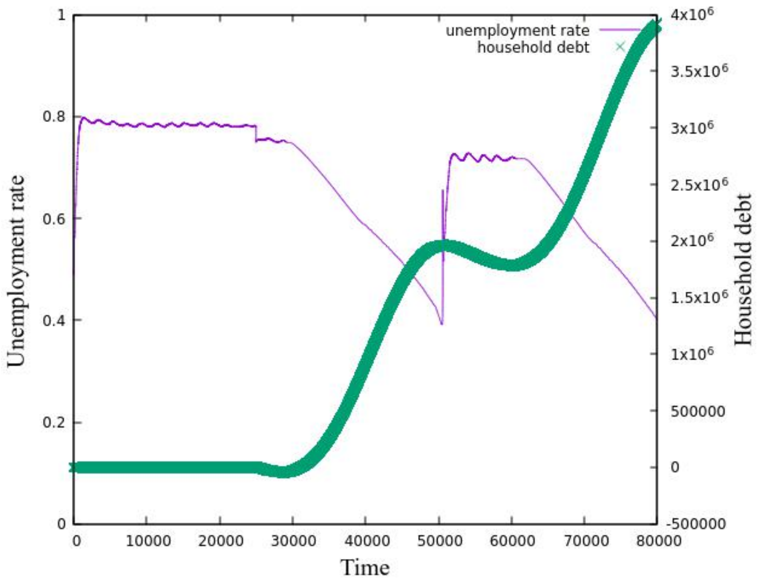
Figure 4.4 Consumption with equal borrowing and saving by setting a=1, β=0, η_+=0.02, η_-=0.01, φ=0.1. (Top) The variation in consumption induces temporary recovery of employment following by big shock of unemployment in a previously stable economy for Θ=3. (Right) In a previously unstable economy Θ=8, the variation in consumption with more borrowing can significantly stabilize the economy and reach a full employment state for a relative long time. However, the cost is an even larger unemployment shock which is still inevitable.

4.1.3.4 Major Borrowing

When an economy is prevailing with borrowing behavior and relying on the debts to boost their demands as coexisting with deep debts in a long period, an interesting transition process can be observed. In Fig. 4.5, we can observe a previously stable phase of an economy transits to an unstable phase which is very much alike of EC phase. On the other hand, we can also observe that the previously unstable economy transits to a stable full employment economy. The state of the economy seems to get flipped regarding to its stability comparing to the previous no borrowing scenario.

The discovered transition phenomenon demonstrates a nonlinear, complicated relationship existing between the household debt and the stability of the economy. Furthermore, this transition should raise more attention on the empirically calibration of the model with data to fit the parameters through identification of phases and their boundaries, which should be done with more careful examination of the household debt data together since the deeply indebted household can alter the stability of the economy if the baseline model to calibrate is one with assumptions of no borrowing. Nevertheless, the results in the above scenarios have shown that household debt is an important factor not only to the crisis occurrence in an economy but also to the phase transition process and the whole system instability.

To elaborate with more details, the household debt creates the crises in an economy through a distinct feedback pathway. With household debt, the demand level is lifted in average and the firms are in average profitable for more demand can raise the price of the products through the borrowing behavior. Previously the main cluster of firms are naturally travelling to the default threshold due to the firm debt accumulation and the self-organization of indebted firms. But during the period of household debt, the self-organization of cluster is offset to be away from the default threshold because the overall firm debts are transferred to household debt who gives a strong tendency of over consumption. However, once the household returns to its affordable consumption rate and restarts their savings, the cluster of firms experiences demand shocks which drag the whole cluster approaching the default threshold and trigger the cascade of bankruptcy very quickly. The absorption of firm debts by the household debts and the final release of the debts back to the firms have created the drift behavior of the indebted firm cluster which affects the phase transition process of the whole economy.



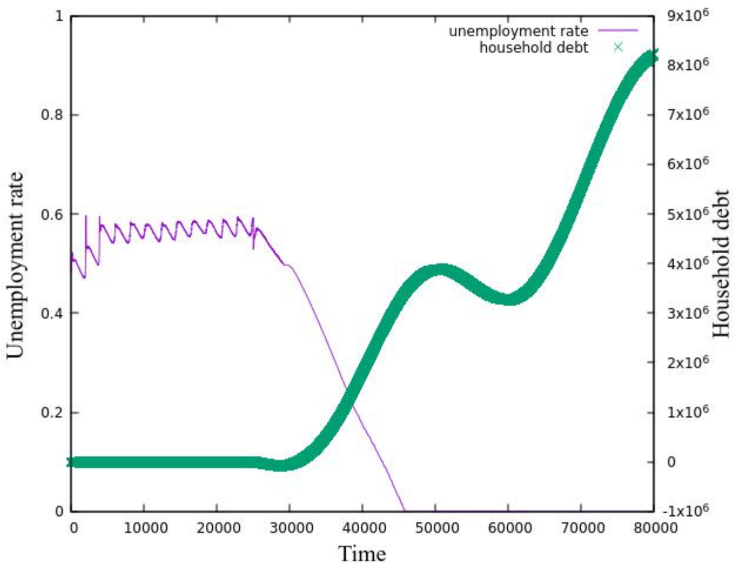


Figure 4.5 Consumption with a major borrowing behavior by setting a=1.03, β=0, η_+=0.02, η_-=0.01, φ=0.1. (Top) The variation in consumption rate with a major borrowing induces a periodic shock-recovery cycle of the economy in a previously stable economy for Θ=3. (Bottom) In a previously unstable economy Θ=8, however, the variation in consumption rate with a major borrowing can stabilize the economy into a full employment state. With a major borrowing, the household debt accumulates over time.

4.1.3.5 Fully Borrowing

In this scenario, the household is deeply indebted and the household accounts on this borrowing culture by spending money beforehand without any savings for each time step, the resulted economy becomes a full employment economy regardless of the stability in the original scenario with no borrowing, as shown in Fig.4.6. As long as the economy keeps borrowing and the household debt keeps increasing (which a similar situation might be found as in Japan), the economy stays in a full employment state given the condition that the household always consumes beyond its maximum capacity.

The results indicate this deep indebtedness of household could provide a buffer to economy to absorb any crisis occurrence. This is particular useful during a series of crisis occurrence and the following recessions. By allowing the household to keep borrowing for enough long period, both the instability and recession problems can be temporarily avoided. However, by doing in this way, the benefit does not come for free. As we can see, there exists the huge risk and potential crash of the economy with the cost if the credit supply to the household is suddenly cut off. An example might be the default of Greece in 2016. Household debt is like a sponge which can absorb most of the distributed risk into itself, at the cost of itself becomes a bomb of accumulated risk which can bring down the whole system if the household debt can not be released properly.

From the model perspective, the huge household debt can eliminate the endogenous crisis phase because it can raise the demand to a level that the cluster is formed in the profitable region which stays far away from the default threshold set by the bank, without the risk for the firms to hit the default threshold as a cluster. Again, this situation can only be sustained by continuous credit supply to the household. Any credit supply shock can trigger the crisis by dragging the cluster of the firms to approach the default threshold.

It is also needed to note that this scenario is only possible when the household does not go bankruptcy itself. Any household bankruptcy could break the balance in this scenario and induce crisis to the economy. The future work along this direction to add the household mechanism into the model could contribute to more realistic scenarios into the discussion of household debts and the crisis occurrence.

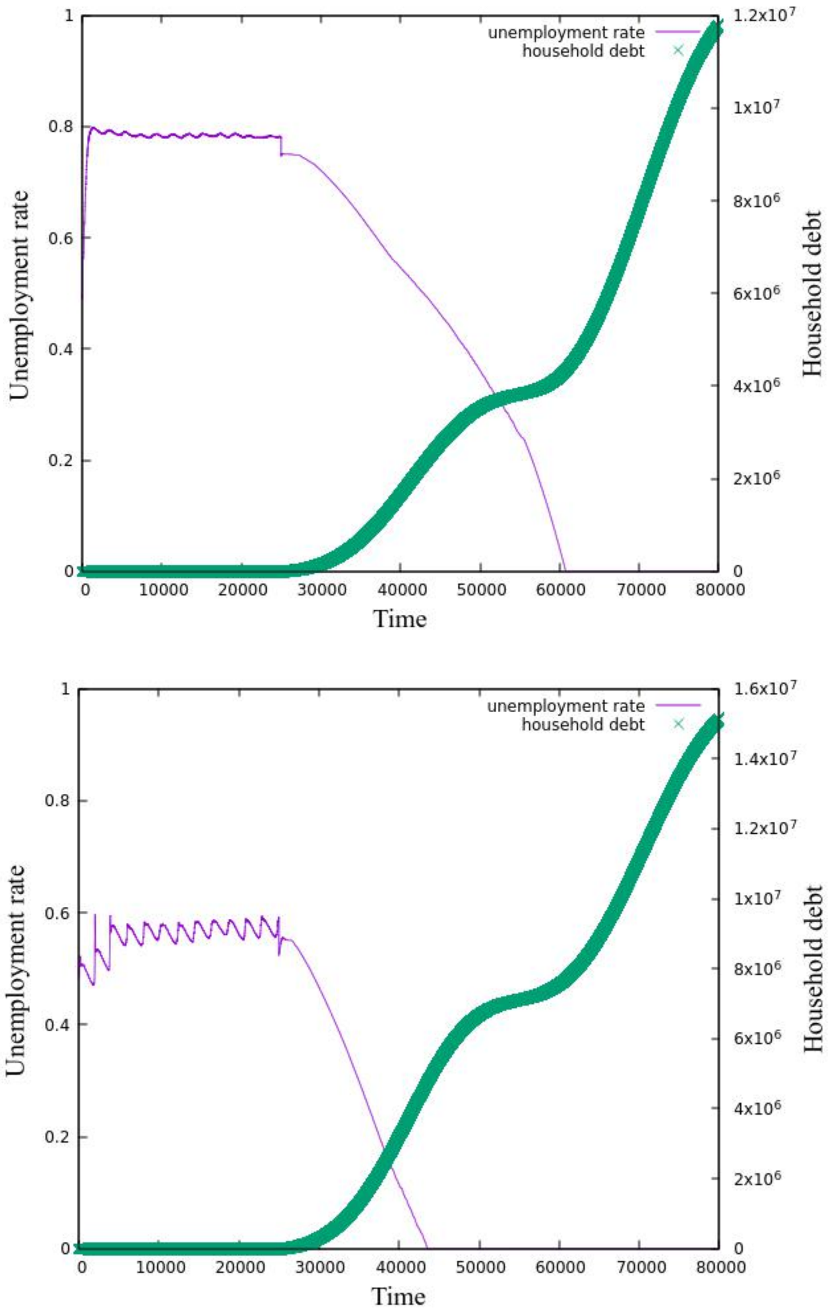


Figure 4.6 Consumption with fully borrowing by setting a=1.06, β=0, η_{+}=0.02, η_{-}=0.01, φ=0.1. (Top) the stable economy becomes to a full employment economy. (Bottom) The unstable economy transit to a full employment economy. Without savings, the household debt accumulates for all the time.

4.1.4 Discussion

4.1.4.1 Precautionary Saving Behavior and Crisis

In this section, we want to investigate more on the cause of the phase transition behind the borrowing behavior of household. To this end, we again utilize the basic crisis mechanism of cluster of indebted firms to explain what happened to the firms as the consumption level varies. In particular, we will focus our discussion in the transition from a stable economy to an unstable economy to elaborate the application of the basic mechanism which we derived as the irreversible self-organization process and the cluster formation condition in chapter 3.

In Fig. 4.7, the relationship between the incurred household debt and the default rate of firms are shown. From the top panel of Fig. 4.7, we can observe that the household saving has little influence on the firm default rate if the household plans the budget within the available savings and wages and no borrowing is incurred in the economy. It seems the phase of the economic system is robust to the variation of consumption variation as long as the households consume within their earning capability, which is indicated in the bankruptcy pattern of the firms in Fig. 4.7. On the other hand, a totally different situation can be observed when the households consume with the borrowed money, as shown in the bottom panel of Fig. 4.7. A minor borrowing behavior can reduce the bankruptcy rate of the firms during the borrowing period as shown in the zero household saving period in Fig. 4.7. However, by doing so, the cost is a shock to the firm default rate when the households start to return to their saving behavior. The shift from the borrowing to saving of household is called a precautionary saving behavior which can be considered as the households try to save money and pay back their previous debts. The finding indicates, the shock to the firm default rate is induced by a precautionary saving action even if the household is only in a minor borrowing scenario. The sudden high firm default rate event only happens at each time when the households switch their borrowing behavior to the saving behavior.

In the top panel of Fig.4.8, a similar pattern can be observed in the major borrowing case as we further confirm that the effect of the precautionary savings is persistent regardless of how much the household borrows. In the bottom panel of Fig. 4.8, we again show that the economy can be stable as a FE phase with fully borrowing when the precautionary saving behavior is absent.

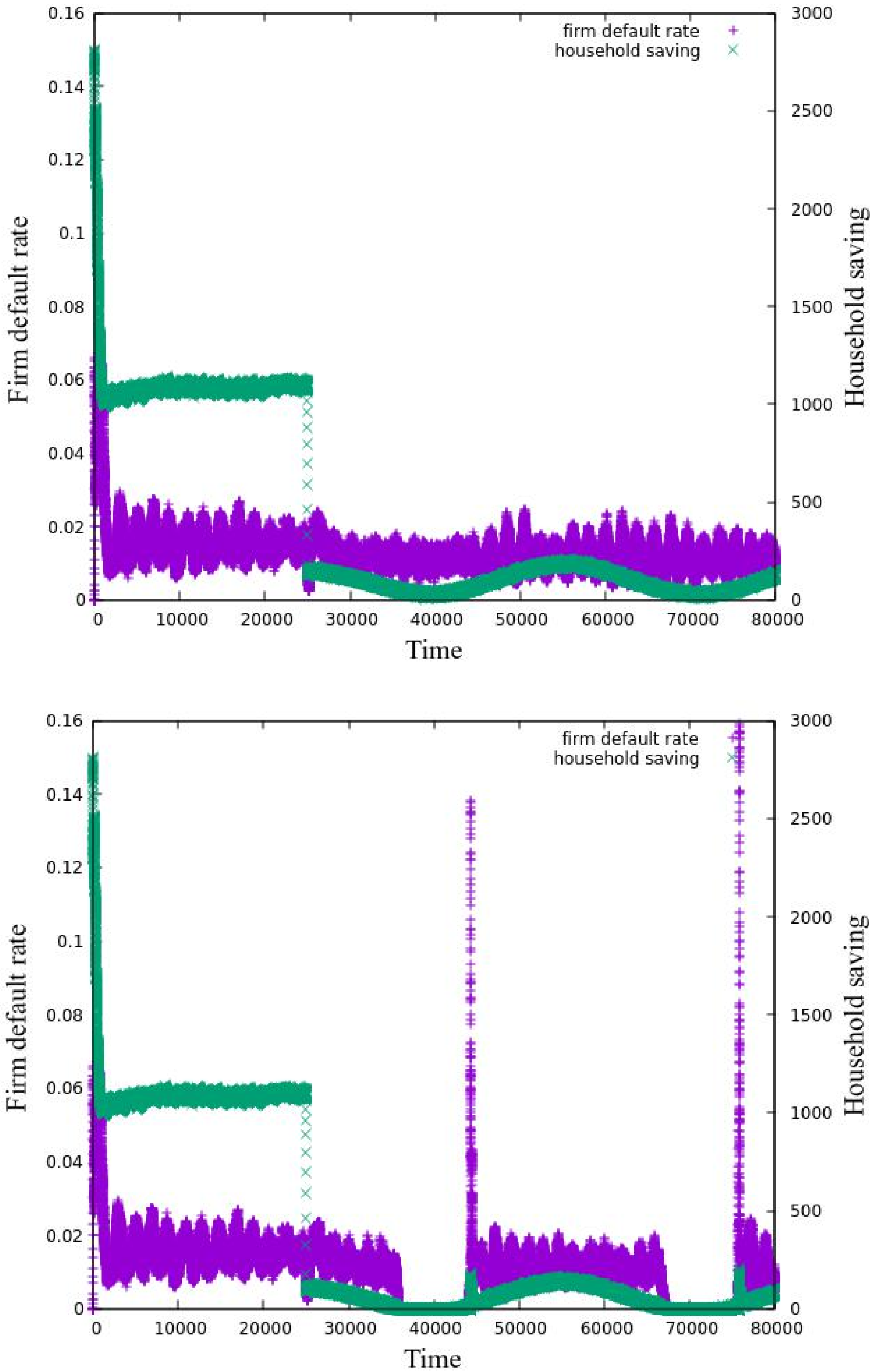


Figure 4.7 The relationship between firm default rate and household precautionary savings in the setting of a stable economy with Θ=3, β=0, η_+=0.02, η_-=0.01, φ=0.1. (Top) For a=0.94 with no borrowing, the variation in household saving has little impact on firm default rate. (Bottom) For a=0.97 with a minor borrowing, at each time spot when the household takes a precautionary saving action from the previous zero-saving state, the firm defaults rate experiences a shock.

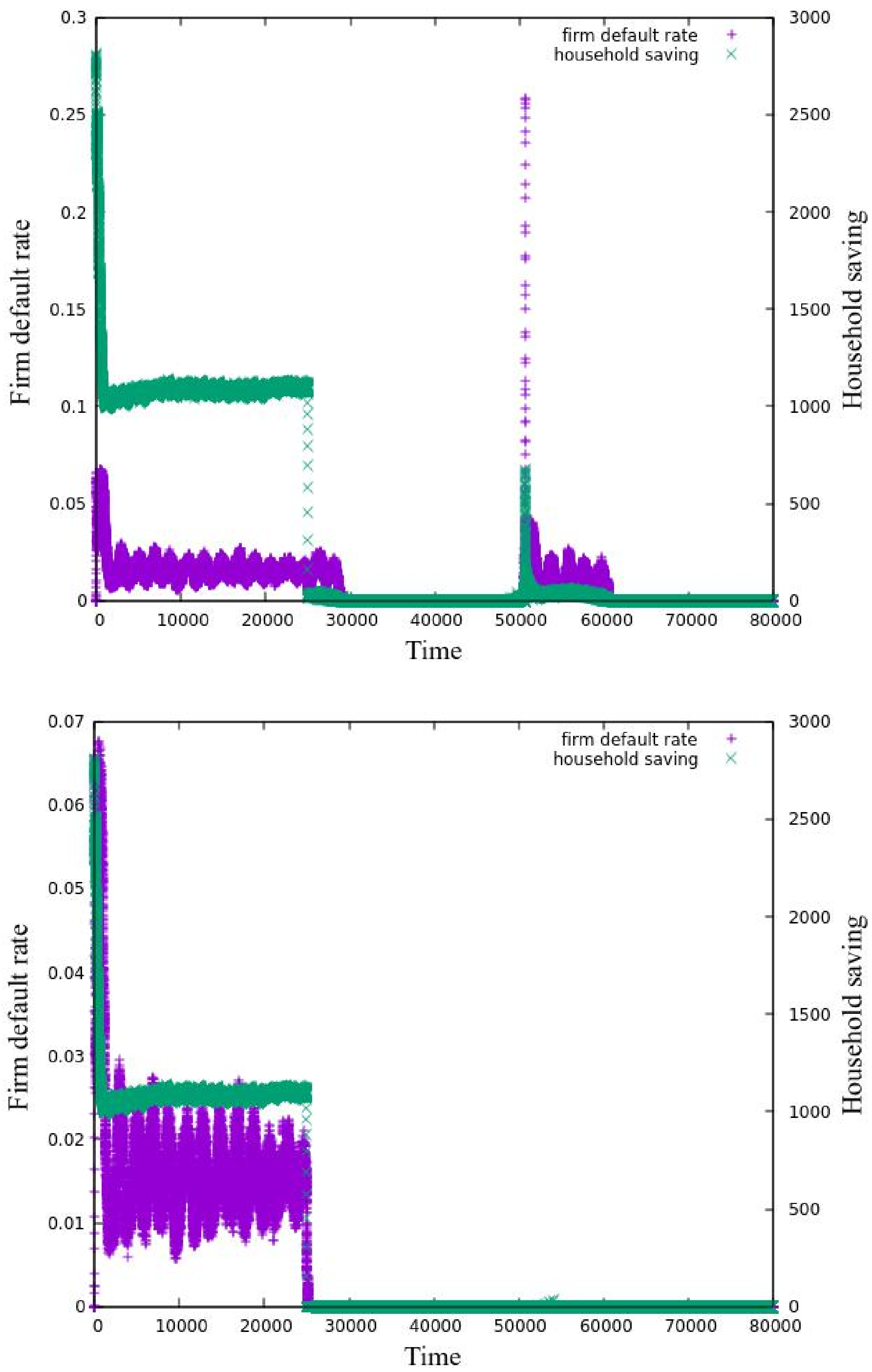


Figure 4.8 The relationship between firm default rate and household precautionary savings in the setting of a stable economy with $\Theta=3$, $\beta=0$, $\eta_+=0.02$, $\eta_-=0.01$, $\varphi=0.1$. (Top) For $a=1.03$ with a major borrowing, the firm defaults rate experiences a shock when a precautionary saving action is taken from the previously zero-saving state. (Bottom) For $a=1.06$ without savings, the economy is stable without shocks to firm default rate.

Now we want to elaborate the mechanism of the precautionary saving behavior as in the observations in Fig. 4.7 and Fig. 4.8. We adopt the concept of clustering of firms' debts as in chapter 3 for the following explanation.

As in the baseline scenario without borrowing behavior as shown in Fig. 4.2, the stable RU phase stays unchanged regardless of the consumption rate variation. This is because as long as the consumption rate is within their available budget which is composed by savings and wages, the increase in demand only has one-time effect as the savings can be spent at the current time which means the savings will be much less for the next time step. In other words, the households adapt and adjust their actually amount of money for each time step, which is within their budget. This negative feedback planning of households ensures the stable and balanced flow of money in a relative long period of time. Therefore, the demand level over a long period is continuously adjusted from the household side so the firms can also adapt the variation of the consumption propensity of the household stably. In this case, the cluster can not be formed as there is no condition for the long term accumulation by slowing down the bankruptcy of firms near the default threshold, which is the necessary condition to sustain the self-organization process of indebted firms.

On the other hand, when the borrowing behavior is incurred, the boost in demand is no longer an one-time effect but a long term accumulation process as long as the borrowing continues. The household side loses its adaptive adjustment in the feedback of the available savings remaining for their use. Rather they simply spend all the savings together with the extra money from borrowing for the consumption. In this way, the extra money flow from the household to the firms creates extra demand which makes the firms can adjust and operate in a profitable region above the default threshold. As a result, the condition for the relatively slow self-organization process is met during the borrowing period of the household and the firms start to form clusters above the default threshold. Equivalently, we can consider the provision of credits to the household side (which in turn creates the feedback to the asset of the firms), is the same as the provision of more credits in the firm side (which can be done by raising the default threshold). If the default threshold is elevated, the transition from RU to EC phase could happen, which is the same to what happened when the household incurred the debts. Finally, when the households take the precautionary saving behavior, the temporary high demand level will drop back for the households start to regain their adaptive consumption again. The already formed cluster of firms can not response to this in a short time, which incurs the defaults of the cluster and the crisis.

4.1.4.2 Household debt and Firm Bankruptcy

In the last section, we focused on the interpretation of the precautionary saving behavior and the mechanism for a transition from a stable economy to an unstable economy due to the introduction of household debts. In this section, we continue this discussion by shifting the focus to the mechanism with which the household debts creates the effect of a transition from an unstable economy to a stable one.

In Fig. 4.9, we compare the firm default rates variation with the increase in the borrowing period in a stable economy and an unstable one. The first observation is that they demonstrate different trends. As in a stable economy, except the fully borrowing scenario, generally the increase in borrowing is positively correlated with the default rate of firms when a crisis strikes, whereas in an unstable economy, it is negatively correlated. This phenomenon creates the two-fold effects of the household debts to the stability of the economy, which is to say, the relative good and bad side of the household debts could depend on the initial phase in which the economy operates. As a result, the disputes on the household debts in the previous literature might need a reexamination on the state of the economy where the data is collected.

Regarding the mechanism of the two-fold effect of the household debts, in a stable economy where the increase in borrowing period gives more time for the cluster of firms to grow, the cluster attracts more firms into it and the crisis will occur from a larger cluster of firms when the precautionary saving behavior is taken by the household. This is an explanation for the generally positive correlation in a stable economy. In an unstable economy, the condition for the self-organization process is already satisfied where the elevation in household debt level through the increase in borrowing period only raises the average asset of the firms in the cluster which pushes away the cluster from the default threshold. Therefore, the cluster now needs to travel a longer distance to hit the default threshold. If during the travel of the cluster, a new borrowing period is triggered, then the cluster is again pushed away from the default threshold. In this scenario, the cluster can bounce back rather than monotonously approaching the default threshold. By pushing away the main cluster enough from the default threshold, only smaller crisis which is close enough to the default threshold can occur, which is interpretation for the appeared negative correlation in an unstable economy.

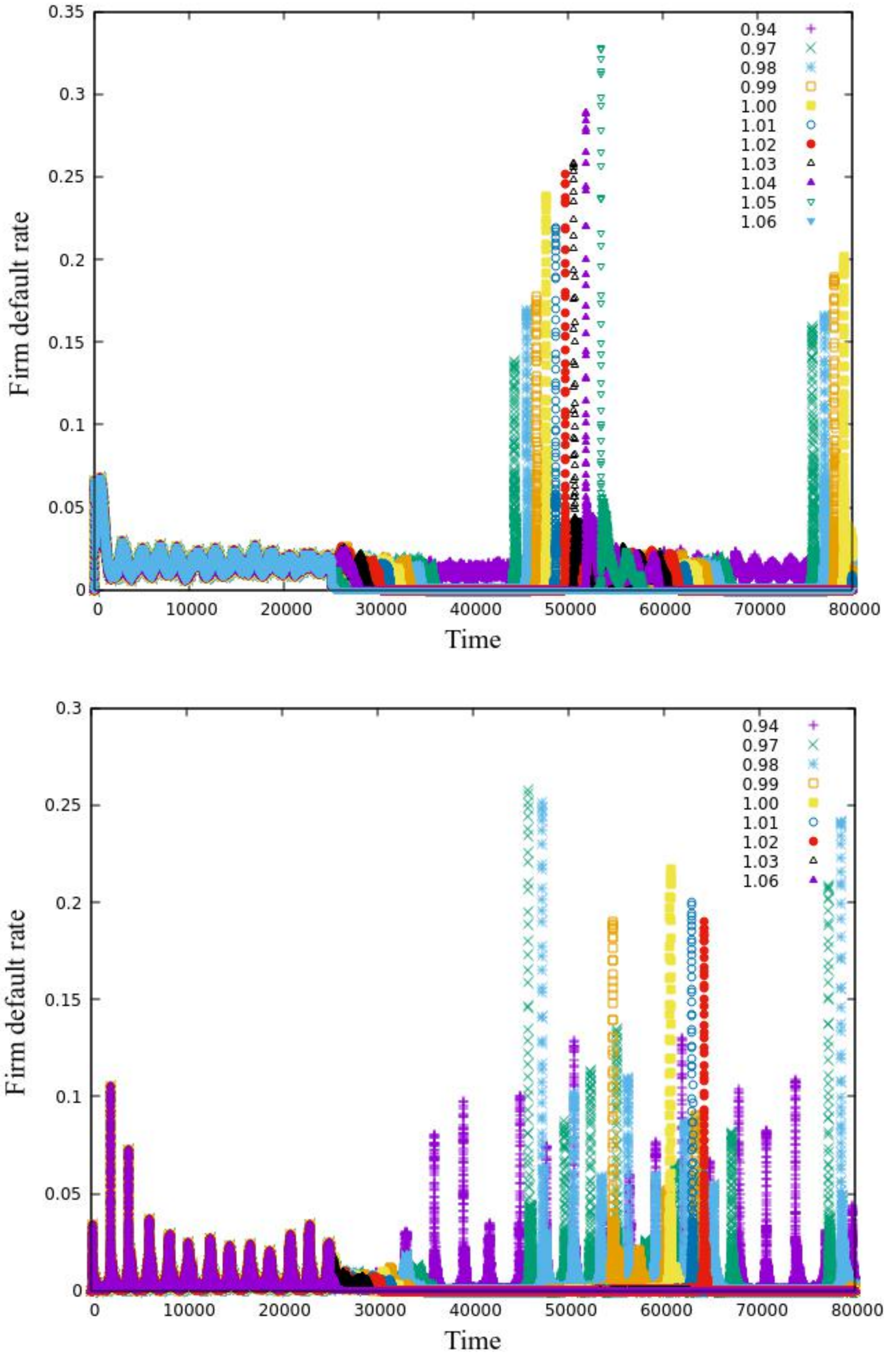


Figure 4.9 The dynamic default rate of firms is shown with different scenarios with the settings β=0, η_+=0.02, η_-=0.01, φ=0.1. (Top) For a stable economy of Θ=3, when *a* varies between 0.94 (without borrowing) and 1.06 (fully borrowing), the firm default rate increases in its magnitude. (Bottom) For an unstable economy of Θ=8, when *a* varies between 0.94 (without borrowing) and 1.06 (fully borrowing), the default rate of firms decrease as a general trend.

4.1.5 Summary

We explore the relationship of the dynamic household debt and the state of the economy. We find that the indebtedness of households and the stability of the economy are in a nonlinear relationship. Especially, the indebted household can alter the stability of the economy by interactions with firm default rate. This further induces a potential critical phase transition in the economy. Furthermore, we find that the transition from a stable economy to an unstable economy is induced by the borrowing behavior which allows the formation of cluster of firms in an economy previously without significant organization of clusters, and then triggered by the precautionary saving behavior of the household. On the other hand, the transition from an unstable economy to a stable one is due to boost in demand which significantly "drifts" the already formed cluster away from the default threshold which allows the cluster to stay safe if the next round of the borrowing behavior of the household can be switched in time.

The presence of the two-fold effect of household debts in the extended model provides evidence for the arguments on both the benefits and potential risk of the household debts in the previous literature. Furthermore, the results from this model suggest to reexamine the initial phase of the economy in the empirical studies since the contradiction might be potentially rooted in the phase of the economy where the data was collected.

We demonstrate the application of the main mechanism of cluster formation to explain the reasons behind the simulation results in a more practical scenario. In the following section, we will continue to use the clustering mechanism and the phase transition mechanism to interpret the results from other key factor simulations.

As limitations, the simple model does not take household heterogeneity and product heterogeneity into consideration. The extension of heterogeneous households and products on this model is expected on the further work to further explore the impact of the indebtedness to the stability of the economy in an agent based socioeconomic system.

4. 2 Government Control Policy and Crisis

4. 2. 1 Background

In spirit of Keynes who emphasized the role of government in an economy, the crisis control policy should also be discussed in the government perspective. Currently, the crisis control policy is largely depending on the monetary policy and the central bank mainly applies the macroeconomic tools of DSGE as the best tool in this situation. The debate on whether the monetary policy is enough for crisis control/recovery, and whether the other government policy such as tax policy is necessary, has been rekindled as a focus of the current crisis-related policy discussions. As Galati and Moessner (2013) summarized, the crisis makes researchers to reconsider the effectiveness of the monetary policy in countering the accumulation of financial imbalances. And as Keynes who had already realized the incapability of the general equilibrium theory on crisis, the application of DSGE is also problematic in this situation of crisis-related policy which regulates recovery from large shocks far away from the equilibrium point. As a result, the understanding on the mechanism of crisis to aid crisis-related policy making is largely missing even with the help of recent development in modern macroeconomics (Tesfatsion and Judd (2006)).

Moreover, the wide applications of DSGE tool in macroeconomic policy can itself be a reason for the incapability of crisis prevention, as the DSGE model can only deal with small shocks but the big shocks is usually a signal of crisis (Stiglitz (2017)). Although, the argument of recent development in DSGE has included more tools in response of the requirement of crisis control policy (Christiano et al. (2017)), unfortunately there is still no breakthrough in DSGE policy recommendations for crisis. As a result, we are left in a position incapable to deploy effective policies to avoid or mitigate incoming crisis from the insight of mainstream macroeconomics (Stiglitz (2017)).

According to Galati and Moessner (2013), the current literature relating to this research gap can be divided into three categories. The first one is DSGE models which we already discussed above. Another direction emphasizes on the financial stability especially under the scope of banking and finance research.

Currently, the financial stability issue is addressed by the so called macroprudential policy but without a common definition (Catte et al.(2010), Galati & Moessner(2013)). The efforts on a definition can be divided into three types in general. The first one defines with the robustness of the system to external shocks (see examples as in Padoa-Schioppa (2003), Allen and Wood (2006)). The second one deals more with the endogenous nature of financial distress which defines the stability with the resilience to shocks triggered inside the system (Schinasi (2004)). The third one adopts the vulnerability of a system in the definition (Borio and Drehman (2009)). The key point of the models under this category (such as example on the dependent attribute of assets in Diamond and Dybvig (1983), Diamond and Rajan (2001)) is that they consider the the propagation of the risk in the system. However, this type of models still suffers the major drawback to reproduce the phenomenon that small shocks can bring huge impact to the system in the macroeconomic level.

The last direction suggested in Galati and Moessner (2013) is very close to the study we conducted, which is the application of network analysis and theories of complex systems. The model with heterogeneous agents can can reproduce the phenomenon of bubbles and sudden crashes (Hommes (2008)). Galati and Moessner (2013) recommended "a promising new direction within this literature strand" as a way to incorporate the roles of banks into an macroeconomic ABM and with a focus on the self-organization of the market system. The important reason is that the default of firms and banks occurs with non-equilibrium consequences (see examples in Ashraf et al.(2011), Howitt and Clower (2000)). Besides, Ashraf et al. (2011) shows that the market can lose its self-regulating capacity if the economy is in a non-equilibrium position.

Following the above strand regarding to the macroeconomic policy in regulation of crisis, this study return to the original standing point to integrate the primitive observation by Keynes that economy is a complex system, and utilize the alternative of the newly developed agent-based model which allow simulation studies on complex system (Farmer and Foley (2009)) to reconsider the resilience of the economic infrastructure in a bottom-up way, with new insights on redesign of the economic intervention in a systematic engineering approach.

ABM has been proposed as a promising tool to address the complexity of an economy recently because ABM, in its nature, provides benefits such as the emergent phenomenon, flexible settings and natural description of a system from bottom-up (Bonabeau (2002)). With the help of the modern computer, the proposed practice by Keynes who had treated an economy as a complex system can be finally realized without the drawbacks from generalizing representative agent under unrealistic assumptions as in traditional macroeconomics. Besides, ABM has the capacity to reproduce crisis phenomenon which equilibrium models have never succeeded (see Naciri and Tkiouat (2016), Farmer and Foley (2009)). The advantages of ABM over other modeling techniques make it a very good candidate to study the famous crisis phenomenon which puzzled economists for centuries. Furthermore, in a more practical sense, ABM has also been proposed as a useful tool for policy recommendation for its simple picture in structure for policymaker and yet powerful accessibility to crucial features such as heterogeneity of agents (Dawida and Neugart (2011)). Rather than DSGE, ABM has developed more models to study crisis, as several examples in Riccetti (2015, 2016, 2017). In summary, not only has ABM the potential of theoretical study on crisis, but also it should be able to provide remedy to crisis for policymaker in practice. With this thinking in mind, we need to choose an agent-based model which could reproduce similar crisis phenomenon to be our target model for this investigation. A simple model without excess details would be ideal for this first attempt.

In this section, our work mainly contributes to two aspect: First, we will reproduce the phenomenon from the empirical study as shown in Fig. 1.1, which is the frequent burst of crises right after one event of crisis occurred. This kind of cascade in the frequency domain of the crisis occurrence has not yet been explained by any model or any macroeconomics theory yet. Therefore, successful reproduction of this cascade phenomenon in the frequency domain with an explanation to its occurrence mechanism will proof the value of the factor analysis based on the extension of the basic model Mark0. Second, we will explain what kind of government reaction to the crisis occurrence is more proper in the model, and we will recommend the necessary policy to fully recover the economy from the crisis. In the end, we will talk about the resilience of the economic system and discuss the measurement of resilience based on the phenomena in this model.

4. 2. 2 Model Modification

Whereas FU, RU, FE, though different in the scenarios of economic states, are all relatively stable, the phase EC exhibits volatile instability in the form of unexpected crisis of sudden unemployment in the economy. In the phase EC, the economy stays at a full employment status in most time which looks no difference from a good economy FE. However, crises in EC, as the name endogenous crisis indicates, are not triggered by external shocks, but embedded in the internal settings and physical rules of an economic system. This sneaking feature of EC hidden behind the mask of FE makes the task distinguishing and foreseeing incoming crisis problematic only by looking at the statistical data of an economy. Moreover, because this type of crisis is endogenous and intrinsic, as long as the base of the economic system or the resilience control is not well engineered, it is almost certain to assume a crisis to occur.

When a crisis is about to happen in reality, the social pressure on the bank would usually reduce the credits for firms, which in turn triggers more firms to default, to form a positive feedback to the crisis rather than a negative feedback we desire. For an effective policy intervention, an independent control parameter is needed to be identified in the first place.

Therefore, we modify Θ so it can respond with expected social pressure. We set a memory for Θ so that the bank can check its memory that whether there is a crisis history. If there is a crisis recently in the memory of the bank, the bank would take a cautious behavior by decreasing the credits for firms' loan, i.e, the default threshold. Otherwise, if there presents no crisis in the memory of the bank, it would increase the credit accordingly.

$$\Delta\Theta(t) = \begin{cases} \nu_+ & cr \in M \\ -\nu_- & cr \notin M \end{cases} \tag{25}$$

As in Eq. (25), *cr* is the crisis event, *M* is the memory of the bank, ν_+ and ν_- represent the adjustment rate by the bank. This defines the dynamics of reaction in credit supply in facing crisis or not. The chart flow in Fig. 4.10 demonstrates this extension to be added in the basic model. The credit supply will be determined by the default threshold with a cautious restriction when a crisis occurs whereas an increase in the credit supply will be the action in a period without crisis occurrence.

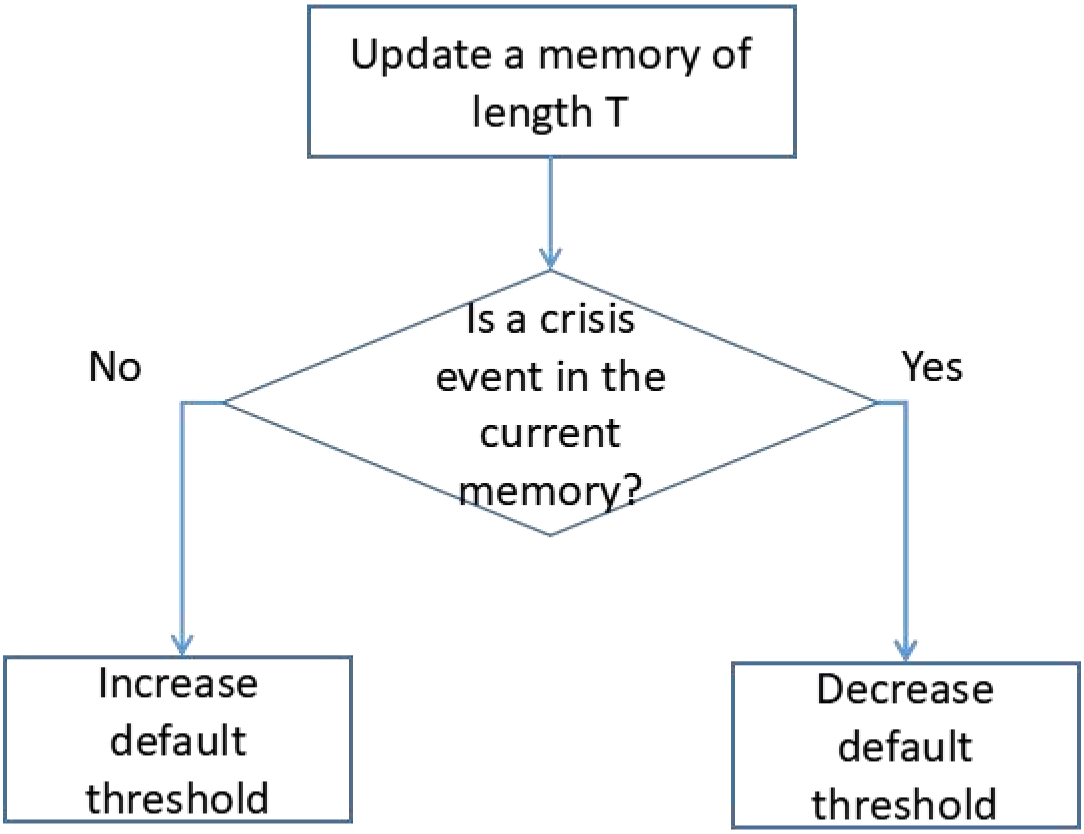


Figure 4.10 The chart flow of model extension with a dynamic default threshold as the resulted credit supply varies in a crisis period and a peaceful period.

4. 2. 2. 1 Control Parameter Selection

To make a useful phase diagram for policy intervention, at least one parameter should be independently controllable by policymakers. By examining the relations and key parameters as shown in Fig. 2.1. we choose the dividend ratio (tax ratio) δ as the independent control parameter for the government.

The reasons for this choice is in two folds: a. it could be a macro-level parameter rather than a micro-level parameter by proper settings (especially in the form of tax rate for profit); b. it is independent from the big economic environment in principle, which could be adjusted by policymaker as possible crisis mitigation policy.

To better present our idea on policy intervention procedure based on the above analysis, we illustrate a feedback control framework as shown in Fig. 4.11. The default threshold Θ serves as a sensor (or indicator) to monitor the the status of true economic variable in concern (here unemployment rate u).

According to the trend of Θ, the policymaker can issue policy to adjust the dividend rate (tax rate of profit) δ to influence the environment in order to dynamically push the economy away from the dangerous phase of endogenous crisis.

4.2.2.2 Phase Diagram for Policy Intervention

The resulted Θ-δ phase diagram is shown in Fig. 4.12. Note that FU phase is excluded in the new phase diagram because, in a real economy, a full unemployment is not likely to happen unless the economy no longer exists. Besides, our focus is on the transition between an essentially good economy FE and a potential risky economic state EC.

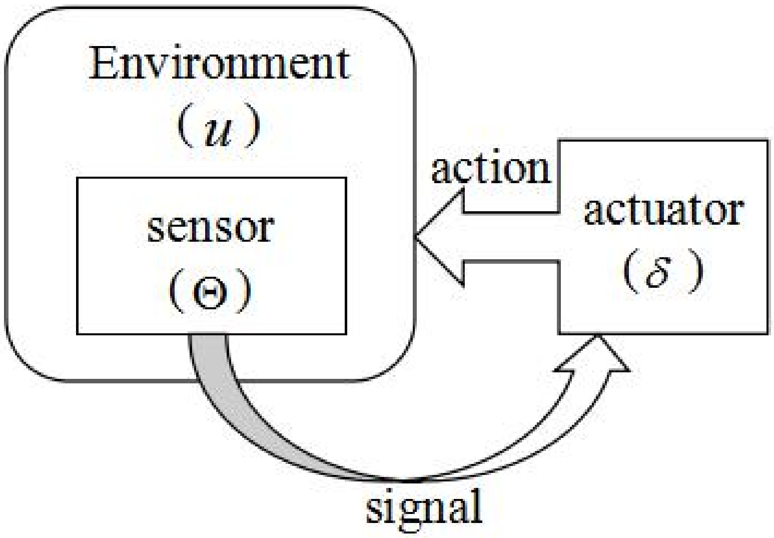


Figure 4.11 Illustration of policy intervention as the feedback control in Mark0. Default threshold Θ, profit tax rate δ and unemployment rate u.

In Fig. 4.12, it reveals that the endogenous crisis region lies along the diagonal of the Θ-δ phase diagram. The region above the diagonal EC region in the phase diagram represents the phase FE, a truly good economic state, while the region blow the diagonal EC region represents the phase RU. With this phase diagram we will show the attractor property of the crisis and the necessity for a dynamic strategy. To keep the economy away from the diagonal crisis band, one possible approach is by adjusting the dividend rate in response to the change of the default threshold (debt credits) set by banks, which is the sensor correlated with the big economic environment.

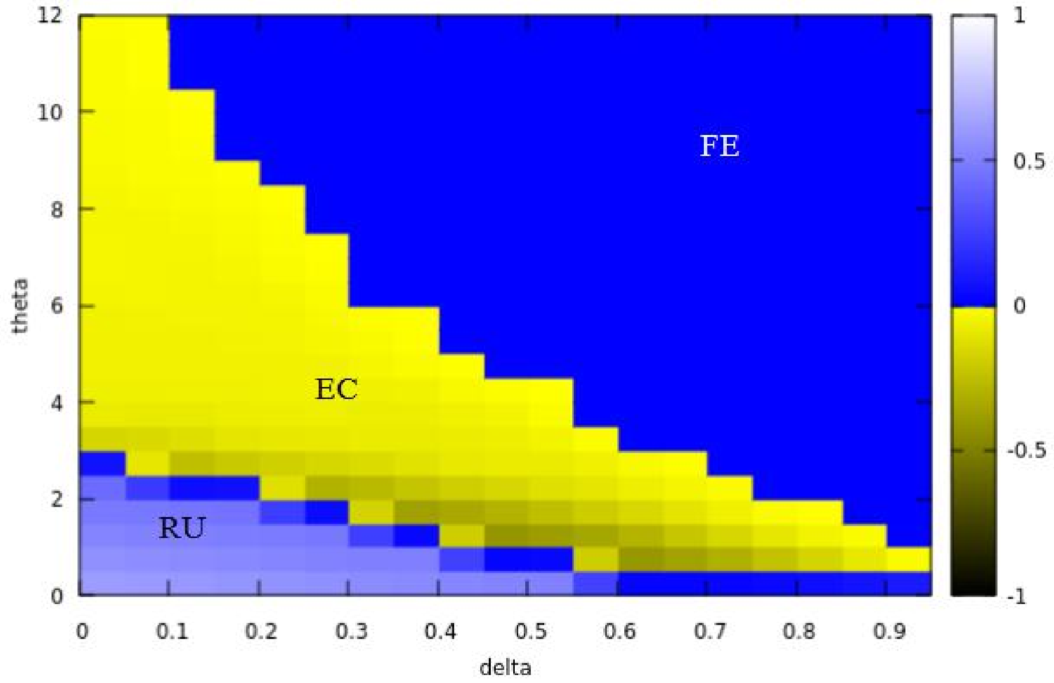


Figure 4.12 Phase diagram with dividend ratio (profit tax) as the policy control parameter which responds to the variation in default ratio (maximum credit).

Scenario	Model Realization
Without policy intervention	Maintain a fix profit tax δ
Traditional policy control	Decrease the profit tax δ
New effective policy control	Increase the profit tax δ

Table 4.2 The scenarios of policy intervention are defined by control of the dividend ratio (profit tax) as variation in δ in the model simulations.

With the key parameter for government intervention is set as δ, different control scheme for policy intervention can be realized in the variation of δ. In particular, a fix δ can be considered as a baseline scenario for comparison of different policy control schemes. A traditional policy control scheme is abstracted into the decrease of δ in order to save the firms from a crisis by allowing more profit for the firms to survive in the form of tax reduction. A new policy control scheme is the opposite operation as the increase in δ to tax more from the firms and feedback to the household during the crisis.

4.2.3 Results

4.2.3.1 Transition without a Control Policy

In this section, we provide a scenario of the transition process an economic system could possibly undergo without policy intervention (i.e. the dividend rate is fixed), by utilizing the phase diagram in Fig. 4.12. The result transition process is an attractor crisis phase, which will be demonstrated in Fig. 4.13.

We assume the economy operates in a FE phase in most of the time, as the state A in Fig. 6. One reason for this assumption is during a good period of an economy, the debt credits set by the bank is high because people believe the economy is good so that the firms has the ability to resolve their debts in future. As the result, the value of the default threshold Θ for firms is large. In the meantime, the firms are more willing to give out their dividend also because of the belief in a good economy. The same could be said that the government may set a higher tax rate for the profit. Hence the dividend (tax) rate δ should have a large value as well. Combining the two reasons, we can assume during a good time of the big economic environment, the economy very likely stays at FE phase denoted by A in Fig. 4.13, which is the region with large values for both parameters.

However, when a shock takes place in the big economic environment, people begin to lose their belief or expectation on the economy. At the same time, the bank would take action to reduce the credits for the firms, which leads to the decrease in the default threshold of the firms. Therefore, the economy experiences a transition from A to B in Fig. 4.13. As we can see, the state B is very likely in the EC phase as the bank keep shrinking the debt credits for firms.

Note that with a phase diagram, we transformed the original time domain crisis into the phase domain for the focus of discussion is the frequency of crisis occurrence here. The region area of EC phase describes the the probability of a crisis breakout during a recovery process of the credit supply increase as defined in Eq. (25). Therefore, the larger the region is, the higher probability for a next crisis strikes during the recovery period which resulted in consecutive crises with high frequency. In this sense, the phase diagram is a useful tool to study the frequency of crises and the policy to reduce the frequency as well.

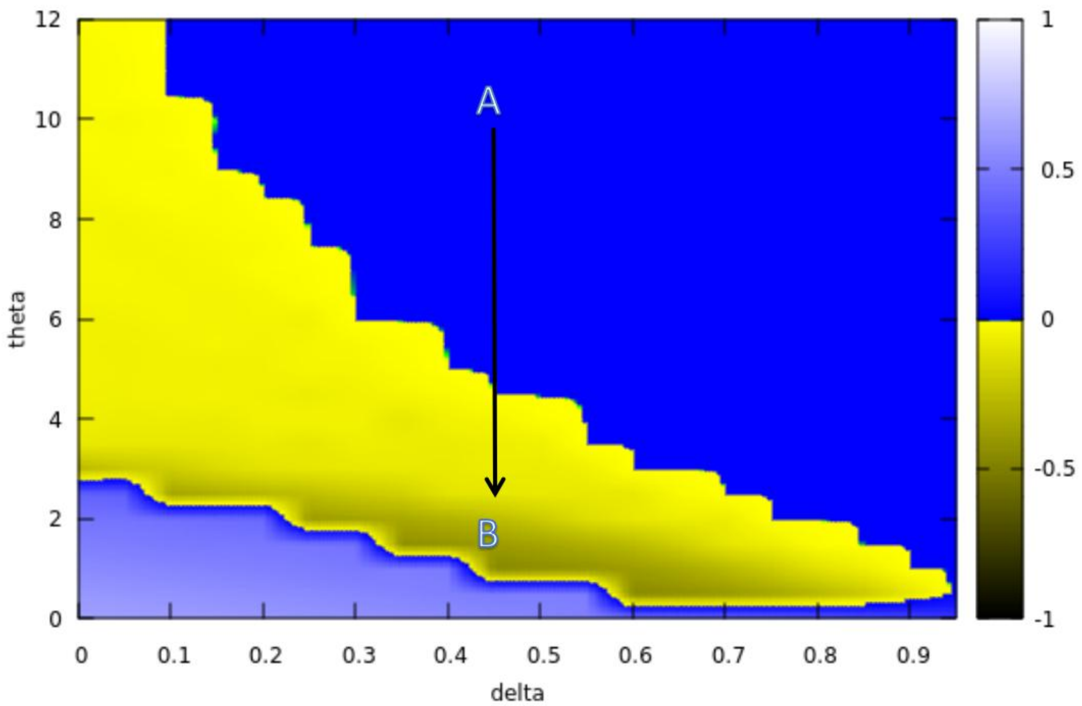
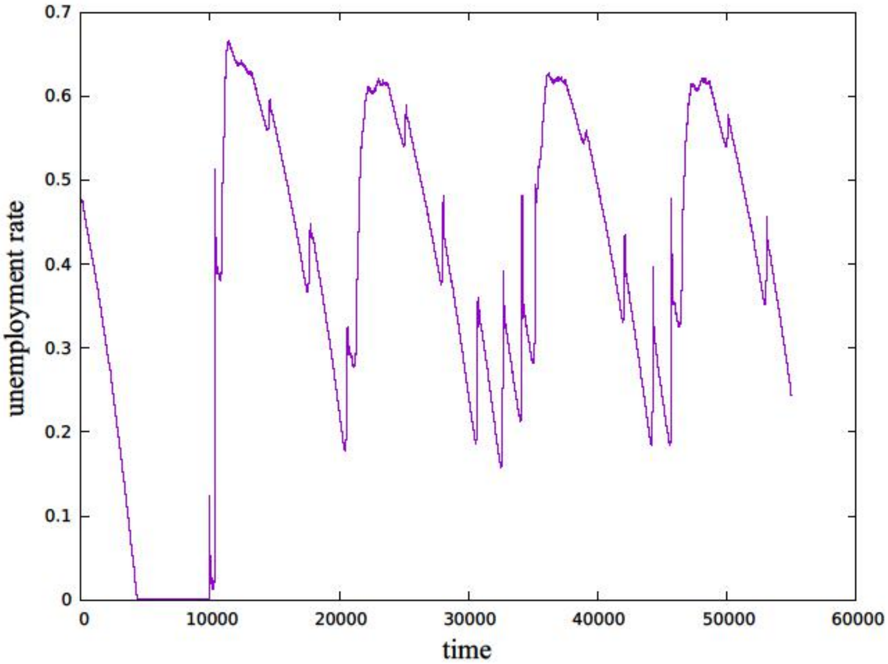


Figure 4.13 System transition process without a control policy. The economy is highly likely trapped in the crisis phase EC as shown in point B because the instability of economy causes the shrink in credit .

In Fig 4.13, a shock in the big economic environment could drag the economy into an endogenous crisis phase inside which the crises keep happening. The crisis phase reinforces itself and becomes a sink to the previous FE state. As a result, without any policy intervention, it is very difficult to believe the economy could get out of the sink by itself. Therefore, though the economy could still recover itself temporally before the next crisis, it is not resilient in the sense that the economy could hardly restore itself from EC back to FE as long as it has been in EC. This also could be seen as a reason why the policy intervention for crisis control is necessary.

To validate the above attraction of phase EC when Θ is adaptive of the environment, we simulate the response of Θ to an initial credit shock, as shown in Fig. 4.14. The first exogenous credit shock is introduced at time 10000, which Θ drops from 8 to 3. Then Θ starts to adjust itself according to the recent crisis events. From the unemployment rate, we can see the onset of an exogenous shock can trigger a series of crises in the following period. And from the threshold variation, we can see that the Θ is indeed trapped in the low threshold region of EC. As a result, without the policy control, an exogenous shock in credit supply will create a long term effect which traps the economy inside the EC phase with frequent occurrence of crises afterward.



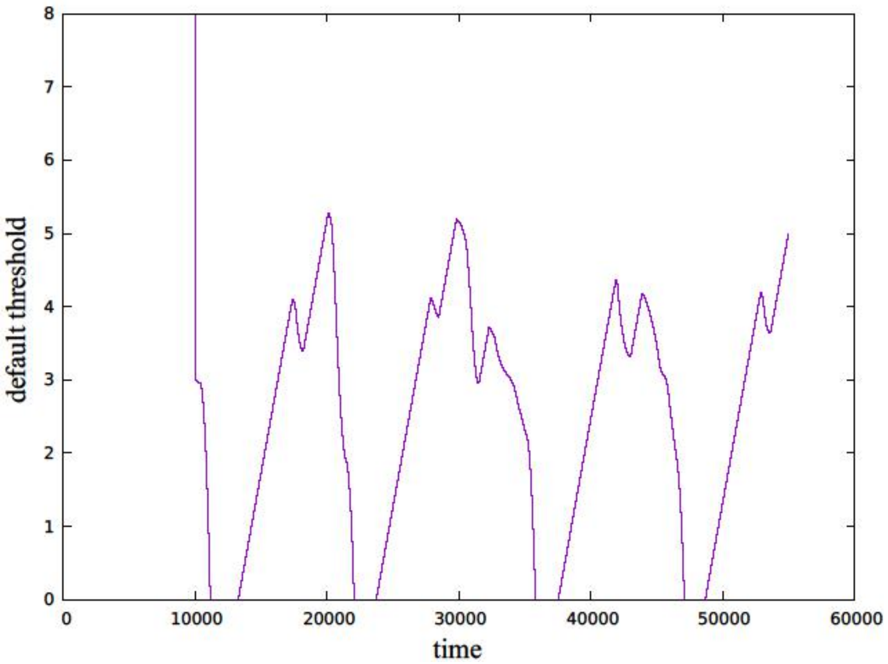


Figure 4.14 R=2, delta=0.5. (Up) the economy is trapped into EC phase after one exogenous shock on the default threshold of the bank . (Bottom) The evolution of Θ after the first shock from Θ=8 to Θ=3.

4.2.3.2 Transition in a Traditional Control Policy

In order to escape from the trap of EC phase, we explain how to use the policy control parameter δ to guide the economic system undergoes a series of transition processes as the big economic environment is evolving, and to finally return to the good economy state FE, with the help of the framework demonstrated in Fig. 4.11. The result is the system transition process along the path of a crisis control cycle as shown in Fig. 4.15. In this policy intervention framework, the system transition undergoes a series of different stages by adjusting the profit tax rate δ.

The transition from A to B in Fig. 4.13 has been already explained. As the economy has stuck in the sink of EC phase, by reducing the value of δ, the economy would eventually shift to state C in Fig. 4.15, which is inside the RU phase. This could also be interpreted in a way that, with reduced dividend rate (tax rate of profit), it gives firms more resource to adjust itself in a bad time. Though the compromise is made that the whole economy is in a RU phase with a certain amount of people out of their jobs constantly, it mitigates the endogenous crisis happenings which could help people to rebuild their correct belief and expectation on the economy.

When the expectation and belief of the society is successfully rebuilt in the phase RU, for it is a stable state and no further crisis triggers people's fear again, the bank would also loose their constraint on the debt credits for firms. The result is the increase in value of default threshold for firms, and the transition from state C to D takes place, as shown in Fig. 4.15.

Unfortunately, as the phase diagram indicates, with the dividend rate staying at a low level, this action by banks would drive the economy back to the EC phase again, which would very likely crash the just rebuilt confidence of the society with another incoming crisis. The state D in Fig. 4.15 also implies a combination of high debt credits and low dividend rate could possibly cause instability in an economy. This transition process also provides another reason why the crisis keeps happening as if the economy was in a sink of crisis, since even the increase in credits without prompt reaction in policy could cause endogenous crisis again surprisingly.

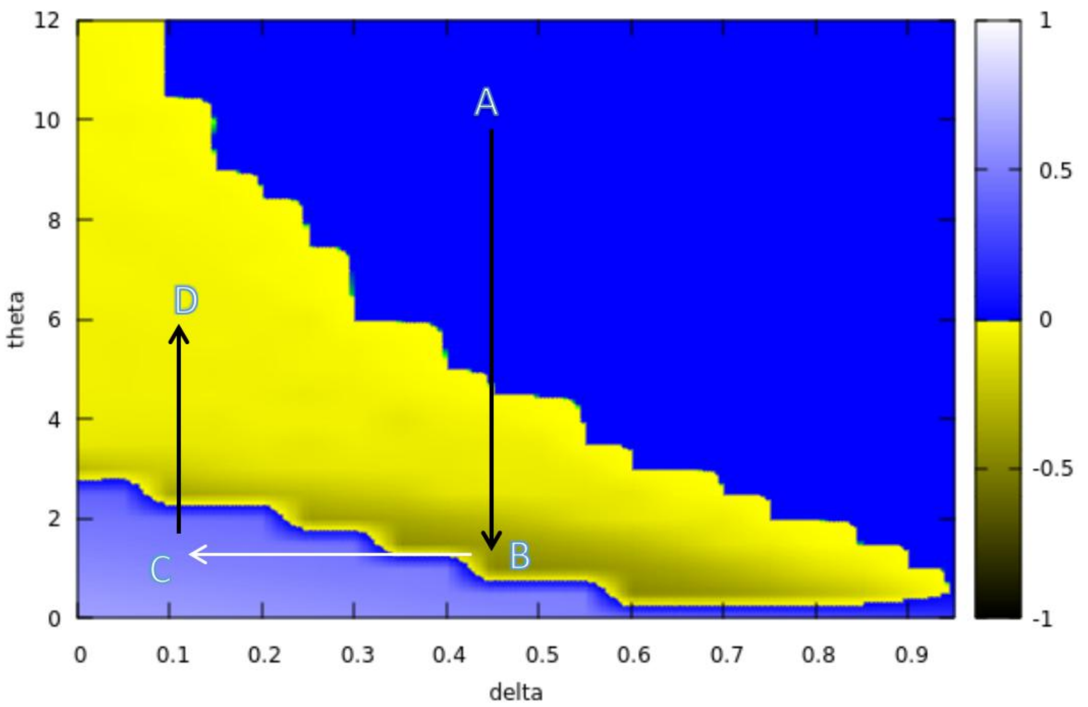


Figure 4.15 System transition with a normal control by adjusting dividend rate.

To validate this ineffective policy control scheme, the simulation test is carried out with different cases by decreasing δ after an exogenous shock is induced. In Fig 4.16, the dividend ratio δ is adjusted after the first external shock at time 10000, from 0.5 to 0.1 to give firms more money to recover from the shock at time 30000. However, if we compare Fig 4.14 with Fig 4.16, there are no improvement at all and obviously the economy is still trapped in the EC regardless of the effort the government has made by adjusting the profit tax with the objective to inject money back to the firms. Further confirmation from the dynamics of Θ in Fig 4.16, the adaptation of bank still keep Θ within a low value. In Fig 4.17, another case shows similar consequence that the Θ can not fully recover to its previous state so that the economy would still experience multiple endogenous crises after the first disturbance.

This scenario with the traditional policy control demonstrates why the occurrence of crises becomes more frequent after one crisis event as the real case in Fig 1.1. We can see that even with the traditional policy control, the economy is still trapped in the EC phase which results in frequent occurrence of crises. The empirical phenomenon in Fig 1.1 can be interpreted as a trap in the EC phase in this extension model of Mark0. The existence of an EC phase in the phase domain plus the onset of an exogenous credit shock can reproduce the phenomenon in Fig 1.1.

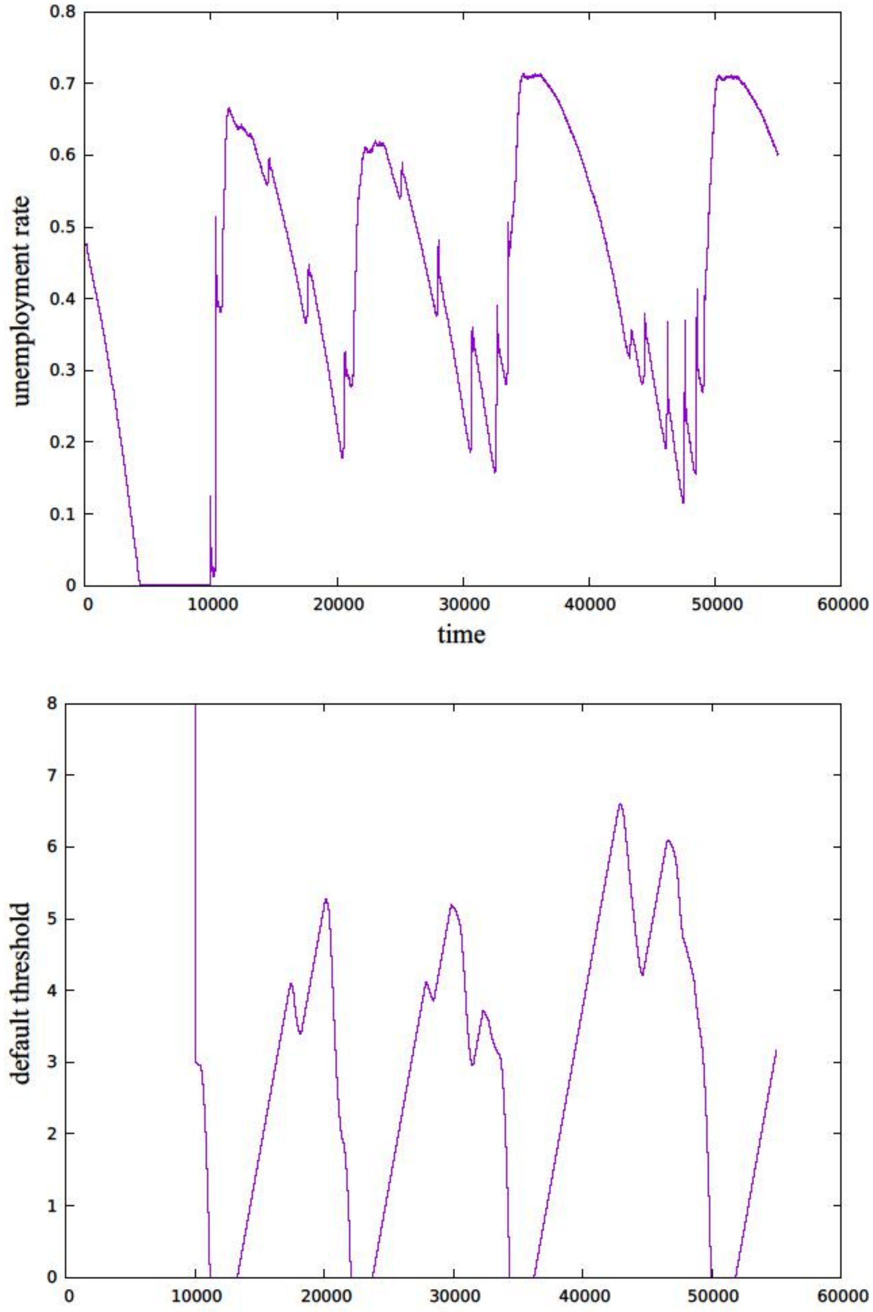


Figure 4.16 R=2, delta=0.5 initially and it shifts to delta=0.1. (Up) the economy is trapped into EC phase even with the traditional government control by injecting more money into the firm sector. (Bottom) The evolution of Θ after the first shock from Θ=8 to Θ=3.

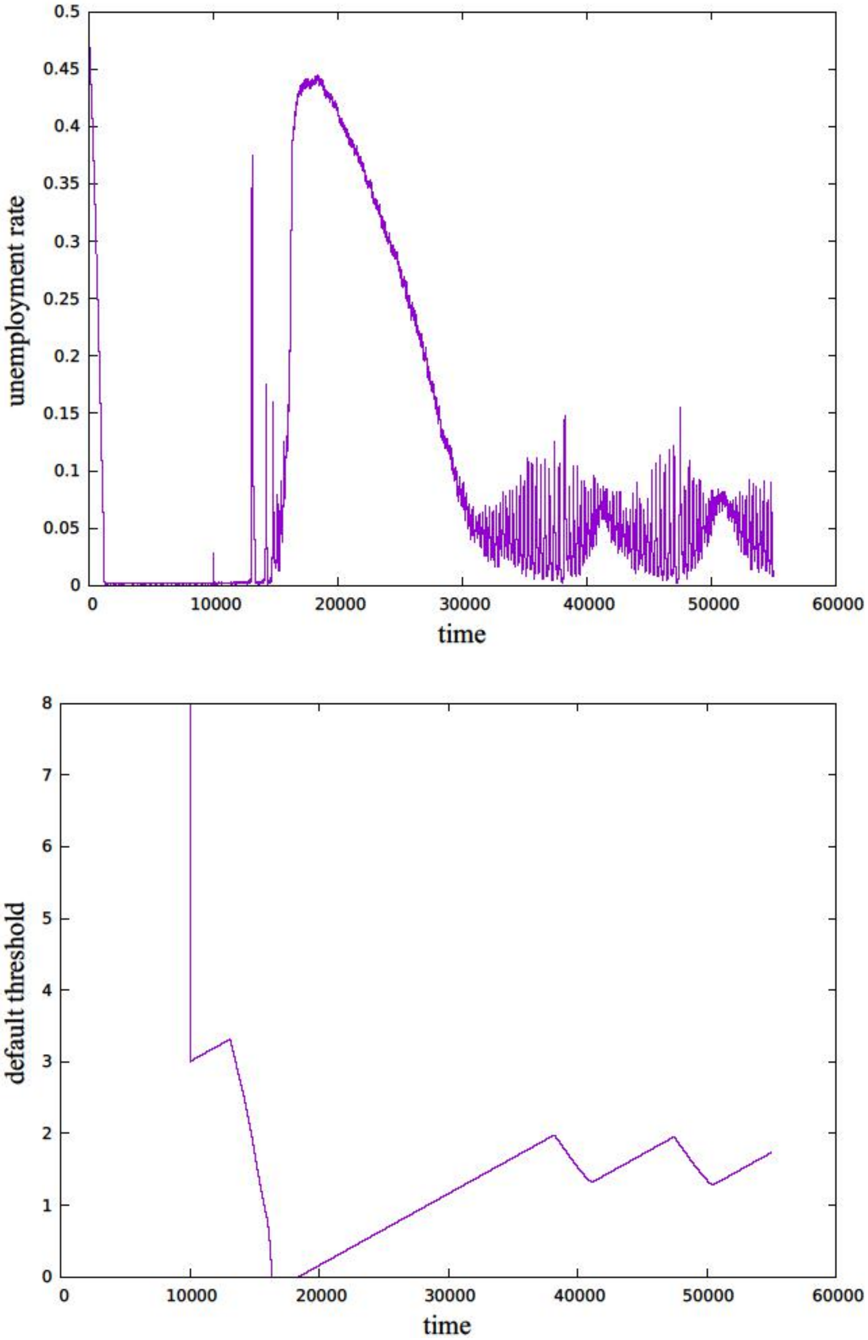


Figure 4.17 R=2, delta=0.2 initially and it shifts to delta=0.02. (Up) the economy is recovered from the big shock but still trapped in EC phase with many small crisis induced later, even with the traditional government control by injecting more money into the firm sector. (Bottom) The evolution of Θ after the first shock from Θ=8 to Θ=3.

4.2.3.3 Transition in a New Control Policy Scheme

From the phase diagram and the above results, we already know that injection of more money to the profitable firms would not change the economy which is trapped inside the EC phase. By observation of the diagram, in fact the region with a high δ value has the most narrow band of EC. Therefore, an idea from the phase diagram is to increase δ during the EC which increase the chance of escape from EC phase only by a reasonable recovery of Θ of bank. This idea of "taking away" money from the market during EC is counter intuitive in economic theory which all stress is on injection of money into the firms. In Fig. 4.18, the recovery process is illustrated by increasing δ, the economy is located very close to boundary of EC and FE in E. Then with a high probability the economy can go back to F as it only requires the memory of the bank without crisis in a short period. After the economy enters to F, the government can decrease the profit tax again to return to A without any stability problem in the economy.

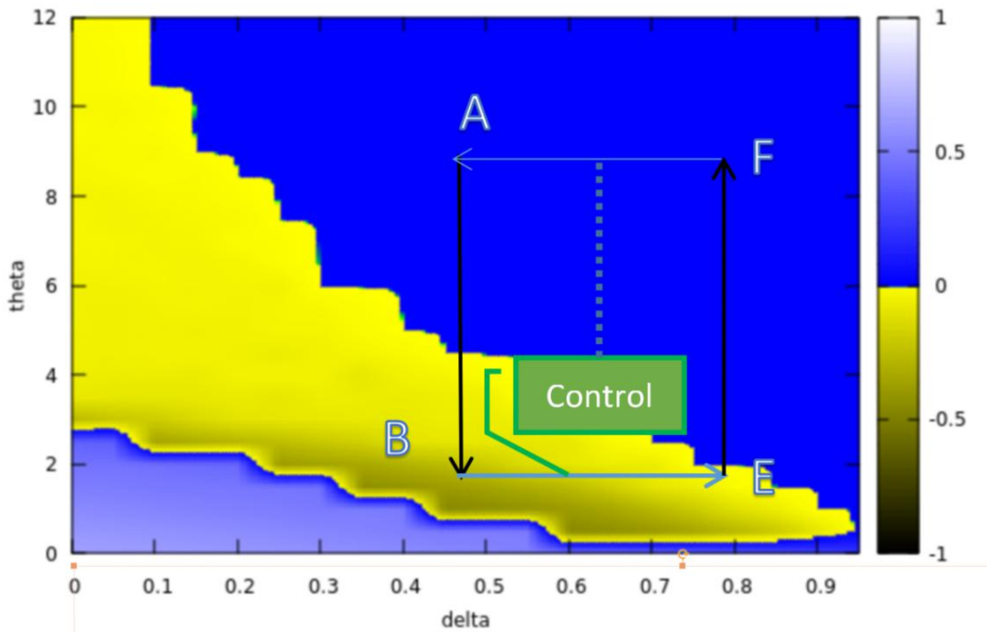
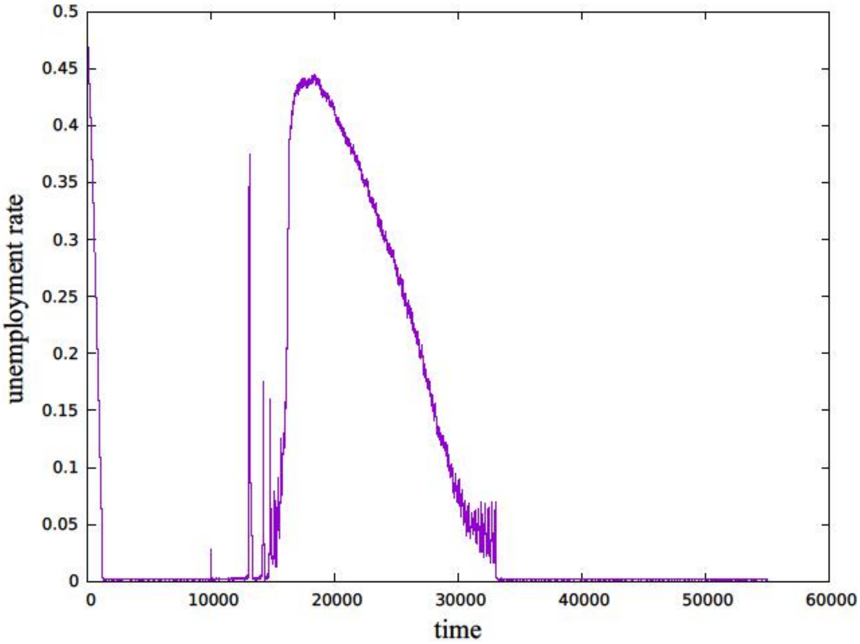


Figure 4.18 System transition with a new control by increasing dividend rate δ.



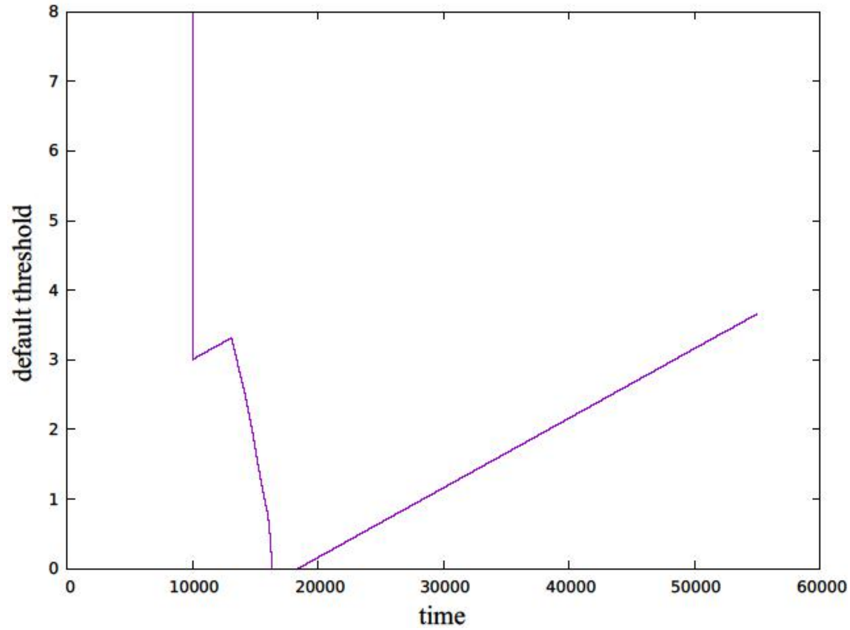
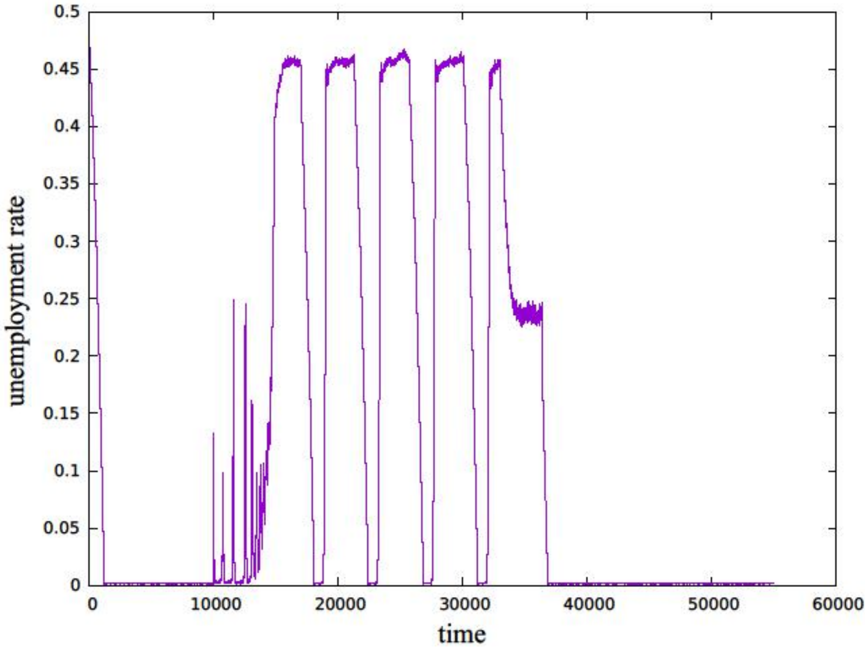


Figure 4.19 R=2 , delta=0.2 initially and it shifts to delta=0.92. (Up) the economy is recovered from the big shock and return back to the FE phase by abstraction of profit from the firms and injection to the household. (Bottom) The evolution of Θ after the first shock from Θ=8 to Θ=3.



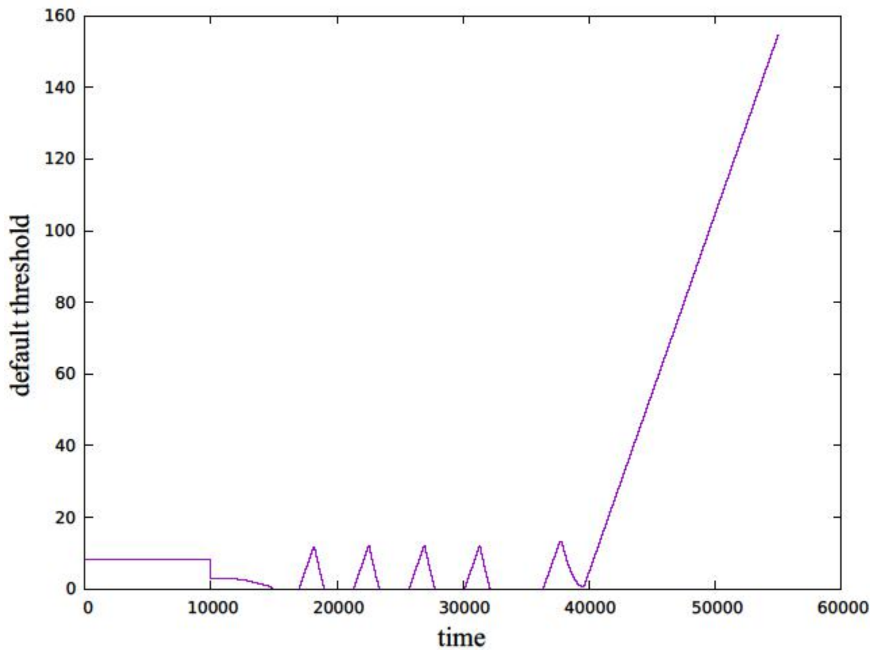


Figure 4.20 R=2, delta=0.1 initially and it shifts to delta=0.8. (Up) the economy is recovered from several crises and return back to the FE phase by abstraction of profit from the firms and injection to the household. (Bottom) The evolution of Θ after the first shock from Θ=8 to Θ=3.

In Fig. 4.19 and Fig. 4.20, we validate the above counter intuitive scenario by numerical simulations. The dividend ratio (profit tax) δ is adjusted to a higher level at time 30000, after the first external shock at time 10000. In both cases, the recovery of the economy can be observed by the fact that the crises disappear in the late half of the simulation. Further confirmation can be done by the dynamics of Θ.

Different than previous trap in the low value region of Θ, in both cases, Θ is finally released to return to a high value. In reality, Θ is not going to increase forever but saturate at certain level. But this part of simulation is out of the scope of our concern on the policy in order to escape from the EC phase, therefore the final stage of ever increasing Θ does not represent any reality but just an artifact.

Our results implies the profitable firm is like a sink of the money flow. More money to the profitable firms does not help the overall economy to recover from the crisis phase which the economy fell into. The whole economy will be trapped into the EC phase with frequent crisis occurrence. On the other hand, the policy which transfer the profits of the firms into the household consumption can fulfill the job to get rid off the crisis phase in our model. Similar to what we have already discussed in the household debt section, the increase in profit tax also has a similar effect by elevation the asset of the cluster of the indebted firms. This "drift" is created by the increase in household incomes in the form of the dividends in one hand, and by pulling close the cluster of the profitable firms and the indebted firms which keeps the cluster of indebted firms staying away from the default threshold.

In fact, the drift of clusters is also the reason why the EC phase lies on the diagonal of the phase diagram in Fig. 4.12. The transfer of the profit in the profitable firms into the consumption of the household can pull the two clusters of profitable firms and indebted firms close to the center of them. The more profit is transferred, the more closer the two cluster are, and the higher asset the indebted firms can possess. Equivalently, we can consider the default threshold is pushed away from the cluster because of the relative motions. Therefore, for the same value of Θ, a higher δ is shifting the phase diagram downward which allows the FE region to be achieved in a relative low value of Θ and compresses the region of EC and RU. This "drift phenomenon" is represented by the almost linearly shift down of the EC region in the phase diagram in Fig. 4.12 with the increase in the value of δ.

4.2.4 Discussion

The dynamic interaction between the credit supply policy of banks and the tax policy of government is an interesting topic. The current literature is more focused on one of them individually in response to the market. For example, Jiménez and Saurina (2006) studied the relationship between the credit risk of banks and loan provision policy of banks. Bank of England (2009) studied the credit supply of banks in response to the asset price bubbles. Jeanne and Korinek (2010) studied the Pigouvian taxation and its impact on asset price. As in Blinder et al. (2008), the communication can support the policy among banks, in our opinion, the communication among banks and government and the studies on the dynamic interaction of them are also important.

In a traditional engineering resilience concept, the resilience is measured by the distance between tipping points. This concept is very useful in pure engineering systems. However, as in a socioeconomic system, the social contents interact with the engineering system and the system can undergo dynamic transformation processes, which is similar to the ecological resilience as in Holling (1996).

The first policy recommendation in terms of recovery of single crisis in time domain is to keep R larger than 1. This is a precondition to keep all the above discussion valid in phase domain. This means, during a crisis, the policy need to keep the hiring propensity not less than the firing propensity in the labor market. Otherwise, even for a single crisis, it can not recover to FE but rather goes to FU according to the discussion in Chapter 3.2. However, in the reality, the crisis is highly likely accompanied by a tendency of low hiring and high firing. This is why in the real world the economy can not be resilient enough because the control parameter R also shift closer to FU phase. As a consequence, the primary policy should be focused on the labor market so that the next step could be carried out.

As it demonstrates that the EC phase is a trap to the economy because the maximum credits from the bank is trapped in the region which labeled as an EC phase, as long as the credit supply is coupled with the social expectation of the prosperity of the economic environment, the labor policy alone is not sufficient. The self-organization of firms (Sun and Chen (2018)), together with the social influence to banks, pushes the system to disorder and crisis. The traditional control policy of government has been demonstrated in the model as ineffective while the new insight is to try to abstract firm profit into household during a crisis.

In the real world socioeconomic system as the discussion in Taylor (2009), it concluded by empirical evidence, the government action and intervention often prolonged the crisis by misdiagnosing the problems in the bank credit markets and focusing on liquidity rather than risk. Our results on the transition processes based on the phase diagram could provide some support for this viewpoint. In our result, if the government responded not properly to the change of bank credits, the transition process could end up with the state D rather than return to A as in Fig. 4.15. Ironically, the improper reaction from the government, is the same as no policy intervention at all from the beginning. Another point is, if we compare the processes in Fig. 4.13 and Fig. 4.15, both B and D are in the same EC phase, which could trigger more endogenous crisis in future and likely prolong the crisis period. Therefore, the policy which can get rid of the EC region is the key to help mitigate the crisis and shorten its duration. And our study actually provides a method for policymakers from the angle of risk rather than liquidity, by identifying the risky EC phase region in the phase diagram.

This ABM and phase diagram approach in system resilience engineering reveals the complex and dynamic system perspective, which is valuable to economic policy makers. Compared with the existing system dynamics approach, our approach does not require a full understanding of all the system feedback directly for we can provide a simple visual phase diagram to help system design. Compared wit real options, our method provides more insights on the physical engineering structure and the system level outputs. For example, one more direction for the future application of this approach is to quantify the traditional engineering resilience with the recovery time length from a crisis. Differences in the recovery time and the relating parameters can be used to aid the design of a more resilient system in terms of the average speed of recovery from a single crisis occurrence in the time domain.

However, as limitations in our approach, Mark0 is only a minimal model which differs itself from the real economic system in many aspects. Therefore, the results in this study need further justification with proper integration of the features which can be tested with the resulted decisions policymakers actually made. Furthermore, the validity of the policy recommendations from the model also need the help and integration of more empirical evidence to test them before the final application to a real economy.

4.2.5 Summary

ABM is a promising engineering approach to address the complexity in the happening of crisis in an economic system and to provide possible policy intervention to mitigate or shorten the duration of crisis. We have showed in Mark0 that the phase diagram is a helpful tool to evaluate crisis risk especially after carefully setting a sensor and an actuator parameter in the system. We have showed the transition processes with/without policy intervention. We found that without policy intervention or with traditional policy intervention could result same failure, which keeps the economy in the endogenous crisis and prolongs the duration of crisis.Thus, the traditional government policy is not effective in crisis control.

Another main novel contribution of this part of work is reproduction of the cascade of crisis occurrence as indicated in the empirical data in Fig. 1.1. The extension on the model in this section demonstrates the frequent occurrence of crisis can be explained by exogenous shock together with the trap inside the EC phase. The presence of an endogenous crisis phase is the key in the interpretation, without which the cascade of crisis occurrence in the frequency domain should still remained challenging for a plausible interpretation.

Finally, we summarize the conditions for crisis control as two-fold: labor supply and money balance. The labor supply which reflects in the employment propensity R is the precondition for the recovery from crisis, without which the resilience of the economy in the time domain shall lose and the recession of the economy should follow the crisis as a consequence. Therefore, the first important factor the government needs to ensure is that a high employment propensity should be maintained by policy during the period of a crisis. The money balance addresses the resilience in the frequency domain which help the economy escape from the trap of the EC phase. The key for this type of policy is to support household rather than firms during a crisis. This has been shown to have a much better consequence in the model simulations. Only by ensuring the labor employment status and a new policy to control money flowing from the firm profit to household consumption, can the economy possibly recover itself in a quick pace. As a result, collaboration between banks and governments with shared information system might be a key to a successful crisis control policy.

4. 3 Labor Market and Crisis

4. 3. 1 Background

In the modern society of developed countries, the population decline and aging has become a very important issue. In Japan, the super aging society and depopulation has created many new problems and uncertainty in security in future (Muramatsu & Akiyama (2011)). Inside the problems, it includes the social security system, the government budget and the economic system as well (Tsutsui & Muramatsu (2007)).

Not only in Japan, in the most populous country China, it will also experience an aging age in the near future. In (Chen & Liu (2009)), it discussed multiple scenarios and different types of uncertainty in coping with the challenge imposed by population dynamics socioeconomically. In summary, not only the financial crisis could happen, the new type of crisis induced by population dynamics can potentially occur in our economic system. To simulate the scenarios and warn the new crisis beforehand, we set the main focus of this section on the population. Unfortunately, the studies of population dynamics and its impact in economic system in ABM is extremely scare. Therefore, this study will take a first step to gain some insight on this issue.

In the available literature, most of them address the economic crisis caused by the population aging through pathway of the health care expenditures. For example, Denton and Spencer (1983) discussed the relationship between population aging and the health cost in Canada. Furthermore, Getzen (1992) showed the population aging is indeed correlated with higher health care expenditures, but rather than the direct cost on patients, the reason is the rise in per capital income. This could have a possible interpretation that the labor becomes expensive. Dalziel (1996) proposed the proper action should be taken to prevent the crisis happening from the health care system in an aging society.

However, few literature has addressed the decline of population and the potential occurrence of economic crises despite Keynes who had already mentioned this in his early work (Keynes (1937)). For example, Buttino (1990) provide an examinations on the the economic crisis with a massive population decline as its consequence in Turkestan during 1920s However, along the direction which Keynes suggested that a population decline could “awaken another monster” of economic crisis, almost no studies have provided any further evidence, which sets the target of the simulations in this section.

4. 3. 2 Model Modification

In order to integrate the labor market into the model, the modification on Mark0 should set its target on the household side. In particular, the previous fixed population setting is replaced by a simple dynamic population flow model to simulate a population declining scenario to address the worry of "a sleeping monster" in Keynes (1987) in simulations.

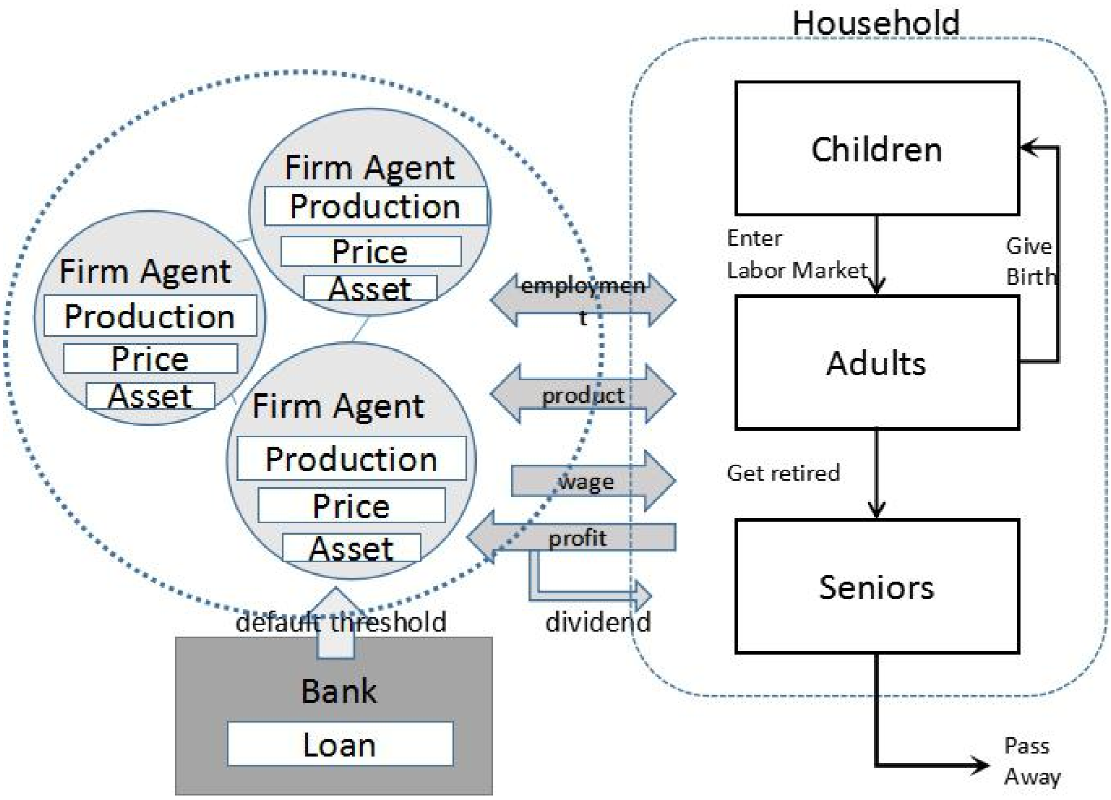


Figure 4.21 The illustration of a dynamic population flow in the household as an extension to Mark0.

In Fig. 4.21, we illustrate the new model with a simple dynamic population implementation which is further explained in Eq. (26,27).

The change made on a dynamic population flow of the household is shown in Eq. (26) as follows:

$$\begin{cases} N_c(t+1) = N_c(t)(1-\Gamma_{ca}) + N_a(t)\Gamma_a \\ N_a(t+1) = N_a(t)(1-\Gamma_{as}) + N_c(t)\Gamma_{ca} \\ N_s(t+1) = N_s(t)(1-\Gamma_s) + N_a(t)\Gamma_{as} \end{cases} \tag{26}$$

Where N_c, N_a, Ns are the population of children, adults and senior people respectively. Γ_a is the birthrate of the adults, Γ_s is the death rate of the senior, Γ_{ca}, Γ_{as} is the transfer rate between the groups.

We set each of the rates to be sampled from a predefined uniform distribution in each time step so that the random fluctuation of population can also be captured to some extent .

Because the population is dynamically changing, the consumption rate should vary as the children and senior do not have income so that we assume they have a fixed consumption rate. In the meantime, the adults earn money through wages so they have a varying consumption rate similar to the one used in section 4.1.2, as shown in Eq. (27).

$$c=0.5*(N_c+N_a+Ns)/N+0.2*\sin(2\pi t/30000)*N_a/N \tag{27}$$

Where N is a constant to calibrate the initial c within [0,1]. Note that we define the consumption propensity with the rules that the senior and children have a flat rate for they do not earn money by providing labor but rather receive from the family or government. The propensity of adults is modeled by a floating rate in the form of sinusoidal function to represent the varying expending and saving behavior of the adults.

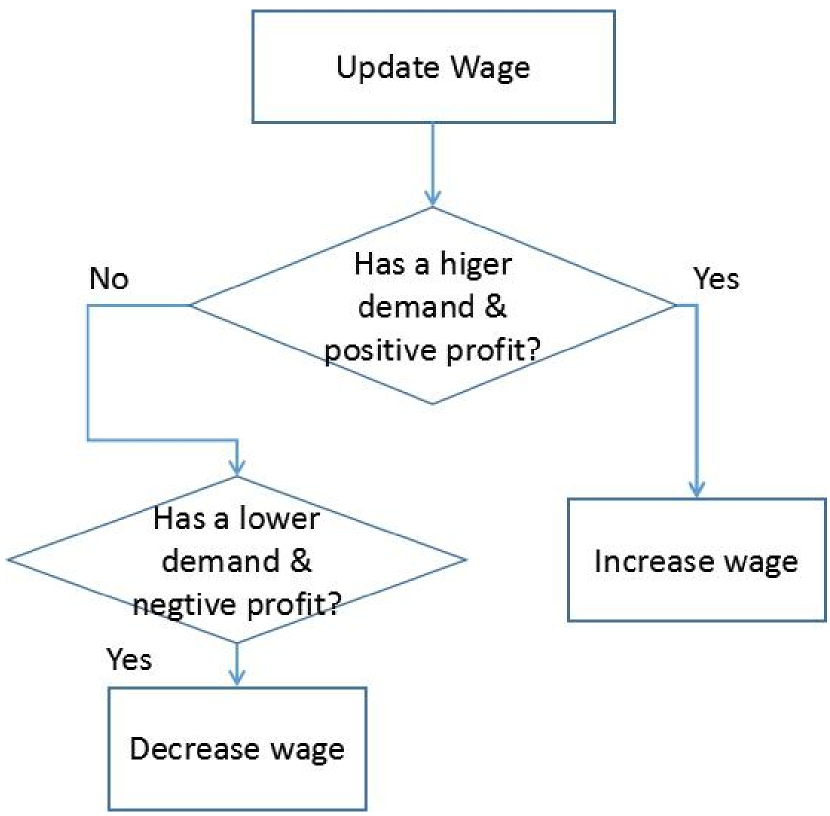


Figure 4.22 The chart flow of model extension with different wage update schemes in Mark0.

Another modification to add to the model is the wage update, the wage update takes the form that

$$W_i(t+1) = W_i(t)(1 + a\gamma_w \xi(t)) \quad \text{if} \quad Y_i(t) < D_i(t) \text{ and } P_i(t) > 0 \tag{28}$$

$$W_i(t+1) = W_i(t)(1 - b\gamma_w \xi(t)) \quad \text{if} \quad Y_i(t) > D_i(t) \text{ and } P_i(t) < 0 \tag{29}$$

Where γ_w is the maximum magnitude of the wage adjustment, $\xi(t)$ is a random number in [0,1]. Therefore, if the firm is in under-supply situation with profit, the firm will increase the wage of the workers, On the other hand, if the firm is oversupplying without any profit, the firm will decrease the wage of the workers.

Note that previous simulations in this study all take a constant wage of value 1. The purpose for this wage update is to investigate the interaction with the variation in the labor market because of the dynamic population. Our intention is to investigate whether wage incentives in the market can cope with the depopulation trend and maintain the balance of the economy. In order to do so, we further consider five wage update scenarios to discuss the potential economic crisis due to population decline and the possible remedy by wage update strategies.

Scenario	**Parameter Setting**
Fixed equal wage update (f)	*a=b*
Fixed strong wage update (fs)	*a>b*
Fixed weak wage update (fw)	*a<b*
Trend following wage update (tr)	*a=u*, *b=e*
Weak trend following wage update (trw)	*a=u/2*, *b=e*

Table 4.3 The scenarios of wage update rules in terms of different degrees of wage incentives and the corresponding parameter setting rules in Eq. (28,29).

The five scenarios are summarized in Table 4.3. Overall, we consider two groups of wage update strategies.

The first group is the fixed update rule, which means the maximum value of wage update in a single time step is fixed. Note that in Eq. (28,29), the wage update still possesses randomness within the maximum possible value. In the fixed update group, three strategies are deployed as the equal update in terms of equal maximum value for both the increase and decrease in wages as in Eq. (28,29), the strong update as the possible maximum value for the increase in wages is larger than the decrease in wages, and the weak update as the possible maximum value for the increase in wages is smaller than the decrease in wages.

The second group is the trend following update rule, which means the possible maximum value of wage update in a single time step is not fixed but a floating value according to the available labor in the labor market. In particular, the first strategy is the trending following update, which refers to the more labor is employed, the bigger the maximum value for the increase in wages, on the other hand, the smaller the maximum value for the decrease in wages, and vice versa. The second strategy is called the weak trend following update in which the only difference is that the maximum value of the increase in wages is only half of the one in the first strategy of trend following update.

We will show the result in two initial FE case with the first one is R=5,theta=3 and the second one is R=5,theta=8, in order to investigate whether the FE can be sustained in a depopulation economy and whether the wage update incentives can be a remedy if any crisis is incurred in the initial FE phase.

4. 3. 3 Results

4. 3. 3. 1 Population Decline

The first thing to confirm in this section is that we can successfully produce a shrinking population in the economy, which is shown in Fig. 4.23.

In Fig. 4.23, by adjusting the rates specified in Eq. (26), a depopulation scenario can be set. We can see that the total population is firstly increasing and then keep decreasing to half of its initial population. The population of children. Adults and seniors can also be found in Fig. 4.23. Especially the initial decrease in children group and the increase in adults and seniors can be observed in this particular simulation scenario. In the end, though every group is decreasing, the relative aging ratio of this economy is fluctuating around a certain equilibrium value. Note that our intention is not to simulate the population decline and aging in an empirical sense, rather under this particular scenario, our goal is to investigate potential risk in crisis occurrence in an initial FE phase of the economy to give alert to the future of depopulation nations in the spirit of Keynes, as well as to investigate on one of the intuitive possible remedy by changing wage incentives in a depopulation nation.

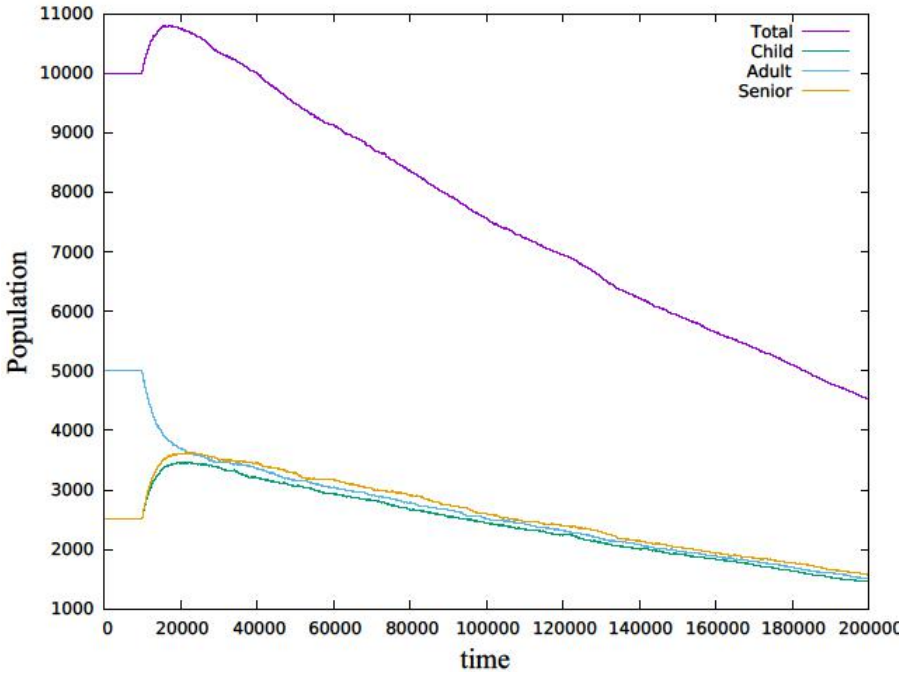


Figure 4.23 The simulation of a declining population in Mark0

4.3.3.2 Fix Wage Update

In this section, the results on fixed wage update strategies are summarized.

We divided the results into two parts. The first part is composed by the three fixed wage update strategies with an economy in the FE phase but close to the boundary of FE and EC in the phase diagram.

In Fig. 4.24, the unemployment rate and average wage in the economy are shown for the fixed wage update strategy. We can observe a cyclic wage behavior of the economy but with most of the time the average wage rate is below the standard situation (which is 1), the economy experiences many crises but still managed to recover in a quick pace. In the end, the crisis occurrence becomes smaller and less frequent while the wage still follows a cyclic pattern below the standard wage of 1.

In Fig 4.25, the unemployment rate and average wage in the economy are shown for the strong wage update strategy with a strong fix wage update rule. The observation is that the average wage maintains stable above 1 and the first half of the simulation in the economy maintain a full employment period the same as the initial phase of the economy with a fixed population. However, even without any external disturbance, a surprising sudden collapse of the economy to a very high unemployment rate follows the temporary full employment period. This is not a sustainable scenario as from the wage update, a sudden drop in wage can be observed. In fact, after the sudden drop in wage, the wage has been raised to an extreme high level to attract labor in the economy. Nevertheless, the economy can not recover and respond quickly to it and the high wage incentive can not sustain itself so that it drops back to the level slightly below the standard value of 1. The economy failed to recover from a single crisis regardless of the temporary strong wage incentive put into the labor market.

In Fig 4.26, the unemployment rate and average wage in the economy are shown for the weak wage update strategy. The economy can not stay in a stable state but with a lot of crisis occurrence. The situation is similar to the fixed wage update but with more volatility, and the average wage is also similar in the sense that it is also stays below the standard value of 1 in most of the time with a more unstable cyclic behavior. Nevertheless, the weak wage update can not stabilize the economy with a declining population neither.

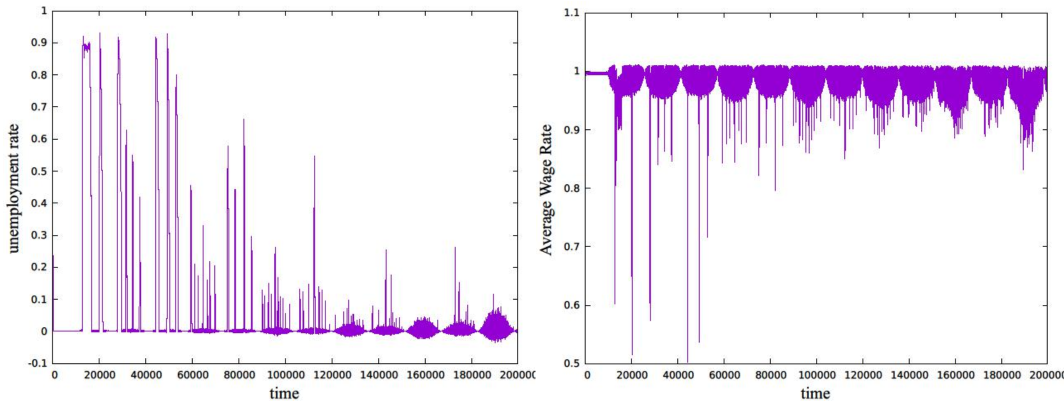


Figure 4.24 R=5,theta=3 of with fix wage update rate for *a*=1, *b*=1 . (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

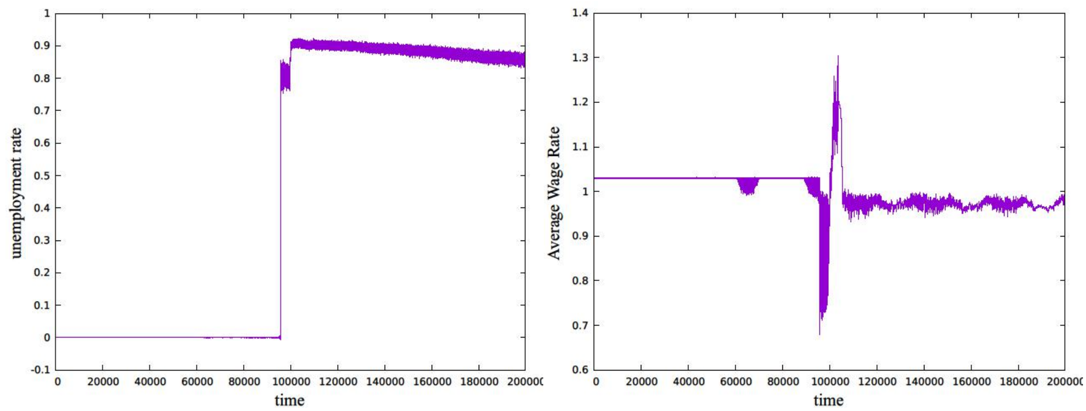


Figure 4.25 R=5,theta=3 of with strong wage update rate for *a*=2, *b*=1. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

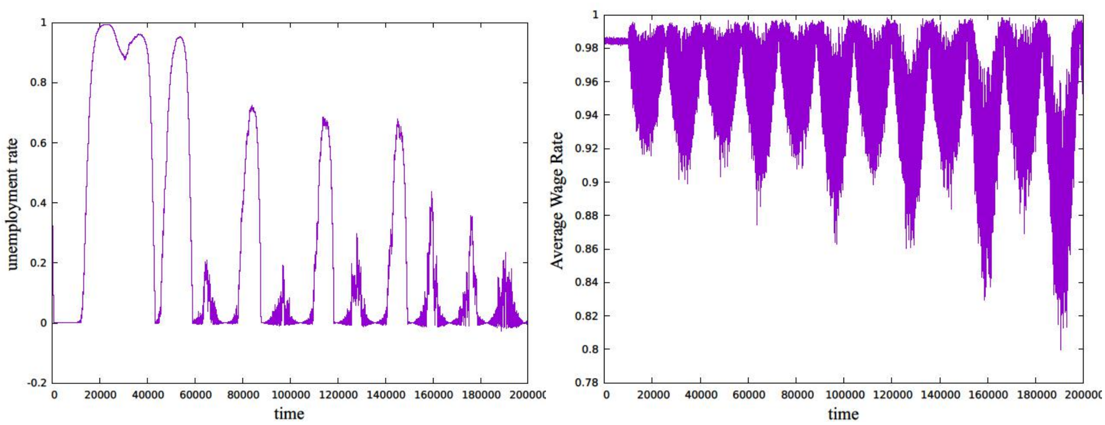


Figure 4.26 R=5,theta=3 of with weak wage update rate for *a*=1, *b*=2. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

Now we will discuss the result of the second part which is composed by the three fixed wage update strategies with an economy in the FE phase and far away from the boundary of FE and EC in the phase diagram.

In Fig. 4.27, the unemployment rate and average wage in the economy are shown for the fixed wage update strategy. Again in the average wage, we can observe a cyclic behavior below the standard wage rate of 1. However with enough credits to buffer the economy from increase in the default threshold of the firms, the economy can maintain a state very similar to the FE phase in most of the time. However, it can also be considered as a standard EC phase as certain big crisis event can occur suddenly. The good thing in this scenario is that the economy seems to be resilient to the crisis as the economy can recover from the crisis. The fix rate update rule together with a high default threshold still creates an EC like phase in the initial FE phase of the economy.

In Fig 4.28, the unemployment rate and average wage in the economy are shown for the strong wage update strategy with a strong fix wage update rule. Again the average wage maintains above 1 for the first period of simulation and then transforms into a cyclic pattern very similar to the case of fixed wage update. As a result, the economy looks very similar to the case of fixed wage update as well. The EC like phase is still prevailing in the initial FE phase regardless of a strong wage incentive.

In Fig 4.29, the unemployment rate and average wage in the economy are shown for the weak wage update strategy. Even with a higher default threshold, a weak fix wage update exhibits a very similar unstable pattern as the one before as if the default threshold is irrelevant.

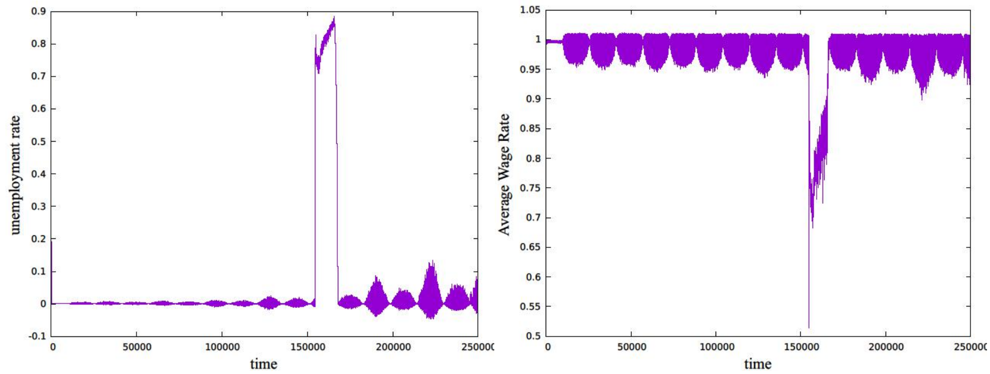


Figure 4.27 R=5,theta=8 of with fix wage update rate. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

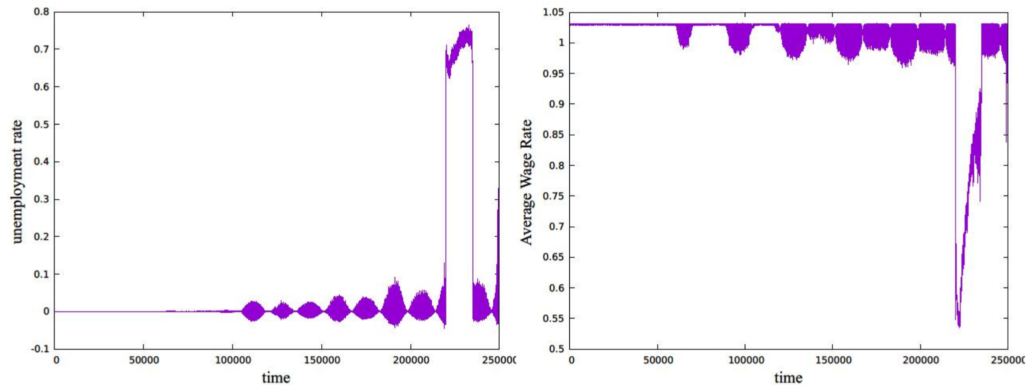


Figure 4.28 R=5,theta=8 of with strong wage update rate. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

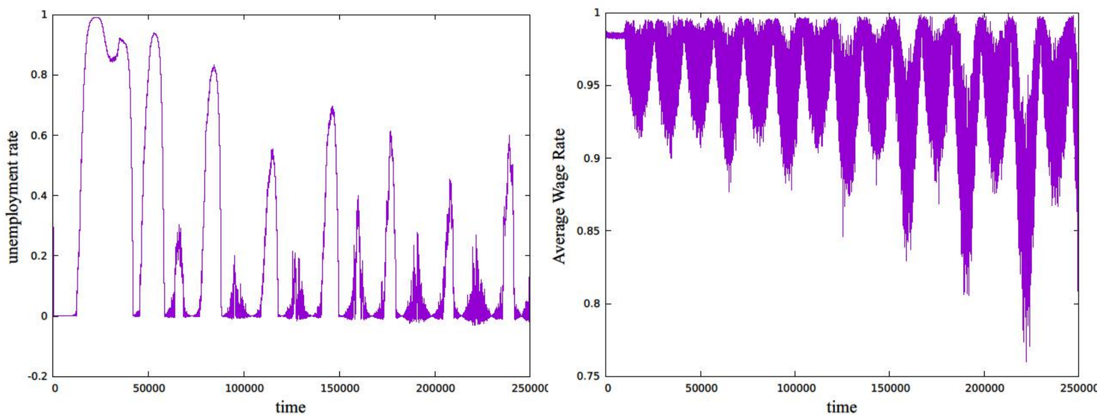


Figure 4.29 R=5,theta=8 of with weak wage update rate. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

4. 3. 3. 3 Trend Following Wage Update

In this section, the results of trend following wage strategies are shown.

In Fig 4.30 and 4.31, the results of an economy located near the boundary of FE and EC phase but in the FE side are shown. We can see both trend following behaviors have induced a transition from full employment to a high unemployment state. In particular, the weak trend following case experiences a transition to FU phase. The observation on the average wage in the two cases revealed totally different trends. In the trend following case, the wage becomes extremely high to adapt to the crisis, whereas in the weak trend following case, the wage steadily drops to the low value as a response to the crisis event. Nevertheless, for both cases, the economy is highly unlikely to recover itself, even in the trend following case where the economy is still alive in a high RU phase.

In Fig 4.32, the trend following case for an initial FE phase with a higher default threshold are shown. The difference in the average wage can be observed as in the trend following case. The average wage stays more above the standard wage rate of 1 and the cyclic behavior shows a upward trend. However, regardless of the difference in the wage pattern, in terms of the unemployment and crisis occurrence of the economy, we can see that the trend following wage update is very similar to the fixed wage update when a higher default threshold is set for the economy. Still, the FE phase can not be obtained but only an EC like phase prevails.

To summarize the above scenarios, the best scenario is to combine a strong wage incentive with a high default threshold, which gives us an EC like phase out of an initial FE phase. The wage incentives alone can not prevent the new type of crisis from arising inside an initial FE phase. It seems that in a depopulation economy, a new type of economic crisis could occur suddenly even in the FE phase of the economy.

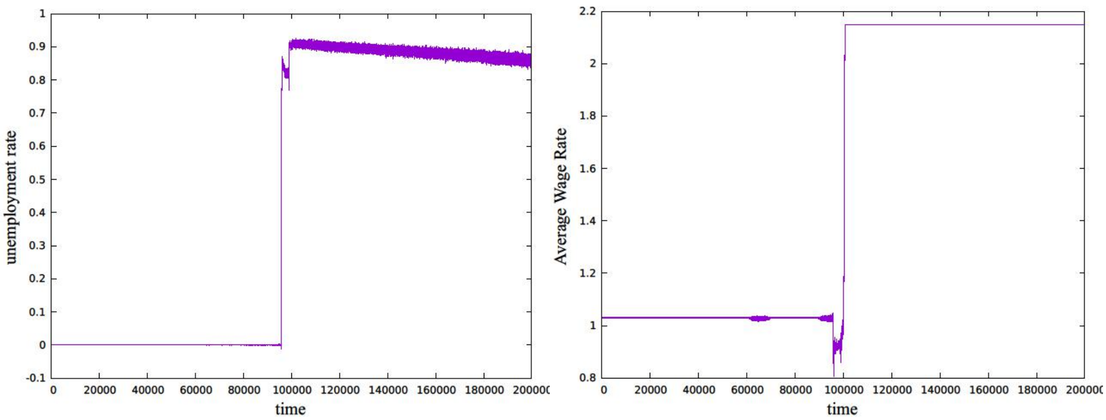


Figure 4.30 R=5,theta=3 of with trend following wage update rate for *a=u*, *b=e*. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

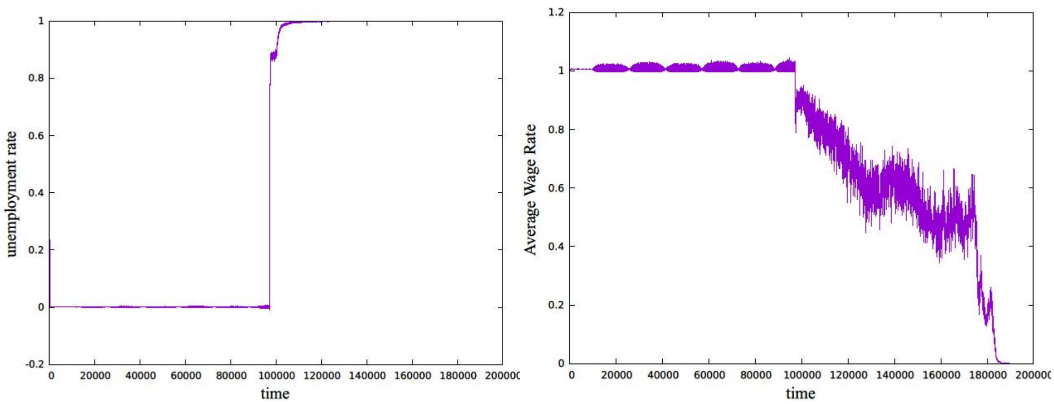


Figure 4.31 R=5,theta=3 of with weak trend following wage update rate for *a=u/2*, *b=e*. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

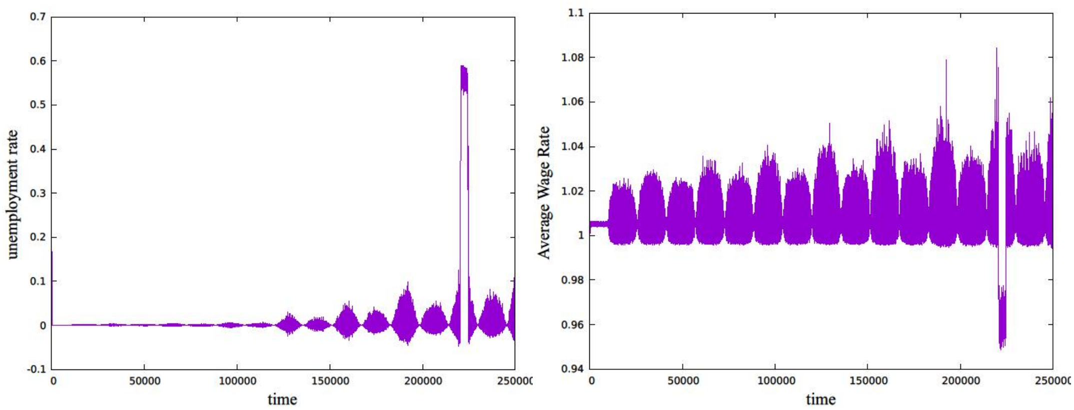


Figure 4.32 R=5,theta=8 of with trend following wage update rate. (Left) the unemployment rate due to the population dynamics and wage update. (Right) the wage dynamics in the current settings.

4. 3. 4 Discussion

The results in this section reveals the possibility of a new type of crisis occurrence because of the population decline, which is warned by Keynes (1937). Furthermore, it seems that the results indicates the ineffectiveness of wage update policy in a depopulation economy to avoid the risk of crisis. In this discussion, we focus on the reason of the occurrence of the new crisis and the ineffectiveness of the wage update to provide more insights on the simulation results.

A plausible explanation based on the common belief might be the decreasing consumption propensity in an depopulation economy. Fig. 4.33 shows that for different strategies and different default threshold, the consumption propensity looks similar in the decreasing trends. However, this is not the real reason based on our theory. The reason for the "inevitable occurrence of crisis" is in chapter 3. We already know that the cluster of the indebted firms have a saturated debt ratio as shown in Eq. (24). However, as in the case of shortage of labor, the unemployment can be asymptotically approaching to zero level. In the limit condition, it implies that the already developed cluster of firms now can travel to infinity of debt ratio in theory. Therefore, the cluster will hit the default threshold given enough time as if the EC phase dominates the whole FE phase. In this sense, the economic crisis occurrence in a depopulation economy is inevitable. It is not because the drop in consumption level due to population decline, rather it is because the cluster of the firms can reach a higher debt ratio. Since the reason is not the consumption side, then it makes no essential difference in wage update scenarios which only affect the household consumption but not the self-organization of firms.

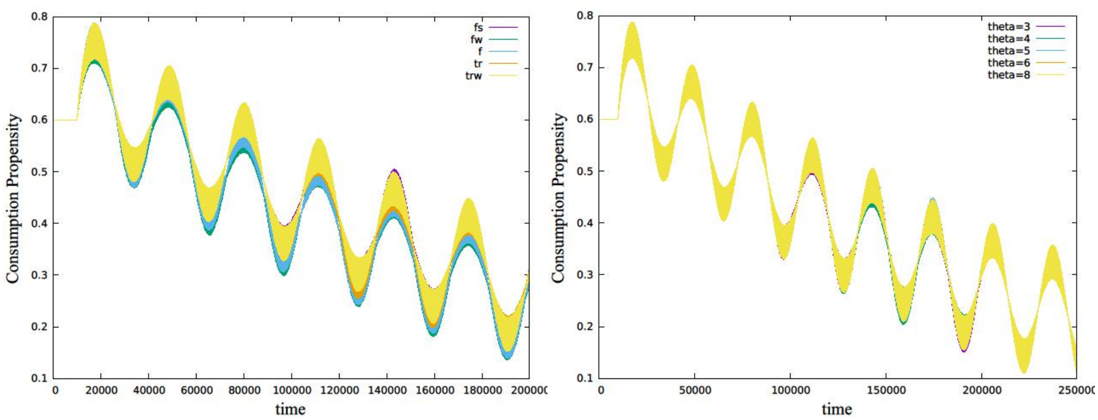


Figure 4.33 R=5,theta=3. The consumption of propensity is decreasing. (Left) comparison based on five strategies (fs, fw, f, tr, trw). (Right) comparison among different default threshold (Θ = 3,4,5,6,8).

4.3.5 Summary

By the simulations of population decline scenario with different wage update rules, we mainly achieved three important insights.

First, we discover that the population decline can induce new type of crisis even in the initial phase of FE. The FE phase is no longer immune to the crisis occurrence in a depopulation scenario.

Second, we show that the intuitive remedy for the population declining as the wage incentives can not work in the model simulation. Though we show that the consumption of the household is indeed declining and the different wage update scenario can have different impacts on the wage pattern of the economy, the instability problem induced by depopulation can not be solved by give more wages to the household in order to stimulate the consumption level. Therefore, it refutes the intuitive policy in the form of wage updates.

Finally, we utilized the theory in chapter 3 to explain why the new crisis can take place and why the decline in consumption due to the depopulation is not the reason for the new crisis occurrence. In particular, we showed that in a case of extreme shortage in labor, the region of EC is prolonged to infinity in theory, where the FE disappears. Therefore, the cluster of indebted firms can reach any default threshold given enough time. This in turn triggered the new type of crisis.

The results in this section demonstrate an “inevitable crisis occurrence” in the long period of labor shortage. It indicates the labor shortage should be addressed properly with the debts of the firms so that the cluster of indebted firms are not overdeveloped.

4. 4 Firm Adaptation and Crisis

4. 4. 1 Background

When the adaptation is considered, we usually consider a slow, adjusting process which is usually termed as “evolutionary economics” after schumpeter considered the technology factors in the process of economic development. As pointed in Fagerberg(2003), the constant innovation and imitation among firms in an economy provide “window of opportunities” for firms on one hand and the “clustering” of firms sharing the same technological contents on the other hand. The learning behavior of firms as the accumulated experience can form an evolutionary path for the states of the whole economy.

The adaptation of firms in their strategy is the essential behavior of firms and a very important issue to the business (Cyert & Kumar (1996)). Firms try do adapt and survive in the economy with different strategies involved. The study about firms behavior has been an active area before ABM comes out. For example, in (Cyert & March (1963)) they conducted a study on firms behavior by concluding a theory. In (Dunn, 1971), it links the socioeconomic development with the process of learning. After that, adaptation has build its importance in economics such as in (Lucas,1986).

In an ABM, the macro-level dynamics can exhibit complex pattern due the the memory and interaction among heterogeneous agents. The excess volatility and clustered volatility can be observed (Hommes (2008)). The asset price fluctuations can exhibit irregular and unpredictable patterns as indicated in Galati and Moessner (2013).

In our study, we are particular interested in the adaptation behavior of firms and its relationship with stability of an economy. Particularly the key question is that how the short term survival of a group of firms to the long term prosperity of the whole economy. For example in (Schindehutte & Morris, 2001), it discusses the strategies and the survival of small firms in an economy. This is a very important issue in our model, since the crisis in our model is a chain reaction of the firms. In the case of a large number of small firms can not survive, the crisis occurs. Our main objective is to combine the ABM study (Holland and Miller,1991) and resilience study (Pike et al. (2010)) to discuss the adaptation of firms to seek a stable economy.

4.4.2 Model Modification

In this section, we discuss two big categories of adaptation behavior in firms and their impact on economic stability. The first type is imitation, which represents firms learn the target firm and mimic its pricing behavior to try to achieve their target. In the imitation, particularly, we will discuss two cases:

1. Profit based imitation

In this category, certain amount of firms check the profit of all the firms in the economy and always copy the price of the most profitable firm. Therefore, at time step *t*, for a subset of firm *i*, we replace the price update in Eq.(4-5) as follows:

$$p_i(t) = \{p_j(t) \mid P_j(t) \geq P_k(t), \forall k\} \quad (30)$$

2. Asset based imitation

In this category, certain amount of firms check the asset of all the firms in the economy and always copy the price of the firm with most asset. Therefore, at time step *t*, for a subset of firm *i*, we replace the price update in Eq.(4-5) as follows:

$$p_i(t) = \{p_j(t) \mid A_j(t) \geq A_k(t), \forall k\} \quad (31)$$

The second type of adaptation, is individual adaptation. We use the profit based adaptation to refer to certain group of firms only focuses on the maximization of profit of itself. The firms in this group will check their expected profits by increasing and decreasing the price and choose the best direction to change the price otherwise it remains the same price, as shown in Eq. (32).

$$p_i(t) = \{p(t) \mid Max(P_i(p = p_i - \Delta p), P_i(p = p_i), P_i(p = p_i + \Delta p))\} \quad (32)$$

We can further group the profit based imitation and the profit based individual adaptation as profit based strategy, while the asset based imitation as the asset based strategy.

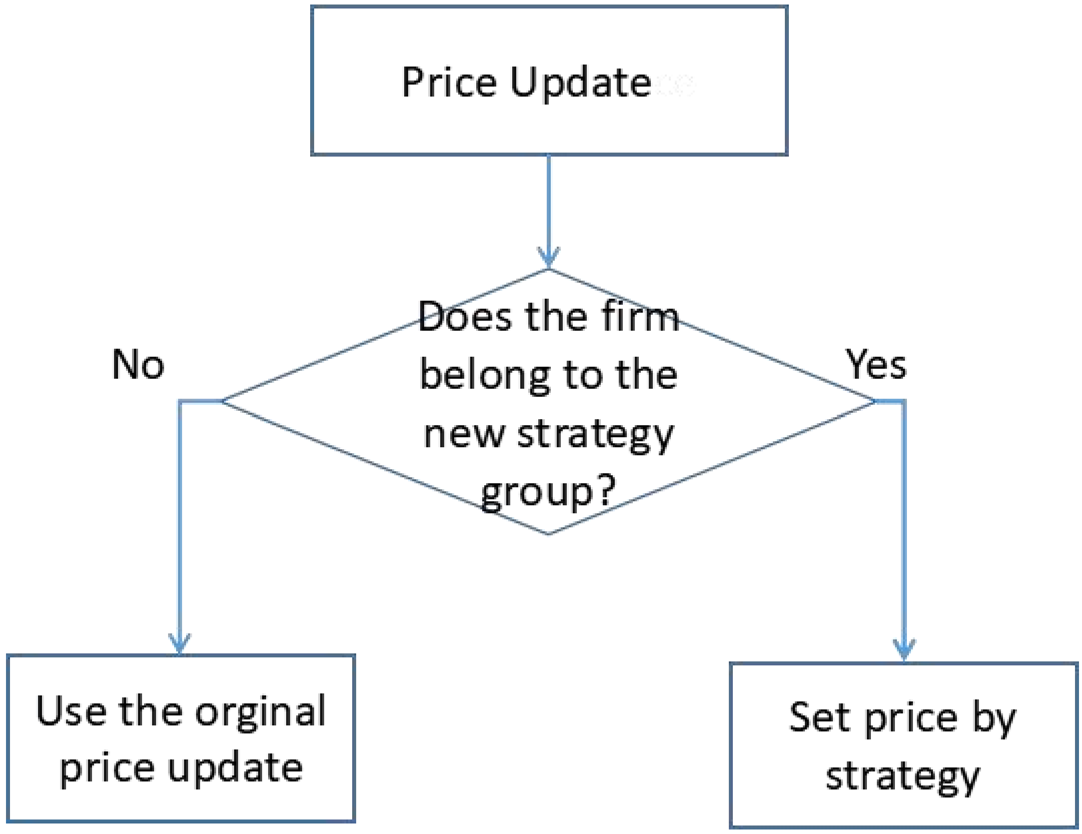


Figure 4.34 The chart flow of model extension with different firm strategies in Mark0.

In Fig. 4.34, the extension of the original model is illustrated. In particular, we compare two scenarios for each strategy, with one economy only dealing with a small amount of the new strategic firms and the other one dealing with a significant amount of the new strategic firms. The goal of this arrangement is to see the whether the transition of the economy can occur because of the increase in the strategic firms.

The maximum number for alive firms in the economy is set to 5000 (the actual number of alive firms could be much smaller than this number due to the bankruptcy of clusters in crisis). We first set 100 firms in the economy to represent the small amount of firms with the new strategy, and 500 firms to represent the significant of firms with the new strategy. However, if no much difference can be observed between the 100 and 500 settings, then the number will be further increased until a significant difference in performance of the economy can be observed.

4. 4. 3 Results

4. 4. 3. 1 Baseline Scenario

In this section we show the baseline performance without any new strategic firms. The purpose for this

From Fig 4.35, an EC phase of an economy is shown with the control parameters R=2, theta=10, together the average price dynamics and total asset as well as total firm savings which only includes the firms with positive asset as a reference point. We can see that the average asset is around zero level and the total firm savings are smoothly increasing before a crisis strikes.

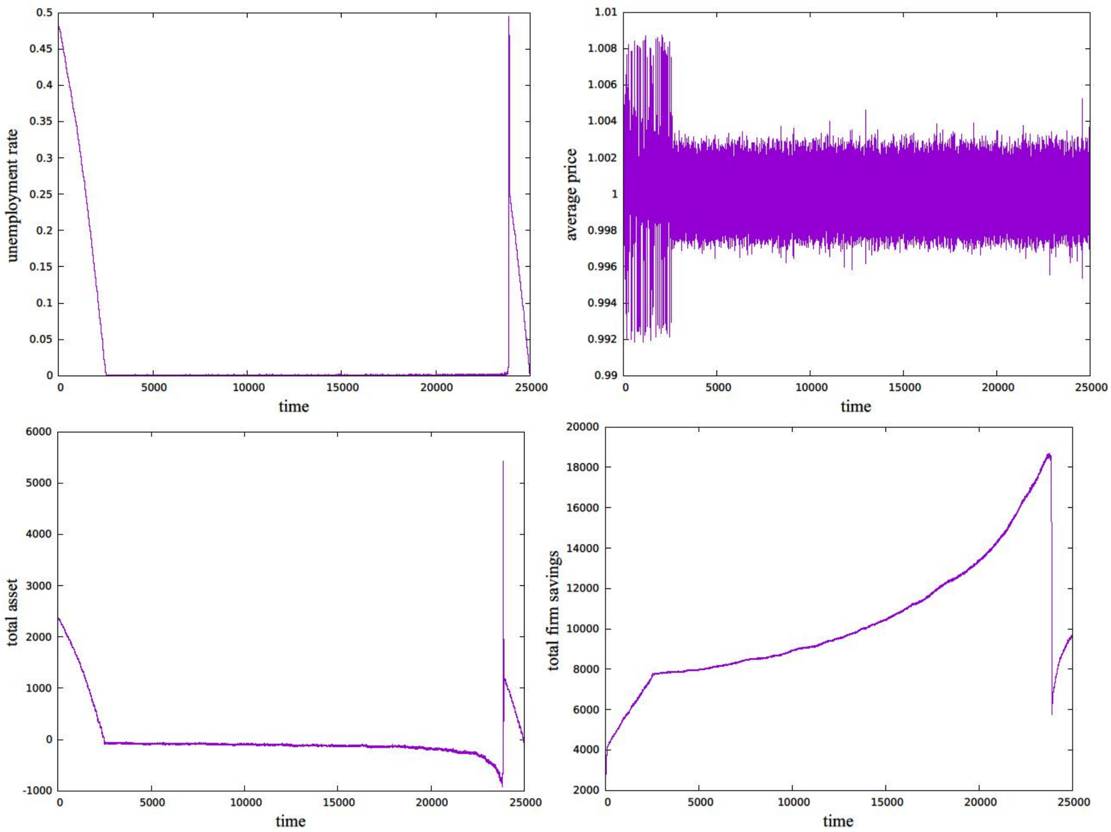


Figure 4.35 R=2, theta=10 baseline for EC phase. (Top left) Unemployment rate (Top right) Average price. (Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

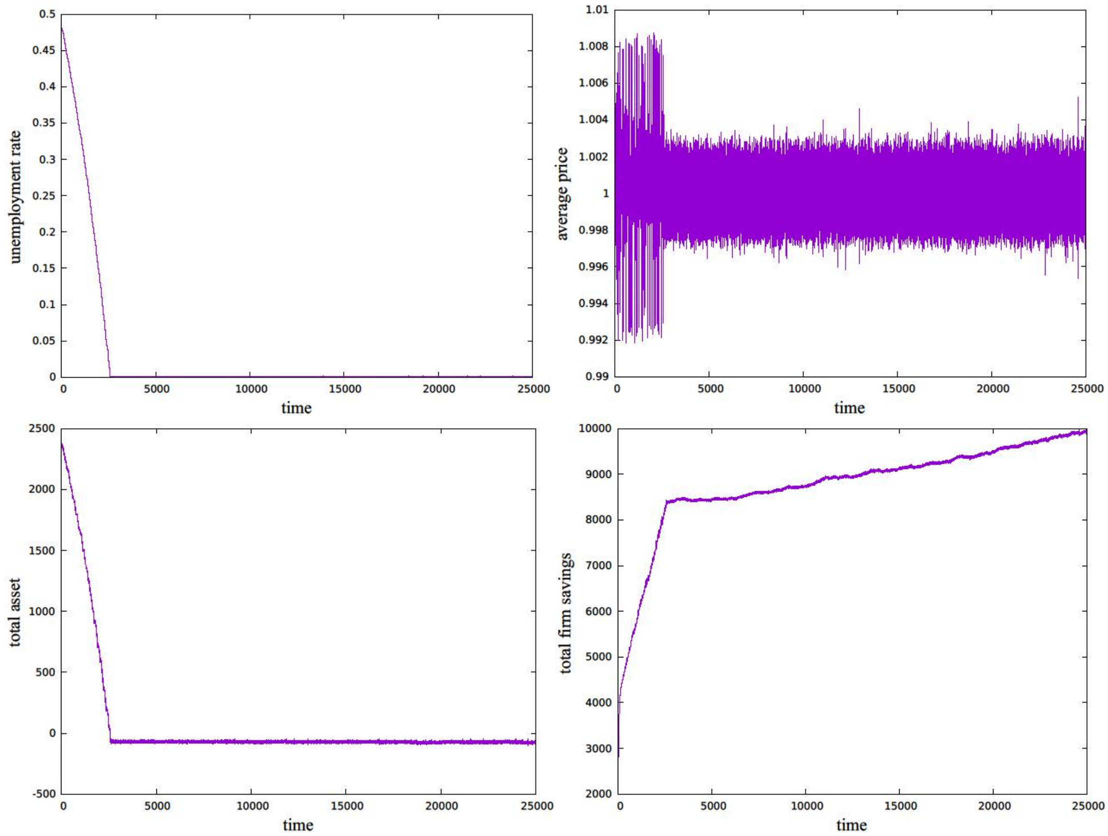


Figure 4.36 R=2, theta=15 baseline for FE phase. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

In Fig 4.36, an FE phase which in particular is close to the boundary of EC phase and FE phase is shown together with the average price dynamics and total asset as well as total firm savings. Because it is still in FE phase, we can observe the full employment state and a very stable total asset around zero level. Interestingly, the total firm asset is still smoothly increasing until it can reach an equilibrium state. This also implies the self-organization of clusters in the economy even in the FE phase for the profitable firms continue to gain profit and the indebted firms slowly accumulate their debts. The two cluster emerged in an initially random economy proves the self-organization of structure and the order establishment in the economy.

4.4.3.2 Profit Based Imitation

In this section, we study the effect of a profit based imitation behavior. We will study two cases: the first case with 100 firms in the economy adopting this strategy, the second case is 500 firms adopting the strategy. Note that the maximum alive firms in the economy is 5000.

The results shows that even for a small number of profit based firms, as in Fig 4.37, we can spot a stronger EC behavior compared with the baseline scenario as in Fig. 4.35. Especially, the price experiences large shocks during the crises. The reason for the crisis enhancement effect of the profit based imitation is that it only increases the positive asset firms by reducing profits of the others and creates bubbles in their asset, which can be seen in the rapid increase in firm savings of the profitable firms.

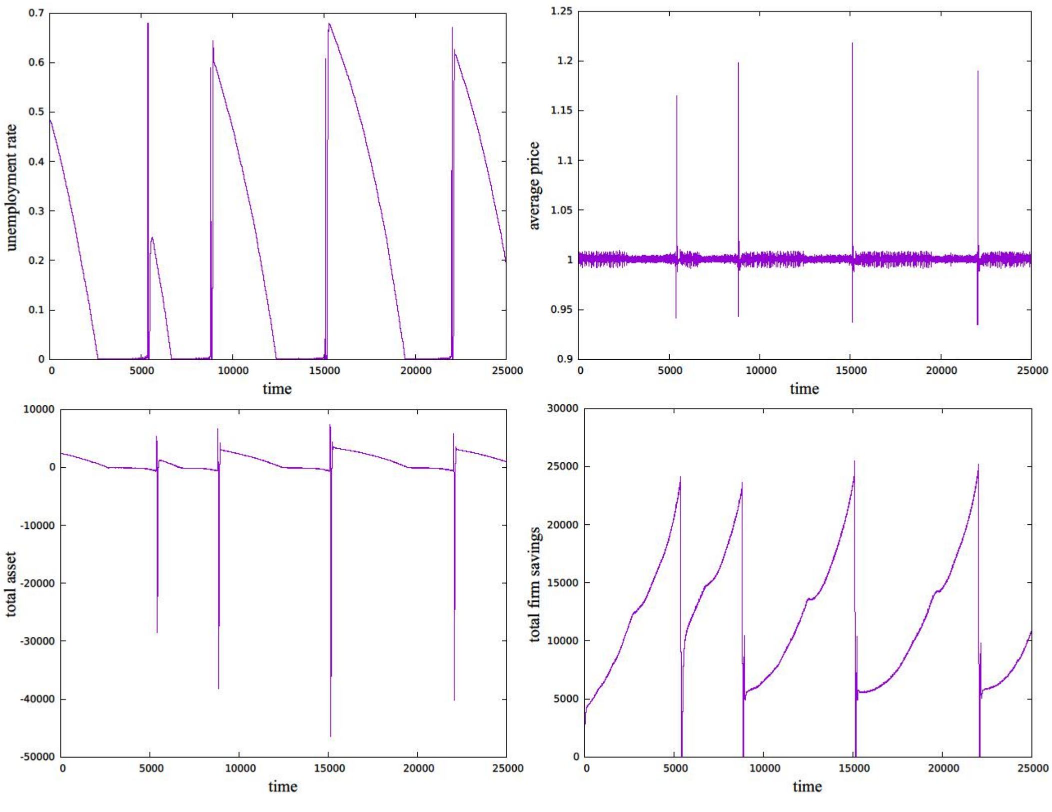


Figure 4.37 R=2, theta=10 for 100 firms out of maximum 5000 alive firms with profit based imitation for enlarged EC region (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

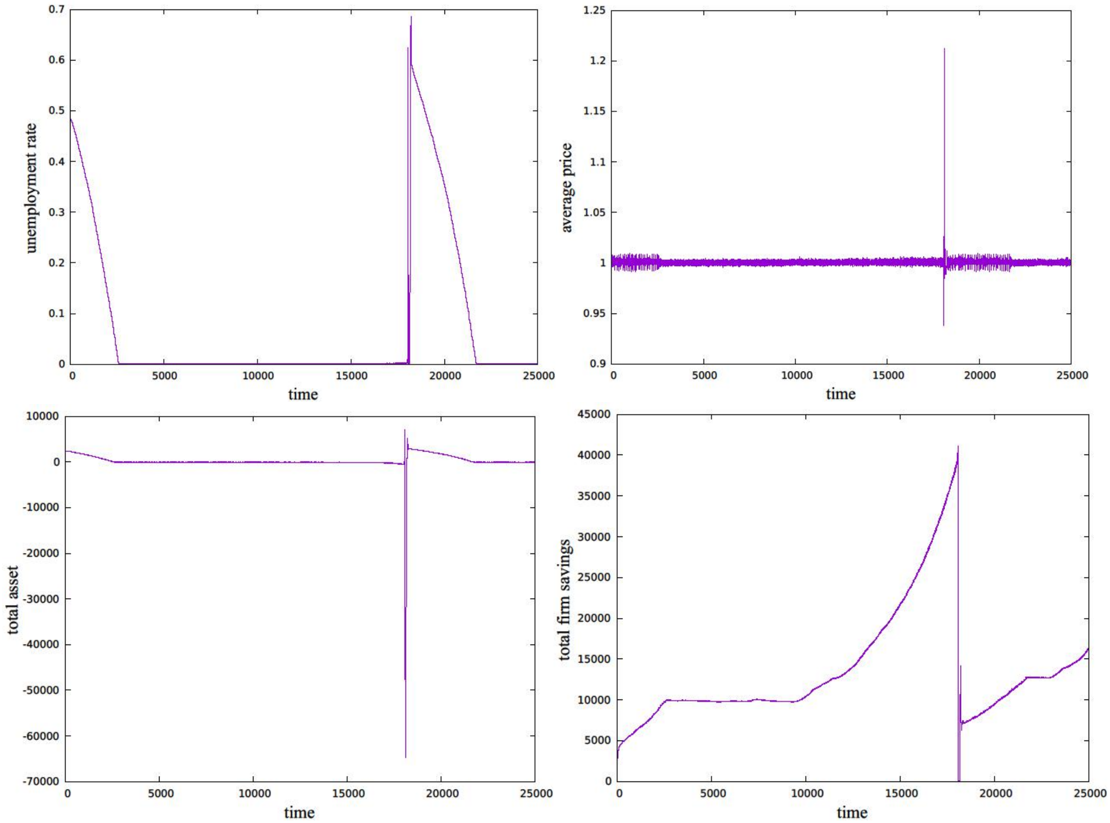


Figure 4.38 R=2, theta=15 for 100 firms out of maximum 5000 alive firms with profit based imitation for enlarged EC region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

In Fig. 4.38, the results again confirms a enlarged area for EC to emerge comparing to the baseline scenario which should be a FE phase as in Fig. 4.36. Again we can observe the shock to the price. And a sudden rapid increase in the firm savings after a stable period. The successful search for profitable strategy creates a bubble like increase in the firm savings of those profitable firms and finally the economy crashes as the bubble breaks.

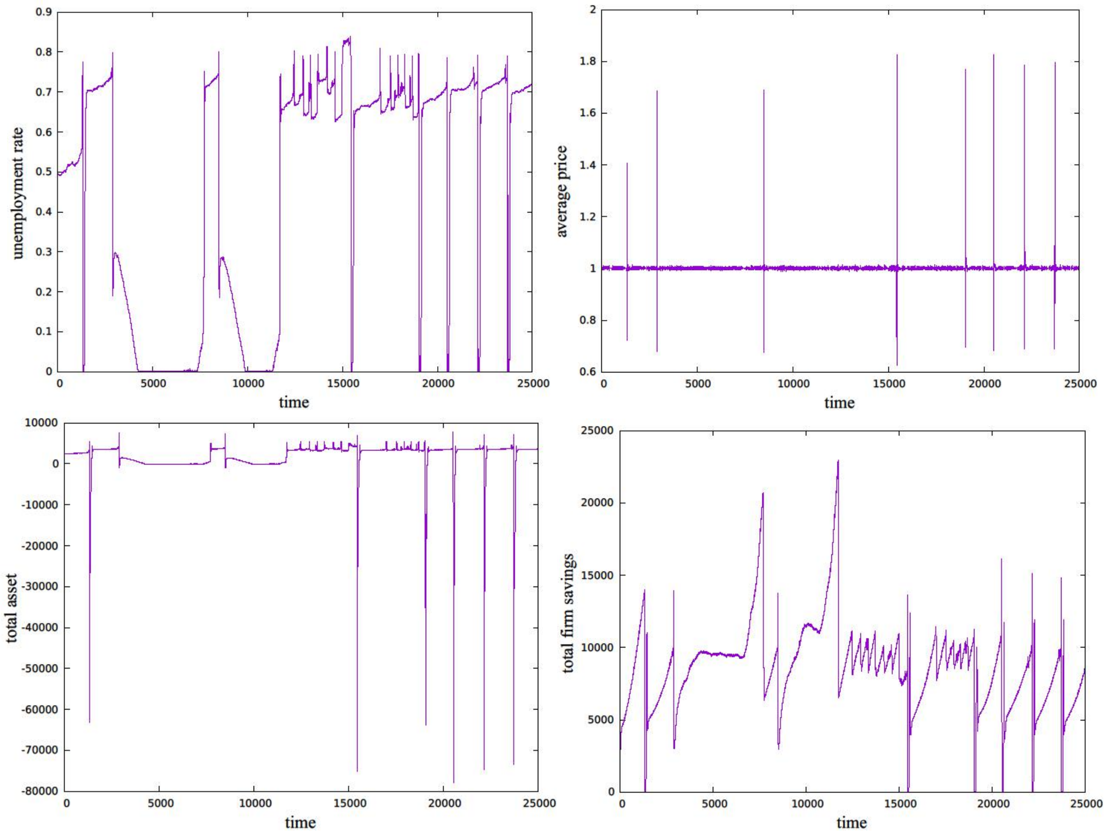


Figure 4.39 R=2, theta=15, for 500 firms out of maximum 5000 alive firms with profit based imitation for enlarged EC region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

As the number of imitation increases to a significant number of 500 in the second case, in Fig. 4.39, we can observe a distorted violent crisis behavior which is very close to full unemployment. The price shocks happens more frequently and the firm savings for the profitable firms exhibits more spikes as the fast development of bubbles. When a significant number of firms are seeking profit, the economy loses its stability and those firms can not gain sustainable profit either.

4.4.3.3 Asset Based Imitation

In the asset based imitation, a small number does not make much difference. Therefore, we will compare the case with 500 firms imitation and 2500 firms imitation, which gives enough difference for the comparison.

In the 500 firms case, Fig. 4.40 demonstrate an EC phase of the economy. We can observe a very similar scenario as baseline in Fig. 4.35 from the unemployment rate. However, asset based imitation does have some effect on the adjustment of firm saving dynamics but still not enough to change the phase behavior.

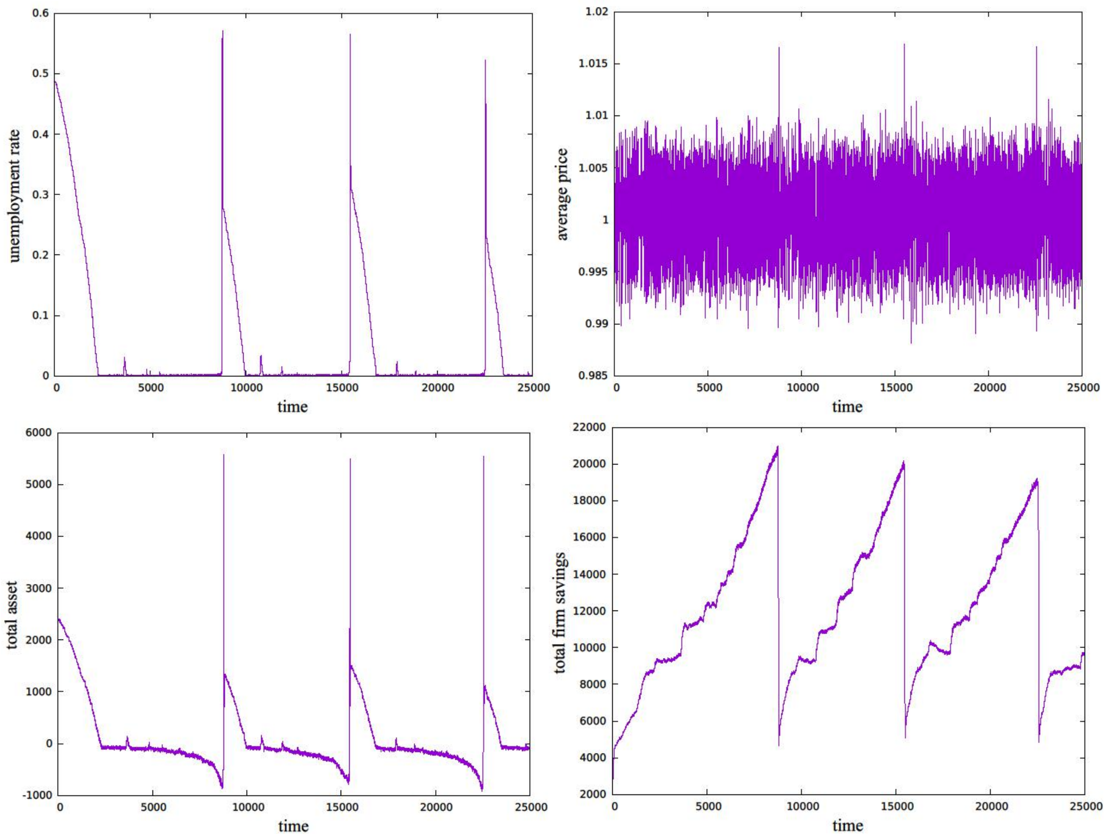


Figure 4.40 R=2, theta=10 for 500 firms out of maximum 5000 alive firms with asset based imitation for EC region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

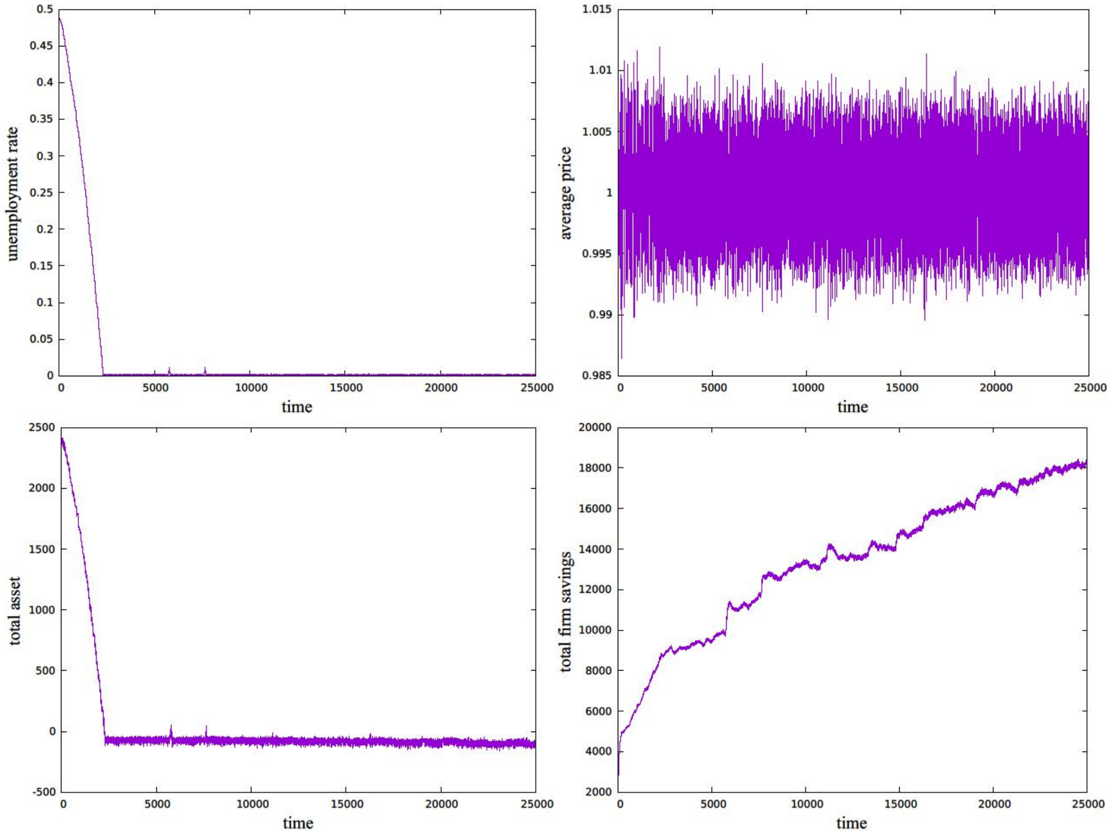


Figure 4.41 R=2, theta=15 for 500 firms out of maximum 5000 alive firms with asset based imitation for enlarged FE region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

Further comparison between Fig. 4.41 and the baseline in Fig. 4.36 still reveals a similar FE pattern. Although from the firm savings, we can still observe some small adjustment but it is not enough to alter the phase behavior. We can see, even with more than 10% of firms with the asset based strategy, the economy does not change as if the asset based firms are invisible for their presence inside the economy.

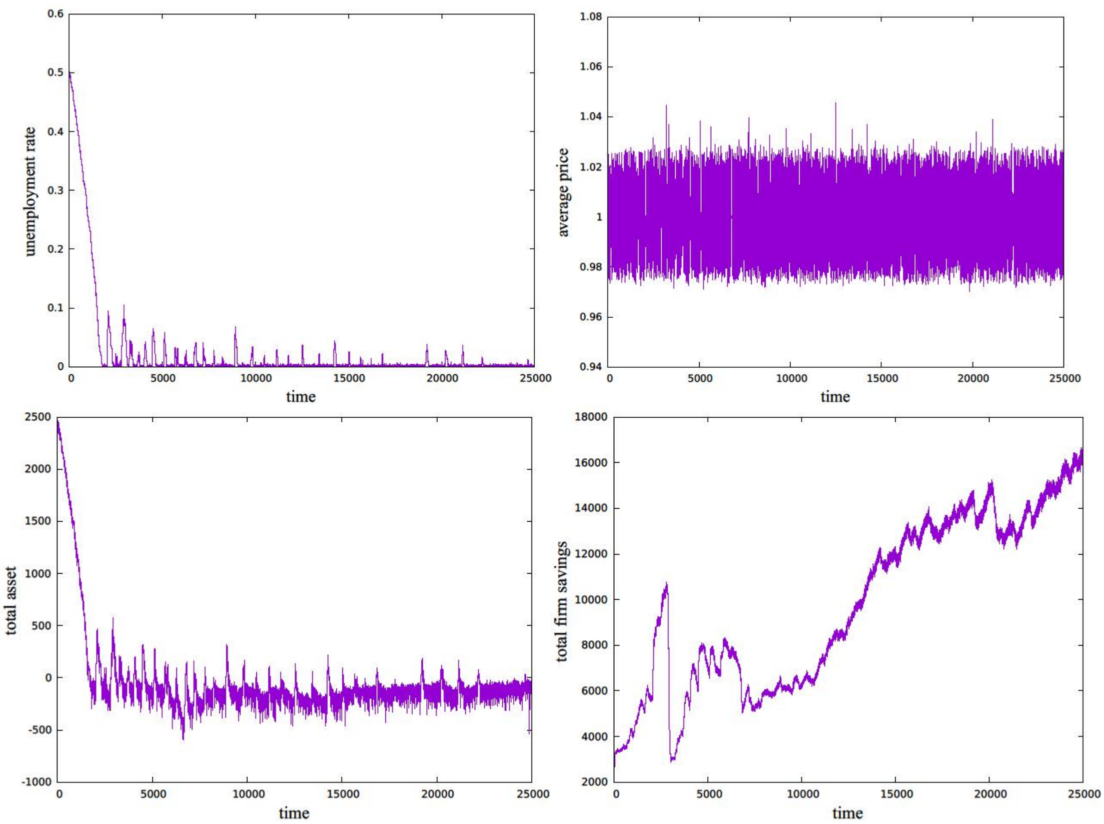


Figure 4.42 R=2, theta=8. 2500 firms out of maximum 5000 alive firms with asset based imitation for an almost FE region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

However, in the 2500 firms case, even for theta=8 which should be in the EC phase, we can observe a stabilizing effect to an almost FE like phase. Especially, through the total firm saving adjusting behavior, we can see that the firm savings are no longer monotonously increasing. For some period of time the firm savings are even decreasing. The overall effect is a steady increase in firm savings without the risk of bubble break. In fact, the bubble is prevented by the global and long term optimization of all the firms in the economy through asset based imitation.

It should be noted that the asset based imitation can only start to impact the economy with its positive stabilizing effect the consequent sustainable growth when the proportion of the firms are significantly large (more than 50% of the economy), whereas a small amount of firms with the asset based imitation can not impact the economy.

4.4.3.4 Profit Based Adaptation

In the profit based adaptation behavior, we still consider two cases: 100 firms or 500 firms with the adaptation strategy. In Fig 4.43, we can observe an enlarged EC region if we compare with Fig. 4.36 which should be in the FE phase. Even for a small number of firms with the profit based adaptation, the EC region is significantly extended. We can also observe the bubbles in the firm savings of the economy. However, in this situation, even the total asset exhibits a crisis like behavior which further indicates that the profit based adaptation accumulates more profit than the profit based imitation, with the result in triggering shocks in the total asset of the economy.

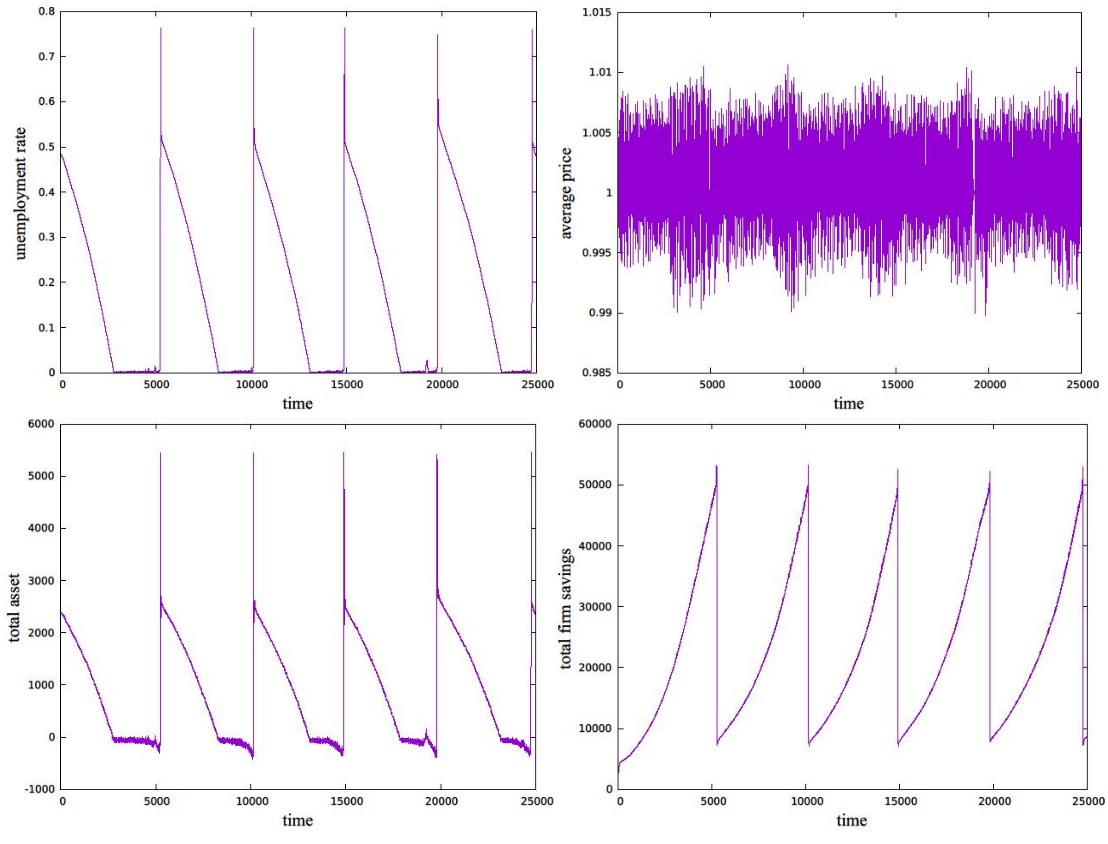


Figure 4.43 R=2, theta=15 for 100 firms out of maximum 5000 alive firms with profit based adaptation for enlarged EC region. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

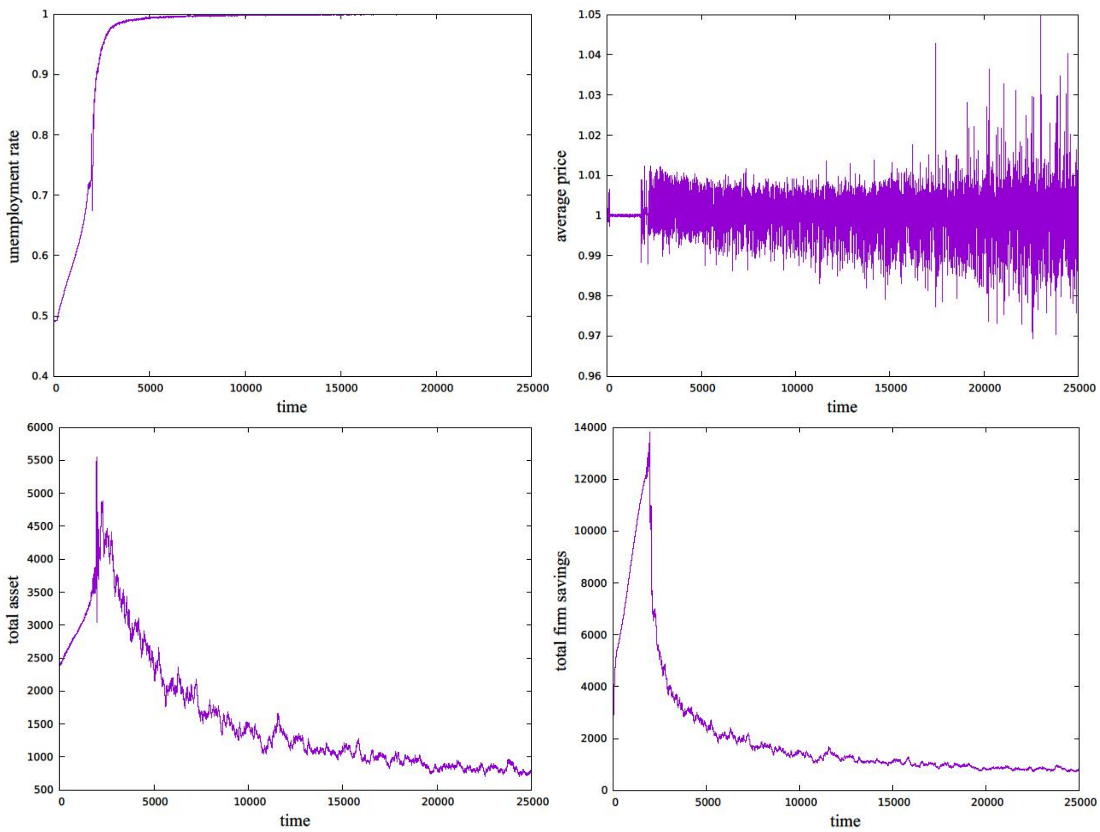


Figure 4.44 R=2, theta=15 for 500 firms out of maximum 5000 alive firms with profit based adaptation for a sudden collapse of the economy to FU phase. (Top left) Unemployment rate (Top right) Average price.(Bottom left) Total asset (Bottom right) Total firm savings only including firms with positive asset.

In the case of 500 firms adaptation, the economy undergoes a transition process from an FE phase to a FU phase with a three time firm savings increase before the shift happens. Both the asset and the firm savings exhibits the pattern of a huge bubble. The extreme profit oriented behavior abstracts the money from the household sector to the firms sector which breaks the balance of demand and supply. As a result, the economy collapse into a FU phase.

4.4.4 Discussion

Bak et al. (1997), Cont and Bouchaud (2000) discussed about the interaction of market participants through imitation and they found that huge fluctuations in aggregate demand can be incurred. Cont and Bouchaud (2000) also defined the "crowd effects" and associates it with the fluctuations in price. This "crowd effect" is the outcomes of the clustering mechanism through self-organization in a market or in an economy as shown in chapter three. About herd behavior in the real market, several studies has demonstrated this point as in Scharfstein and Stein (1990), Trueman (1994), Grinblatt et al. (1995), Golec (1997). For example, The imitation behavior also brings theoretical interests in using the "crowd effects" to explain the excess volatility in the market (see examples in Topol (1991), Bannerjee (1993), Orléan (1995)). Bikhchandani et al. (1992) also introduced a concept of "information cascades" to give theoretical insights on the behavior of agents.

Bak et al. (1987) introduced self-organized criticality and later in Bak et al. (1993) an economic system model with the this property is introduced. Later, Lux and Marchesi (1999) also adopted this concept to give theoretical insights to the herd behavior. Cont and Bouchaud (2000) explains the crash of the system is from the the collapse of the giant cluster with only a short lifetime. They also emphasized this is not a stable state that the market can restore itself to the normal state when the disbelief and fear fade away. This is actually the basic mechanism for the modification of the bank behavior in disbelief and restoration on the credit supply. Furthermore, they termed this type of dynamics as a process with "repulsive" feedback besides attractors. In chapter 3, we illustrated a similar process with both an attraction (the control parameter employment propensity, see section 3.2) and repulsion (the control parameter default threshold, see section 3.3) during the peace period of FE phase. As Cont and Bouchaud (2000) claims "a nonlinear coupling between the two competing process can form a control mechanism which maintains the critical region".(In section 3.2, this critical region is realized by the self-organization to cluster process)

Besides clustering, the threshold is also considered as a key theoretical element for the collective phenomena in economic systems. As an example, Granovetter (1983) studies a threshold models and considered the threshold mechanism as an origin of the emergence of macroeconomic phenomena.

Again, we apply the basic clustering mechanism in chapter 3 to discuss the difference in firm strategies in their impacts in the system stability and the crisis occurrence. In both of the profit based strategies, the firm cluster are formed based on the most profitable pricing conditions. Once this cluster starts to gain profits, they will search for more profit at next time step. The result is an accelerating process of cluster formation in one side with the most profitable firms, and in the other side it pushes the clustering of the indebted firms. This is the reason that the profit based strategies causes more unstable economy.

On the other hand, the asset based imitation searches for the best long term strategy for the accumulation of asset. The cluster is formed to adapt itself with the possibility to lose profit temporarily. As a result, this cluster serves as a buffer which can both release their profit to the economy and absorb the profit from the economy. Because this buffer effect, the distance between the extremely profitable firms and deeply indebted firms is reduced to a more uniformly distributed economy. However, for the buffer cluster with asset based imitation can dominate the two extreme clusters, the precondition is that the size of it should be big enough so that it can attract the two extreme cluster towards itself. This also explains why a small number of asset based strategic firms seems to be invisible in the economy.

4.4.5 Summary

In this section, we discuss the adaptation or strategy of firms and its impact on the stability of the economy. In particular, we find that the profit based strategy can harm the economy even with a small number of agents trying to seek the profit. The reason for this effect is that the profit based strategies enhance the formation of the two extreme clusters which are the cluster of most profitable firms and the cluster of deeply indebted firms. The results indicate that the profit based strategy is not good to the stability of the economy especially when the strategy only optimize its local profit.

On the other hand, the asset based strategy can stabilize the economy but it requires a large number of agents doing so to make a difference. For a small number of firms with the asset based strategy, the effect can be neglected.

The results in this section demonstrate the difference in firm strategies and the proportion of firms with the same strategy can affect the stability of the economy. The recommendation could be to develop policy which increases the number of firms with asset based strategies to introduce the buffer cluster for prevention of crisis occurrence.

Chapter

5. Conclusions

On the outcomes of this study, the theoretical insights on the general model reveal that the endogenous crisis state does exist in a modeled economy, which can also be observed in simulations where the sudden unemployment shocks arise in the so-far quiescent economy unexpectedly and repeatedly. The significance of discovery of the endogenous crisis in a general economic system is twofold: it proves that the fundamental crisis mechanisms can root inside the basic settings of our socioeconomic system rather than the previously believed external shocks or behavior of investors. What is more, its presence cannot be studied in the normal resilience framework, for the presence of shocks can still cause large scale negative effects on the society because of its uncertainty, regardless of the fact that the economy can eventually recover from these shocks. This imposes the necessity of a new explanation for the mechanism of this kind of endogenous crisis occurrence. By further exploring the phases of the modeled economy in parameter space and studying the critical values for transitions between the endogenous crisis phase and other phases in the economy, we theoretically prove the mechanism of the endogenous crisis in the modeled economy is a self-organized clustering phenomenon controlled by an economic variable called diminishing debt ratio gap of firms. The covert nature of this self-organization with an irreversible transition process to crisis is embedded in a subgroup of deeply indebted firms, which causes the sudden burst-and-bust effect. Besides, another phase transition mechanism has also been theoretically demonstrated by the demand-supply gap in another subgroup of firms sharing irreversible features. By applying these general insights, we further investigate different key factors in various sectors of a socioeconomic system, such as the precautionary saving behavior of household, the macroeconomic policy by banks, the profit tax control by government, the wage variation due to population change, etc., which can either trigger new crisis or control the crisis phase from emergence.

In chapter 1 we introduce the background of this study. We firstly introduce the history and studies of crisis in a socioeconomic system. Starting from Malthus, the studies on crises in human society have shaped themselves into a growing transdisciplinary field which brings together the macroeconomics, system dynamics, econophysics, catastrophe theory, chaos, complex system and agent-based social studies. The empirical evidence of economic crisis occurrence has been revealed, followed by the famous discussion on the incapability of macroeconomic theory. The failure of traditional economic theory to address systematic crisis is shown with the unrealistic perfect rationality and optimization strategy of homogeneous agents such as in the DSGE. In summary, the traditional economic theory only includes equilibrium without any mechanism for sudden collapse of the system. Then the chaos and catastrophe theory entered territory in hope of provision of explanation and solutions to the crisis in our socioeconomic system. The reasons behind 'boom and bust' of catastrophe theory on crisis study in history are discussed. However, the unnecessary conditions imposed on the application of catastrophe theory such as the existence of a potential function limit the further application of catastrophe theory in studying economic crisis. Other alternatives, such as evolutionary economics with adaptive transformations and system dynamics with simulation in 'The limits to growth', are also reviewed to mention their contribution to deepen the understanding of crisis occurrence. With the lessons learnt from all the above fields, econophysics emerged as an independent field equipped with statistical methods and agent-based models. While the statistical econophysics deals with another extreme situation so called interaction among 'zero intelligence agents' without theorizing the behavior rules of the agents, the agent-based econophysics realized a more realistic micro-foundation with bounded rational heterogeneous agents. In the current stage, most of the literature regarding the future direction of crisis research has pointed out that the econophysics together with agent-based model to be the most promising candidate in shaping our profound understanding about the micro-foundation and the mechanism of crisis occurrence. Furthermore, to better address the theoretical interpretation in the agent-based econophysics model, we introduce another new field of complex system. In particular, we adopt the key concepts such as self-organized criticality to form a unified approach to study crisis in a socioeconomic system. Although the future direction of crisis research is one of the main field in which econophysics is suppose to address, currently the research is actually very few for it is just started. To bridge this research gap and contribute to new knowledge directly on the crisis occurrence and socioeconomic system stability, we explicitly set our objectives as to be a pioneer agent-based econophysic crisis study, in order to: 1) reproduce crisis phenomenon in an agent-based socioeconomic system; 2) develop a theory for the occurrence of crises; 3) propose a numerical validation process through stylized facts and structure complexity comparison of data; 4) investigate various socioeconomic factors and their relationship with crisis systematically; 5) recommend the directions for policy of crisis regulation; 6) predict and give alerts of new types of crises in future.

Chapter 2 firstly introduces the basic structure of the target model adopted from previous studies, which is a macroeconomic hybrid agent-based model called 'Mark0' developed in the Europe CRISIS project. Mark0 contains the firms as heterogeneous agents. In the meantime, the household, the bank and the government are only representative agents. [

?]The reason for this hybrid arrangement is to maintain the balance between the analytical tractability and the complexity of agent-based model at the same time. In addition, Mark0 can be considered as a minimal conceptual framework of macroeconomic systems. We summarize the basic structure of the Mark0 of previous work as follows: the household sector calculates its budget based on their savings and wages earned from the firms. The firms hire labor from household to produce their products and pay wages to the labor. Different firms compete with each other by price. They adapt their production by hiring/firing labor based on the demand-supply gap of their products. They also adapt their price in the hope to shrink the observed demand-supply gap. During the employment and sales, the firms accumulate their asset by their profit. If the profit is positive, the firms give dividend back to household. If the asset becomes negative, the firm are indebted, and need loans from the bank. The bank controls the default threshold of a firm. If a firm is deeply indebted and hits the threshold, the bank declares the default of the firm, together with unemployment of the labor and distribution of the debt to the whole economy. We also introduce the four phases of Mark0 identified in previous research as full unemployment, full employment, residual unemployment, and endogenous crisis. The four phases are separated by two control parameters, namely the employment propensity and the default threshold. We conduct the original work of validation on the complexity of the model against the real data by examining the stylized facts observed in the bankrupted firms before crisis. In particular, we show that the model can reproduce three stylized facts as: the Zipf distribution in the debt of the firms, the exponential decrease in the lifetime of the firms, and the correlation of sales and debts. We conclude this chapter with a brief discussion on the order generation and self-organization of the economy which is revealed in the statistical property in the stylized facts.

Chapter 3 presents our contribution on the theoretical analysis of the mechanism on the phase transition based on the roles of the two control parameters introduced in chapter two. This chapter provides the theoretical foundation for the whole thesis especially for understanding the factor analysis in the following chapter four. More importantly, the mechanism of endogenous crisis occurrence is revealed with detailed analysis and rigorous mathematical physical proof. We first analyze the control parameter for the labor dynamics, namely, the employment propensity of firms. We show that the employment propensity can create two attractors in the economy, i.e. full unemployment and full employment, with a single critical value for the transition between the two phases. In particular, we show the attraction of the two phases is from the undiminished demand-supply gap from a group of oversupplying firms in the economy. While the demand-supply gap of the whole economy is fluctuating around zero level as if the economy is in the equilibrium state, the non-equilibrium process in the subgroup of the firms will ultimately drag the economy into one of the attractors because the labor adjustment is based on the demand-supply gaps which can be proved that it is modulated by the control parameter employment propensity. After the mathematical proof, we conduct numerical validation on the demand-supply gap of the whole economy and of the group only composed by oversupplying firms. The numerical validation confirms that the demand-supply gap is stable and undiminished, which is much larger than the gap in the whole economy. This justifies our theoretical treatment in this control parameter. Next, we move to the theoretical analysis on the other control parameter, the default threshold. We firstly identify the group of firms with high risk of bankruptcy and formulate the conditions for a firm to belong to this specific group. Then we prove a property in the debt dynamics of a firm, which showed the debt ratio of a firm has a marginal diminishing effect during its increment. With the help of numerical simulation, we further prove that the difference among the debt ratios of the specific group of firms with high risk of bankruptcy is vanishing over time, which we term as ‘the diminishing debt ratio gap’. This diminishing debt ratio gap has three consequences: 1) it creates a cluster of deeply indebted firms. 2) it stimulates the differentiation among firms in the economy. 3) it generates the order and structure inside the economy automatically. As the order of the economy established, random default events are possible to trigger a cluster default event which is the cause of the large crisis occurrence in the economy. The default threshold controls the formation of cluster and the establishment of order by controlling the debt ratios of the firms. If the threshold is low, the order is not allowed to be established, therefore no cluster is formed but rather the economy is in an equilibrium of residual unemployment. If the threshold is high, the order of the economy and the cluster of the firms are already in its maximum size, but still it is too far away from the threshold therefore the economy is attracted into the full employment phase. Only in the middle band, the two conditions of cluster and possibility to reach the threshold are satisfied. As a result, the endogenous crisis phase emerges. To numerically validate our theory on control parameter default threshold, we show the evolution of debt ratios in the high risky group of firms, which confirm the property of 'the diminishing debt ratio gap' proposed in our reasoning. We conclude this chapter by discussion on the herding effect and threshold effect which are mentioned by previous researcher, with an emphasis that our theory is firstly proved that the herding behavior can automatically emerge by the interaction among firms inside an economy whereas the previous studies only started with a preset cluster to investigate its relation with the stability of an economic system.

Chapter four presents four import factors in the economic system we have modeled: firm, household, government/bank, labor market. We make extensions to the basic model to closely investigate the impact these factors bring to the economy and their relationship with the crisis occurrence. In the extension of the firms, the strategies of firms are the main focuses as we want to know the impact of strategy on the stability of the economy. We deploy three types of strategies: profit-based imitation, asset-based imitation, profit-based learning, together with two type of scenarios. They are: a scenario that small number of firms adopt the strategy, and that significant number of firms adopt the strategy. Our results show that the profit-based strategy brings instability or even full unemployment to the economy (when the number is significant), whereas the asset-based strategy can stabilize the economy instead when the number is significant. Therefore, the asset-based strategy could be a future direction to recommend to the firms in order to reach a sustainable growth. In the extension to household, we increase the consumption variation in the sense the household can have debts also. We find out that the household debt has two different effects based on the phase of the economy. The deep household debt can cause instability problem in an original stable phase whereas it can stabilize the economy if it is originally in the endogenous crisis phase. This finding provides the support for both arguments in the previous literature and suggests to reexamine the data with a precondition of identification of the phase of the economy. Furthermore, we find that the new type of crisis can be triggered by the precautionary saving behavior of the household which increases the bankruptcy rate of firms. Therefore, the household debt can postpone a crisis especially when it is in the endogenous phase but at a cost of future crisis when the household takes a precautionary saving behavior. The policy to smooth the precautionary saving behavior is a future direction which is suggested by this study. In the extension to government and bank, we add adaptive rules for the default threshold to tackle the consecutive crisis occurrence and the effectiveness of government money policy. The bank adapt the default threshold by increasing it when no recent crisis has occurred or decreasing it when recently a crisis has occurred. Given the labor policy which maintains a high hiring propensity, we discover that the consecutive crisis occurrence is due to the improper government policy by put money into the market by which the economy is still trapped in the endogenous phase. Through our simulation, we notice that the quick recovery in a crisis period depends on the proper government action which should maintain the needs for labor, limit the profit of firms by tax, and pay subsidy to the household from the tax of profit of firms. In addition, our result is the first one to directly provide an explanation for the consecutive crisis occurrence phenomenon from the historical empirical data, with simulation validation. In the extension to labor market, we aim to tackle the depopulation and aging situation such as in Japan and future China. We add a population dynamics to the basic model which provides a simulation scenario of depopulation and aging in the model. In addition, with the strategy of balancing the money flow by wage incentives during a depopulation period, we deploy five different wage incentives in our simulation. Unfortunately, our results show that the wage incentive alone is not enough to maintain the balance of the economy in a depopulation scenario. The results show new crisis could occur even in the original full employment phase. The worst case can be a full employment to full unemployment crisis suddenly during the depopulation process. The reason for this transition is the decreasing of consumption propensity of the household side. Therefore the simulation result suggests the policy should shift from the wage incentives of the market to subsidy of household through institutional arrangement (e.g. basic income) in a highly depopulation era.

As it has been pointed out, the agent-based econophysics is the promising candidate to tackle the crisis and instability of our socioeconomic system in future, contribution in this direction is surprisingly scarce. Built upon a basic model Mark0 in the previous study, we firstly try to justify complexity of the model with comparison through stylized facts, in order to conduct further crisis-related investigation based on this basic structure. We make our contribution to theoretically analyzing the phase transition and crisis occurrence in this model. Especially we prove that the herding behavior can automatically emerge in this modeled economy as the self-organization of order inside the economy. By applying this theoretical insight, we further investigate key factors in crisis occurrence in this economy. We observe that the profit-based strategies of firms, the precautionary saving behavior of household, the traditional intervention of government and the depopulation trend of a society, can either deteriorate the stability of the economy or even induce new type of crisis which is not in the basic model configuration. In the meantime, the asset-based strategy of firms, the household debt during the endogenous crisis, the proper government action can mitigate the crisis and stabilize the economy. All in all, this study provide a first case of the future study in this agent-based econophysics crisis study, which the insights from this study is going to be tested by future research.

Overall, this study shows that theoretically the emergent crisis from the interactions of individuals in a complex socioeconomic system does always exist and occur unexpectedly, which refutes the assumption of the mainstream macroeconomic theory. Furthermore, the transdisciplinary econophysics-oriented agent based model has the potential to be engaged to shed new lights on the crisis mitigation policy in our economy eventually. One limitation and the important future direction of this work is to empirically validate of the phenomena through the indicators and predictions made by this general theoretical model study. A systematic approach to deal with crisis in a complex system is necessary if the sustainable development of our socioeconomic system is imposed.

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