Financial Stress Testing

A model based exploration under deep uncertainty

Christos Vasilopulos

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A model based exploration under deep uncertainty

Delft University of Technology

Faculty Technology, Policy and Management

Master Engineering and Policy Analysis

EPA Msc Thesis Project

Chairman graduation committee: Prof.dr. A.H. Kleinknecht

1st Supervisor TU Delft: Dr. E. Pruyt

2nd Supervisor TU Delft: Dr. S. Storm

Author: Christos Vasilopoulos

St.number: 4183568

Acknowledgements

The challenge of realization of this thesis project was extremely high and despite difficulties and obstacles I am glad that I managed to succeed. However, I am grateful to people that supported me in any possible way to complete it.

I am grateful to my supervisor Erik Pruyt and I want to thank him for time and guidance he offered me. From the starting point of this thesis project, he was the inspiration for my dealing with System Dynamics Modelling. His valuable feedback and his support were the main reasons I stayed on track. He assisted me with the scope definition and the directions of the research.

I am thankful to Prof. Kleinknecht and Dr. Storm, members of my committee for their feedback and their proposals to what I could focus on and what I should try to include in the System Dynamics model. Although they were not familiar with System Dynamics modelling, their perspective and their knowledge regarding financial and banking issues had been extremely important and helpful to me. Their opinion was valuable during the model's development, but also in the final stages of the whole process.

Lastly, I want to thank the most valuable contributors to my effort to handle the stress and overpass the difficulties during all this period, my friends George, Thanos, Sylvia, my parents and my sister who always kept faith with me. All of them supported me mentally and they were always next to me during tough moments. Furthermore, I want to thank my parents for their financial support all these years of my studies. If it was not their support, I would not have been here.

This master thesis project is devoted to all of you! Thank you all!

Delft, 2013

Christos Vasilopoulos

Executive Summary

Years of turmoil in the banking sector have revealed the need to assess the performance of banks and explore the resilience of the banking system under adverse futures. Banks are not the safe houses everyone believed them to be, as the recent crisis of 2007 showed. Today, banks are highly uncertain dynamically complex systems that are permanently at risk due to internal and external stresses and uncertainties. Although external uncertainties and stresses cannot be controlled and accurately forecasted, system's exploration under plausible futures can lead to the identification of its weak points.

Monitoring a complex system like a bank and identifying vulnerabilities to different types of risks requires advanced tools. Monitoring and analytical tools, like financial stress tests, are developed by regulatory authorities and financial institutions to identify causes and vulnerabilities of the system under adverse future scenarios. Financial stress testing allows assessing the financial system stability or even individual bank's performance. During the last decade, the evolution in this field is significant, in an effort to enhance the resilience of financial institutions, especially after the severe financial crisis.

New methodologies and more elaborated tools are implemented in risk management practices of banks. Common techniques can be summarised in simple sensitivity tests and historical or hypothetical scenario analyses. To this direction, focusing on an approach that could simulate multiple future hypothetical scenarios, exploratory System Dynamics modelling could offer a new tool for a model based exploration in order to support monitoring of bank's financial state. This research illustrates a pilot System Dynamics approach towards financial stress testing in view of making banks more robust by identifying possible weaknesses.

A System Dynamics model was developed to represent the core endogenous operations of a bank. The bank model represents a medium sized commercial bank and not a systemic bank of a country. The level of aggregation provides an example of its balance sheet but it is not an accurate and detailed representation of a bank. Although, further research is needed for a more detailed model, an analysis of plausible scenarios that could have effects on bank's balance sheet, regarding its net worth and liquidity, is performed.

The model is constantly or periodically attacked by unforeseen risks and shocks in order to generate insights into all sorts of plausible bank system behaviours under stress. The use of EMA workbench can assist in the exploration of those behaviours by plotting all the plausible future scenarios. Based on the observed behaviours we identify the causes of undesirable dynamics, vulnerabilities and levers. The combination of uncertainties that lead to those undesirable outcomes is revealed with the use of machine learning algorithms. Using these insights, basic policies are designed and applied in an effort to improve bank performance under particular undesirable scenarios.

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1. Introduction

1.1 Introduction

The severe financial crisis of 2007 emerged in the USA and spread around the world, especially in the Eurozone, revealed the vulnerabilities of the entire financial system. Multiple factors had a significant contribution to the severity of the crisis that affected extensively the banking sector. FED' s policy to offer cheap credit with low interest rates till 2004 and the continuously increasing real estate prices lead to the booming of subprime mortgages. Those subprime loans and mortgages created instability and uncertainty in the American financial system when FED's interest rates highly increased. As a result, many subprime borrowers could not repay their loans. Links between the American financial markets and the European financial system spread the financial crisis in an unexpected degree after the collapse of Lehman Brothers, leading to recession and European sovereign debt (Lapavitsas 2012).

The subprime lending was based on expectations and belief that real estate prices would continue increasing "forever". When this turned to be inaccurate and the mortgages began to default at high rates, the reactions could not have been forecasted. Sharp increase in defaults on loans leaded into uncertainty and instability in the global banking sector, which resulted in an unforeseen number of bank failures or last minute bailouts after regulatory authorities' intervention (Wray 2009; Nersisyan & Wray 2010). Multiple banks have been "in distress", meaning that they were unable to continue their normal activities because of lack of funding or capital (Dewatripont & Freixas 2012).

The interconnection of financial systems and the extensive exposure of banks to interbank lending accelerated the expansion and diffusion of financial crisis to global scale (Ryan-Collins et al. 2011). It turned to be a credit crisis because of financial institutions failures that lead to domino-effects and collapse of interbank markets. Central banks, regulatory authorities and the states had to intervene in an extensive scale in order to stabilize the system (Drehmann & Nikolaou 2010; Lapavitsas 2012). Multiple banks were "too big to fail" and needed to be rescued in order to prevent further catastrophic consequences (Morrison 2012).

All those facts and events clearly showed that banks are not as secured as people believed. Banks are highly uncertain dynamically complex systems that are permanently at risk due to internal and external stresses and uncertainties. Banks' role is not limited to be the intermediaries among borrowers and lenders, but they fulfil multiple activities by engaging themselves into riskier investments, increasing the complexity and the uncertainty of the system.

Monitoring such a system has become crucial and regulatory authorities discuss the need for immediate improvements and further research in risk management practices. Part of such risk management practices are the financial stress tests, utilized to gain a deeper insight of the banking environment and provide an in-depth exploration of possible vulnerabilities. Stress testing could be either focused on a single bank, or on an aggregate level of a country's banking system.

Simple sensitivity tests to single risk factors and scenario analyses represent the main trend of the existing financial stress testing. Simulating historical or hypothetical scenarios, risk managers estimate the effects on banks' position. In some cases, stress tests are accompanied with value-at-risk (VaR) models to assist in identifying the exposure of the bank on regular basis. However, the majority of existing models failed to capture the extreme events of the recent crisis as they were based on statistical data. Furthermore, based on assumptions that interbank lending market is always easily accessible, stress testing models did not capture further difficulties regarding the financing of a bank during stress events.

Moreover, sensitivity analysis just explores small changes in different elements and factors, which does not provide sufficient insights regarding extreme events. Exploring multiple shocks in one scenario with existing stress testing models and VaR is feasible. However, the outcomes cannot be sufficiently interpreted, since risk factors that influence mostly the bank, are not distinguishable. The risk management has to analyze the outcomes after running tests with individual shocks.

This is where this research intends to contribute by illustrating an exploratory System Dynamics approach towards financial stress testing in view of making banks more robust in order to perform satisfactorily in plausible stressful futures. A pilot model-based Stress test could provide a deeper understanding in underlying mechanisms and the dynamics of a bank's system. The developed tool allows the exploration and investigation of effects and causes under multiple adverse scenarios. Moreover, EMA workbench enables the identification of particular factors that are responsible for particular behaviours of the bank. Using these insights, policies are designed and tested in an effort to assist the decision making under certain adverse scenarios.

1.2 Thesis structure

In Chapter 2, the research problem is analysed, the social and scientific relevance of this research topic are defined, followed by research questions and the scope of this project. In Chapter 3, the existing stress testing techniques are explored after a generic discussion about banks and their potential risks. Next, Chapter 4 clarifies and describes the applied research methodology in an effort to address the research objectives. Chapter 5 shows the bank model's structures and performs a detailed analysis of each component of the model, including its boundaries. The uncertainties that this research focuses on are also presented in chapter 5. In chapter 6, the analysis of the outcomes is discussed. All plausible scenarios and uncertainties are analysed in an effort to identify the causes of undesirable behaviours in catastrophic and sustainable scenarios. In chapter 7, policies are explored and tested. In chapter 8, conclusions are presented, followed by the reflection and recommendations for future research in chapter 9.

2. Research Problem

Formulating the goal and analysing the objective of the research is the first step of the process. Therefore, in this chapter, the problem of this research is defined, followed by the clarification of the social and scientific relevance. The social relevance emphasizes on the contribution of this topic to the society and its impact. The scientific relevance focuses on its contribution to science. Finally, the scope is defined and the research questions are presented.

2.1 Social relevance

Recent crises highlighted the fact that banking sector was unprepared and exposed to risk factors which lead to bank failures or last-minute bailouts (Lapavitsas 2012). The turmoil that occurred in multiple banks, in the USA and in the Eurozone, created space for further discussions about the problematic state of the banking sector. It clearly revealed the need for analytical methods and tools in order to explore financial issues in-depth.

Banks have an important impact and they are key components of each country's financial system. Banking system's stability contributes to social stability and vice versa. This is the reason why monitoring this complex system is crucial in order to prevent adverse futures and possible disruptions. Regulatory authorities promote stress testing exercises as an important tool in monitoring the resilience of banking institutions and financial system (Swinburne et al. 2008). This thesis intends to contribute in the existing financial stress tests by developing a model-based approach that could assist in identifying weak points in a bank's system and crucial macro-level and micro-level risk factors.

As it is important for banks to have their own monitoring tools, this thesis focuses on one relatively small hypothetical bank and not on a country's entire banking system. The goal of this research is to explore the behavioural modes of a bank under stressful futures and identify the factors that played the most important role in undesirable behavioural modes. This study intends to address the lack of insights regarding underlying mechanisms in a bank environment and its behaviour in relation to uncertainties and risks that could generate potentially undesirable disruptive dynamics.

The applied side of the project is particularly relevant for risk management of a bank, and thus it could assist the problem owner, a bank, in strategic decision making. Defining the components of stress test and understanding its results is a critical issue for decision making and planning for the senior management of a bank. This model-based approach could be a key tool for assisting decision maker in designing policies and preventive actions by testing them, gaining insights on a bank's behaviour under all plausible futures and scenarios to avoid exposure to risks before their occurrence.

2.2 Scientific relevance

The scientific relevance lies on the fact that this project intends to be a model-based stress testing approach with the use of a System Dynamics (SD) model and Exploratory System Dynamics Modelling Analysis (ESDMA) methodology.[1] Despite the existence of System Dynamic models that deal with banking system or specific banks (MacDonald 2002; Rafferty 2008; Pruyt 2009; Pruyt & Hamarat 2010; Lansink 2011), approaching the uncertainties and risks of such a system with ESDMA is innovative. The choice of this methodology is clarified in Section 4.2, followed by a detailed description of the aforementioned concepts and EMA workbench that is used as the main tool.

The only existing attempt to use a System Dynamic model in order to apply a Dynamic stress test and secure the position of the banking system is conducted by Anderson et al (2011). In their paper, a banking system model is stressed under different adverse scenarios. That System Dynamics model-based stress test is created for a central bank of a middle eastern country in order to stress the entire financial system and assess its performance (Anderson et al. 2011).

2.3 Research questions

The research objective is clarified through research questions that this thesis intends to address. The main question that this thesis project is expected to elaborate on, is the following one:

- *What are the uncertainties and the underlying mechanisms that affect the dynamics of a bank and how can we identify and deal with crucial stressors using a model-based approach?*

In order to address the main research question, sub-questions have been formulated. More specifically, the project has to elaborate on the following sub-questions:

- Which are the main mechanisms and sub-systems in a bank?
- Which are the uncertainties and potential risks that could result in undesirable dynamics?
- What is the bank performance under plausible stress scenarios?
- Which are the stress scenarios that create undesirable outcomes?
- Which policies may reduce effects of a stress event in a bank?
- What are the effects of policies on bank performance?

2.4 Scope

The model and the analysis that are presented in this thesis project is a proof of concept, not a valid model with valid real-world conclusions. The bank represented is hypothetical and not a real one.

---

[1] System Dynamics Modelling and Exploratory System Dynamics Modelling Analysis compose the applied research methodology and are discussed in detail in chapter 4.

The objective is to explore and present the ability of a new model- based approach to deal with stress testing using a generic model that could be adapted in real cases after the consultation with the commissioner.

The scope of this research focuses on gaining deeper insights of the behaviour of one bank under various uncertain stressful futures, looking for micro-prudential risk assessment. Therefore, an endogenous bank model is developed for exploratory purpose, representing core operations of a bank and simple portfolio structures and decisions. Exploratory Modelling Analysis is performed on the model in order to explore and assess behavioural impacts of different stressful scenarios on a bank, which is the primary purpose of this research. After the analysis of various behavioural patterns, the parametric space that is responsible for undesirable outcomes is identified.

The System Dynamics model contains structures and parts that resemble typical operations of a relatively small hypothetical European bank and not a systemic bank. It is assumed that a systemic bank will be rescued in cases of stress events with extreme effects as they are "too big to fail" and this is the reason to be left out of our scope. Parts representing assets and liabilities of a bank and internal decisions regarding allocation of funds are included in the model. Internal parameters and relations of the endogenous model are influenced under various scenarios by exogenous parametric uncertainties that represent plausible stress events. The model is considered to be on an aggregated and abstract level and not related to any particular real-world bank.

A generic view of how the system is approached is illustrated in Figure 2.1.

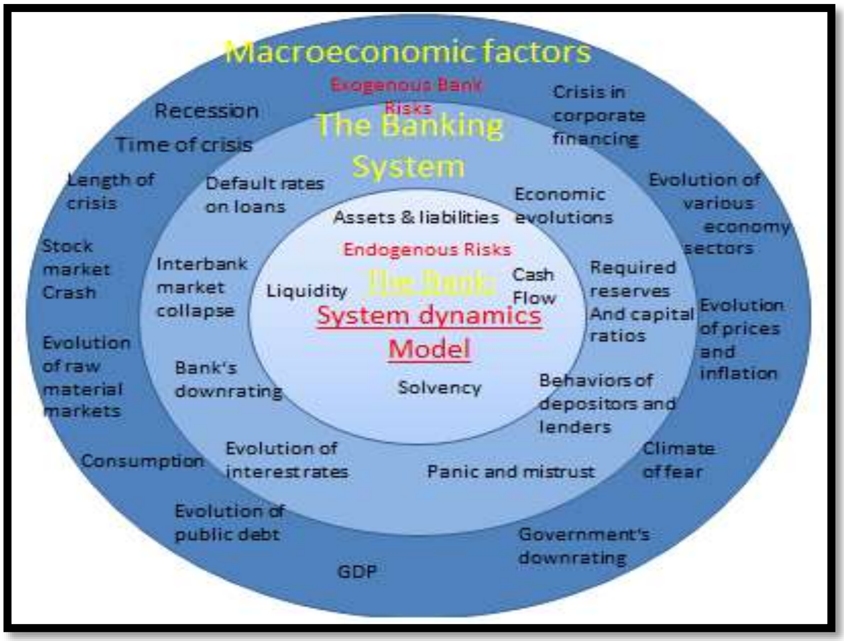
Macroeconomic factors
Exogenous Bank Risks
Recession
Time of crisis
Crisis in corporate financing
The Banking System
Length of crisis
Default rates on loans
Evolution of various economy sectors
Economic evolutions
Assets & liabilities
Stock market Crash
Endogenous Risks
Interbank market collapse
Liquidity
The Bank:
Cash Flow
Required reserves And capital ratios
System dynamics Model
Evolution of prices and inflation
Evolution of raw material markets
Bank's downrating
Solvency
Behaviors of depositors and lenders
Consumption
Evolution of interest rates
Panic and mistrust
Climate of fear
Evolution of public debt
Government's downrating
GDP

Figure 2.1 A generic view of the system

The scope of this research is summarised in Figure 2.2 and it focuses on the inside core of the above view. Subsystems of the bank are influenced by its internal decisions. When a stress event occurs, parts of the bank and its overall performance are influenced depending on the scenario.

Detailed decision- making structures are not included in the model. As it is a generic model, the decision maker is mostly able only to decide the allocation of available funds, by changing the percentages in each run. Responsive actions or specific decisions are not further included in the model and they are treated as policies in next steps of the analysis. Furthermore, structures related to stock market are not included, limiting the ability of the bank to get additional funding in case of problematic financial position. This poses further limits to the decisions and solutions available to the management of the bank. However, in the future, mechanisms and structures that could describe positive automatic response in plausible scenarios could be included in the model.

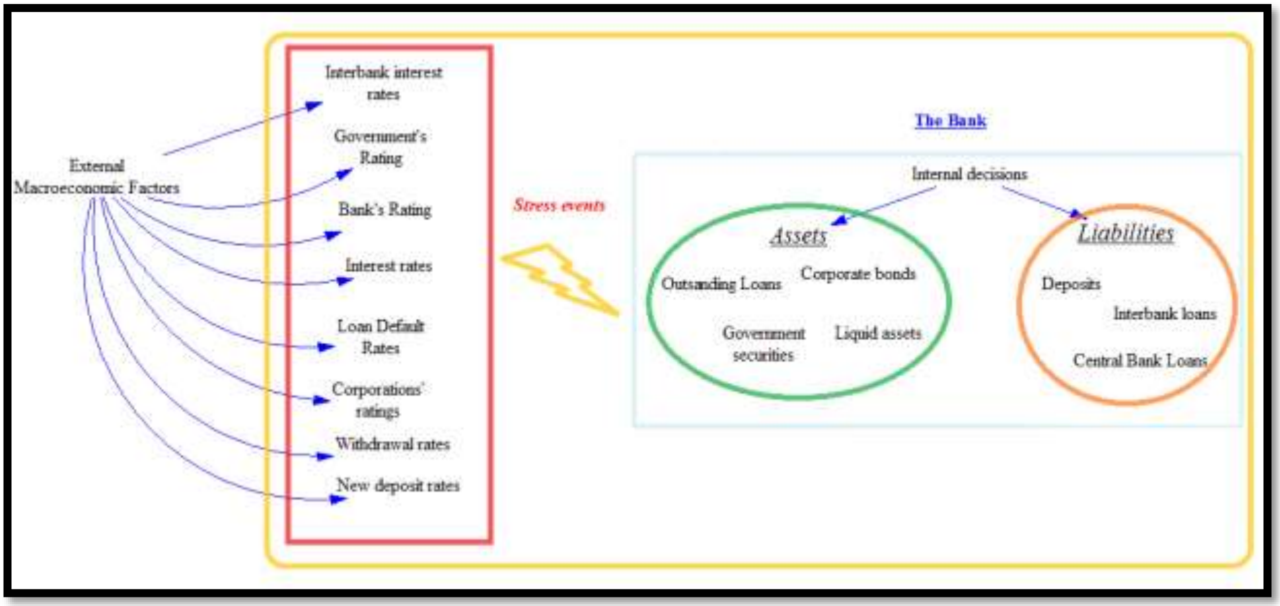
External Macroeconomic Factors
Interbank interest rates
Government's Rating
Bank's Rating
Interest rates
Loan Default Rates
Corporations' ratings
Withdrawal rates
New deposit rates
Stress events
The Bank
Internal decisions
Assets
Outsanding Loans
Corporate bonds
Government securities
Liquid assets
Liabilities
Deposits
Interbank loans
Central Bank Loans

Figure 2.2. Research Scope

3. Banks, Risks and Stress Testing

In this chapter, theoretical background regarding banks and risks they could face is provided as a basis for the development of the model. Moreover, the existing stress testing techniques are explored and discussed.

3.1 Banks and financial risks

The financial system is an extremely complex system that consists of many different parties, where funds change hands through various channels. Financial intermediaries like banks and financial markets (bond and equity markets) are the nodes of the system and determine the channels through which lenders and borrowers are connected. Mishkin (2007, p.24) depicts the structure of the financial system as in figure 3.1.

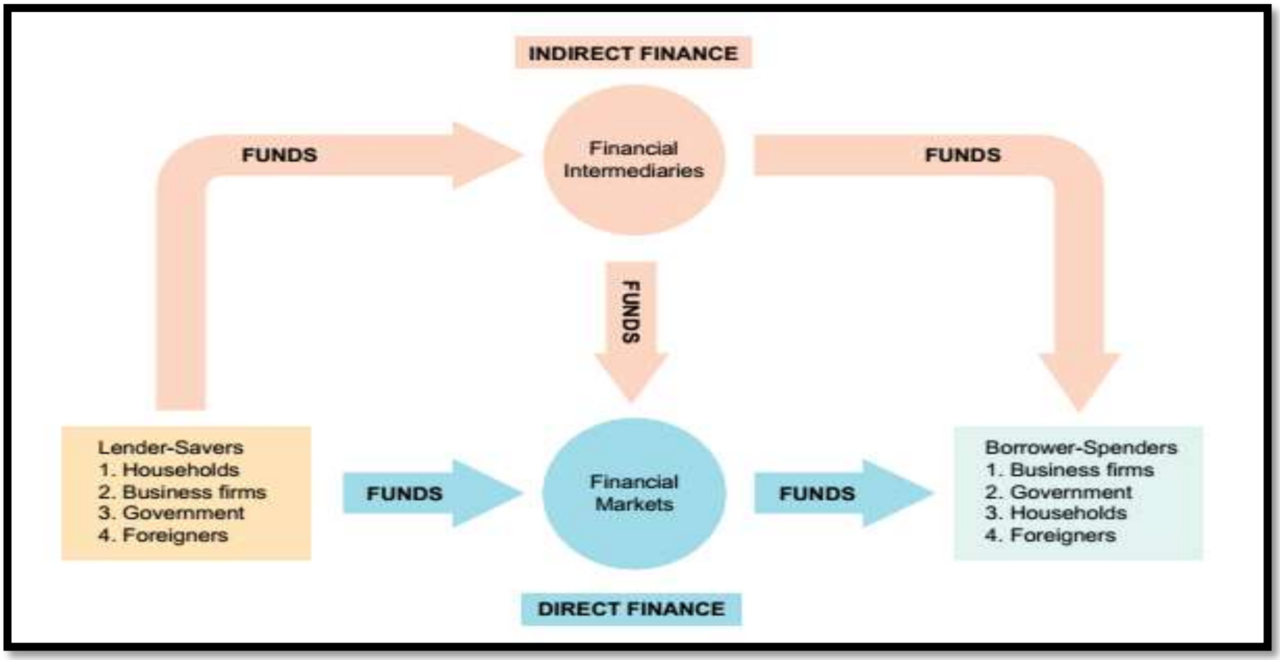
INDIRECT FINANCE
FUNDS
Financial Intermediaries
FUNDS
FUNDS
Lender-Savers
1. Households
2. Business firms
3. Government
4. Foreigners
FUNDS
Financial Markets
FUNDS
Borrower-Spenders
1. Business firms
2. Government
3. Households
4. Foreigners
DIRECT FINANCE

Figure 3.1. Overview of the Financial system (Mishkin 2007)

Banks as financial intermediaries fulfil multiple roles regarding the channels of funding. The role of commercial banks is extremely important for the entire financial system. Households and small firms are not able to borrow from financial markets directly and commercial banks are the main source of their funding (Hubbard & O'Brien 2011). Banks as financial intermediaries receive deposits from savers which in turn they partially invest by lending to borrowers or purchasing financial instruments in financial markets (Berry et al. 2007).

In the balance sheet, the financial state of a bank is summarised by listing its assets and its liabilities. Bank’s capital is equal to the difference between assets and liabilities. Assets represent what the bank owns and liabilities what the bank owes to an individual, a firm or another bank. The bank receives interest from its assets and pays interest for its liabilities. The difference of interest earnings and interest payments describes the interest margin, which contributes to bank’s profit (Ryan-Collins et al. 2011).

Bank must ensure that the value of assets is always greater or at least equal to the value of its liabilities. If this is not the case and the bank is not able to raise its own capital, it becomes insolvent (Ryan-Collins et al. 2011). An insolvent bank is not allowed to continue its operations and is declared bankrupt. The value of the assets can fall because of certain risk factors depending on the operations of the bank.

The operations of a bank are associated with risks that could lead into bank failure if not efficiently controlled. A bank could face various types of risk, which are able to cause instability in its financial state in cases of a stress event. It is important for a bank to monitor all its operations and be in position to assess its exposure to those risks on time. Efficient management of those risks sets the nature and the core of banking business, which defines the role and the importance of risk management practises.

3.1.1 Liquidity risk

Liquidity risk is defined as the likelihood that an individual institution will not be able to meet its liquidity needs (Hubbard & O’Brien 2011). Banks are obliged to hold a fraction of money they borrow in reserves in order to meet their daily liquidity needs and they invest the rest into certain activities. In cases of bank runs[2], the bank may not be able to meet the demand even if it is forced to sell assets at a loss. In many countries, states and regulatory authorities have introduced a policy called deposit insurance to protect bank depositors, but also prevent bank runs. By ensuring the payment of a particular amount to small depositors, policy makers provide the system with confidence limiting the fear of a bank run and promoting financial stability (Angkinand & Wihlborg 2010; Hwang et al. 2009).

To manage liquidity risk, banks are forced to set aside a fraction of its short-term liabilities. The fraction that the bank is obliged to keep as reserves depends on the regulatory framework of each country. However, Basel Committee on Banking Supervision [3]has introduced three instalments of Basel Accords (I, II, III) in order to set ratios and actions needed for keeping financial institutions stable in possible future crises. The last Basel Accord (III) was introduced after the financial crisis, in 2011 and 2013 (2 parts), in view of enhancing the resilience of banking system. Increases in capital and liquidity requirements will be implemented until 2019 and all banking institutions have to adapt their strategies until then (BIS 2011).

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[2] Bank runs: cases in which depositors rush into a bank to withdraw their deposits simultaneously because of a fear that bank will be bankrupt. If all the depositors ask their money at once, the bank will not have enough liquid assets to repay the entire amount, which will lead into its bankruptcy (Diamond & Dybvig 1983).

[3] Basel Committee on Banking Supervision is a committee composed of multiple countries, in view of providing a forum for cooperation on banking supervisory matters. “ Its objective is to enhance understanding of key supervisory issues and improve the quality of banking supervision worldwide.” (http://www.bis.org/bcbs/)

Although increasing capital and liquidity requirements could possibly assist in managing efficiently the liquidity risk, banks face the challenge that their profitability will suffer. By holding higher ratios of bank reserves and vault cash, banks are not able to invest more funds in issuing new loans and purchasing securities, which means that interest earnings will decrease. Reducing their profitability causes future concerns to bank management and policy makers.

In cases of increased liquidity needs, banks are able to borrow funds through short-term loans or repurchase agreements (REPOS)[4] in interbank lending market or directly from the Central Bank. Those two channels of funding can provide "cheap" and quick credit in emergency situations. However, interbank lending is not always feasible as in cases of severe widespread crises, like the one of 2007, in which interbank lending market could freeze. Central bank could act as a "lender of last resort"[5] facility and intervenes in last-minute bailouts for banks in distress.

3.1.2 Credit risk

Credit risk describes the risk that loans, which were granted by the bank, will not be repaid because borrowers are not able to meet their commitments on time (Hubbard & O'Brien 2011). Each loan that cannot be repaid is written off the balance sheet of a bank, compressing the assets' part. Asymmetric information and bank's risk- seeking strategies increase the likelihood of credit risk, as it occurred in the financial crisis of 2007 with subprime mortgages and loans. Banks are not always well- informed about the financial health of the borrower but they are willing to issue new loans to increase their interest-bearing assets, providing short-term profitability. Their exposure to borrowers with low credit-worthiness could create extensive losses in crisis' periods.

Diversification of loans and securities portfolio would reduce the likelihood of credit risk for a bank (Hubbard & O'Brien 2011). Banks that grant only real estate loans will be highly exposed in a case of real estate market crisis in which prices of buildings collapse. Investing in various sectors, regions, industries and products, while limiting the exposure to low- creditworthy borrowers could prevent adverse scenarios of bankruptcy due to defaults.

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[4] REPOS: Repurchase agreements are short-term (even overnight) loans in which the bank provides assets (mainly securities) as collateral that the lender possesses if the bank does not repay the loan (Hubbard & O'Brien 2011; Mishkin 2007).

[5] Lender of last resort: The Central bank operates as a lender of last resort facility by providing liquidity to financial institutions and the market when an unexpected increase in demand for liquidity appears because of stress events and crises. If this upsurge in demand cannot be met by other sources, Central bank fulfills this role in exchange for assets as collateral. (Freixas et al. 2000; Kindleberger & Aliber 2005; Carlson & Wheelock 2012)

In many cases, banks request collaterals from borrowers in order to secure part of the loan in case of borrowers' default. For example, residential loans which are granted to individuals are mostly secured by a mortgage. Houses and assets are used as collateral, which the bank possesses if borrowers cannot repay the loans. As a result, bank decreases its losses in possible defaults, but keeps illiquid assets that cannot be easily traded.

Furthermore, the evolution of financial markets and financial innovations offered new mechanisms to banks to transfer credit risk through the process of securitization. Securitization is the process of converting loans (illiquid assets) into tradable securities in order to sell them in financial markets (Hubbard & O'Brien 2011; Wray 2009; Nersisyan & Wray 2010). With this process the banks turn illiquid assets into highly-tradable liquid instruments. Securitization is extremely important for two reasons, as it appears to be another source of liquid funding, but also the bank transfers the underlying credit risk to investors that purchase those securities. The bank is able to securitise part of the loans' portfolio in order to reduce the potential risk of default. However, securitization process and securitised financial instruments, managed by specialised bank intermediaries composing the shadow banking system[6], played a key role in the surge of global financial crisis of 2007 (Pozsar et al. 2010; Adrian & Ashcraft 2012; Bakk-Simon et al. 2012; Nersisyan & Wray 2010).

3.2 Stress testing

Financial stress testing is defined in the literature as *"… a risk management tool used to evaluate the potential impact on portfolio values of unlikely, although plausible, events or movements in a set of financial variables*" (Alexander & Sheedy 2008). However, it is not clear in the literature what can be defined as "plausible" and stressor events are subjectively chosen in each analysis (Quagliariello 2009).

The last decades, an on-going evolution appears in the field of stress testing frameworks, as more and more attempts to create sufficient and efficient techniques for stress testing appear, mostly under the observation of International Monetary Fund (IMF) and World Bank (Sorge & Virolainen 2006). During the global financial crisis, the IMF applied stress test in multiple countries to assess the performance of banking systems under adverse events (Swinburne et al. 2008). Their Financial Sector Assessment Program (FSAP) includes stress testing as part of their practises to assess a country's banking sector.

Since 1997, the Basel Committee on Banking Supervision frames guidelines and introduces international regulations for bank, including the incorporation of stress testing exercises in financial institutions (Alexander & Sheedy 2008). Developing stress testing frameworks to assist a banking organization to conduct repeatable exercises (stress tests) that focus on its risk exposures is crucial in order to assess risk factors and secure future bank's position.

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[6] The shadow banking system is a "*web of specialized financial institutions that channel funding from savers to investors through a range of securitization and secured funding techniques*" (Adrian & Ashcraft 2012). Those financial institutions provided credit by converting loans and mortgages into tradable financial instruments, but without the insurance and the supervision of regulatory authorities. Since 2000, the shadow banking system has enormously increased and its collapse is considered one of the main factors of financial crisis of 2007 (Nersisyan & Wray 2010; Pozsar et al. 2010; Adrian & Ashcraft 2012; Bakk-Simon et al. 2012).

In the literature, a variety of stress test techniques can be found, mainly implemented by central banks and regulatory authorities (Virolainen 2004; Burrows et al. 2012; Vazquez et al. 2012). Existing stress tests vary in terms of methodology used, degree of complexity, aggregation levels and the types of risk they focus on (Sorge 2004; Sorge & Virolainen 2006; BIS 2009). Different perspectives can be found and the scope of each analysis varies depending on the aggregation level, the factors and the environment that are captured (Sorge 2004). The majority of approaches are based on econometric models. However, it seems to be subjective to the developer what the macroeconomic shocks that could affect the financial system or a banking entity are and how their performance should be assessed, as the level of aggregation also depends on an analyst's choice.

Sorge & Virolainen (2006) propose two approaches to financial stress testing modelling, balance sheet models and probabilistic Value at Risk (VaR) models, while they implement them to the Finnish banking system. In the balance sheet models, changes in macroeconomic factors influence particular balance sheet items. VaR models use probabilities to estimate the distribution of loss based on the sensitivity of portfolio items to risk factors. In the majority of the stress tests, risk managers focus on credit risk linked with macroeconomic variables (GDP growth, unemployment, etc) in developing macro credit risk models (Drehmann 2005, Cihak 2007). Cihak (2007) discusses the design of scenarios, focusing on an extensive range of risk factors and proposes a logistic model for the inputs.

In the literature, an important model that focuses on the systemic risk is the model that the Bank of England applies, called RAMSI (Risk Assessment Model for Systemic Institutions). It is a sophisticated model that includes credit risk, network interrelationships, interest risk and generally a large range of potential risk factors and their feedback effects. This focus on second order effects of RAMSI model makes it valuable as those feedback effects seem to create further system instability and uncertainty (Burrows et al. 2012).

In Financial Sector Assessment Program (FSAP) stress tests, a distinction is made between bottom-up and top-down approach. Bottom-up approach refers to stress test methodologies that are conducted in individual banking organizations, instead of top-down that focuses on the performance of the entire financial system and are conducted by supervisory authority like IMF or a Central bank in an aggregate level(Swinburne et al. 2008). Sorge (2004) distinguishes stress testing in terms of "piecewise approach" and "integrated approach". The difference lies on the fact that in the first case, the focus is on assessing the performance on single risk factors while in the second the focus is on the performance on a combination of multiple risk factors (Sorge 2004).

After defining the risk factors that a stress test focuses on in its scope, the scenarios and the ranges of the risks are important to set down. However, as it was already discussed shock calibration is mostly based on a person's judgement (Quagliariello, 2009). For example, in simple sensitivity tests that do not explore feedback effects but just impacts on portfolio values, interest rate risk and credit risk due to non-performing loans are the most usual stressors. Currency exchange rates are also included in most of the stress tests.

4. Research Methodology

In this section, limitations of existing stress testing are discussed in order conceive the differences and the contribution of this research in the next steps. The choice of research methodology which is implemented in this research is clarified followed by its description. A System Dynamics model is built in order to represent the system. This model is used in an exploratory way as the applied research is the Exploratory System Dynamics Modelling and Analysis (ESDMA) (Pruyt 2010; Pruyt & Kwakkel 2011). This is a multi-method that combines System Dynamics Modelling (Forrester 1968; Sterman 2000) with Exploratory Modelling Analysis (EMA) (Bankes 1993; Lempert et al. 2003). Each part of this multi-method is described in order to provide sufficient knowledge regarding the use of ESDMA in this project.

4.1 Limitations of existing stress testing

The recent crisis revealed weaknesses and limitations in the majority of existing stress tests. Fundamental limitations turned the models into ineffective risk management tools. However, most of the available stress testing tools are mainly focused on the aggregate level and not on a single banking institution in their scope, which is not the focus of this project.

One crucial limitation appeared to be that the majority of the models used historical data to predict the severity of plausible shocks. However, forecasted future stress events and their consequences proved to be insufficient and too optimistic, as they have been based in assumptions coming from a relatively stable and booming period for banks (BIS 2009). This is what the Basel Committee on Banking Supervision (2009) stated:

"*... given a long period of stability, backward-looking historical information indicated benign conditions so that these models did not pick up the possibility of severe shocks nor the build-up of vulnerabilities within the system. Historical statistical relationships, such as correlations, proved to be unreliable once actual events started to unfold."* (BIS 2009)

Historical scenarios mainly reproduce crises that have already appeared. Their advantage is that their results are more easily interpreted because of the observed past experience. However, as the recent crisis showed, they are not forward-looking, like hypothetical scenarios. Only in cases that future crises could be similar to previous ones, historical scenarios could capture similar behaviours but they are not able to include new products or new markets. For example, in stress tests before the recent crisis, the focus was only on the banking sector and the funding from non-financial institutions had not been sufficiently explored.

Furthermore, in various stress tests, because of historic data and assumptions, reactions and feedback effects that could further reinforce the severity of crisis events had not been sufficiently accounted for. Combinations of stress scenarios, second order factors, interactions and interrelationships among actors were not included in the models and as a result the amplified consequences could not have been predicted (BIS 2009). Only in more sophisticated stress tests, scenario analysis stress tests, a more comprehensive view of aggregating risks and scenarios had been provided, but still in most of the cases their duration and severity were based on historical data providing insufficient ranges (BIS 2009).

A major shortcoming of sensitivity stress tests is that they only explore changes in single risk factors that have an impact on a particular portfolio value. They are easier to be implemented, but they do not capture any feedback effects and they do not explore any correlations between risk factors. They have short horizon and they do not explore any decisions and policies of the bank during this horizon. Their outcomes are more straightforward and easily interpreted and they can offer only a first simple attempt for assessment and not a sophisticated stress test framework.

On the contrary, scenario analysis offers a more assiduous approach since it contains multiple risk factors and feedback effects in a longer horizon. This approach overcomes the shortcomings of simple sensitivity analysis, but the outcomes are not easily interpreted. Although it enables simultaneous shocks and correlations of risk factors, the analyst is not able to identify which combination of risk factors leads to undesirable impacts. This is an important limitation of this approach that new researches should focus on.

Existing stress tests are only designed based on known relations described by econometric equations and they are implemented in order to predict future stress events and their impacts. However, prediction cannot be accurate especially when the econometric model is founded on assumptions excluding relationships and feedback effects that could occur but are not yet proven. Their purpose is based on what it is already known in order to provide numerical outcomes regarding possible losses, but not to explore the dynamics of a bank and the banking system in general and identify possible disruptive dynamics.

4.2 Choice of methodology

New methodologies and modelling techniques should be applied in an effort to overpass those limitations. This is what this new model based approach intends to address. All those limitations justify the effort to promote and apply a novel model-based approach in financial stress testing techniques. The suitability of Exploratory System Dynamics Modelling and Analysis is explored in this research in an effort to provide a comprehensive stress test.

In the SD model, subsystems, mechanisms, decisions, feedback effects and interactions are described, while performing ESDMA enables the exploration of an enormous uncertainty space in which multiple adverse scenarios are combined providing the analyst with insights of all plausible futures. This research is not based in statistical and historical data and explores extreme scenarios by changing values of bank’s model. Stress testing the bank and observe its performance could deliver insights in scenarios that have not been explored in existing works. The identification of parametric combinations that could result to undesirable modes of behaviour and their analysis could allow testing the effectiveness of preventive actions and interventions by policy makers focusing on the most crucial risk factors. System Dynamics models can be an alternative to existing econometric models, but the EMA workbench could further deliver insights in scenario generation and risk identification. However, this is a simple version that needs to be adjusted in each case, and it is a considered as a first step for further targeted research if data are available.

This novel model-based approach provides a proof of concept, focusing on the exploration of the system without needing well-founded mathematical equations for each relation that we can identify. System Dynamics models are combinations and links made of hypothesis (causal links) made by assumptions on how system works. Some of those links are already known and defined by mathematical equations while on the contrary others are unknown and need to be explored. However, here is a key advantage of this method as in the existing stress tests only defined links are stressed without taking into consideration possible unknown links. Furthermore, traditional System Dynamics modellers model only what they assume they know. Those limitations can be overpassed as structural and parametrical uncertainties can be explored by applying EMA on multiple models, providing an overall image of plausible futures.

The overall image of all plausible futures could further assist in designing more robust and effective policies after categorising behaviours and the outcomes of the model. This model based approach enables the identification of the crucial risk factors, which can be targeted by automatic responses- action. ESDMA serves an exploratory methodology that does not look for accurate predictions but for exploration of all plausible futures that can be occur in an effort to support decision making by providing high level messages.

4.3 System Dynamics Modelling

System Dynamics (SD) is a modelling technique introduced and developed by Forrester (1961, 1968) to support policy analysis and decision making. System Dynamic models are applicable to simulate complex systems in view of investigating and analysing their non-linear modes of behaviour over time (Forrester 1961; Forrester 1968; Sterman 2000). System Dynamic simulation models are developed in view of providing deeper insights in the behaviour of the modelled system through its structure. Forrester states that system's structure and its dynamic behaviour "*…are intimately interwoven because it is the structure which produces the behaviour*" (Forrester 1968).

System dynamic models are not developed and used for accurate forecasting and prediction, rather than the exploration of the dynamic behaviours. As Sterman states "*Because all models are wrong, we reject the notion that models can be validated in the dictionary definition sense of 'establishing truthfulness'*" (Sterman 2002). Models are based on assumptions and they are characterized by uncertainties that remain unexplored during the experiments.

Quantitative System Dynamic models are developed as stock-flow structures linked with causal relations. In those stock –flow structures, causal links create feedback loops, which are important elements of System Dynamic models. Feedback loops appear as chains of causal links that create a circle and starting from any element in them, you return to it. Depending on the polarity of the causal links a feedback loop is either positive or negative (Forrester 1968).

Stocks, flows, auxiliary and constant variables are included in the models. Stocks (boxes) represent state variables that are increased/ decreased only by flows (inflow/outflow). Feedback loops should contain at least one stock variable. In the models, auxiliary variables are used to contain nonlinear functions (graphs also) and time delays that influence other elements of the structure. In each variable (stocks, flows, auxiliary, constant) mathematical equations define the relationships and interdependencies. In Figure 4.1, a simple representation of a stock-flow structure is illustrated.

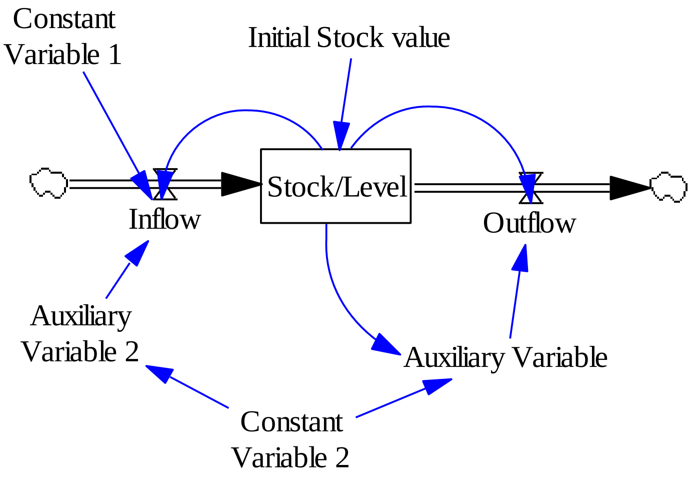

Figure 4.1. Simple stock-flow structure

A bank is a complex system with multiple mechanisms and subsystems that play important role in its behaviour. The interconnections among those mechanisms and the decisions that have to be made in a bank create feedback loops that drive to particular behaviours. This is a reason that System Dynamics could be an appropriate modelling approach. The ability of System Dynamics modelling to incorporate qualitative information is significant as all the components of a bank's system, the interdependencies and the casual relationships are quantified providing a deeper understanding of how the system is influenced over time.

Traditional stress test models describe links depending on empirical estimations with the use of statistical data. However, they mainly identify final effects but do not allow the design of policies and decisions of the bank or the regulatory authorities in a macroeconomic scope. Decisions and transactions of the bank are characterised by periods of times and delays that can be crucial for the final financial state of the bank. System Dynamics model could include and represent all those delays and relationships between bank's transactions, investments, decisions and its cash balance.

Focusing on the complex financial system and how it could be approached with the use of System dynamics, it can be seen that existing projects could assist in different perspectives. Studies present SD models related to the bank system or linked to one banking institution. Pruyt examined used the case of Fortis bank (Pruyt 2009) and the case of DSB bank (Pruyt 2010) with two System Dynamics models. The case of DSB collapse is explored also by Lansink (2011) in his thesis project. Lansink developed a SD model to capture the behaviour and key incidents that lead into DSB bankruptcy (Lansink 2011). Macdonald (2002) in his PhD dissertation presents an extensive bank model that includes operations and decisions of a commercial bank. His model offers a detailed structure of the commercial bank in an effort to explore how deposit insurance policies could affect the operations and decisions of a commercial bank (MacDonald 2002). All these models offer a starting point for the model that is built for this thesis project, by describing key variables and mechanisms included in a bank's system.

4.4 Exploratory Modelling Analysis

Traditional System Dynamics approach may not be enough to deal with systems that are characterised by high degrees of dynamic complexity, and deep uncertainty. The need to explore the system in depth calls for Exploratory Modelling Analysis. The main concept of Exploratory Modelling and Analysis is the fact that computational model-based experiments are performed in the view of analysing complex systems characterised by uncertainties in order to support decision making (Bankes 1993; Lempert et al. 2003).

The definition of deep uncertainty is given by Lempert, Popper, and Bankes (2003) as: "… *where analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes*" (Lempert et al. 2003).

Exploratory Modelling and Analysis (EMA) is implemented (i) to explore the influence of uncertainties, and (ii) to test the effectiveness and robustness of policies given all these uncertainties (Pruyt 2010; Pruyt & Kwakkel 2011). To implement EMA, models required, which are used to perform a series of computational experiments is used. In the computational experiments, uncertainty ranges are explored generating an ensemble of various futures. Dynamic behaviours are analysed, using machine learning techniques, to identify and compare of alternative policies.

EMA is an explorative approach: "*…In EMA, the question is not 'when to measure more' nor 'when to model better', but 'how to explore and analyse dynamically complex systems under deep uncertainty', and 'which policies effectively and robustly improve system behaviour under deep uncertainty'* " (Pruyt 2010; Pruyt & Kwakkel 2011).

In this research, EMA is applied by exploring uncertainties regarding the future and the effects of stress events on a bank's financial state. Computational experiments include thousands of runs in which multiple parametric uncertainties are explored in different values. The selection of those parametric uncertainties is driven by the scenarios of plausible stress events that we focus for the purpose of this study.

4.5 Exploratory Systems Dynamics Modelling and Analysis

The combination of the aforementioned methodologies leads to Exploratory System Dynamics Modelling and Analysis (ESDMA) (Pruyt 2010; Pruyt & Kwakkel 2011). This method is used to explore dynamics and all sort of uncertainties that influence a bank's system behaviour.

In this research, the System Dynamics bank model needs to fulfil the exploratory purpose, as our focus is to explore bank performance under uncertain future. In ESDMA a SD bank model is used for performing EMA through the use of a Python shell. The modeller uses Python scripts to manipulate the SD model and extract the outcomes needed for further analysis. Thousands of runs are simulated in order to explore the entire uncertainty space while the values of all those parametric uncertainties change. The uncertainty space includes parameters related to the future of a bank under stressful events and their severity.

4.5.1 EMA Workbench

For performing EMA on the SD model, the EMA workbench is used. EMA workbench is a software toolbox (http://simulation.tbm.tudelft.nl/ema-workbench/contents.html), developed by a team at Technische Universiteit Delft, TBM Faculty (Policy Analysis Section). Particular machine learning algorithms and advanced visualization tools are used to perform multiple experiments and analyse the results, providing the ability to explore possible uncertainties and identify causes based on the inputs.

4.5.1.1 Visualization techniques

ESDMA methodology generates a large amount of data. All those experiments executed in different runs could be illustrated in graphs so as the reader is capable of conceiving different behaviours and their differences. EMA workbench provides multiple tools for the visualization of the outcomes.

In the analysis below, the reader finds the lines graph and the envelopes graphs that illustrate the outcomes of the simulation. Lines graphs show all the behaviours of the performance indicators of the model observed in all runs. The graph is composed by multiple coloured lines, each of which represents one run with one particular set of values of parameters. Each run is drawn with a different colour for reader's convenience. An example is illustrated in the following figure with time illustrated on the x-axis and the liquid assets on the y-axis.

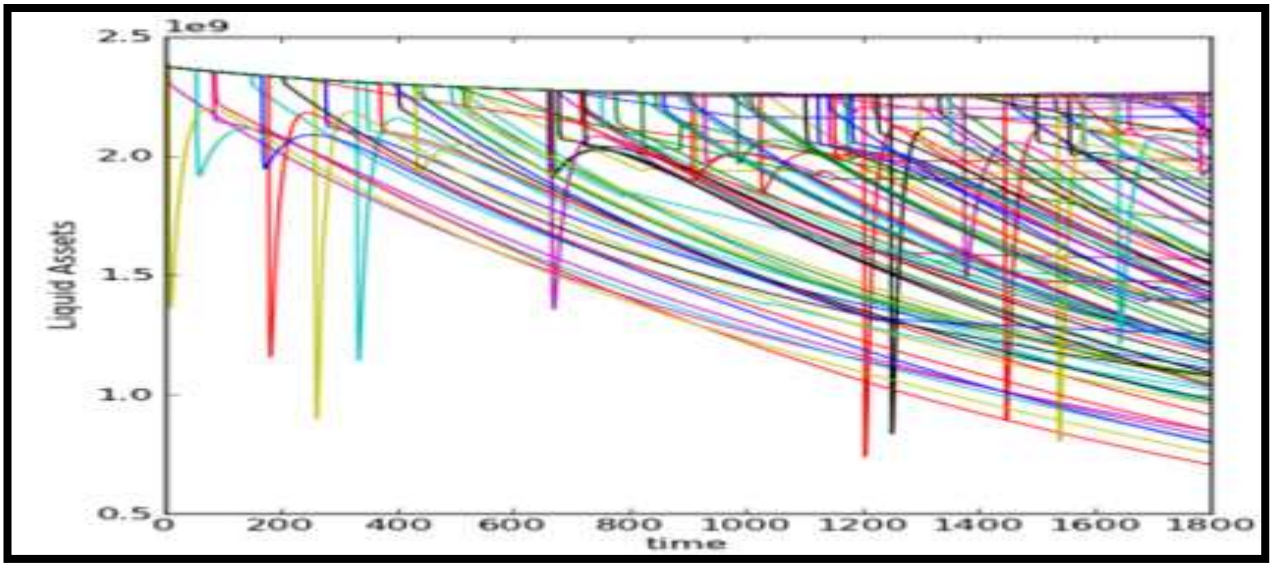

Figure 4.2 Example of Line graphs

The envelopes graph in Figure 4.3 shows the range of the outcomes and they are created by the highest and the lowest value of the variable during all runs. The envelopes graph provides the boundaries of the behaviour of the illustrated performance indicator. Next to those graphs, the reader can find a kernel density estimation (KDE) (Rosenblatt 1956; Parzen 1962) graph which illustrates the distribution of the values outcomes at the final time of the simulation of all the runs. It provides the analyst with a view of the most possible end- values of the model revealing model's tendency to particular behaviours. KDE could possibly be replaced by a boxplot. This graph will be illustrated next to the lines graph in the analysis section.

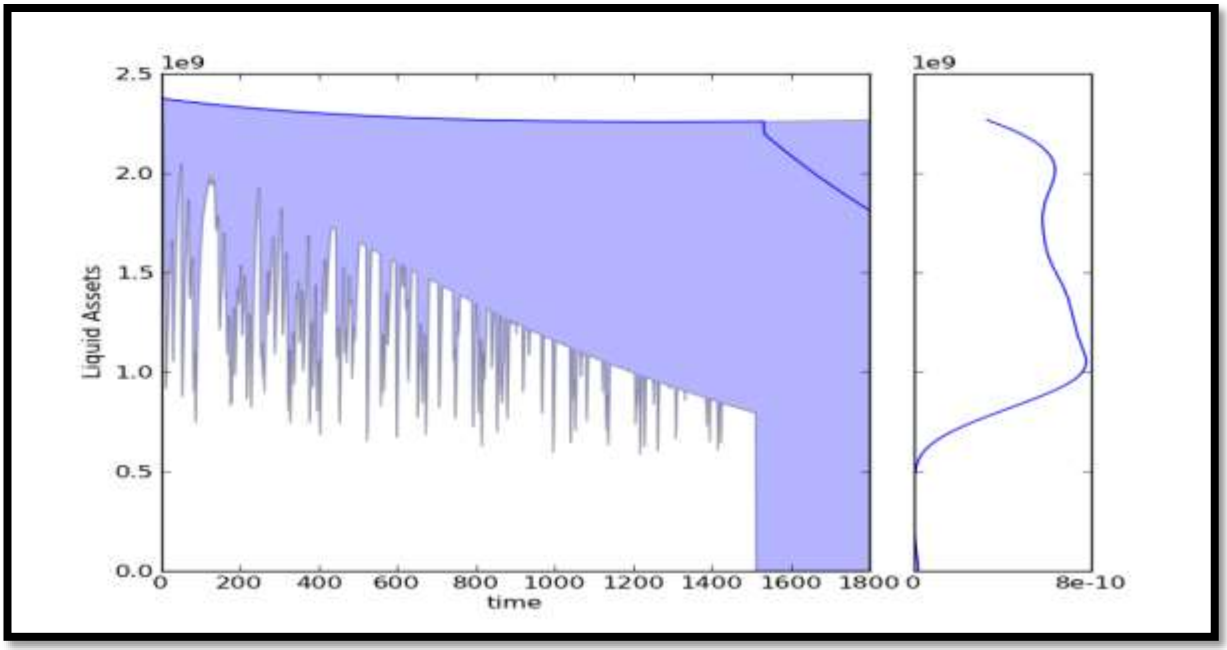

Figure 4.3 Example of Envelopes and KDE graph

4.5.1.2 PRIM Algorithm

Clustering based on the output data enables the identification of the causes of undesirable scenarios. Thus, the outcomes are required to be clustered based on the modes of behaviours we need to focus on. In order to identify the factors, it is vital to discover combinations of values of the uncertainties that generate similar outcomes. For the purpose of the identification, the Patient Rule Induction Method (PRIM) (Friedman & Fisher 1999; Lempert et al. 2006; Groves & Lempert 2007; Chong & Jun 2008; Polonik & Z. Wang 2010) is applied here. The PRIM algorithm is included as a tool in the EMA workbench and it enables the identification of subspaces of the uncertainty space that generate outcomes of particular interest with a classification function.

The identification of (un)desirable scenarios is achieved by defining a value as threshold for the final state outcome of the performance indicator. For example, we can set PRIM algorithm to isolate runs in which the net worth is negative (“Net worth”< 0). Then, sets of values of the uncertainty space (boxes) responsible for those outcomes are assorted. Those boxes are defined by a limited fraction of positive matching cases and a mass of scenarios relative to the overall space, meaning that they include the parametric space (ranges of the uncertainties) that is responsible for a particular number of the scenarios we look for. The graphs that illustrate the PRIM results are similar to the Figure 4.5 and Figure 4.6. In Figure 4.5, each colour describes a combination of the uncertainty space -box and is a graph that combines all the boxes for a better comparison of the results. Figure illustrates each box separately.

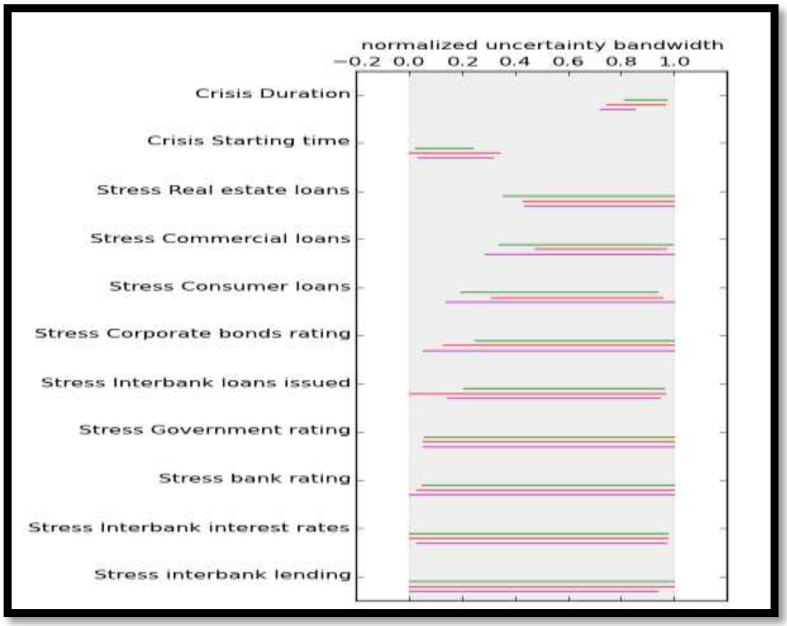

Figure 4.4 Example of PRIM graphs-combined boxes

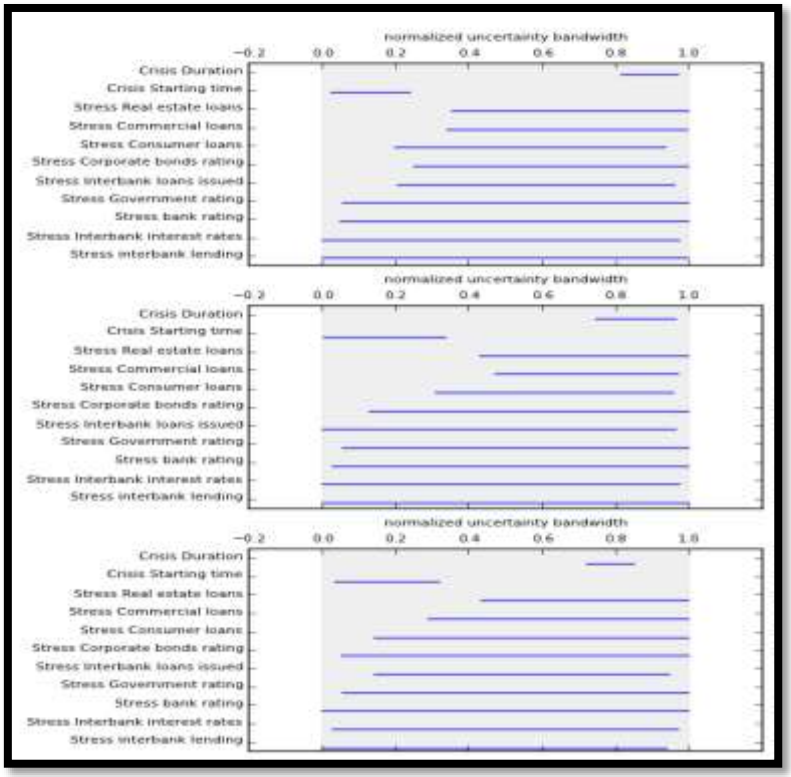

Figure 4.5 Example of PRIM graphs- Separate boxes

The resulting boxes (lines in the graphs) illustrate sets of normalised parametric ranges. For example, it can be seen above that we have 3 different boxes (green, red and purple) composed by different ranges of each of the 11 parameters. Those 11 parametric ranges in those boxes are normalised, but the exact values of those ranges can be found in the Appendix 3 as they are also printed by the software. In the example of Figure 4.5 and 4.6, it can be concluded that Box 1contains scenarios defined by extremely long crisis duration, with an early starting time and relatively high default rate for real estate, commercial, consumer loans and corporate bonds.

5. Bank model

This chapter describes the structure of the banking System Dynamics model[7] which is developed for the purpose of this thesis project. Different sectors of the model are examined and their use is explained. The model is built based on a bank's balance sheet; in which bank's financial position is summarized. The model is mainly separated in two main parts containing the liabilities and the assets of the bank.

5.1 Boundaries and Assumptions

The bank SD model is the backbone of this thesis project and the tool for the analysis and the description of the dynamic behaviour of the system. The purpose of the model is not to reproduce existing historic data or provide precise and accurate numerical results, but to generate multiple scenarios and provide the analyst with insights of various dynamic behavioural modes of the system over time. Due to the objective to develop a generic framework of a stress testing tool the model is not a representation of a specific real bank.

The complexity of the system increases the level of difficulty to represent it in a model. This is the reason that boundaries have to be set and assumptions have to be made. The model cannot be considered as an accurate representation of a bank because of the simplifications and the assumptions that have been made regarding bank's operations and mechanisms that compose the structure of the system. The model does not include all the functions and the activities of a bank as each institution is able to offer multiple financial instruments and products to its customers. However, the model can be adopted and further adapted in case of a real bank.

In the scope of this model, mechanisms representing stock market and exchange rates are not included. Stock market mechanism and share price of the bank are not designed, remaining out of the boundaries of the model. In cases of crises, in which the bank needs to meet significant liquidity needs, raising capital through issuing new shares in stock market is not possible as the share price will probably suffer and it is assumed that it is not available to the bank as a funding mechanism. Furthermore, exchange rates are not stress tested as it is assumed that the bank does not keep large number of assets and liabilities in a foreign currency and it is not exposed to interbank loans in another currency.

The physical capital of a bank like buildings and equipment is not included in the model as part of the assets. Although they could be sold, it is assumed that when the bank is in distress, it is difficult to raise funds by selling physical assets that are considered highly illiquid. Commissions and other fees are becoming an important income source in commercial banking in an effort to increase their revenues.

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[7] Regarding the modelling process, in this research, the SD model is built in Vensim DSS.

However, in this research, it is not included as a stream of income. Furthermore, wages and operating costs are not simulated in the model as a flow of expense.

The time horizon of the model is 1800 days (5 years)[8]. The unit of time is one day, meaning that the model provides data regarding the behaviour of the system per day calculated. The unit of time could have been a week or a month. However, the decision lies on the fact that observing daily behaviour of the bank is crucial as a severe shock can cause undesirable outcomes and lead to bankruptcy in very short periods of times like few days.

5.2 Model description

Figure 5.1 shows the complete model, which mainly consists of two parts in an effort to include liabilities and assets of a bank and a third part that includes indicators showing bank's position. Deposits (generic structure for savings accounts), interbank loans that a bank can take from other banks and loans that it can take from the Central bank are the main parts of the liabilities' sector. On the other hand, assets' sector is composed of loans that the bank issues (3 categories and loans to other banks), liquid assets, securities and corporate bonds. The allocation of funds and the decisions of the bank are defined by auxiliary variables which can change depending on policies. All the variables and the equations of the model are defined in the Appendix 2.

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[8] Each year is assumed to be 360 days.

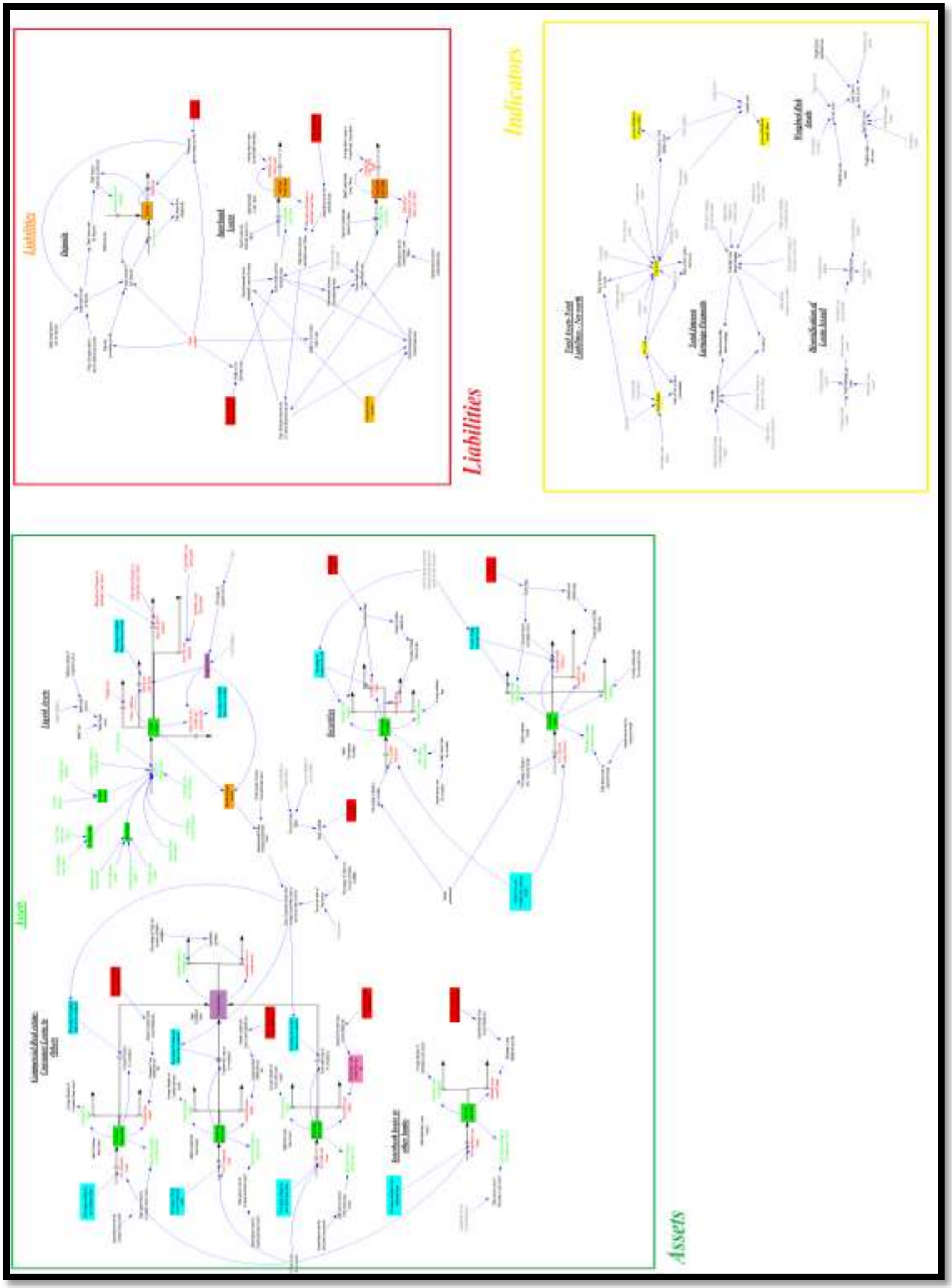
Liabilities
Indicators
Assets

Figure 5.1 Overview of Bank SD model (illustrative reasons only)

5.2.1 Liabilities

In this model, interbank loans taken, central bank loans taken and the deposits of customers in the bank are considered as its liabilities. Total liabilities (variable) are the sum of all the aforementioned elements.

5.2.1.1 Interbank loans and Central bank loans taken

If liquid assets fall beneath the required reserves, the bank seeks for loans in order to meet its liquidity needs. The available options to the bank for borrowing funds are two, as the bank is able to receive loans through interbank market or directly from the central bank. In normal conditions, when the bank is credible and the (perceived) value of its total assets is higher than the amount needed, the bank borrows the whole amount via interbank market if the interbank interest rate is not extremely higher (>3 times) than the Central bank rate. If the interbank rate happens to be extremely higher than the central bank rates, the bank prefers to seek for loans from Central bank, which acts as a "lender of last resort".

When bank's credibility is under question or interbank lending is not possible because other banks are not reluctant to lend money, the ability of bank to borrow through interbank market is restricted and it has to seek for loans from Central bank again. In the model, the variable "Desired amount of new interbank loans to be taken" defines the amount of funds the bank seeks from interbank market. The "Ability to get interbank loans" describes the ability to get those funds in a scale of 0 to 1, which actually shows a percentage of the funds available to the bank in the interbank market. This relationship is illustrated with a lookup function linking bank's credibility and the aforementioned percentage.(Appendix 2) However, the amount that the bank is able to borrow in each case has to be valued less than the "perceived value of the assets" of the bank. The "Perceived value of the assets" is defined as the value of the "Total assets" decreased in a percentage depending on the variable "Bank's credibility". If "Bank's credibility" is decreased for any reason, then the "Perceived value of the assets" is also decreased in a percentage.

If the bank is not able to raise part or the total required amount, it searches for loans from Central Bank. To get loans from Central bank, the bank should be credible enough (but less strict than the interbank market) and the value of amount needed is less than the "perceived value of the assets" of the bank. The "Ability to get Central bank loans" is another lookup function exporting another percentage (Appendix 2).

Finally, in the model, the average terms of the loans taken are included with the variables "Average time to repay interbank loan taken" and "Average time to repay Central Bank loan taken". Depending on the average annual interest rates, the daily interest rate is derived from the Equation 1. $DailyRate = (1 + AnnualRate)^{1/360} - 1$. "Daily Central Bank interest rate" and "Daily interbank interest rate" multiplied by the stocks "Central bank loans taken" and "Interbank Loans taken" respectively, define the daily interest bank's payments. Both mechanisms for interbank and central bank loans taken are demonstrated in Figure 5.2.

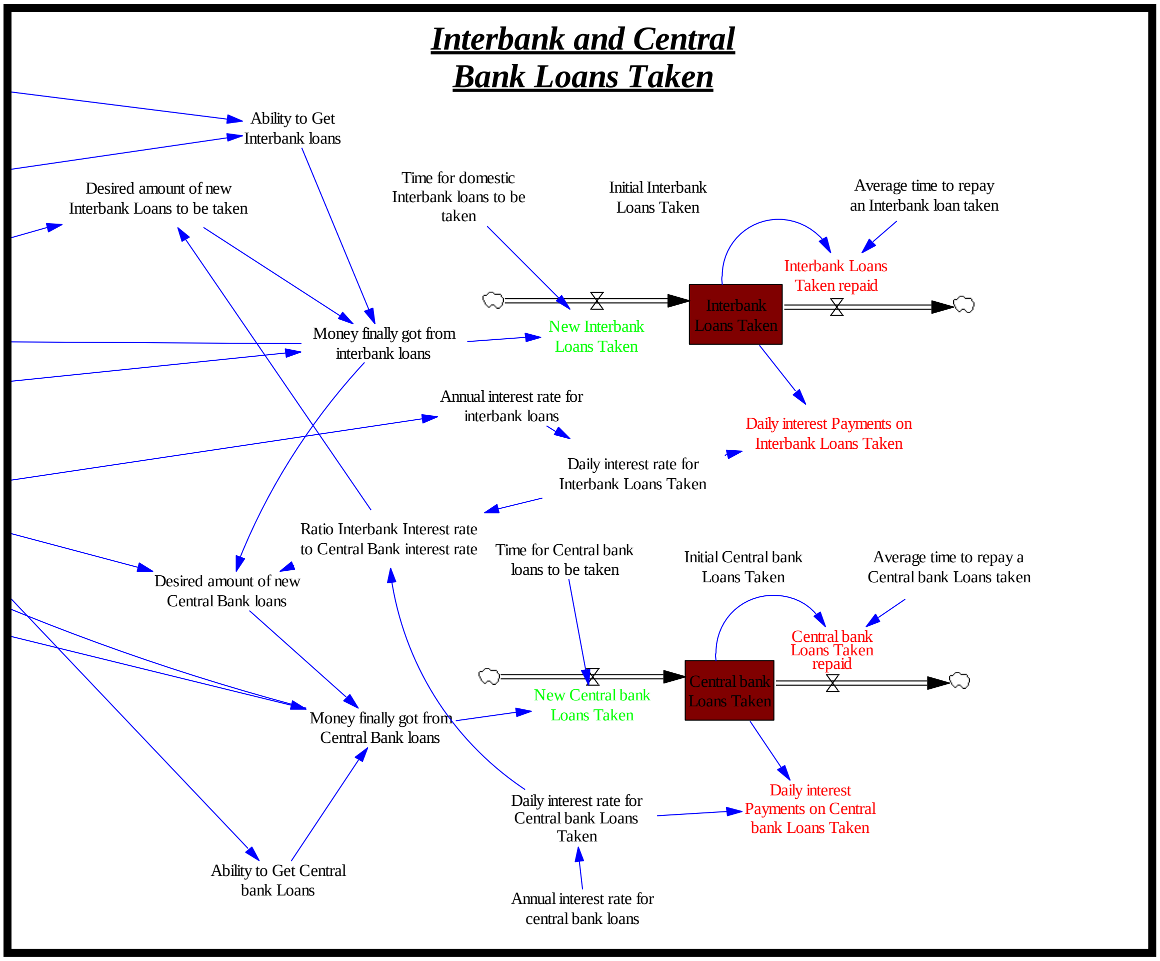
Interbank and Central Bank Loans Taken
Ability to Get Interbank loans
Desired amount of new Interbank Loans to be taken
Time for domestic Interbank loans to be taken
Initial Interbank Loans Taken
Average time to repay an Interbank loan taken
Interbank Loans Taken repaid
Interbank Loans Taken
Money finally got from interbank loans
New Interbank Loans Taken
Annual interest rate for interbank loans
Daily interest Payments on Interbank Loans Taken
Daily interest rate for Interbank Loans Taken
Ratio Interbank Interest rate to Central Bank interest rate
Time for Central bank loans to be taken
Initial Central bank Loans Taken
Average time to repay a Central bank Loans taken
Desired amount of new Central Bank loans
Central bank Loans Taken repaid
Central bank Loans Taken
New Central bank Loans Taken
Money finally got from Central Bank loans
Daily interest rate for Central bank Loans Taken
Daily interest Payments on Central bank Loans Taken
Ability to Get Central bank Loans
Annual interest rate for central bank loans

Figure 5.2. Interbank and Central bank loans taken structures

5.2.1.2 Deposits

The sub-system (Figure 5.3) that consists of the Deposits stock, two inflows and one outflow represents customer's actions to deposit or withdraw amount of money. Although, in majority of banks, a customer can find a variety of products-savings accounts, in this model deposits represent a generic structure. Deposits are the most crucial liability, because new deposits are available to the bank as liquid assets, which can invest to issue new loans or purchase securities and bonds. Nevertheless, they are key factor for liquidity risk, because if all depositors withdraw their money simultaneously, the bank will not be able to meet the demand.

The stock describes the aggregated amount of Euros that depositors have in their accounts each day. Deposits increase (inflow) whenever customers make new deposits and they decrease whenever customers decide to withdraw (outflow) an aggregated amount of Euros per day. The amounts that customers deposit or withdraw are defined by two percentages. Both those percentages change depending on the exogenous conditions that influence the bank's credibility and the relationships are defined with lookup functions (Appendix 2). If bank is credible, new deposits are coming, withdrawals are stable and the bank meets its every day liquidity needs. On the other hand, if bank's credibility suffers because of an exogenous shock, then new deposits decrease and withdrawals increase as the bank does not attract customers. Severe shocks can cause bank runs as withdrawals highly increase and customers stop depositing, which can drive the bank into bankruptcy.

The structure includes a second inflow that increases the deposits, the interest payments. In the model, the deposits increase with interest payments in a daily basis, which is not accurate as banks place interest payments in customers' accounts in various periods depending on the product (1, 3, 6, 12 months). However, daily interest rate is derived from the Equation 1 based on annual interest rate paid on depositors.

Bank's credibility is determined by a lookup function and is measured on a scale from 0 to 1, with 1 meaning the bank is highly credible. Bank's credibility is influenced by either the perception that the bank will be bankrupt ("Perceived bank failure") or the bank's rating, meaning that if the bank is downgraded its credibility suffers. The perception that a bank could be bankrupt ("Perceived bank failure") is derived from a possible solvency fail or liquidity fail depending on two ratios, the total assets to total liabilities ratio and the liquidity ratio defined as liquid assets and government securities value to total liabilities ratio (Appendix 2).

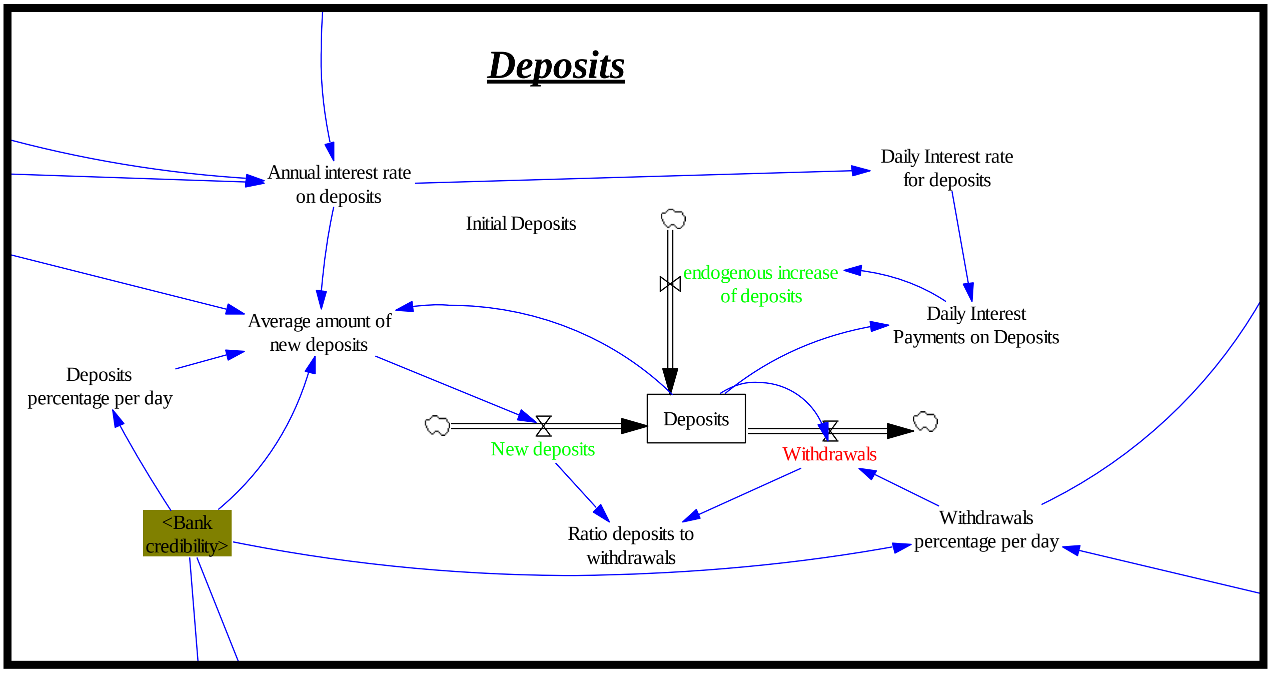
Deposits
Annual interest rate on deposits
Daily Interest rate for deposits
Initial Deposits
endogenous increase of deposits
Average amount of new deposits
Daily Interest Payments on Deposits
Deposits percentage per day
Deposits
New deposits
Withdrawals
<Bank credibility>
Ratio deposits to withdrawals
Withdrawals percentage per day

Figure 5.3. Deposits structure

5.2.2 Assets

In this model, total assets (variable) are considered the sum of all the loan categories and the interbank loans that have been issued by the bank (stocks), adding the securities and the corporate bonds that the bank possesses and the liquid assets.

5.2.2.1 Loans issued

Loans issued by bank to borrowers are considered as part of the assets' sector and they are important as they bring interest earnings. In an effort to keep the model simple, but also include more options for bank products, consumer, commercial and real estate loans are what the bank is able to issue. In the model, those different categories of loans are represented by similar structures and mechanisms but with different characteristics like average time to be repaid (loan terms), interest rates and default rates.

Medium and small firms, households and individuals are not able to get funding through other financial markets, but only through commercial banking. As the model represents a commercial bank, the portfolio of loans is mainly comprised of commercial loans, real estate and consumer loans. Consumer loans refer to loans that an individual can take for meeting personal consumer needs, like buying a car. They are considered short-term with higher interest rates. Real estate loans represent loans that are granted to individuals for purchasing residences or other buildings. The majority of those loans are long-term agreements with low interest rates that have to be paid by borrowers. Commercial loans describe loans that a firm can take so as to meet its credit needs regarding expansions or their inventories. The horizon of commercial loans is also long-term but with higher interest rates than real estate loans.

The stocks decrease when loans are repaid, when loans default and/or when the bank decides to securitise part of the portfolio of the loans. New loans are issued when the bank has available liquid assets. Available funds for loans are divided in different categories depending on the percentages that the bank decides (those percentages are constant). The exact structure of outstanding loans is illustrated in Figure 5.4.

With the use of default rate of each category, the likelihood that borrowers default on their loans is included in the model, meaning that a percentage of loans is not repaid, which causes unexpected losses to the bank. High default rates could lead to bankruptcy, as the bank will not be able to collect back its money. Each category's losses are represented and calculated by the default outflows and their sum equals the total losses that the bank expects to have from loans. In the model, daily interest earnings from each category are calculated by multiplying the daily interest rate (equation 1 is used) and the current portfolio of outstanding loans.

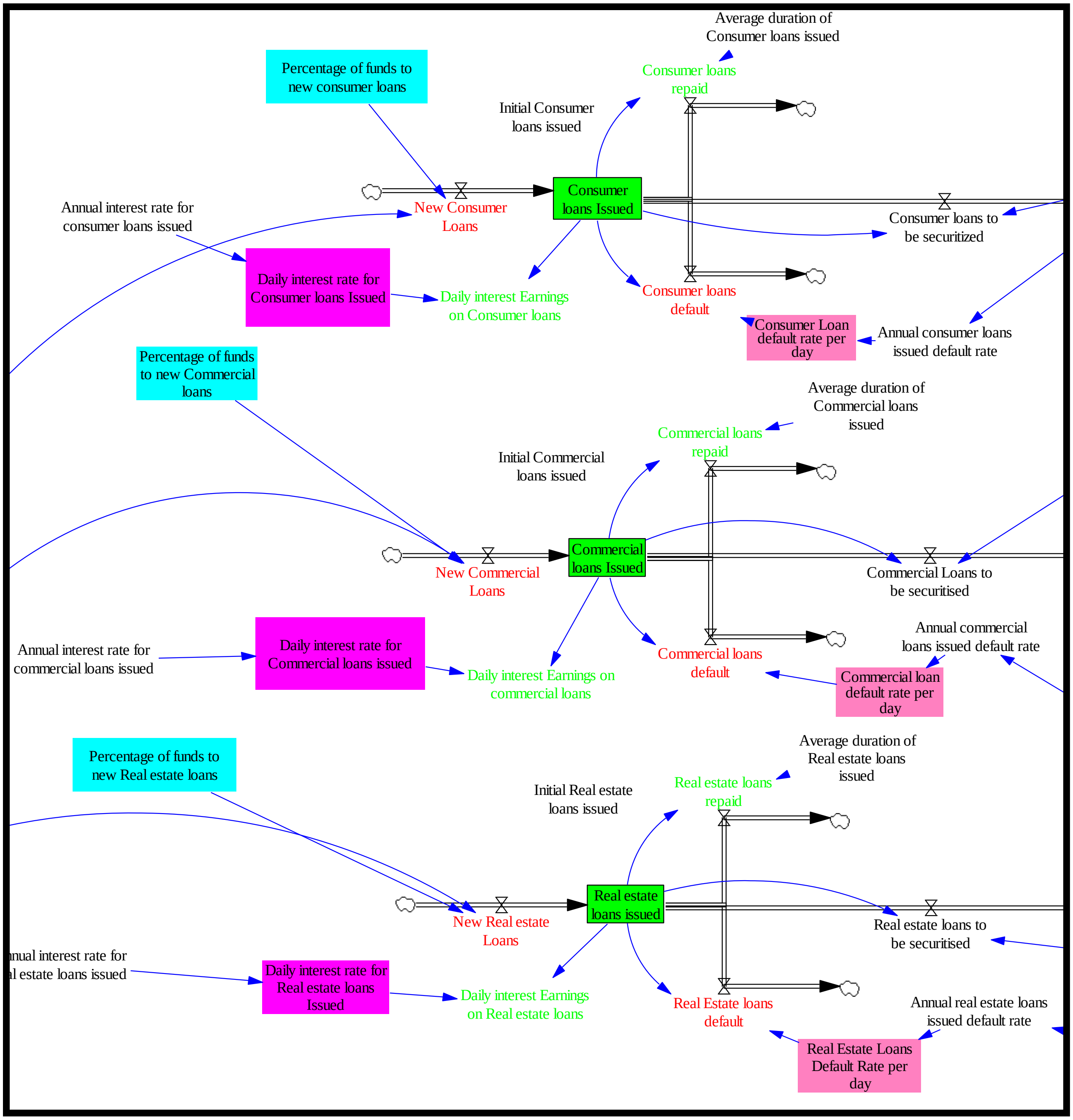
Average duration of Consumer loans issued
Percentage of funds to new consumer loans
Consumer loans repaid
Initial Consumer loans issued
Consumer loans Issued
New Consumer Loans
Annual interest rate for consumer loans issued
Consumer loans to be securitized
Daily interest rate for Consumer loans Issued
Daily interest Earnings on Consumer loans
Consumer loans default
Consumer Loan default rate per day
Annual consumer loans issued default rate
Percentage of funds to new Commercial loans
Average duration of Commercial loans issued
Commercial loans repaid
Initial Commercial loans issued
Commercial loans Issued
New Commercial Loans
Commercial Loans to be securitised
Annual interest rate for commercial loans issued
Daily interest rate for Commercial loans issued
Daily interest Earnings on commercial loans
Commercial loans default
Annual commercial loans issued default rate
Commercial loan default rate per day
Percentage of funds to new Real estate loans
Average duration of Real estate loans issued
Real estate loans repaid
Initial Real estate loans issued
Real estate loans issued
New Real estate Loans
Real estate loans to be securitised
nual interest rate for l estate loans issued
Daily interest rate for Real estate loans Issued
Daily interest Earnings on Real estate loans
Real Estate loans default
Annual real estate loans issued default rate
Real Estate Loans Default Rate per day

Figure 5.4. Consumer, commercial and real estate loans issued structures

5.2.2.2 Securitization of loans

Securitization of loans is an important function of the banking sector. The bank is able to collect an amount of different loan categories and sell them as financial instruments, like bonds or securities, to investors in order to gain liquid assets and reduce the default risk to which it is exposed.

In the model, an effort to capture this securitization mechanism is included (Figure 5.5). Based on the needs of a bank for liquid assets, a percentage of each type of loans issued is subtracted to be securitised. All of them are pooled in a stock and the bank is able to sell them. The bank sells more if liquidity needs increase in any case. The percentages of loans which are to be securitised are defined with lookup functions (Appendix 2) and they increase when the bank is not able to receive loans from interbank market or Central Bank. Liquidation premium represents the cost (losses) of the bank during the process of selling those assets. The percentage of loss on the value of those securitised loans is derived from a lookup function and depends on bank's credibility rate. If a bank faces problems then percentage of losses are higher. Liquidation earnings are added to the sum of new liquid assets.

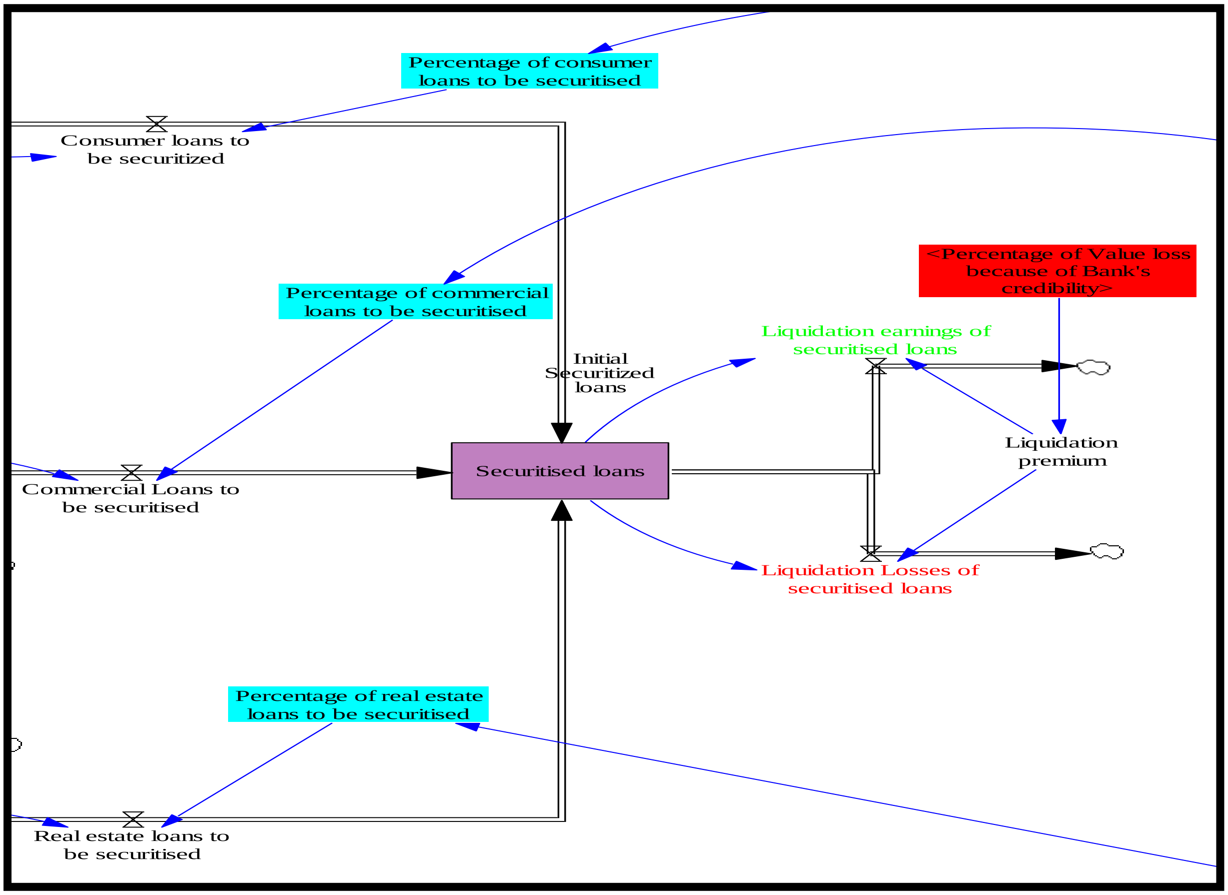
Percentage of consumer loans to be securitised
Consumer loans to be securitized
Percentage of commercial loans to be securitised
<Percentage of Value loss because of Bank's credibility>
Liquidation earnings of securitised loans
Initial Securitized loans
Liquidation premium
Securitised loans
Commercial Loans to be securitised
Liquidation Losses of securitised loans
Percentage of real estate loans to be securitised
Real estate loans to be securitised

Figure 5.5. Securitisation structure

5.2.2.3 Interbank loans issued

When the bank's liquid assets excess the required reserves, the bank is able to issue loans to other banks through interbank market. Interbank loans are mainly short-term and the interest earnings are considered low, so the bank decides to allocate only a low percentage of funds to issue interbank loans to other banks. The structure is the same as the aforementioned loans issued without the choice of securitization of those loans. In this case, initially, the interbank loans default rate is low (close to 0) because failures of banks are extremely rare in normal periods. Figure 5.6 shows the detailed structure of interbank loans issued.

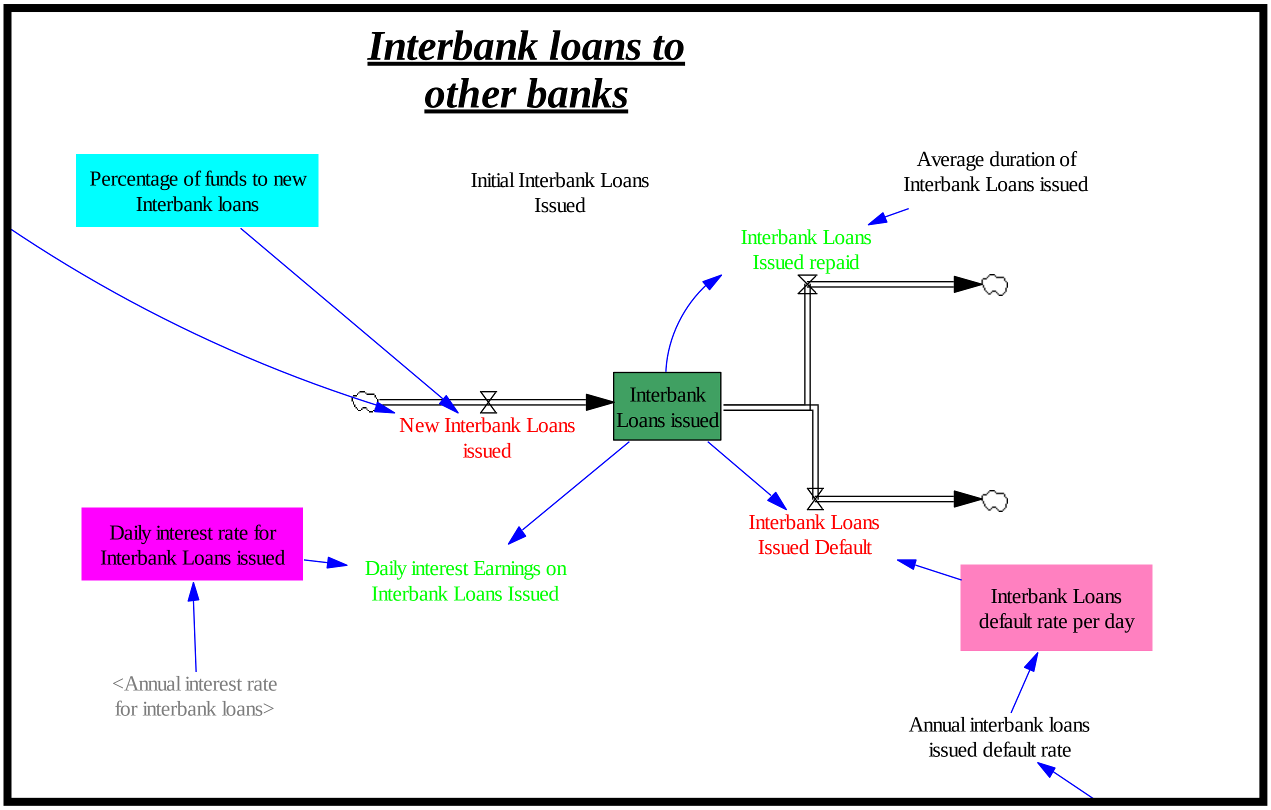
Interbank loans to other banks
Percentage of funds to new Interbank loans
Initial Interbank Loans Issued
Average duration of Interbank Loans issued
Interbank Loans Issued repaid
New Interbank Loans issued
Interbank Loans issued
Interbank Loans Issued Default
Daily interest rate for Interbank Loans issued
Daily interest Earnings on Interbank Loans Issued
Interbank Loans default rate per day
<Annual interest rate for interbank loans>
Annual interbank loans issued default rate

Figure 5.6. Interbank loans issued structure

5.2.2.4 Government securities

Government securities are debt instruments issued by the government of each country. They are considered low risk investments as it rarely happens for a government to default on its commitments, even in cases of a crisis. This is why they are described as highly liquid assets and the bank can sell them quickly without losses in order to obtain cash for meeting its liquidity needs. However, cases in which governments were unable to repay the face value on a certain date exist and it is significant to be modelled as the stability of the bank will be under threat. A recent example was the case of Greece in 2012, where an applied haircut created losses to banks possessing Greek government's securities. [9]

In the model, government securities stock represents the portfolio of securities that the bank owns. Based on the allocation of available funds for investments, the bank purchases new securities (inflow). Those securities are repaid (outflow-securities maturing) with an average maturity time of 5 years. The likelihood that a government will default (default rate) depends on the government's rating[10], the highest the rating, the lowest the risk to default (lowest default rate). If the bank decides to sell parts of government securities portfolio because of immediate liquid needs, possible losses because of government downgrading can occur. The annual default rate is determined by a lookup function depending on government's rating. (Appendix 2) Government's rating values are between 0 and 1, with 1 representing the highest rating and 0. When government's rating is close to 0 it means that the Government is not able to repay the securities and the overall amount of securities possessed are default. However, this case is considered extreme. In Figure 5.7, the securities' structure is demonstrated.

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[9] In February 2012, Greek Government and Eurogroup agreed on a policy package to reduce the debt-to-GDP ratio in sustainable levels. In this package, a decision for implementation of a debt restructure program was included. Part of this debt restructure program was a direct 53.5% haircut to the nominal value of all governmental bonds. This haircut was called PSI (Private Sector Involvement) referring to the participation of the private sector (banks and individuals) in an exchange of governmental bonds with lower valued ones. (Kalfaoglou 2012; Cline 2011)

[10] Corporate bonds and government securities credit ratings are delivered by rating agencies for assessing the credit strength of a corporation or a government respectively. Each agency provides its own ratings characterising the likelihood of a corporation or a government to default on its commitments. High ratings mean less or no risk to default; lower ratings describe an increased risk of default. Low-rated bonds and securities are considered high yield bonds or "junk bonds" as they carry high risk.

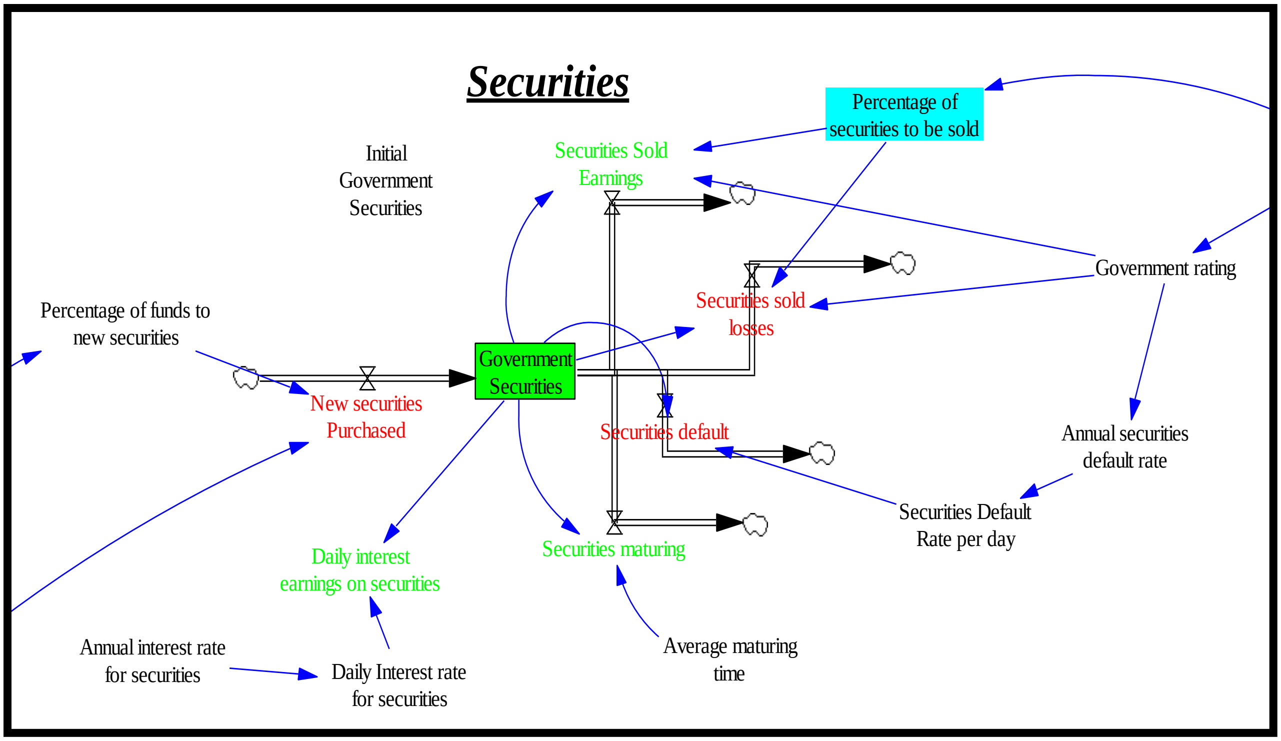
Securities
Initial Government Securities
Securities Sold Earnings
Percentage of securities to be sold
Government rating
Securities sold losses
Percentage of funds to new securities
New securities Purchased
Government Securities
Securities default
Annual securities default rate
Securities Default Rate per day
Daily interest earnings on securities
Securities maturing
Annual interest rate for securities
Daily Interest rate for securities
Average maturing time

Figure 5.7. Government securities structure

5.2.2.5 Corporate bonds

Corporate bonds structure represents another channel of funding for corporations. The bank purchases those corporate bonds in an effort to provide corporations with credit. They are long-term debt instruments and their value and the interest payments vary over time. Depending on the rating of the bond the value of a bond changes and the extra yield for carrying extra risk also changes. If corporate bond is down (up) -graded its value decreases (increases), but the extra yield on the interest payment increases (decreases).

In the model, a stock represents the current value of the corporate bonds that the bank possesses. This stock increases when new bonds are purchased and decreases when the current bonds are repaid. In addition to this outflow, two other outflows decrease the current portfolio of corporate bonds when the bank decides to sell part of its corporate bonds if it needs more liquid assets. Depending on the bond's rating, the bank sells them with losses or not. The likelihood that part of this portfolio can default is modelled with an outflow that decreases the stock (corporate bonds) when the bond is down-graded, meaning that the risk for defaulting increases. Bonds' rating values are between 0 and 1, with 1 representing the highest rating and 0 the defaulted bond. Corporate bond's percentage of loss and annual bond default rate are determined by lookup functions (Appendix 2). The higher the bond's rating is, the lower the loss of the bond's value and the lower the annual default rate. In Figure 5.8, the structure of corporate bonds is illustrated.

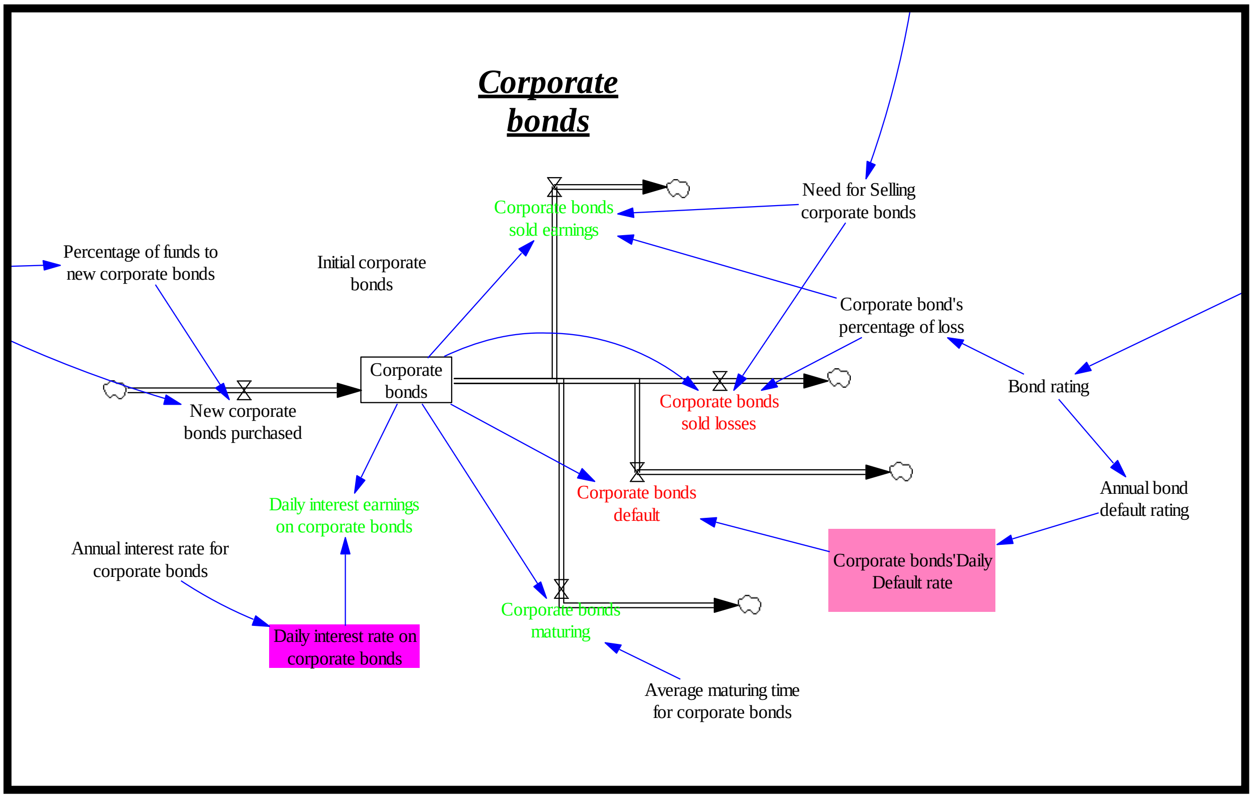
Corporate bonds
Corporate bonds sold earnings
Need for Selling corporate bonds
Percentage of funds to new corporate bonds
Initial corporate bonds
Corporate bond's percentage of loss
Corporate bonds
Corporate bonds sold losses
Bond rating
New corporate bonds purchased
Daily interest earnings on corporate bonds
Corporate bonds default
Annual bond default rating
Annual interest rate for corporate bonds
Corporate bonds'Daily Default rate
Daily interest rate on corporate bonds
Corporate bonds maturing
Average maturing time for corporate bonds

Figure 5.8. Corporate Bonds structure

5.2.2.6 Liquid assets

In the liquid assets' part of the model, the stock represents the amount of liquid assets that a bank possesses in each moment. As liquid assets are considered the vault cash and the bank reserves[11] that a bank holds at a certain point of time. Each bank needs an amount of money to meet its daily liquidity needs. The stock includes the reserves that the bank is obliged to keep aside. The required reserves and liquid assets that our bank is obliged to keep aside is 10% of the total current liabilities. If the liquid assets are above the required reserves, it means that the bank has available capital to issue new loans or purchase securities and corporate bonds. The management has to decide how available funds are allocated by defining percentages related to news loans to be issued, new securities or corporate bonds to be purchased. Those percentages are stable in the simulation, but they can change in cases of different policies.

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[11] Required reserves: Banks are obliged not to lend out the entire amount of their deposits but keep aside a certain percentage in order to meet their daily needs and decrease the level of liquidity risk. The bank reserves are not interest-bearing assets and they do not offer any income to the bank. Each bank is allowed to hold more reserves than those necessary to meet the reserve obligations, which are called excess reserves. (Hubbard & O'Brien 2011)

The stock increases by an inflow in which the sum of all interest earnings, new deposits, new loans taken by the bank, repayments of outstanding loans, corporate bonds and securities, is calculated. Furthermore, liquid assets increase when securitised loans are liquidated, government securities and corporate bonds are sold. On the other hand, liquid assets decrease by multiple outflows each of which represents different operations of the bank. The model calculates as reserves a percentage of total liabilities that should be available for the bank at any time.

Liquid assets decrease whenever a withdrawal takes place. Moreover, liquid assets decrease when the bank needs to repay loans that have been taken from interbank or central bank or interest payments on those granted loans. If the available liquid assets are above the level of the required reserves, liquid assets decrease because the bank decides to invest by issuing new loans or buying new securities in a certain percentage. If the stock of liquid assets falls under the required reserves, the bank seeks for loans through interbank market or Central Bank. The amount needed is calculated in the variable “Amount of money needed”. In Figure 5.9, the structure of the liquid assets is illustrated.

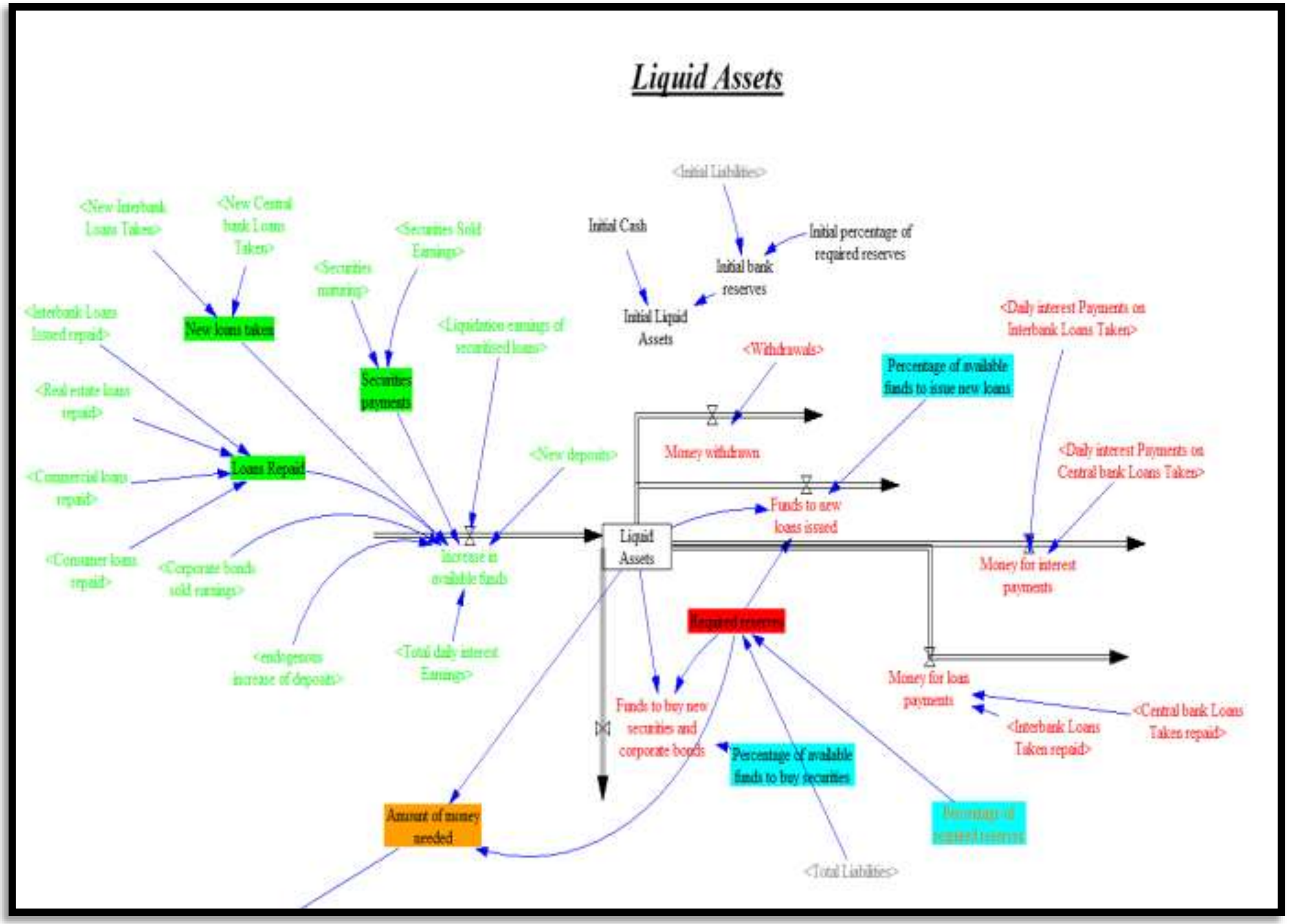
Liquid Assets
<Initial Liabilities>
Initial Cash
Initial percentage of required reserves
Initial bank reserves
Initial Liquid Assets
<New Interbank Loans Taken>
<New Central bank Loans Taken>
New loans taken
<Securities Sold Earnings>
<Securities maturing>
Securities payments
<Liquidation earnings of securitised loans>
<Interbank Loans Issued repaid>
<Real estate loans repaid>
<Commercial loans repaid>
<Consumer loans repaid>
Loans Repaid
<Corporate bonds sold earnings>
<endogenous increase of deposits>
<New deposits>
<Total daily interest Earnings>
Increase in available funds
Liquid Assets
<Withdrawals>
Money withdrawn
Percentage of available funds to issue new loans
Funds to new loans issued
<Daily interest Payments on Interbank Loans Taken>
<Daily interest Payments on Central bank Loans Taken>
Money for interest payments
Money for loan payments
<Central bank Loans Taken repaid>
<Interbank Loans Taken repaid>
Required reserves
Funds to buy new securities and corporate bonds
Percentage of available funds to buy securities
Percentage of required reserves
<Total Liabilities>
Amount of money needed

Figure 5.9. Liquid Assets Structure

5.3 Uncertainties

The exploration of various crises scenarios is based on different ranges on parameters of the model. During the experiments, thousands of runs are simulated with different values of those parameters based on the defined ranges. In each run, a single scenario is tested, which is defined by a combination of those parameters. One or more stress events are simulated in each run providing a comprehensive illustration of bank behaviour given the crisis starting time.

Uncertain futures are considered unexpected crises with unknown duration and severity that occur in an unpredictable point of time. To simulate unexpected crises, the point of time that a crisis will burst and the period of time they last, are treated as uncertainties and in each run they differ. It is extremely uncertain when a stressful event can appear in the future as no-one can predict the starting time of a crisis. This is the reason that in the model exists a variable “Crisis starting time” representing the point of time that a stressful scenario starts. Using this variable in a range of values enables the investigation of different behaviours of the bank.

The duration of the crisis is also a significant uncertain factor that could influence in various ways the performance and the stability of the bank. Crises that last for long periods would not allow the bank to recover as the bank would be continuously in distress. On the other hand, severe short-term crises would need immediate decisions and automated responses in order to meet high liquidity needs. The duration of each crisis that occurs is explored with the use of one variable (“Crisis Duration”) in a range of various values.

After the definition of the uncertainties regarding the time and the duration of the crisis, the severity of each stressful event needs to be explored. To understand how a bank can be affected by certain stress events, it is needed to explore and examine the factors that could trigger them, but also second order factors that could amplify negative effects. Several variables influence structures and constant variables of the model exploring different degrees of severity. In cases of a crisis, the bank faces multiple risks that could result in unstable problematic behaviours. Macroeconomic shocks can influence variables of the bank system.

The major risk that influences the financial state of the bank is a dramatic increase in the default rates of the loans issued. Unexpected increases in loan defaults will make the bank suffer losses while the value of its assets decreases. “Crisis on Real estate loans”, “Crisis on Commercial loans” and “Crisis on Consumer loans” are variables included in the model, triggering sudden increases in default rates of each different loan category. The bank suffers various losses depending on its exposure to each loan category.

Uncertainty in the banking sector and possible bank failures could cause an interbank market collapse leading to a scenario in which the bank is not able to take any loans from other banks. If liquid assets are needed and bank’s ability to receive interbank loans is restricted because of market collapse, the bank asks for Central bank loans and they sell assets in emergency. In the model, this stress event is explored by altering the variable “Crisis on ability for interbank lending” in different values between 0 and 1. If “Crisis on ability for interbank lending” is equal to 0, it means that the bank’s ability to take interbank loans is 1 (highest value) and the bank is able to receive loans from interbank market. On the other hand when “Crisis on ability for interbank lending” increases, the ability of the bank decreases and interbank lending is not available. In scenarios that the bank does not need any new loans to be taken, the effect of this risk factor is not distinguishable.

Furthermore, in cases of an increase in bank failures, more interbank loans that the bank has issued will default. This particular case is explored in the model with stressing the default rates of interbank loans with a variable called “Crisis on interbank loans issued”. Although, it is not usual for banks to declare bankruptcy, but if this happens, the exposure and contagion risk is extremely high. Because of initial low value for interbank loans issued default rate, the uncertainty of possible future values range is up to 100 times the initial value.

A dramatic increase in the interbank interest rates would also cause problems regarding the channels of financing for the bank. If interbank interest rates increase in extremely higher values than Central Bank rates, the bank will not be able to receive loans via the interbank market. This could be a disastrous scenario in cases of increased need for liquid assets. “Crisis on interbank interest rates” explores the uncertainty regarding interbank interest rates.

Public mistrust and the fear of depositors could cause a dramatic increase in withdrawals which can lead into bankruptcy as the bank will not be able to meet short-term liquidity needs. In the model, this increase is simulated with the use of a variable “Crisis on withdrawals” which unexpectedly amplifies the percentage of withdrawals in different degrees. Moreover, public mistrust and possible downgrading of bank’s rating would distress bank’s credibility. “Crisis on bank credibility” is used in the model to explore bank’s rating distress. If bank is downgraded unexpectedly, bank’s credibility will suffer which will lead in increasing withdrawal rates and decreasing “Perceived value of total assets”.

Uncertainty in financial markets, e.g. stock market crash, or recession that could affect firms and corporations, would cause down-grading corporate bonds held in the portfolio of the bank. This would increase the default rates of the purchased bonds and a value loss of bank’s bonds assets. To explore the performance of the bank under this scenario, a variable called “Crisis on corporate bonds” is used, which downgrades bonds’ rating in a certain value between 0 and 1.

Uncertainty on Government’s status, political and/or economic or appearance of a sovereign-debt crisis will affect the government securities’ rating. The portfolio of the bank that includes government securities will suffer devaluation and losses if the bank decides to sell them. Government securities’ high downgrading would increase the default rates of securities. Testing different scenarios with possible crises regarding the government securities’ downgrading, a variable called “Government crisis” stresses securities’ rating between values 0 and 1.

Table 5-1 shows all the uncertainties and stress events explored in the model. Their ranges and the influenced parameters of each shock are illustrated.

Table 5-1 Uncertainties

Crisis	*Parameter*	*Range*	*Influenced Parameter*	*Range of influenced Parameter*
-	*Crisis Starting time*	*0-1800*	-	
-	*Crisis Duration*	*0-1800*	-	
Crisis on corporate bonds	*Bond rating*	*0-0.9*	*Annual bond default rating*	*0-0.2*
Crisis on interbank loans issued	*Annual interbank loans issued default rate*	*0.001-0.1*		
Government crisis	*Government rating*	*0-0.9*	*Annual securities default rate*	*0-0.2*
Crisis on bank credibility	*Bank rating*	*0-0.5*	-	-
Crisis on interbank interest rates	*Annual interest rate for interbank loans*	*0.003-0.06*	-	-
Crisis on Commercial loans	*Annual commercial loans issued default rate*	*0.03-0.60*	-	-
Crisis on Consumer loans	*Annual consumer loans issued default rate*	*0.02-0.4*	-	-
Crisis on Real estate	*Annual real estate loans issued default rate*	*0.01-0.2*	-	-
Crisis on withdrawals	*Withdrawals percentage per day*	*0.0008-0.09*	-	-
Crisis on ability for interbank lending	*Ability to Get Interbank loans*	*0-1*	-	-

6. Analysis

In this chapter, the outcomes of the analysis are displayed and analysed. The dynamic behaviour of the system under various scenarios is illustrated using visual plots, showing differences observed in those scenarios. The most important key performance indicators regarding the financial position of the bank are discussed and explained in detail. The performance of the bank under various scenarios assists in the identification of the structures and the elements of the model that drive particular behaviours which could lead in undesirable outcomes. Finally, the uncertainty space in which the bank faces bankruptcy is determined.

6.1 Performance indicators and Data set

To observe different behavioural modes of bank and conceive its financial state, multiple variables are used as performance indicators, focusing on their outcomes. The performance indicators illustrated in the analysis are mainly stock variables which provide a clear view of the state of each bank's part in every run.

'Liquid Assets' and *'Net worth'* are the ones that we focused on as they show the cases that a bank faces bankruptcy because of increased liquidity needs or because of the fact that the value of the assets has become smaller than the value of its liabilities. However, visual diagrams with the behaviour of *'Total Liabilities'*, *'Total assets'*, *'Deposits'* are also illustrated here to provide a clear view of key parts of the model which are responsible for the final outcomes. Graphs that illustrate the behaviour of the variables *'Consumer loans Issued'*, *'Commercial loans Issued'*, *'Real estate loans issued'*, *'Corporate bonds'*, *'Interbank Loans issued'*, *'Government Securities'*, *'Interbank Loans Taken'*, *'Central bank Loans Taken'* can be found in the Appendix 1.

A data set of the outcomes is generated. The data set consists of 2000 runs with different combinations of the parametric space and they are generated with the use of Latin Hypercube sampling method (McKay et al. 1979; Iman et al. 1981).

6.2 A sense of sensitivity

An indicative sensitivity analysis provides the reader with an idea of how sensitive the model and the performance indicators are to small changes. The aforementioned external variables are just varied with maximum ±10% of their initial value. However, this experiment is a multivariate sensitivity analysis as variables are varied simultaneously in a run, in different values. Furthermore, they are not considered as stress events as the changes on the variables happen at the starting point and they are constant till the end of the simulation. The data set consists of 500 runs, in an effort to illustrate all possible behaviours of key performance indicators.

The ranges of the variables that we explore are illustrated in the following table.

Table 6-1 Sensitivity Ranges

Variables	***Ranges***
Consumer loans default rate	0.018-0.022
Commercial loans default rate	0.027-0.033
Real Estate loans default rate	0.009-0.011
Corporate bonds default rate	0-0.001
Withdrawals rate	0.0008-0.001
Securities default rate	0-0.001
Interbank loans issued default rate	0.0001-0.0003
Interbank interest rates	0.0027-0.0033

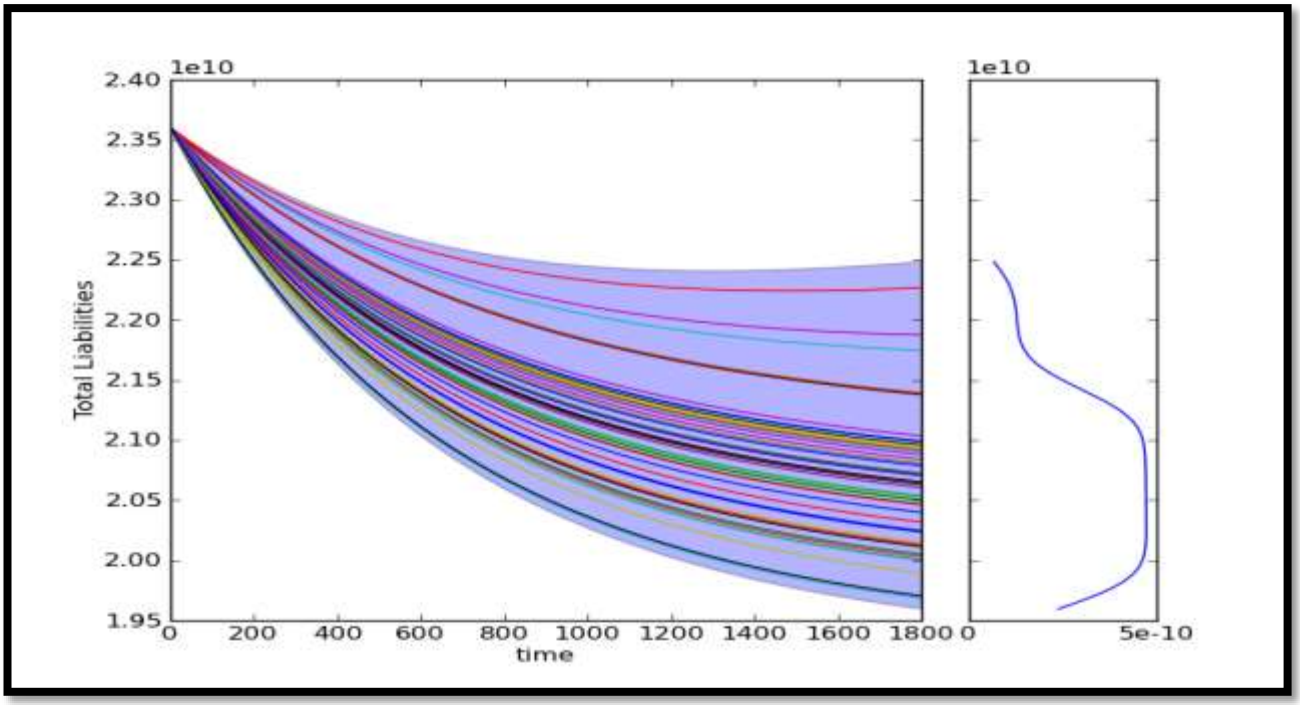

Figure 6.1 Sensitivity of total liabilities

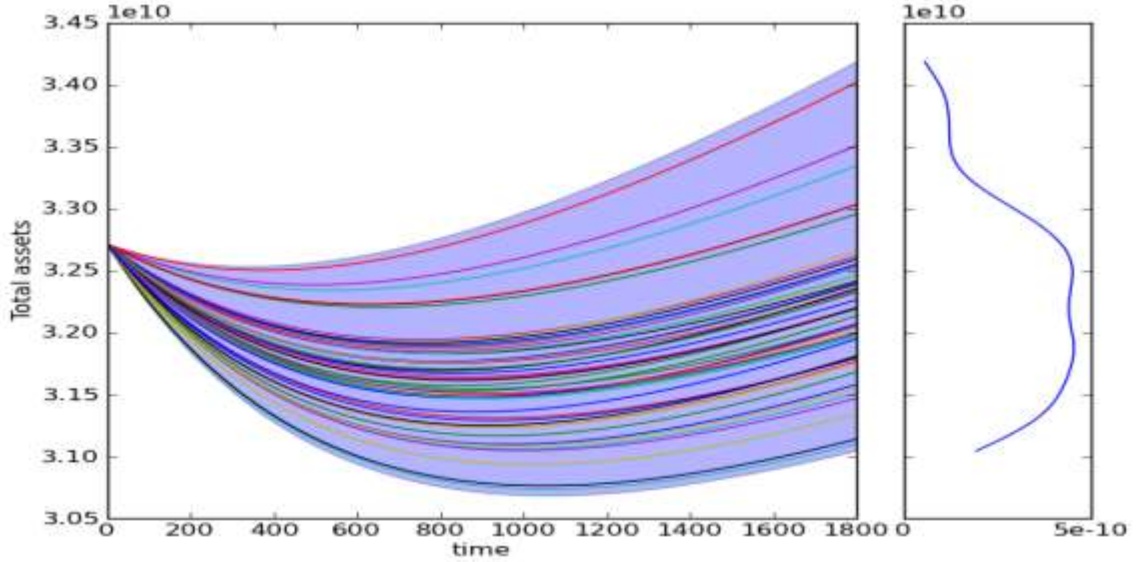

Figure 6.2 Sensitivity of total assets

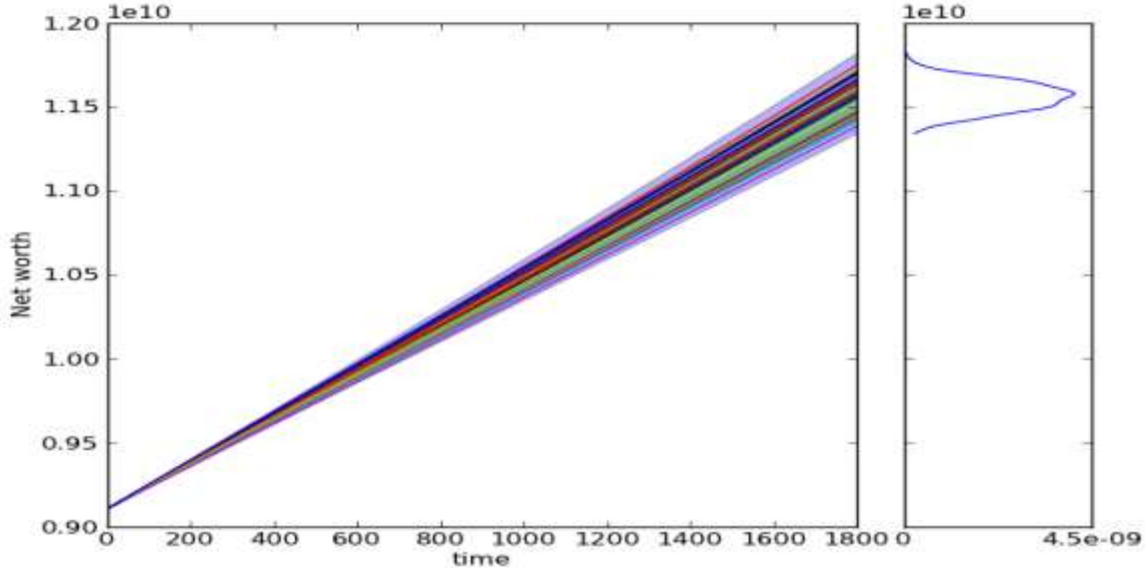

Figure 6.3 Sensitivity of Net worth

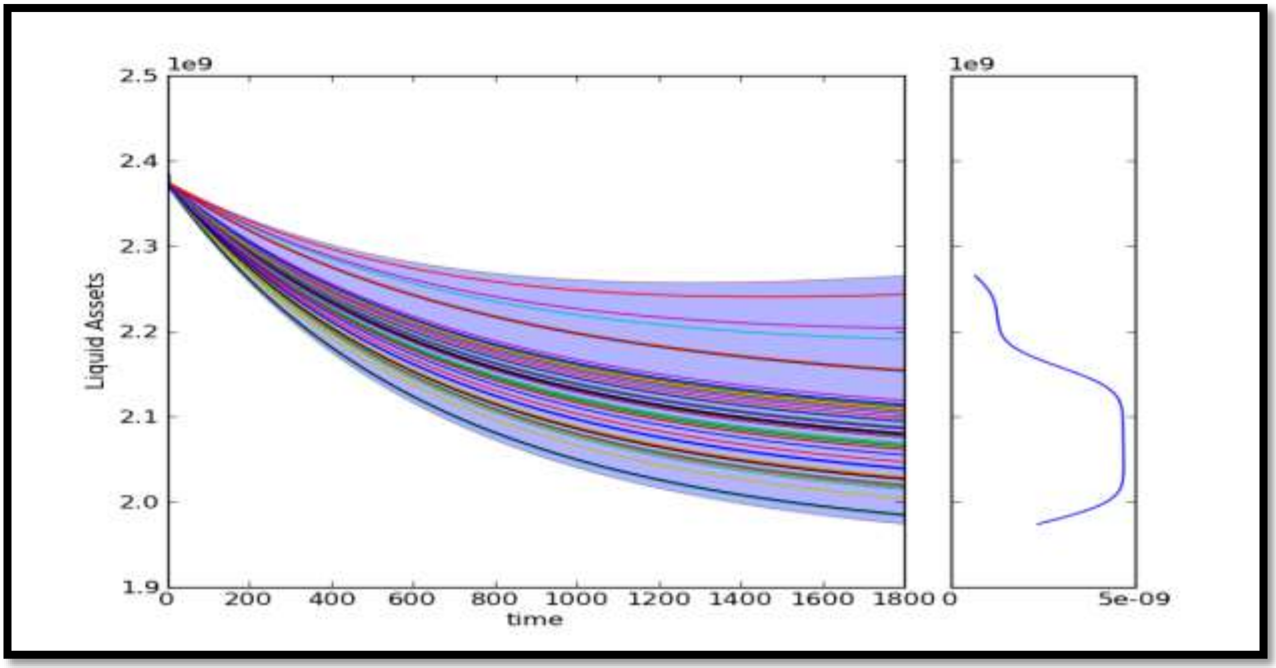

Figure 6.4 Sensitivity of Liquid assets

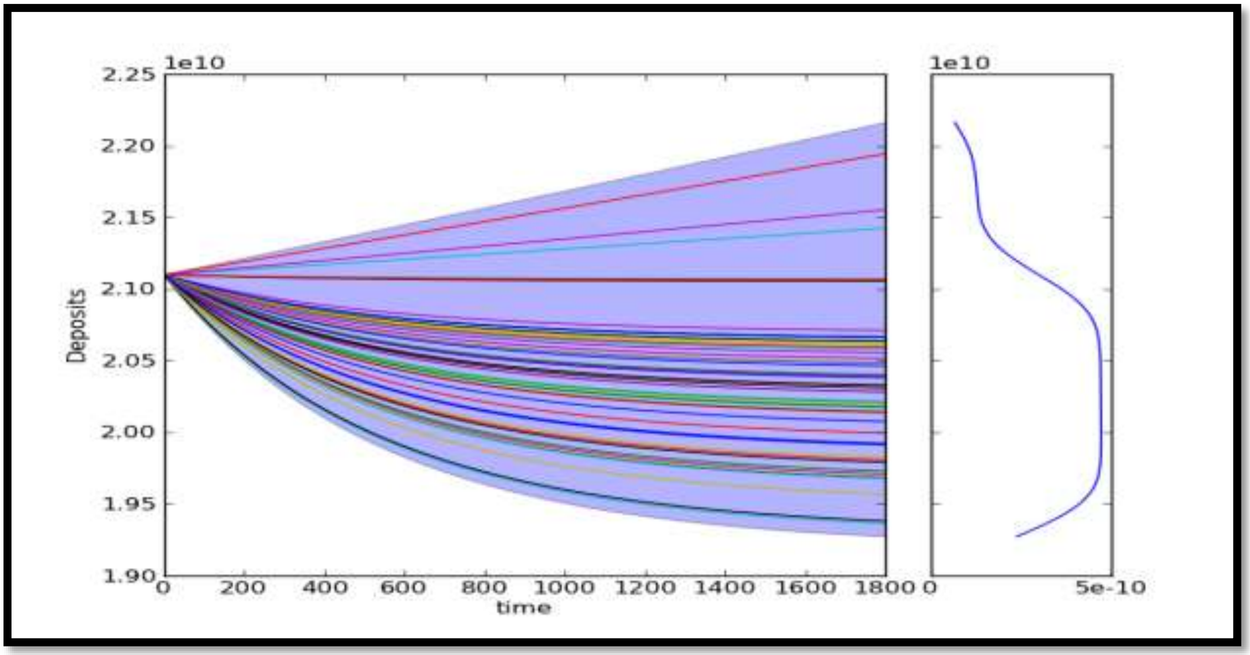

Figure 6.5 Sensitivity of Deposits

All the above figures illustrate that small changes of the above parameters do not influence the behavioural mode of each of the performance indicators. The final numerical outcomes of the model in each case are substantially different depending on the simulated scenario. However, in this uncertainty analysis we also decrease by -10% the strength of each stress, which cannot exist in the main analysis part as we only stress the model negatively.

Changes in numerical outcomes on the values of the assets are observed, as it was expected. In some cases, losses are substantial in terms of millions. Runs with higher final asset values exist mainly in scenarios with positive or null parametric changes. In all scenarios, assets firstly decrease and then follow an increasing trend, which can be explained because the bank has to repay loans that have been granted to them and do not invest. This is the reason that total liabilities decrease as loans that have been taken from the bank are repaid and no new loans are needed. Depending on the losses of each run, calculated by increased default rates, the bank loses more or less assets. After repaying all the loans granted, the increase of the assets is observed as more funds are available for investing.

Net worth is not substantially sensitive, but differences in the final numerical result can be observed. Only deposits appear to have more ample behavioural modes as it can be seen that runs exist in which deposits continuously increase. However, the tendency of the model appears to be that in the majority of the scenarios the bank suffers losses in deposits in the initial state, but then the situation is stabilised.

6.3 Ensemble of Behaviours

After the sense of sensitivity of the model that was provided to the reader, the model is stressed with extreme changes (ranges described in Table 5.1) in multiple scenarios. Different plausible future scenarios of the model revealed various behavioural patterns regarding the performance of each part of the system. In many scenarios, generated mainly by extremely severe conditions, the bank faces bankruptcy because of depletion of its total assets or negative net worth. In other cases, the bank survived with various losses. In general, particular behaviour patterns are observed in the majority of the runs like extensive withdrawals driving the depletion of deposits, sudden decreases in liquid assets, sudden decreases in total assets and total liabilities. In the next sections, observed behavioural modes of different performance indicators are discussed and illustrated by graphs.

6.3.1 Liquid assets

In the line graphs Figure 6.7, it is observed that the bank in a number of scenarios needs liquid assets to meet the demand for withdrawals. Those are only 100 lines out of 2000 experiments, but the envelopes graph in Figure 6.6 illustrates the maximum and the minimum value of the liquid assets. It appears that in all scenarios the bank is able to meet the immediate needs as no negative values of liquid assets appear even in extreme scenarios. In many runs, extreme sharp decreases in liquid assets are observed, mainly because of cases of extreme withdrawal rates as a result of different severe stress events. In the KDE graph of Figure 6.6, next to the envelopes graph, the distribution of those scenarios is demonstrated, showing that in a high number of scenarios the bank needs immediate funding which actually decreases the reserves and the liquid assets that are available.

In each case that a stress event influences in extreme degree the financial state of the bank, a perception that the bank will fail is created. This perception of liquidity problems or solvency problems generates a behaviour that reinforces the rates of withdrawals as a second order effect. This is the reason that sharp decreases exist driving to spikes in the envelopes graph. The model demonstrates such an extreme behaviour in many scenarios because this hypothetical bank has not applied any preventive action and the entire amount of deposits is available to the customers to be withdrawn. However, this does not apply to a real world bank.

Nevertheless, this extreme behaviour is presented in the real world when bank runs are taking place and the bank needs to be able to meet its liquidity needs. In cases of extreme scenarios that a bank run appears and the depositors ask to withdraw till to 9% of the current total deposits per day in our scenarios, the bank meets the demand with substantial losses. It may be the number of undesirable scenarios higher than expected, but this occurs because the model is stress tested under extremely undesirable scenarios and preventive actions do not exist.

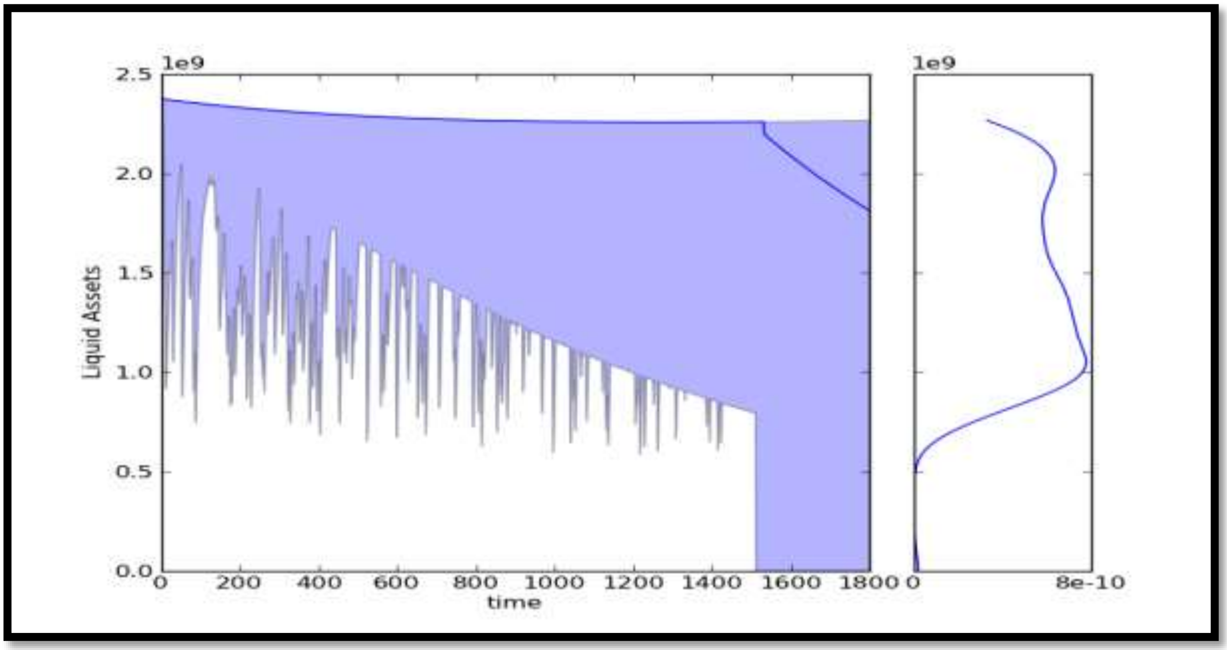

Figure 6.6 Envelope and KDE graphs of Liquid Assets

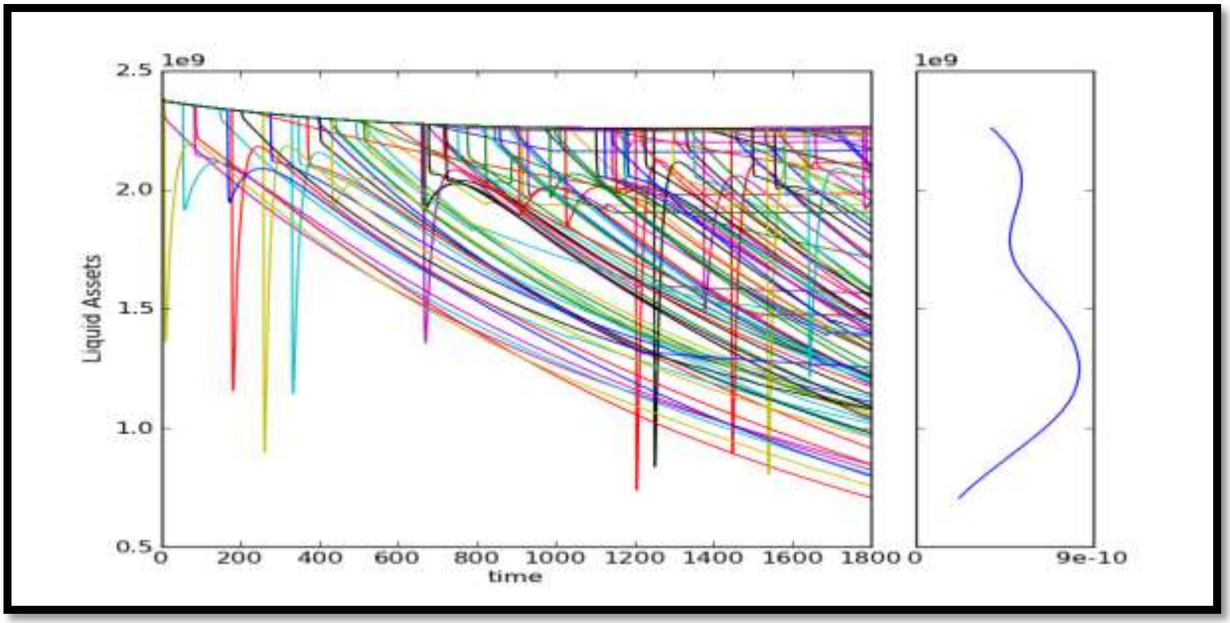

Figure 6.7. 100 selected runs of Liquid Assets

6.3.2 Deposits

The envelope graph in Figure 6.8 illustrates the range of the values that deposits take in all the experiments. As it can be seen, scenarios in which the deposits are depleted exist and following the KDE graph the number of scenarios that this happens as a final state is extremely high. The distribution of the KDE graph shows that a high number of hazardous scenarios have been simulated, in which bank’s deposits are completely withdrawn.

In the line graphs in Figure 6.9, the state of deposits in each run (100 out of 2000) is illustrated. In multiple runs, sharp decreases are triggered by stress events leading to catastrophic outcomes, explaining the behavioural patterns of the aforementioned liquid assets. In other cases, deposits suddenly decrease but after a while the amount is stabilised. It is observed that the bank does not recover its deposits in any scenario as it is assumed that no preventive actions are introduced from the bank at this point. In some scenarios, a continuous but not extremely sharp decrease appears which means that the bank has to deal with a scenario that the crisis' duration is long enough.

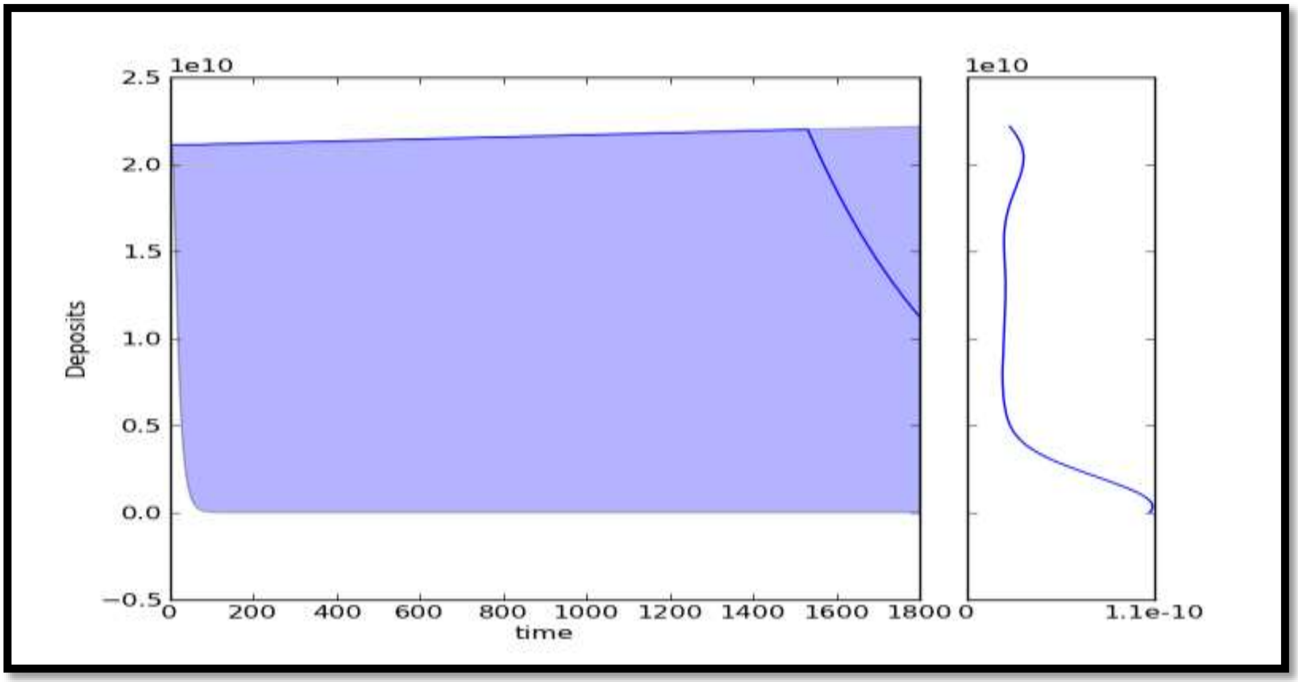

Figure 6.8 Envelope and KDE graphs of Deposits

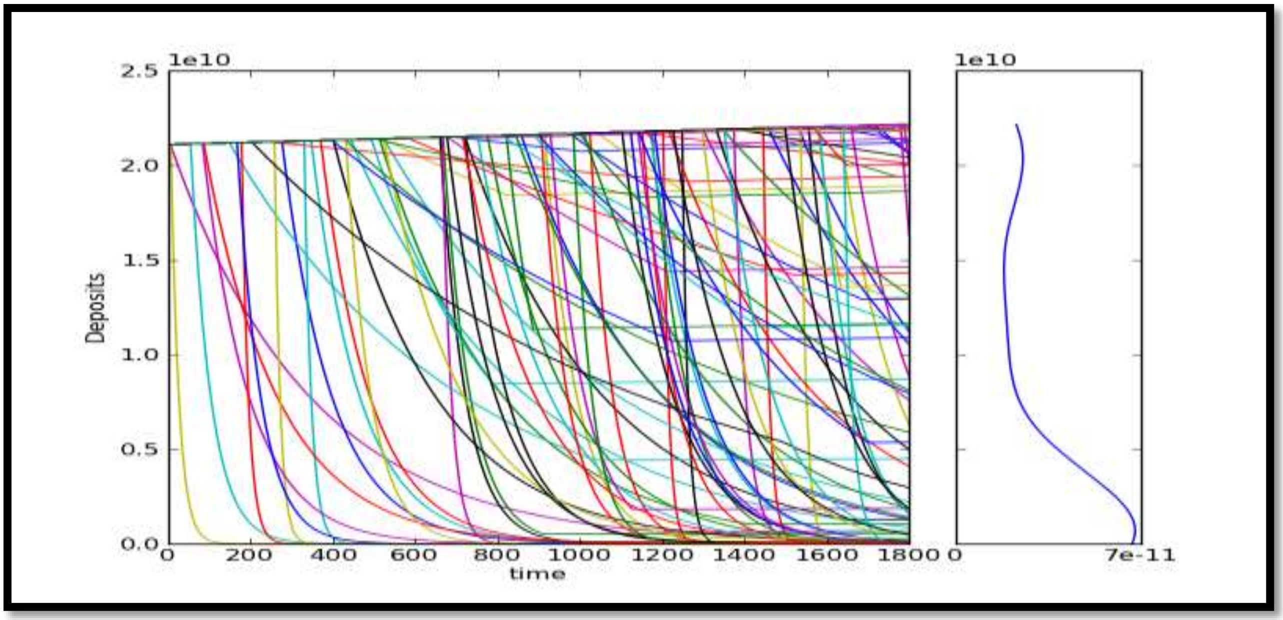

Figure 6.9. 100 selected runs of Deposits

6.3.3 Total assets

The observed behavioural patterns of bank's total assets are more ample regarding their distribution. As it can be observed in Figure 6.10, in a number of runs, the bank has its total assets depleted. This mainly happens in cases that the bank is stressed for a long period and this is the reason that depleted assets appear only in the last days of the simulated runs. The bank losses are substantially important in scenarios that the final value of the bank total assets is decreased to 1/3 of their initial value. Spikes and sharp decreases do not exist despite the appearance of scenarios with high liquidity needs. The bank is not forced to sell parts of its assets while it is in an unstable position.

Figure 6.11 illustrates a number of runs. Depending on the duration of the stress scenario, the assets' losses are substantial. However, none of the runs illustrated in this line graph results in full depletion of total assets. Furthermore, in a number of scenarios, small spikes appear because of a sudden increase in demand for withdrawals. A sudden decrease of the total assets appears following the spikes of liquid assets. Then, the bank is able to receive loans and make a small recovery while high withdrawal rates can continue or not, depending on the scenario. Behaviours with losses but not extreme ones are explained in scenarios in which default rates of loans, securities and bonds increase and the bank has to write them off its balance sheet.

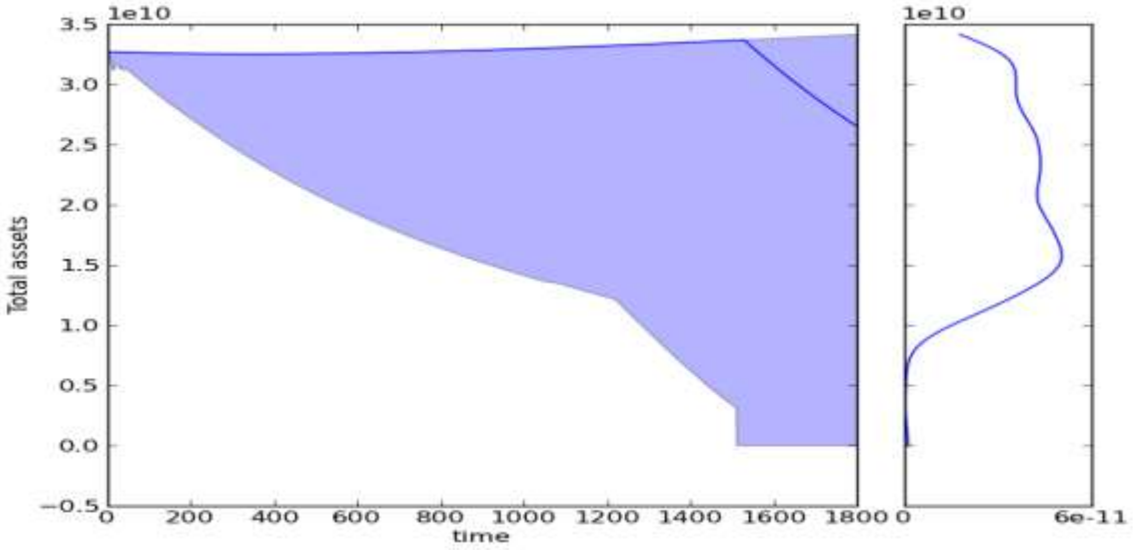

Figure 6.10 Envelope and KDE graphs of Total Assets

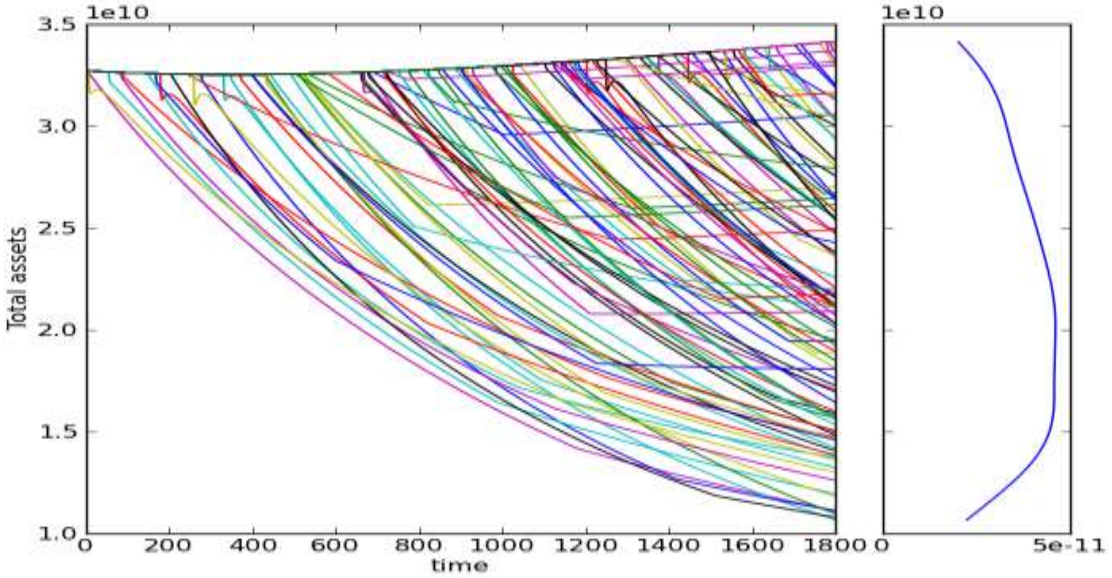

Figure 6.11. 100 selected runs of Total Assets

6.3.4 Total liabilities

In the lines graph Figure 6.13, the behaviours of the bank's total liabilities demonstrate similar patterns with the bank's total assets. Their distribution shown in the KDE graph of Figure 6.12 is also ample and in a large number of runs, the bank's liabilities decrease. The lines graph Figure 6.13 shows again small spikes like the ones in total assets Figure 6.11. Sharp decreases are explained by sudden increases in withdrawal rates. The small upward movements are created because of new loans that are being taken by the bank, which increases its liabilities.

KDE graph of Figure 6.12 illustrates that runs in which the liabilities of the bank end to 0 are extremely rare. Those runs are only illustrate extreme scenarios in which high withdrawal rates continue for an extended period and the bank at the end is not able to take new loans. In all the cases, in which total liabilities decrease but do not show any upward movement, are explained when loan that the bank has received are repaid and deposits also decrease (not extensively).

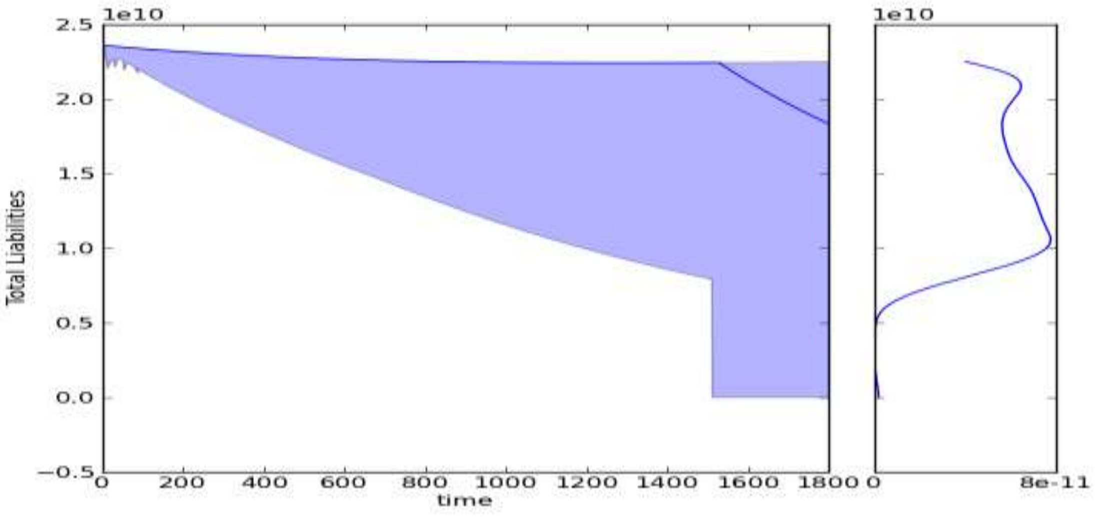

Figure 6.12 Envelope and KDE graphs of Total Liabilities

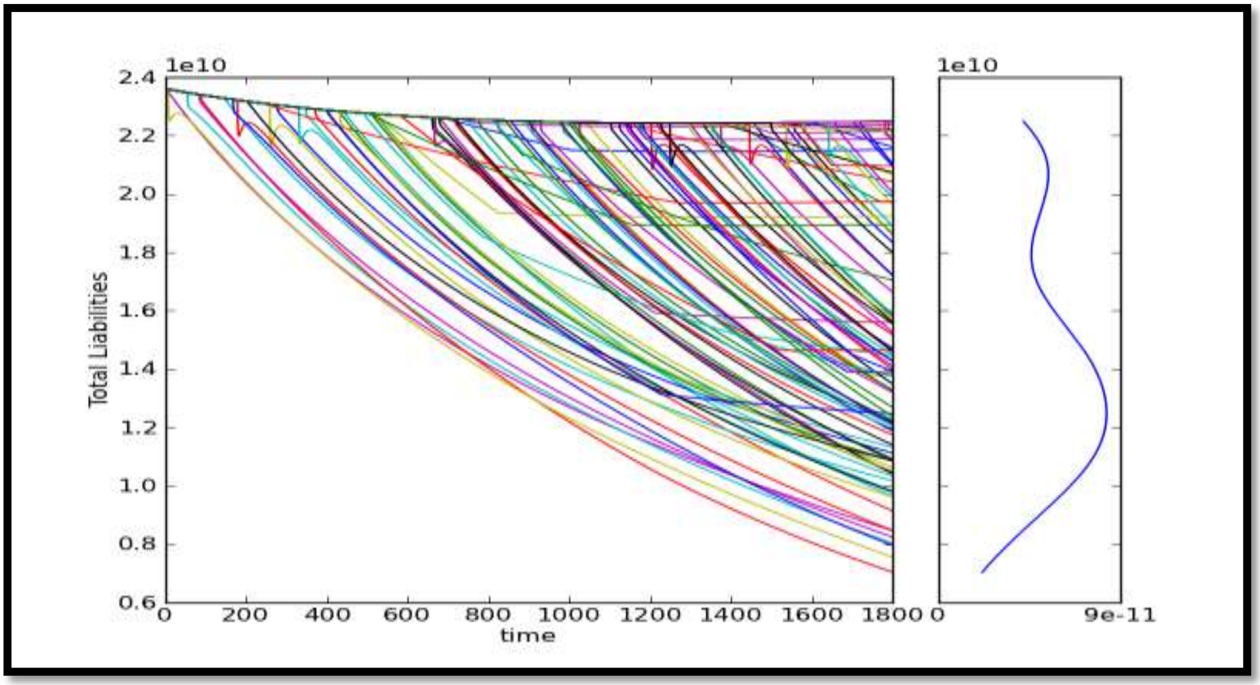

Figure 6.13. 100 selected runs of Total Liabilities

6.3.5 Net worth

The distribution of the KDE graph, in Figure 6.14, shows three different categories of final outcomes regarding the net worth of the bank. First of all, only in a very small number of simulated runs, the bank's net worth becomes negative or 0, meaning that the bank is bankrupt. Those are extreme scenarios that need to be further explored in next steps as they will drive the bank into a position that it will not be able to survive. The bank becomes insolvent as it sells its assets in extreme losses in order to obtain liquid assets or it receives loans increasing the liabilities part, while bank is not able to invest and its total assets decrease.

As a second outcome, the bank survives with losses in its assets' part, but the value of which keeps being higher than the liabilities' part, meaning substantial losses in the net worth of half a billion. In the majority of those runs, a minor recovery can be observed when the bank survives as Figure 6.15 illustrates. Finally, in a number of runs the bank ends with a higher net worth than the initial one as it is able to recover from plausible stresses or the stress events occur in the very last days of the simulated runs and not substantial losses can be recorded.

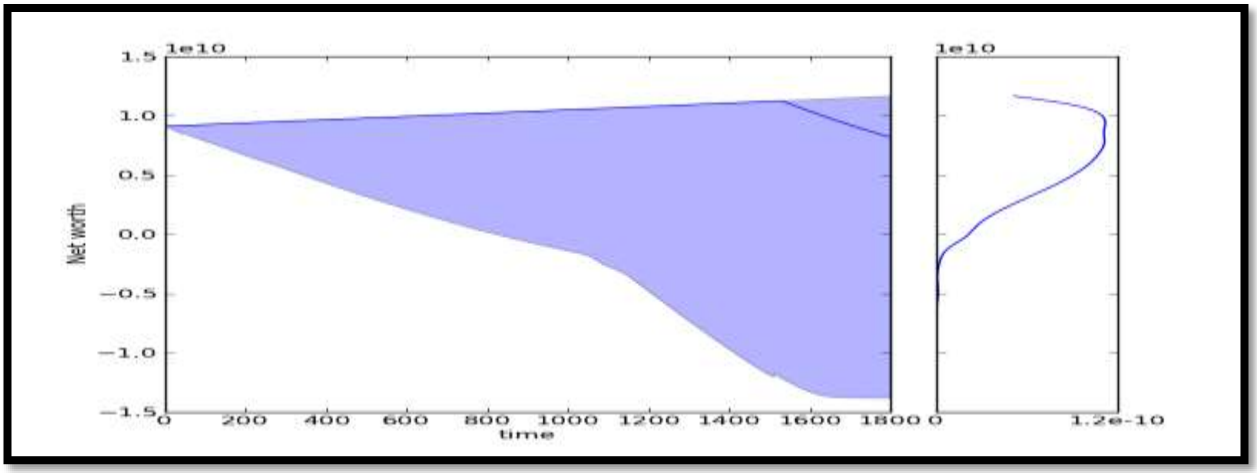

Figure 6.14 Envelope and KDE graphs of Net Worth

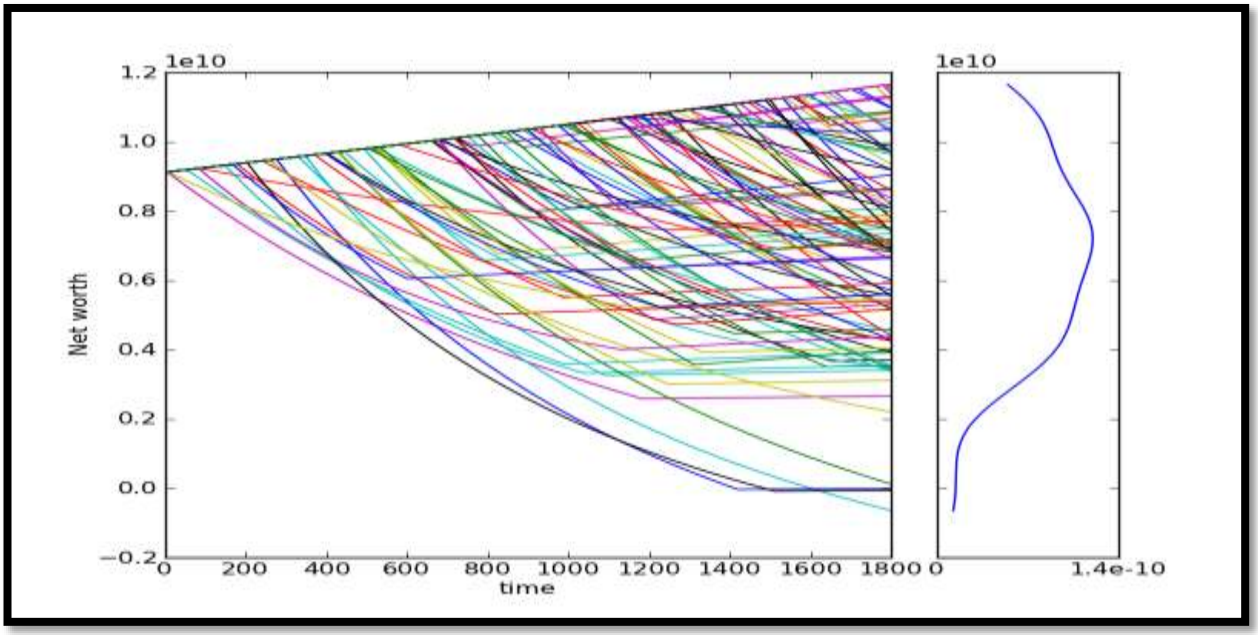

Figure 6.15. 100 selected runs of Net Worth

6.4 Analysis and identification of Catastrophic Scenarios

The observation of undesirable behaviours and dynamics of the system reveals the need to investigate the causes and identify scenarios (combinations of values of the uncertainty space) that lead to the most undesirable catastrophic behaviours of the bank, in which it is considered bankrupt. For the scenarios that the bank had been stressed, it appears that the bank would be able to deal with liquidity needs even in extreme cases. As we do not observe any scenarios that liquid assets have become negative, we identify catastrophic scenarios, the ones that the "Net Worth" is negative or 0. Negative net worth would mean that the bank becomes insolvent as the value of total assets of the bank becomes smaller than the value of total liabilities.

6.4.1 PRIM Analysis for catastrophic scenarios

As it is discussed in section 4.4.1.2, PRIM algorithm provides a tool that enables the identification of the parametric space that it is responsible for the undesirable final outcomes. For the case of undesirable catastrophic scenarios, a PRIM algorithm for the analysis part is applied to discover the subsets of uncertainties that drive the "Net worth" to become negative.

Scenarios with negative (and 0) "Net worth" are classified as category 1, while all the others are classified as 0. Hence, PRIM seeks for boxes of the input space that contain at least 80% of cases of category with a minimum mass of 0.001. Apart from the graphs presented below, the algorithm calculates the accurate limits of each box, which are available in the Appendix 3.

PRIM discovers three boxes, illustrated in Figure 6.16 with different colours (green, red, purple). In this Figure all the boxes are combined and each box is represented with one colour. The background grey area shows the normalised range of values of uncertainties between 0 (lowest value) and 1 (highest value). In Figure 6.17, the 3 boxes are demonstrated separately.

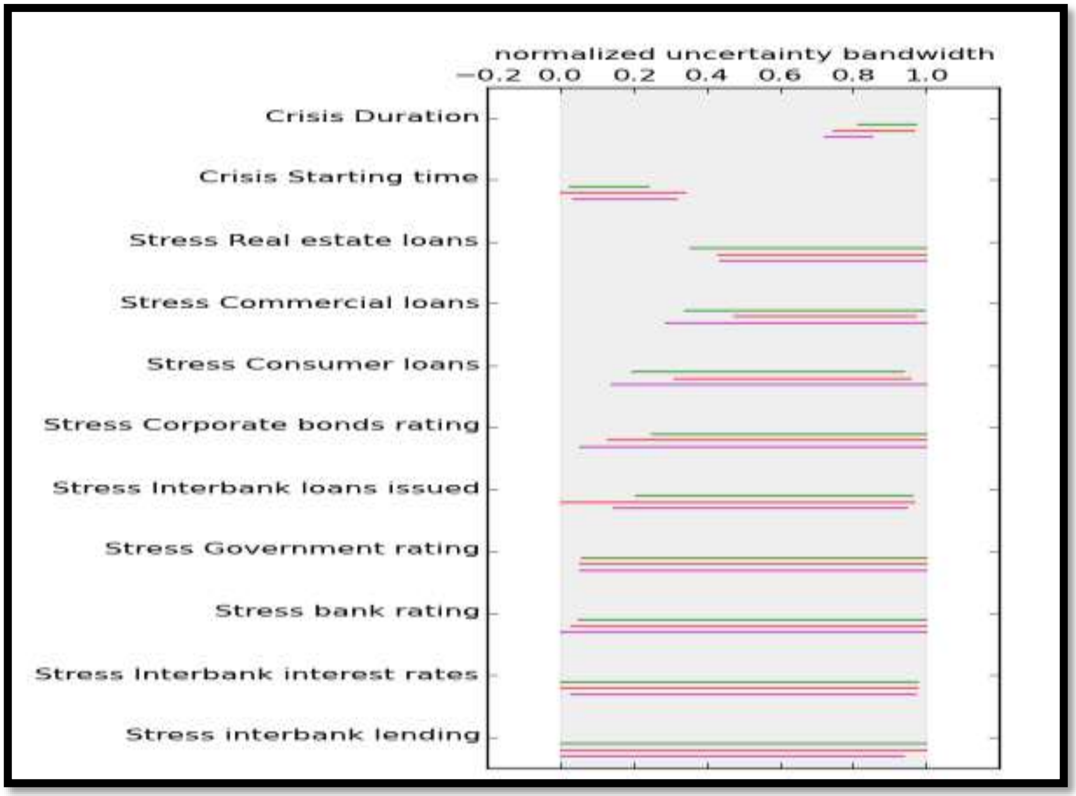

Figure 6.16. Combined boxes for Negative Net worth

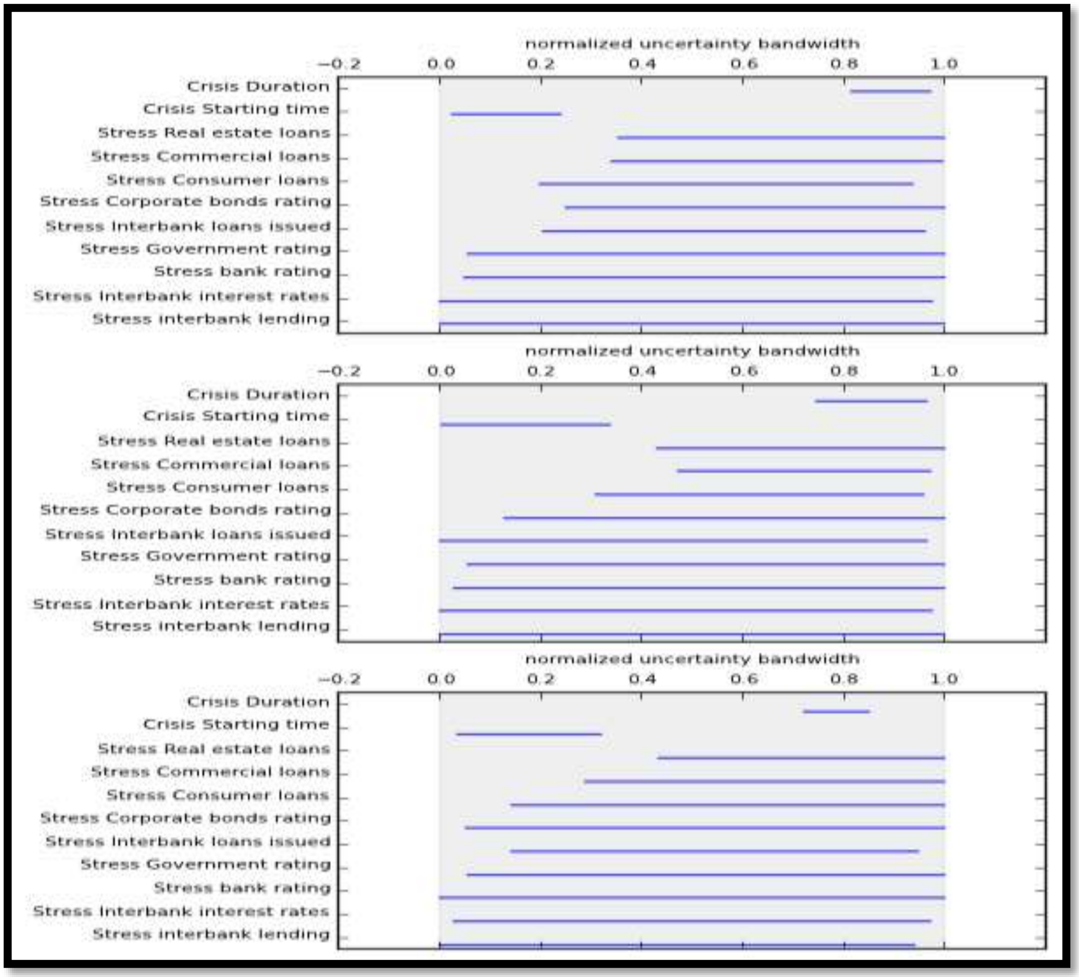

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Figure 6.17. Boxes for Negative Net worth

The interesting cases discovered by PRIM are only 59 out of 1100. Those boxes cover almost 75% of the undesirable scenarios we focus on. The other 25% were not identified. The results of the first box illustrate that the bank will be possibly bankrupt in cases of stress events characterised by long duration (1460-1750 days) that started early in the simulation (43- 435 days from the starting point of the simulation). In those cases, stress factors are mainly high default rates of commercial and real estate loans (more than 6 times their initial value) combined with high default rates of consumer loans (more than 4 times their initial value). When this combination occurs the bank suffers extensive losses that it is not able to absorb.

The second box includes more scenarios that lead to the undesirable negative net worth. Again, it is observed that we have scenarios with long duration (1300-1700 days) and early appearance (2-600 days). However, the combination of risk factors is higher default rates (more than 9 times their initial value) than the previous box including again losses in all loan categories simultaneously.

The third box demonstrates stress events with duration of 1300-1500 days that occurred in the first days of simulation runs (60-570 days). In those cases, which represent 20% of interesting cases, a combination of higher default rates in real estate loans (more than 14 times) and commercial loans (more than 6 times), associated with high default rates of consumer (more than 3 times) and interbank loans issued (more than 9 times), is responsible for the bank's net worth suffer and present negative final values.

6.5 Analysis and identification of sustainable scenarios with PRIM

The ensemble of behaviours presented in section 6.3 revealed a large number of scenarios in which the bank was subjected to losses without going bankrupt. These are cases that the bank could recover when the effects of stress events are moderated. Applying a similar process as in the previous section, the causes and the parametric space that leads to those behaviours are identified. For this purpose, PRIM algorithm is again applied to discover the boxes of uncertainty space. For the case of undesirable but sustainable scenarios, PRIM algorithm searches for the subsets of uncertainties that drive the "Net worth" to be positive. PRIM is performed three times after defining three different categories with high losses, moderate losses and minor losses.

6.5.1 PRIM analysis for sustainable scenarios with high losses

In this case, we classify scenarios of positive "Net Worth" with value lower than 4 Billion Euros as category 1, while all the others are classified as 0. PRIM seeks for boxes of the input space that contain at least 80% of cases of category with a minimum mass of 0.02. Accurate limits of each box for each parametric uncertainty are available in Appendix.

PRIM discovers four boxes, illustrated in Figure 6.18 with different colours (green, red, purple, blue). In Figure 6.19, the four boxes are demonstrated separately. Interesting cases discovered by PRIM are 346 out of 2000. Those boxes cover 52% of the scenarios with high losses we focus on.

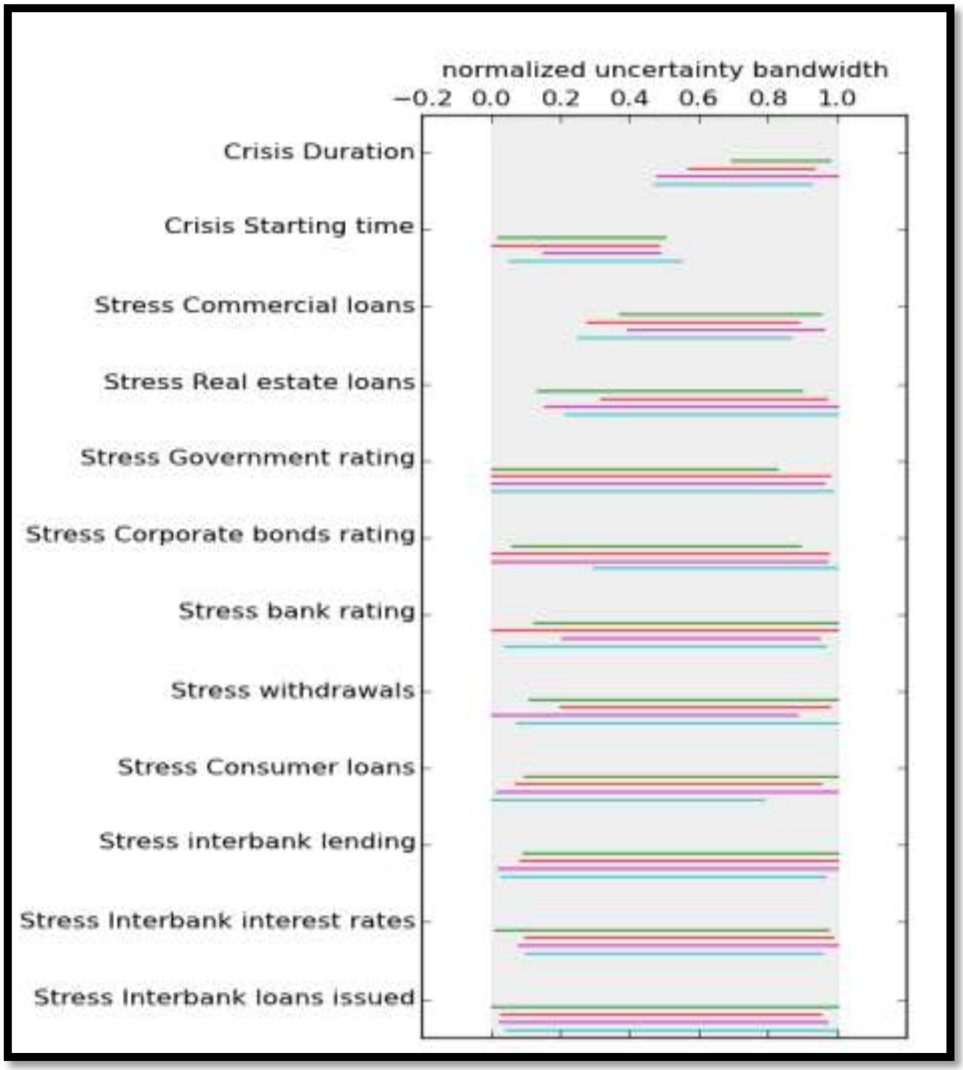

Figure 6.18. Combined Boxes for Positive Net worth with high losses

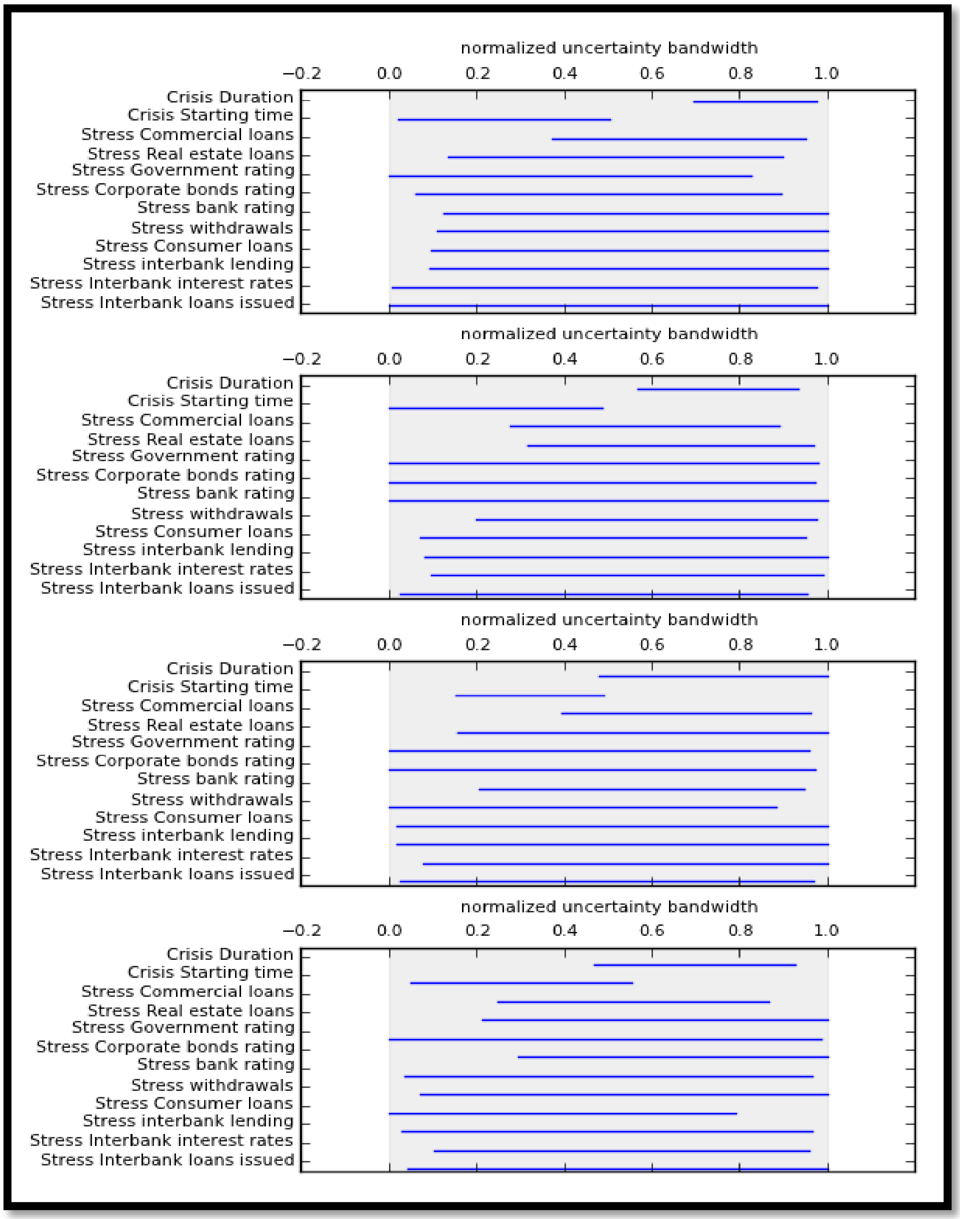

Figure 6.19. Boxes for Positive Net worth with high losses

The first box of PRIM, regarding positive net worth but with extreme losses, contains 15% of scenarios we look for. In those scenarios, in which early occurred stress events (35 to 900th day) with medium and long duration (over 1200 days) characterized with high default rates for commercial loans (more than 7 times), medium default rates for real estate loans (2 times the initial value). Furthermore, those stress events include minor changes in bank's downgrading that in combination with the aforementioned stress factors leads to high losses.

The second box illustrates that stress events with duration over 1000 days, characterized by extremely high default rates in real estate loans (more than 7 times) in this case will drive the bank to high losses. However, this happens only if the commercial loans are also stressed and sudden increases in withdrawal rates appear. The third box contains stress events similar to the second box but with a different starting time period. It illustrates cases with long duration but starting from the 270th till 880th day of the simulation. Furthermore, in those cases, the real estate loans default rate does not have a significant contribution.

Finally, box 4 includes stress events that are characterized by multiple risk factors. It appears that in those scenarios commercial and real estate loans are again of significant importance, but now bond's downgrading is also included with high values. This means that if simultaneously bonds that the bank possesses are downgraded and the losses of commercial and real estate loans increase, the bank suffers high losses.

6.5.2 PRIM analysis for sustainable scenarios with moderate losses

In this case, we classify scenarios of positive "Net Worth" with value higher than 4 Billion Euros and lower than 8 Billion Euros as category 1, while all the others are classified as 0. PRIM seeks for boxes of the input space that contain at least 80% of cases of category with a minimum mass of 0.1. Accurate limits of each box for each parametric uncertainty are available in the Appendix.

PRIM discovers three boxes, illustrated in Figure 6.20 with different colours (green, red, purple). In Figure 6.21, the 2 boxes are demonstrated separately. Interesting cases discovered by PRIM are 801 out of 2000. Those boxes cover only 42% of the sustainable scenarios we focus on. The rest 58% was not identified.

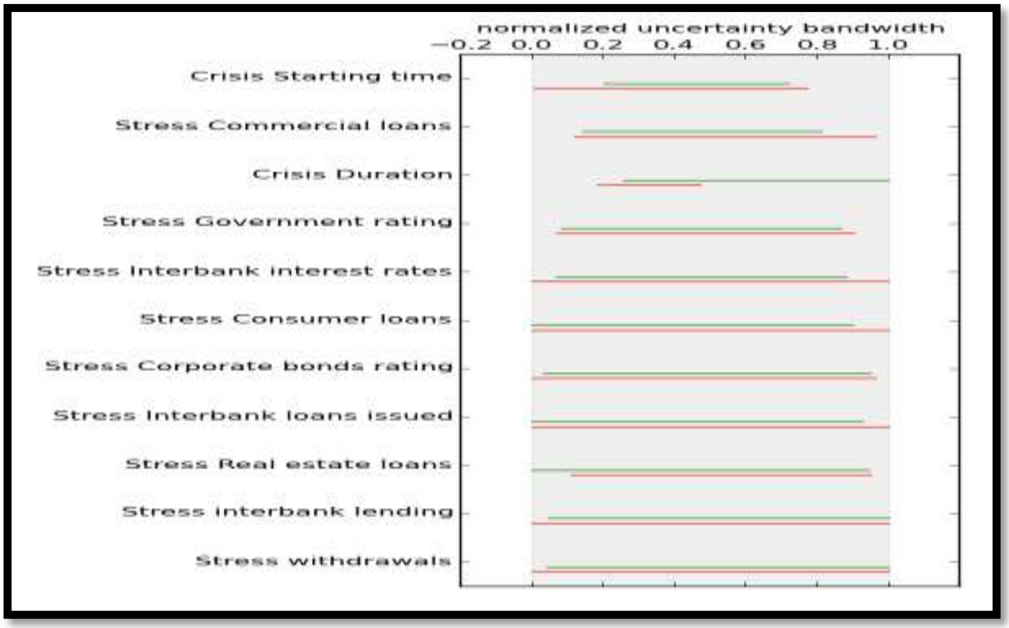

Figure 6.20. Combined Boxes for Positive Net worth in moderate losses

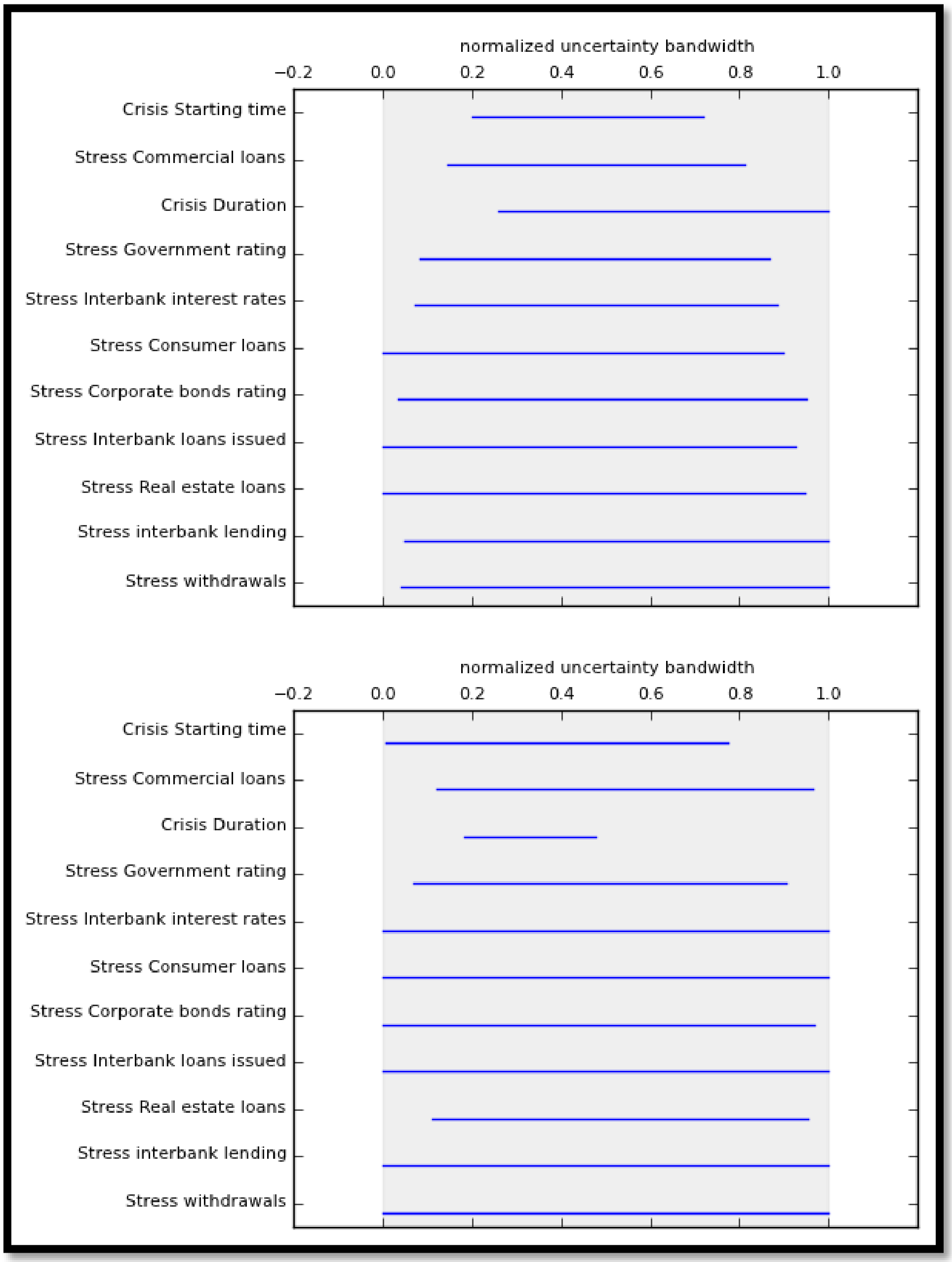

Figure 6.21. Boxes for Positive Net worth in moderate losses

The first box contains 21% of scenarios we look for. In those scenarios, in which stress events occurred after the 500th day with medium duration (300-1300 days) characterized with medium for commercial loans and low stresses in government securities downgrading and interbank interest rates.

The second box illustrates that stress events with shorter duration (15-1390 days) and starting time between 330th and 860th day, characterized with medium and high default rates for commercial loans

(2 -15 times) and medium default rates for real estate loans (2 times the initial value). It means that only in cases of medium shocks in commercial and real estate loans with shorter duration and later appearance time will drive the bank to moderate losses.

6.5.1 PRIM analysis for sustainable scenarios with minor losses

In this case, we classify scenarios of positive "Net Worth" with value higher than 8 Billion Euros as category 1, while all the others are classified as 0. PRIM seeks for boxes of the input space that contain at least 80% of cases of category with a minimum mass of 0.02. Accurate limits of each box for each parametric uncertainty are available in Appendix.

PRIM discovers five boxes, illustrated in Figure 6.10 with different colours (green, red, purple). In Figure 6.11, the 3 boxes are demonstrated separately. Interesting cases discovered by PRIM are 794 out of 2000. Those boxes cover 77% of the scenarios with minor losses we focus on.

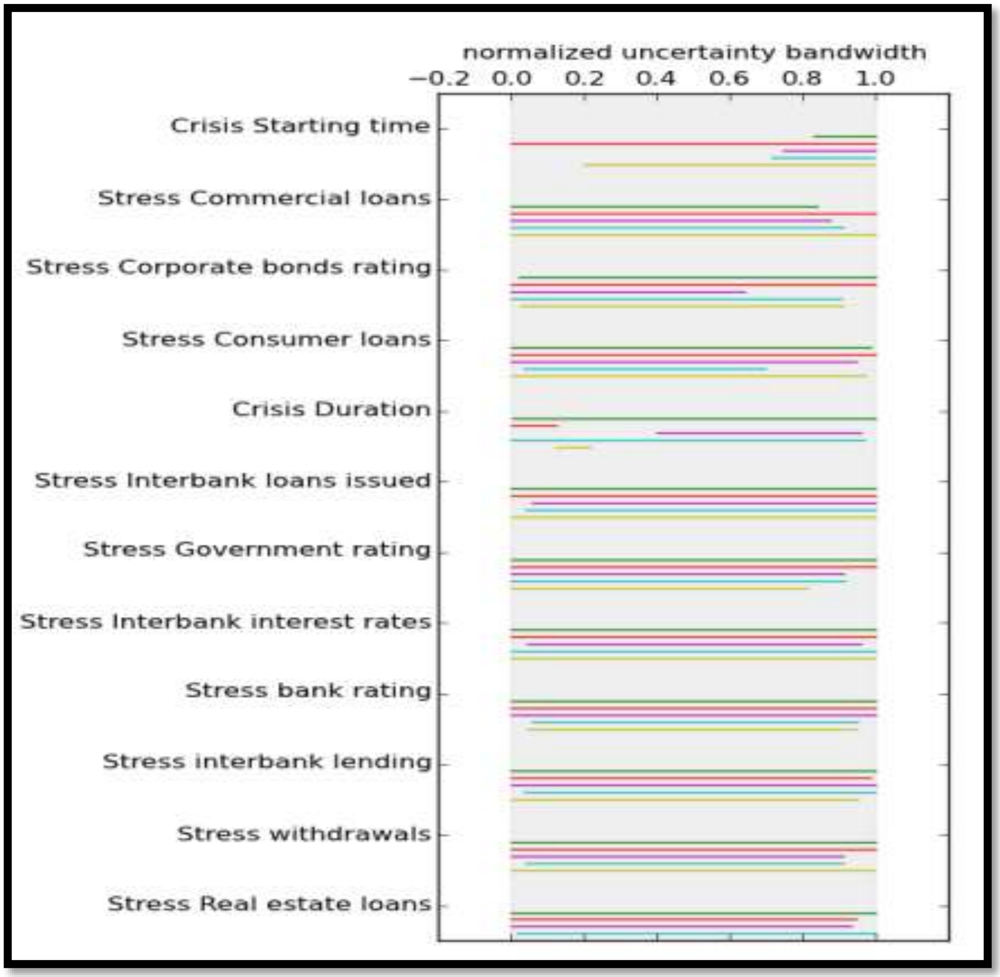

Figure 6.22. Combined Boxes for Positive Net worth in sustainable scenarios

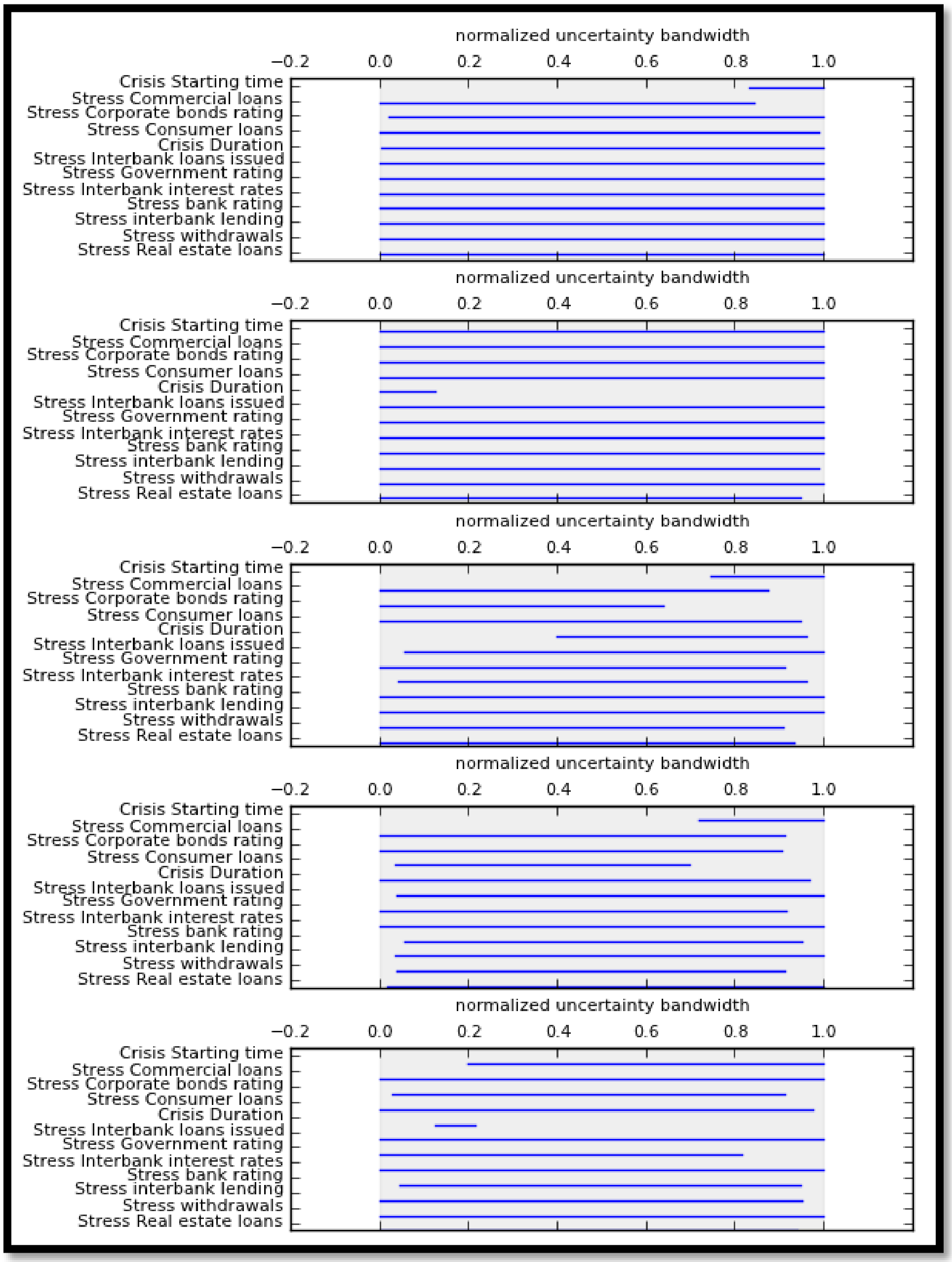

Figure 6.23. Boxes for Positive Net worth in sustainable scenarios

Box 1 describes 36 % of the desirable scenarios we search for (net worth >8 Billion Euros). In scenarios with stress events that occur in the final days of the simulation (after 1500th day) the bank does not suffer high or moderate losses. Mainly, this occurs because we observe only part of the crisis as the simulation stops and the impacts are not clearly illustrated.

Box 2 contains 25% of the desirable scenarios. As box 2 illustrates, only in cases that a stress event lasts for a short period (1-230 days) the bank can survive with minor losses. It is the only significant factor that defines the final outcome in this case. The third box contains a small number of scenarios, defined by late starting time (after 1350th day), low stress on bonds and commercial loans (0-15 times, but not higher. It means that only in cases of small shocks in commercial loans with late appearance time will drive the bank to minor losses.

Box 4 is similar to Box 2 but bond’s downgrading is not a significant factor in those cases. It describes stress events with late starting time and low stress on consumer loans. Finally, Box 5 provides scenarios that are characterized by extremely short duration (220-390 days) and late starting point after the first year of the simulation (>360th day). The only stress event limitation in those scenarios is that government securities cannot have been extremely downgraded.

7. Policy design

In this chapter, simple policies are designed and tested in view of supporting the bank to prevent undesirable behaviours or limit the effects of adverse scenarios. Following the analysis of the behaviours observed, the tested policies are presented and discussed in detail. Developing policies is not the primary focus of this study, but they are tested in an effort to assess how the bank could respond in adverse but not in catastrophic events in order to recover.

In the previous chapter, two categories of scenarios were determined and in each category their causes were identified. After identifying the underlying mechanisms, policies are designed to be adapted in those cases in an effort to prevent or smooth the undesirable behaviour patterns and prevent collapse of the bank. The policies proposed are basic and they are not considered as innovative and proper adaptive policies. Three policies are tested separately. To test the behavioural patterns of the bank after the application of each policy a new set of 1000 runs is executed per case. The behavioural patterns of the model are assessed in the same way as in the previous chapter with the use of line graphs and envelopes of the values of the performance indicators.

A clear generic observation following the analysis of the previous chapter 6 is that crisis duration and extremely high default rates of the outstanding loans appeared simultaneously could drive the bank to bankruptcy. Early occurred stress events with long duration put the bank into difficult position depending on its losses in different parts of its portfolio. If simultaneously the bank suffers losses in those different parts, the bank is not able to recover and stop "bleeding".

7.1 Policy 1: Attract new deposits

The first policy introduces a responsive action of the bank when a certain decrease in total deposits occurs. The bank increases the interest rate paid to depositors in order to attract new deposits. In cases of highly decreased deposits, the bank offers even more increased interest rate in an effort to stop its deposits "bleeding". This policy is developed in the model by adding a new structural mechanism, as it is visualised in Figure 7.1, in which a multiplier defines the times that the initial interest rate is multiplied depending on the degree of deposits decrease (ratio Current deposits to initial deposits). The mechanism captures also second order effects as only in minor increases (2 to 5 times the initial interest rate), new deposits are attracted. If the bank increases more than this threshold the interest rate, the bank cannot attract any new deposits. So, it can be proposed as a measure implemented only in the early stages of a stress event. The bank needs to attract new deposits in early stages before being in a situation in which it is not able to convince its customers that it is not in "trouble".

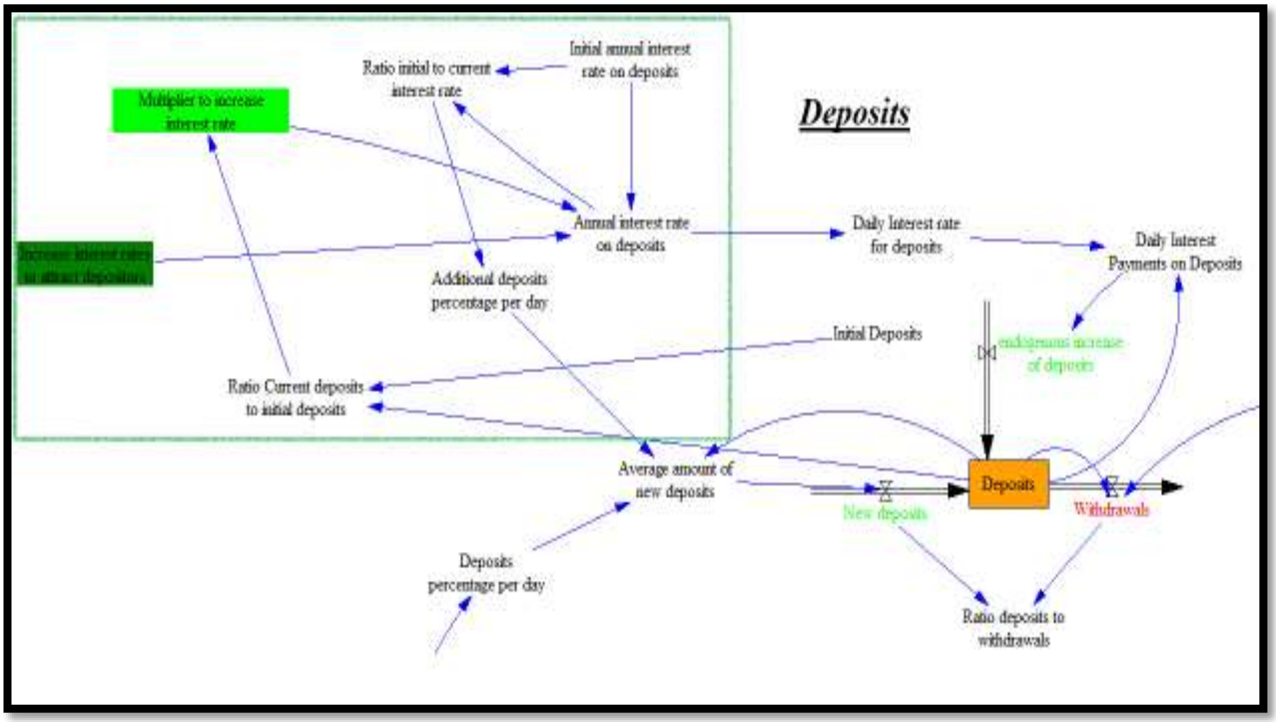
Initial annual interest rate on deposits
Ratio initial to current interest rate
Multiplier to increase interest rate
Deposits
Increase interest rates to attract depositors
Annual interest rate on deposits
Daily Interest rate for deposits
Daily Interest Payments on Deposits
Additional deposits percentage per day
Initial Deposits
endogenous increase of deposits
Ratio Current deposits to initial deposits
Average amount of new deposits
Deposits
New deposits
Withdrawals
Deposits percentage per day
Ratio deposits to withdrawals

Figure 7.1 Policy 1 for new deposits

The line and KDE graph of liquid assets in figure 7.2 illustrates that the bank faces again increased liquidity needs due to high withdrawal rates. It appears that this policy does not affect the demand for withdrawals and the figure is almost identical to the one without this policy Figure 6.7. However, now, the behaviour of the bank shows a recovery in scenarios in which liquid assets are not depleted. By attracting more deposits the bank is able to recover part of the liquid assets needed, but it remains unable to stop the bank run.

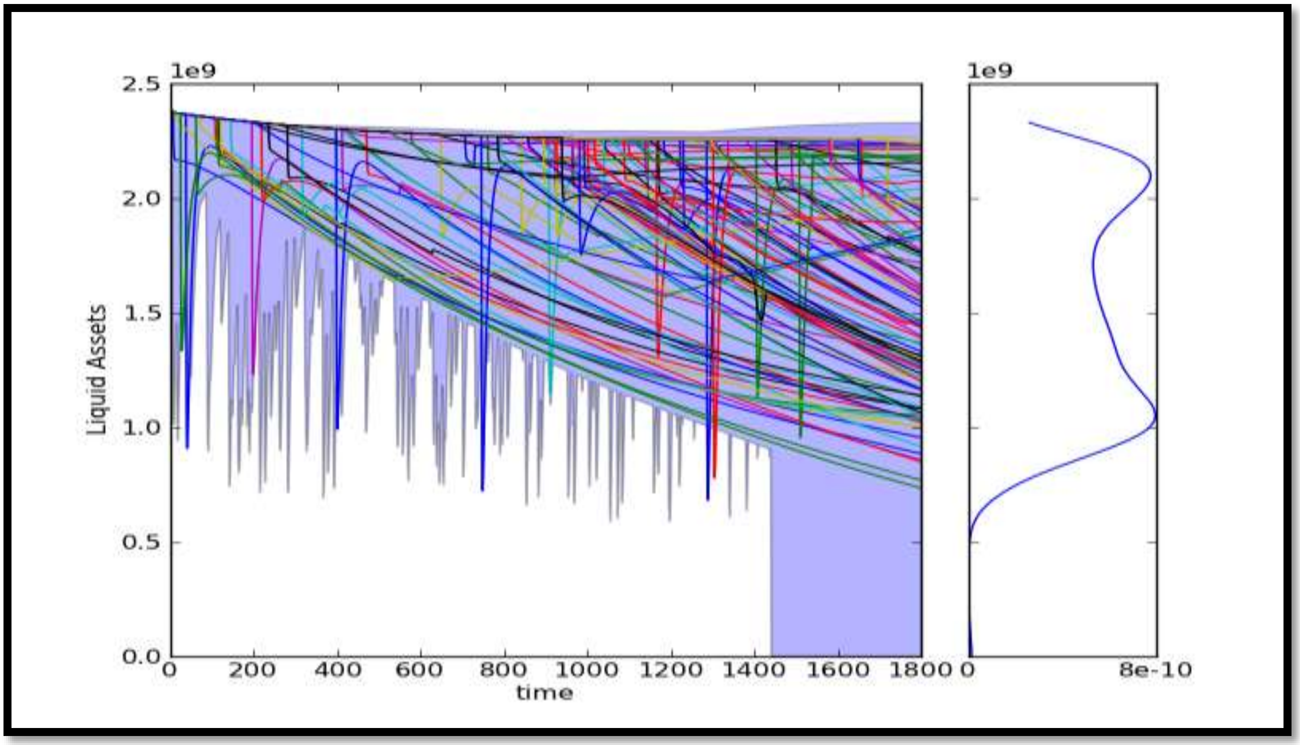

Figure 7.2 Liquid assets after policy 1

The behaviour of liquid assets could be better explained when we analyse the exact behaviour of deposits as it is demonstrated in Figure 7.3. In this graph the recovery of deposits (and as a consequence the liquid assets) is clearly observed in various runs. In cases of severe events, bank's deposits become 0 and the bank is not able to attract new clients. The density of those cases remains high, but cases with recovered deposits exist. The number of scenarios that the bank kept its deposits in sustainable limits is higher than the number of cases without policy 1 applied (Figure 6.9). Specifically, in scenarios without extreme severity and early appearance, the bank appears to recover to values close to initial deposit values.

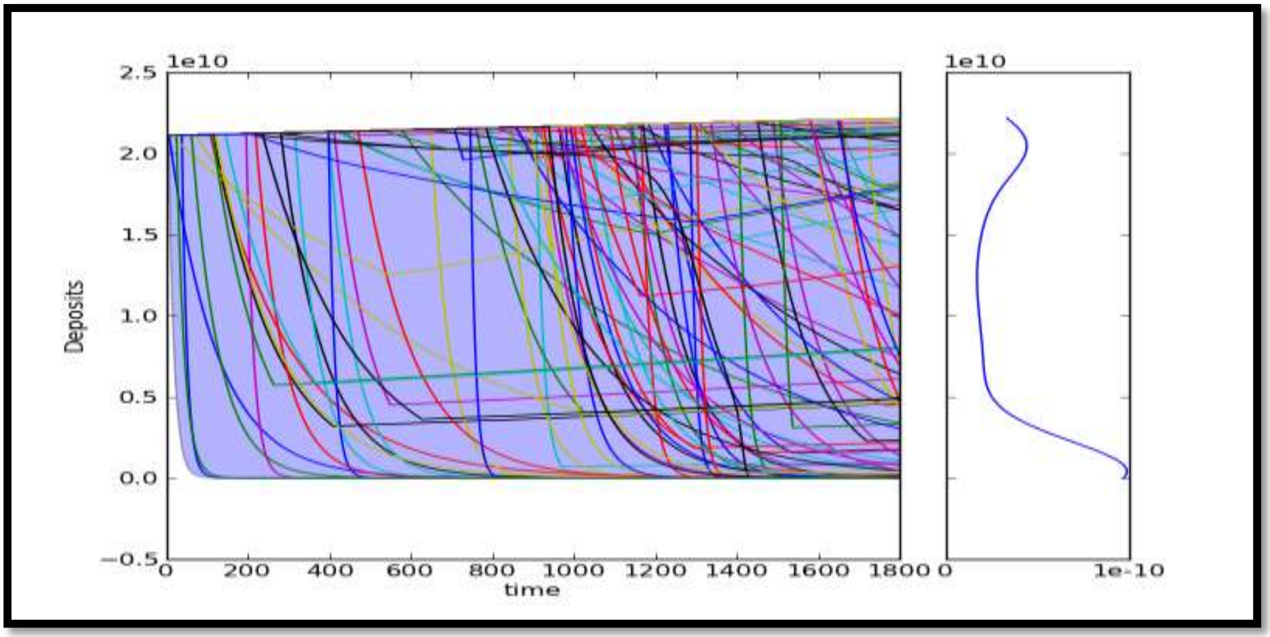

Figure 7.3. Deposits after policy 1

As can be observed in Figure 7.4, still in a number of runs, the bank has its total assets depleted. The behaviours of total assets are similar to those of Figure 6.11, but an increase appears in the number of cases that recover bank's assets and reach values close to initial value.

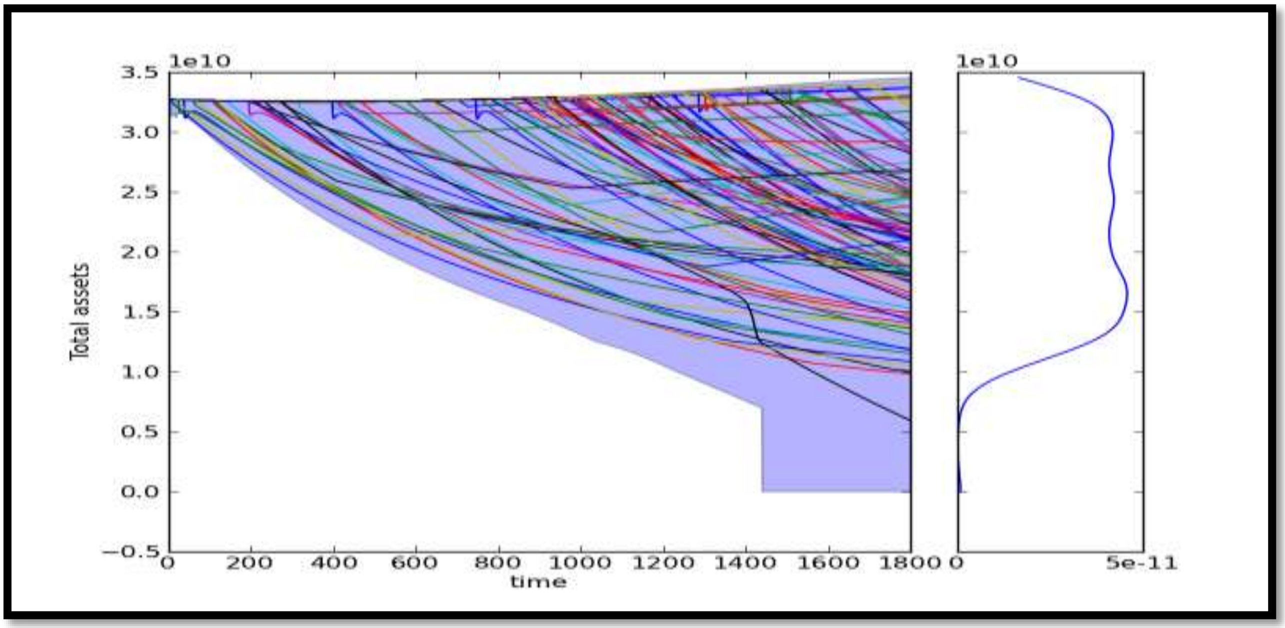

Figure 7.4. Total assets after policy 1

Following the behaviour of deposits, total liabilities recover in a number of scenarios. The distribution of KDE graph (Figure 7.5) visualise the fact that in a high number of cases the bank increases its liabilities close to initial value by receiving loans and attracting new deposits. However, differences appear against Figure 6.13 (without policy), as more scenarios with higher values of total liabilities occur in Figure 7.5.

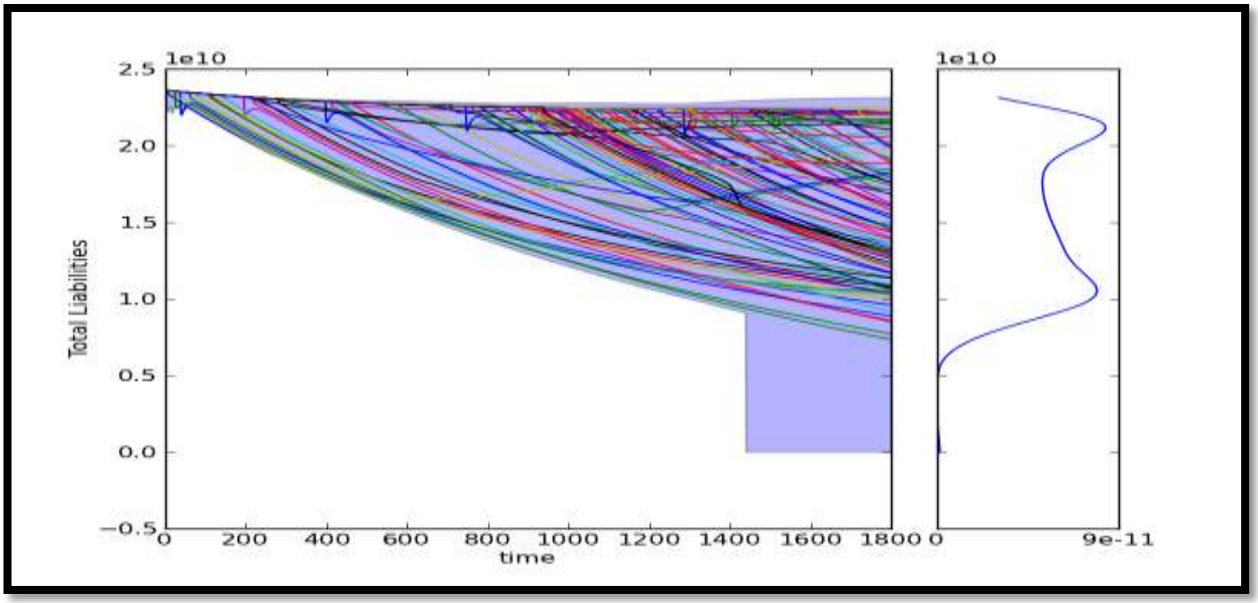

Figure 7.5. Total liabilities after policy 1

Finally, net worth's behaviours (Figure 7.6) are almost identical to those of Figure 6.15. The bank faces bankruptcy in scenarios with negative net worth. Even if deposits increase, the net worth of the bank will not increase immediately or it will even decrease as the liabilities and the interest payments also increase. Increased interest payments decrease the interest margin and if the bank sells part of its assets, net interest margin can be even negative, causing net worth's declining behaviour.

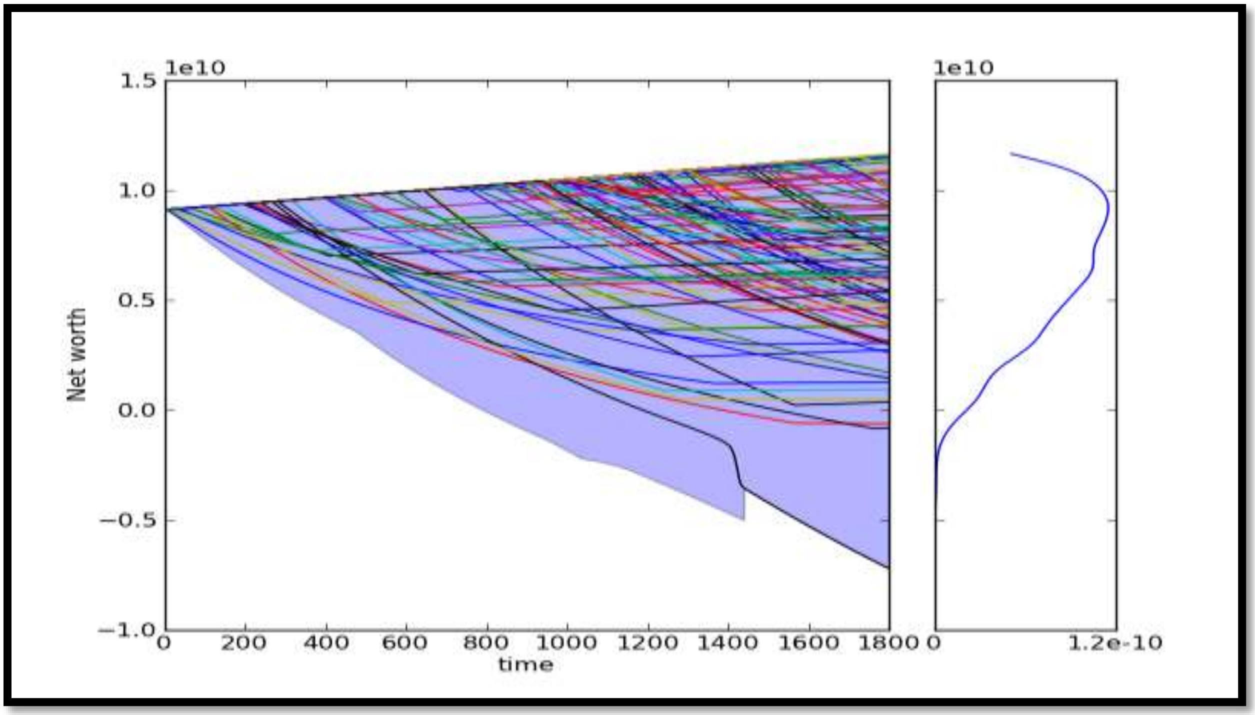

Figure 7.6 Net worth after policy 1

To conclude this section, it is observed that the application of a policy to attract new deposits did not substantially decrease the number of catastrophic scenarios for the bank but it supported its recovery in sustainable scenarios. Attracting new deposits by increasing the interest rate paid to depositors, the bank increases its interest payment obligations (liabilities), but it receives “hot” money that could help meeting short-term liquidity needs and then reinvest in order to increase its revenue. However, in severe stress events, this policy will not prevent customers from demanding their deposits and only in early stages when the bank realises that its deposits decrease the bank has the chance to recover. In cases of extreme and sudden crises the bank will not have the time to recover its deposits.

7.2 Policy 2: Debt restructuring

The second policy that is designed to be implemented focuses on the loans that the bank has taken or it takes during the simulated runs. The policy proposes the change of the terms of the loans taken from the bank in cases of stress events by increasing the time available to the bank to repay the loans. In this case, we decided to double the duration of the loans meaning that the amount of money that the bank has to repay per day is halved. This will give the bank the opportunity to invest more and recover faster.

Figure 7.7 reveals the behaviour of liquid assets. It appears that the bank is able to meet liquidity needs. By decreasing the amount that the bank has to repay to other banks or Central Bank, the bank has a greater buffer to meet its liquidity needs from increased withdrawals. However, the contribution of this policy to liquid assets is not substantial as Figure 7.7 resembles Figure 6.7.

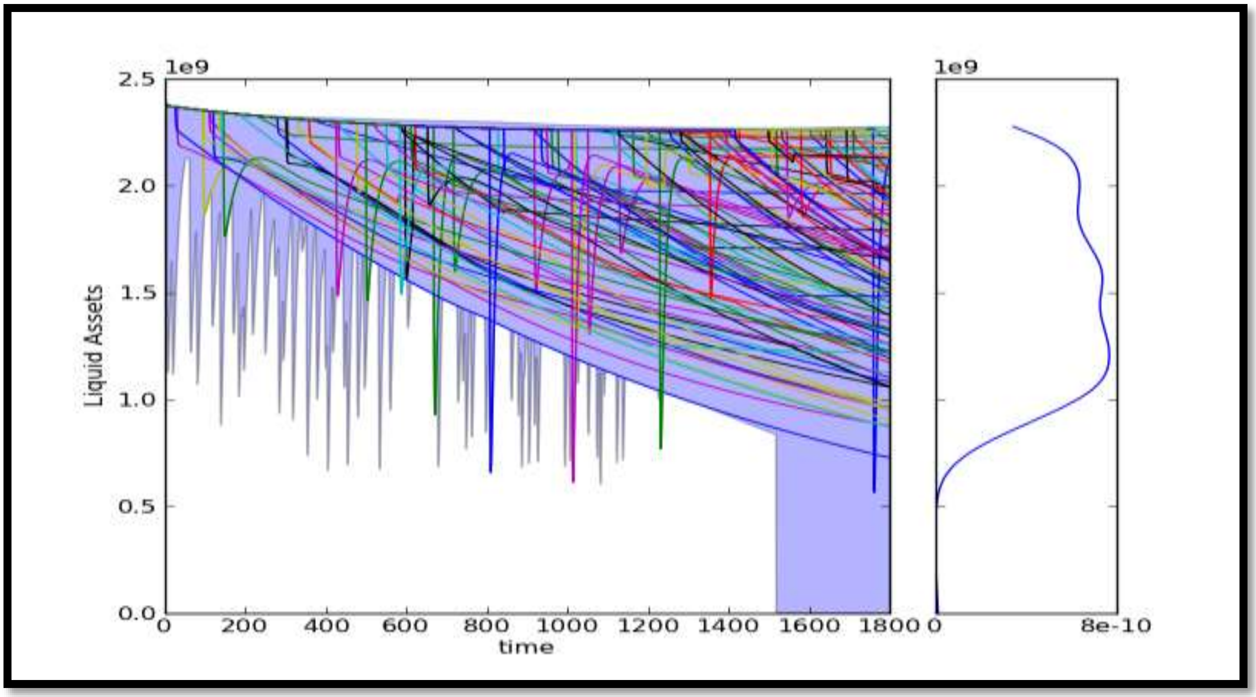

Figure 7.7 Liquid assets after policy 2

In Figure 7.8, total assets do not illustrate any recovery in contrary to what was expected. Even though the bank has available higher amounts of capital saved from the payments to loans, the bank uses them to meet liquidity needs and not to invest more. This keeps the total assets decreased but maybe only because of defaults and not because the bank has to sell them in emergency situations.

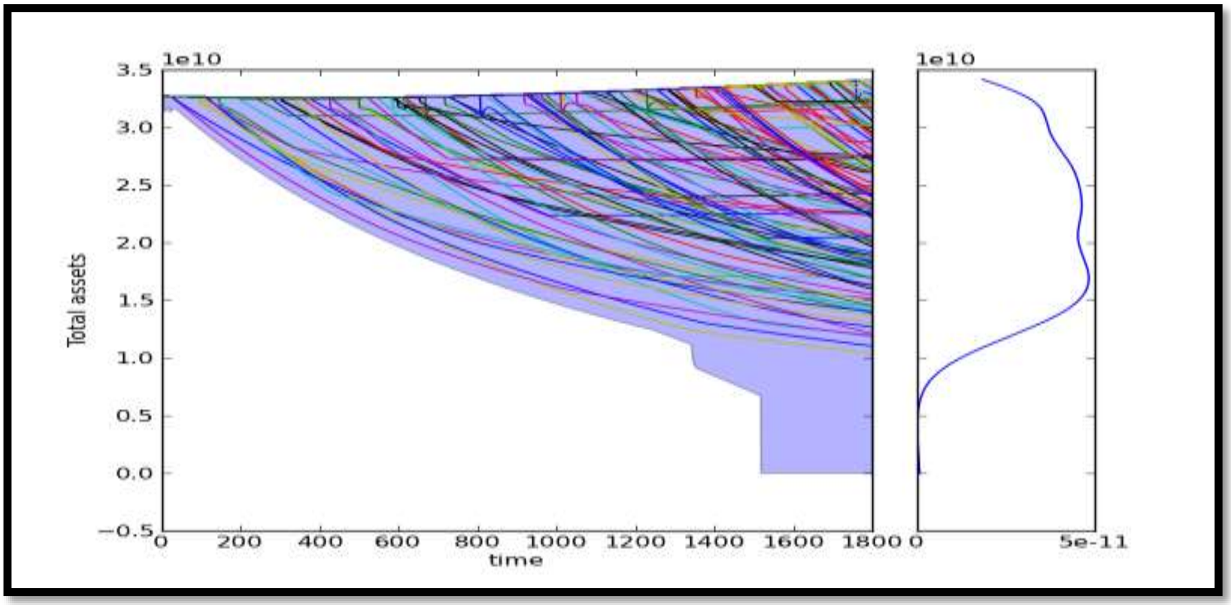

Figure 7.8 Total assets

Figure 7.9 illustrates total liabilities are rarely nullified, meaning that they are kept in higher values because of loans that have been taken by the bank. However, reconstructing the debt of the bank to other banks and Central bank makes the liabilities decrease in a slower pace. Any sudden decrease is only due to deposits and not because of repayments.

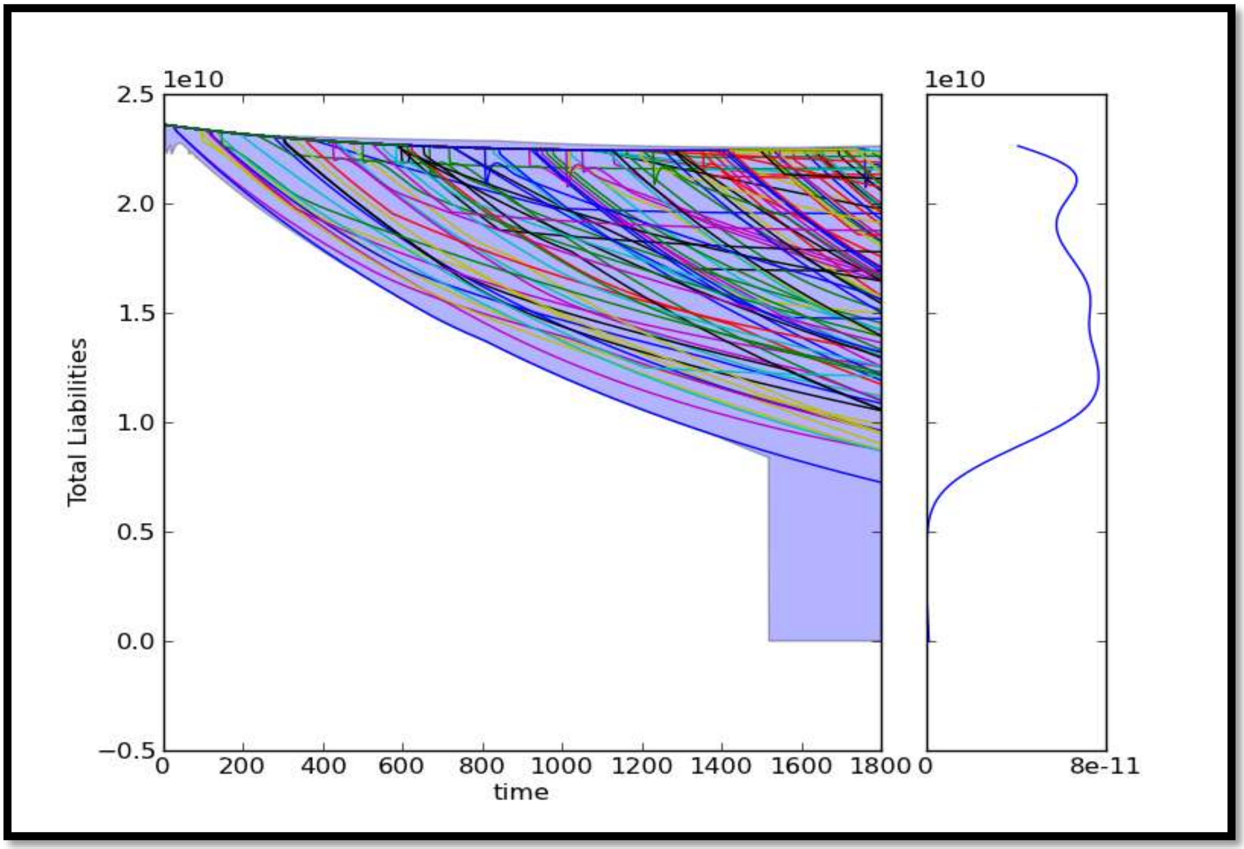

Figure 7.9 Total liabilities

Finally, net worth's behaviours provide another view of the effectiveness of this policy. Bank in some cases illustrates a recovery in its net worth, but still the outcome is not substantially important. In most of the scenarios, bank keeps positive net worth and survives from insolvency risk. The value of the net worth in the majority of the cases keeps being close to the initial value allowing the bank to further recover in the future.

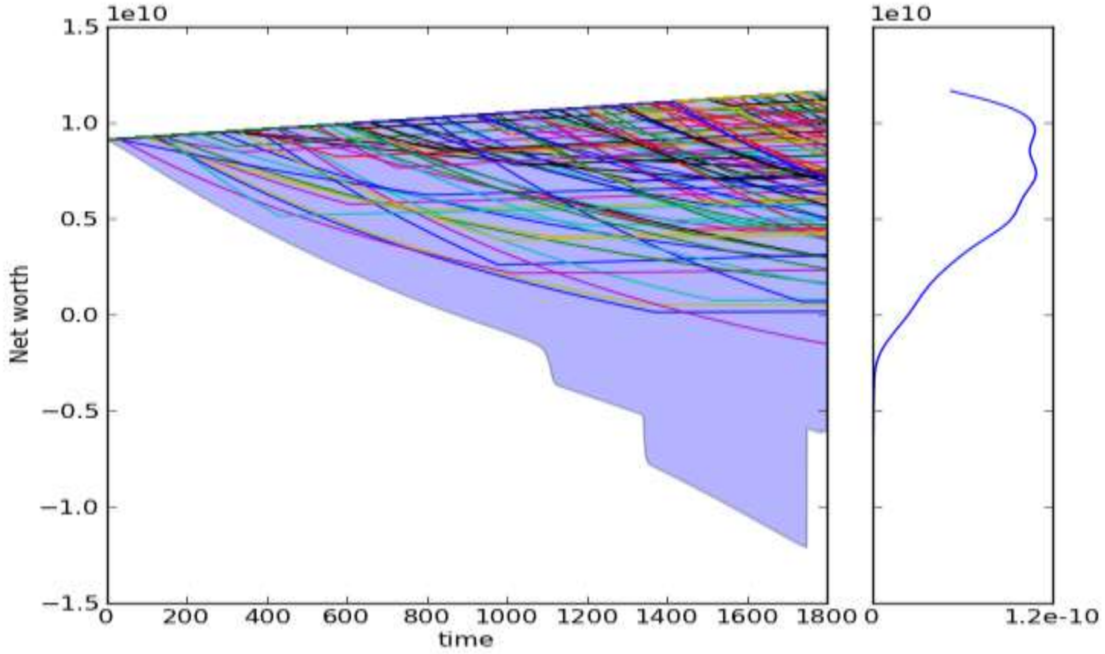

Figure 7.10 Net worth

To conclude this section, reconstructing the debt during a stress event and increasing the repayment time assists the bank in meeting its liquidity needs but do not provide any help in recovering faster after the stress event. To the contrary, it possibly delays the recovery as the bank has to repay loans for a longer period which means that decrease the capital available for further investments.

7.3 Policy 3: Stop investing in problematic loan categories

In this section, a third policy related to internal decisions of the bank for investments during stress events is tested. This policy tests the decision of the bank to stop investing in categories of loans when they experience a higher default rate than the normal initial one. For example, when the bank realises a higher default rate in consumer loans, stops investing in this field in an effort diminish its exposure to those losses. The bank invests the available amount in interbank loans to other banks, which helps the stability of interbank market. They are considered less risky as banks are less possible to default than another client. However, the bank should invest in various bank institutions and do not expose themselves to one particular bank which in case of bank's failure will lead to extensive losses.

In Figure 7.11, total assets behaviour illustrates better final outcome than previous policies. The scenarios that the total assets are totally depleted are extremely rare in this case and the losses appear to be lower. However, still no significant recovery is recorded. In Figure 7.12, consumer and commercial loans behaviours are illustrated. In some scenarios, recovery is demonstrated, which cannot be observed in total assets behaviour.

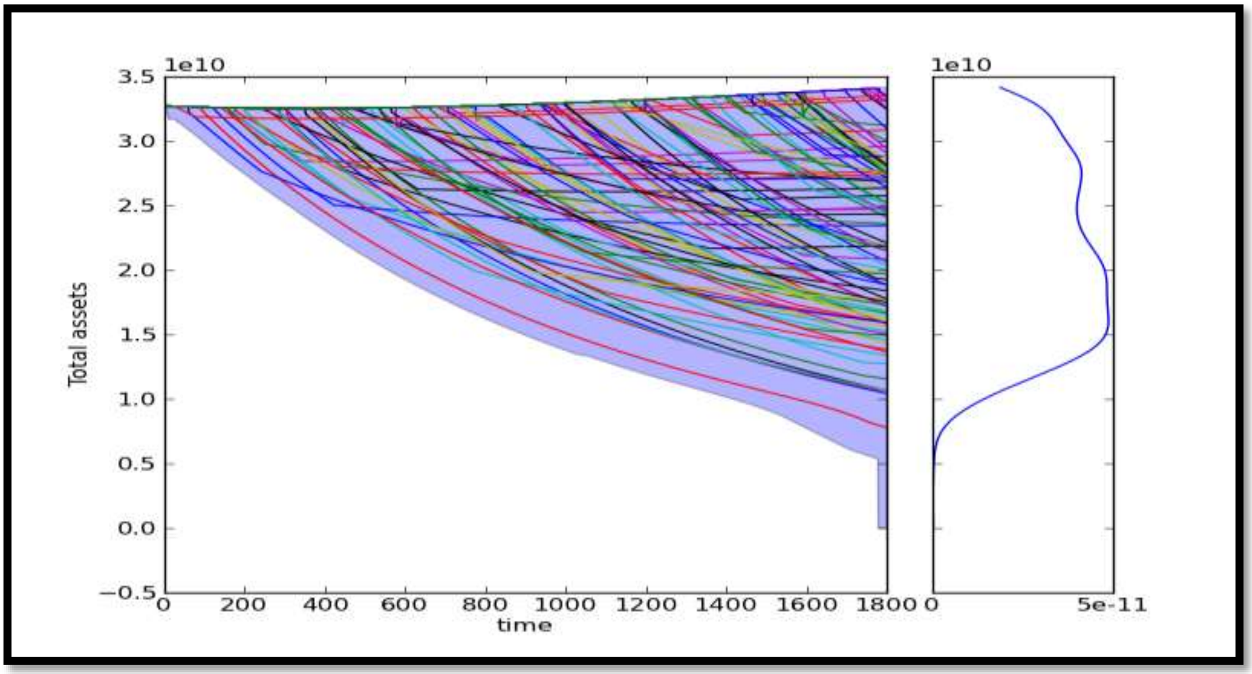

Figure 7.11 Total Assets after policy 3

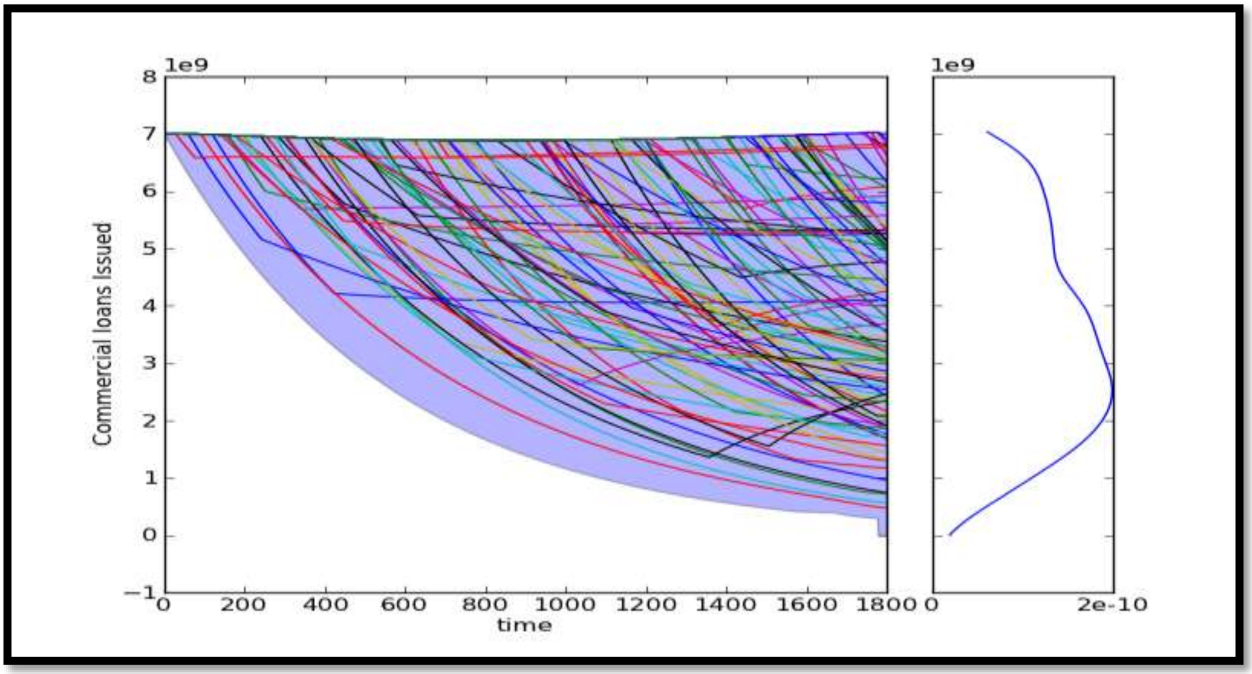

Figure 7.12 Commercial loans after policy 3

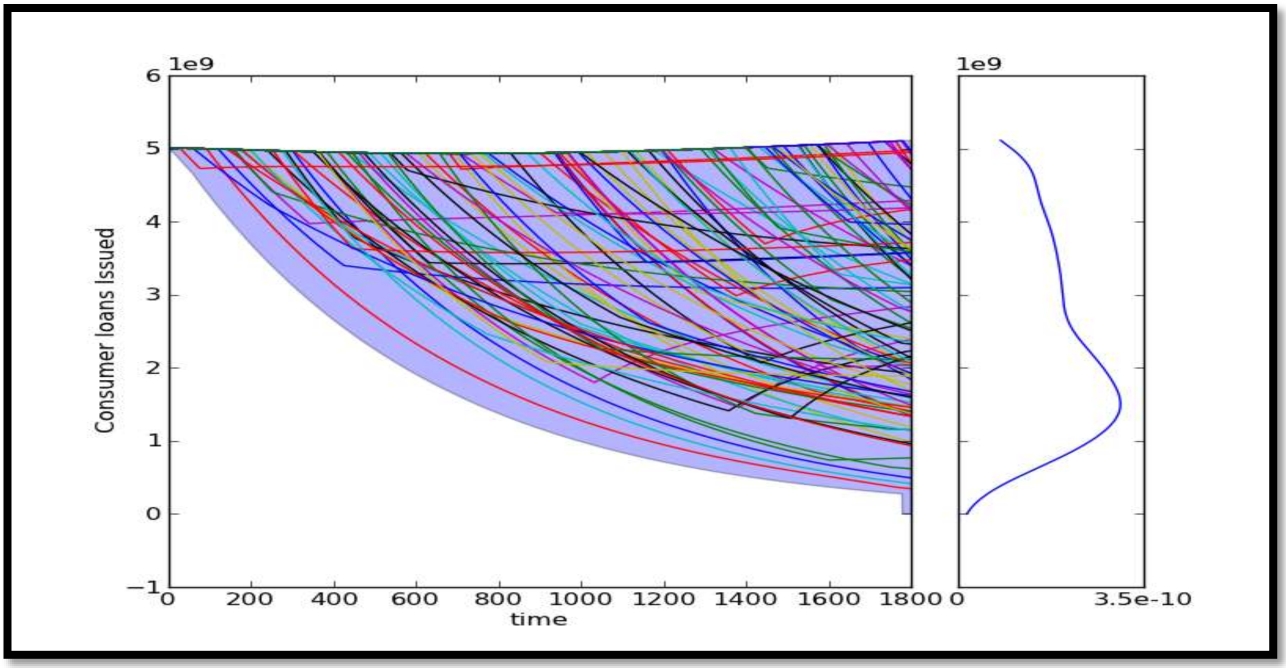

Figure 7.13 Consumer loans after policy 3

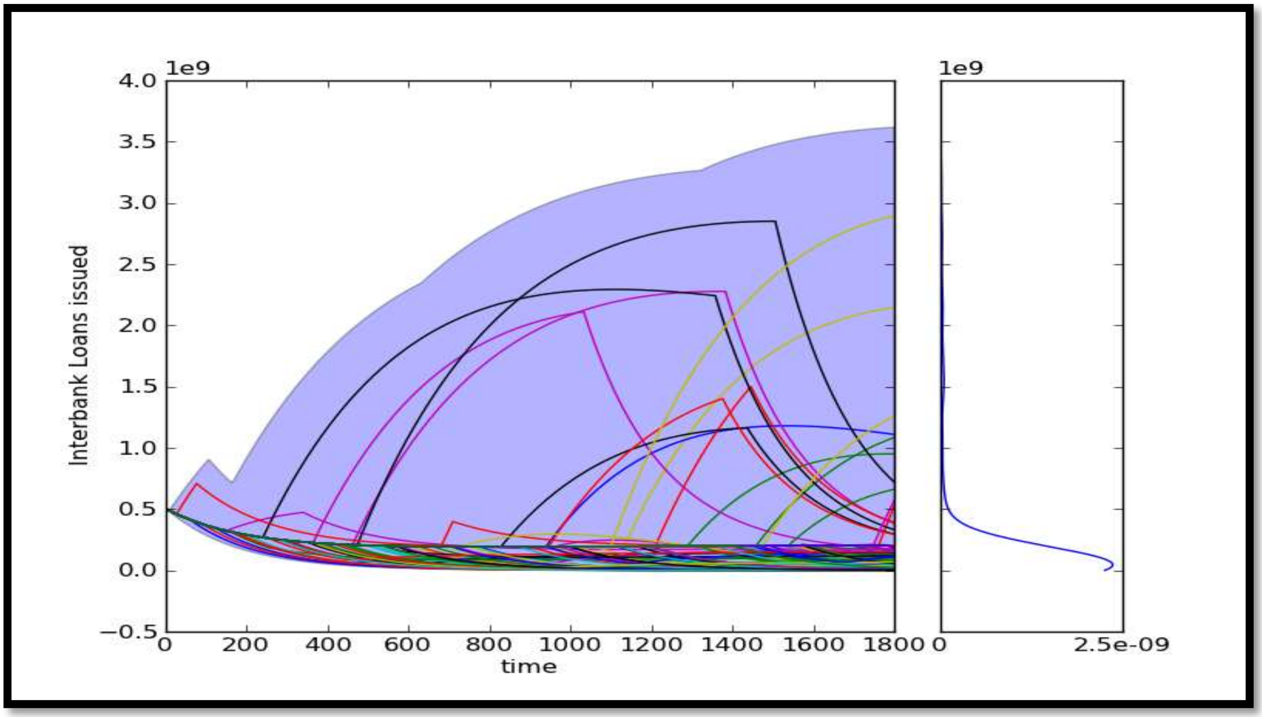

Figure 7.14 Interbank loans issued after policy 3

Figure 7.13 illustrates increases in the value of interbank loans issued, which is what we expect as the bank invests more in interbank loans. In those cases, the bank gains capital and improves its position and investments as Figure 7.14 shows. Corporate bonds and government securities portfolio increase. However, the number of simulated runs that show such behaviour is small. In the majority of the scenarios, the bank does not invest at all as the capital available is needed to meet liquidity needs.

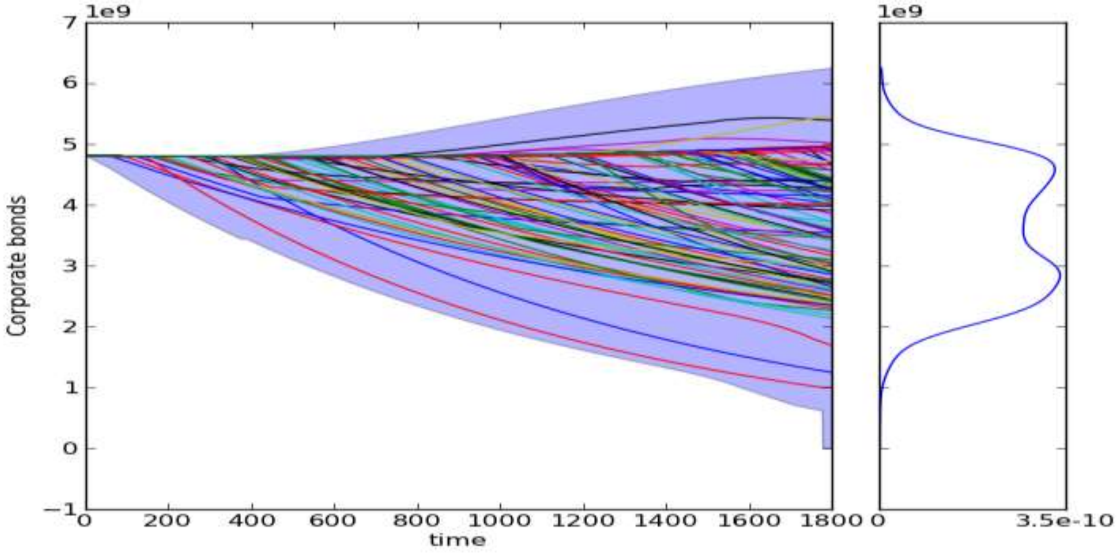

Figure 7.15 Securities after policy 3

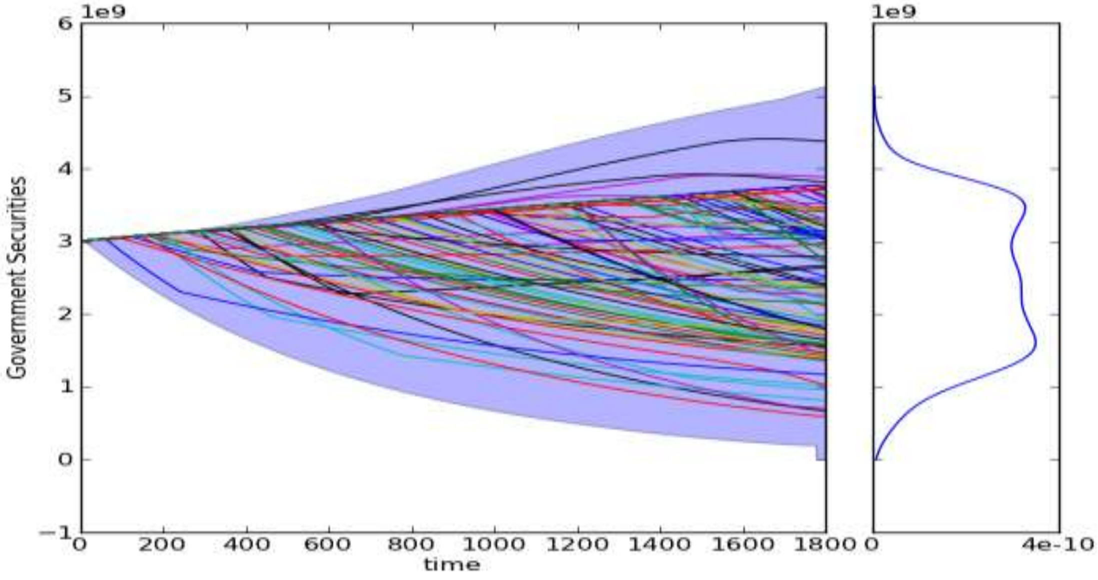

Figure 7.16 Corporate bonds after policy 3

Finally, net worth's behaviours demonstrate the effectiveness of this policy. It can be observed that no sudden drops exist like in previous cases, but still recovery in not clearly illustrated. The final results keep being close to the initial values or even better despite stress events appearance.

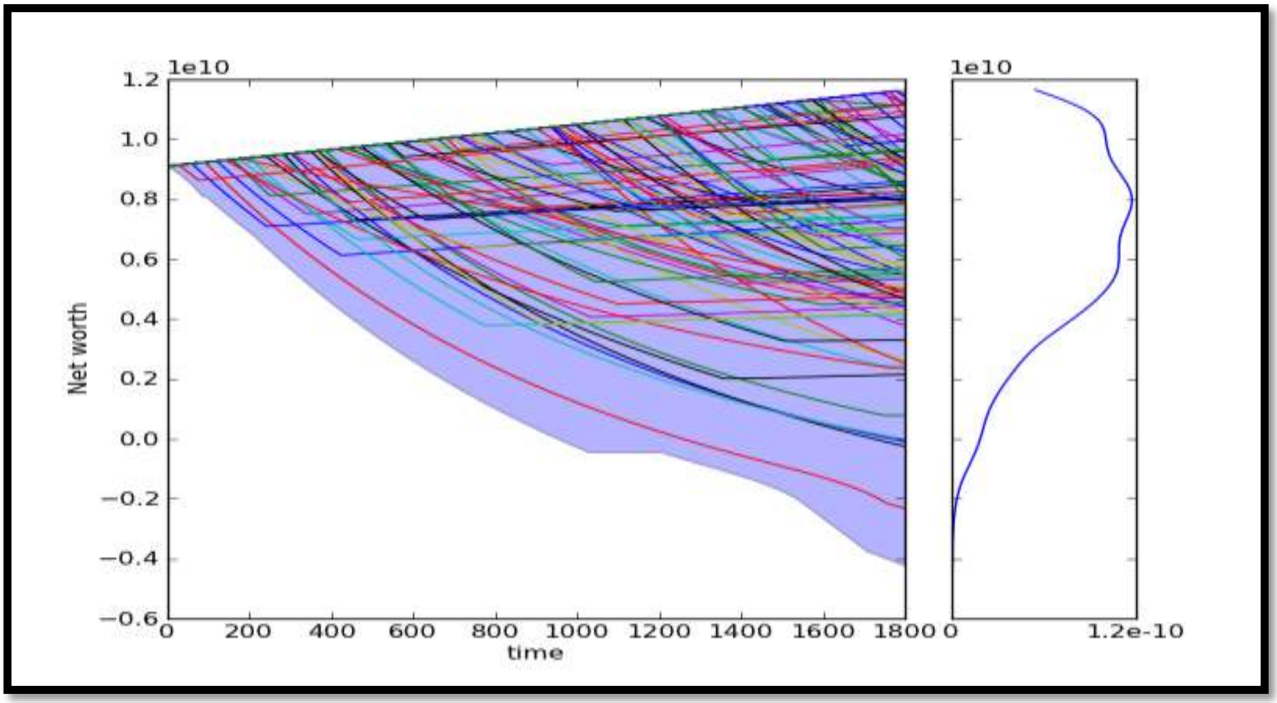

Figure 7.17 Net worth after policy 3

To conclude this section, stopping to invest in sectors (real estate, commercial, consumer loans) when they create losses could decrease further exposure of the bank to risk factors. Investing the available capital to interbank market could offer a more secured investment (with low interest revenue), but also help the stability of interbank market which can provide a critical solution in case of capital needs.

8. Conclusions

The inspiration for this project has been the application of System Dynamics modelling combined with Exploratory Modelling and Analysis in the field of financial stress testing. In this study, the aim was to develop a novel model-based approach in view of stress testing with the use of a System Dynamics model to represent basic functions and mechanisms of a hypothetical bank. Stress testing this model under multiple adverse future worlds allowed the exploration of possible modes of system's behaviours and the identification of its weaknesses. Those insights are important in order to support the decision making.

In this research, the implementation of EMA workbench investigated the ability of Exploratory System Dynamics Modelling and Analysis to assist in monitoring the performance of the bank. During the process of SD model's development a deeper understanding of the main mechanisms and subsystems in the bank was achieved. After the definition of uncertainties and risks that could affect bank's financial state, with the use of EMA workbench the bank performance under all those plausible scenarios was explored and analysed. The analysis of the results with machine learning and clustering algorithms provide the reader with critical information regarding the causes of undesirable behavioural modes. The identification of the causes was critical, but also testing basic policies delivered insights in how preventive actions could reduce the effects of stress events and improve bank performance under unexpected adverse futures.

The analysis of the observed behavioural patterns leaded to the identification of causes regarding the undesirable futures of the bank. The outcomes, which do not represent a real world case, revealed that without the application of any preventive action the main drivers for a bankruptcy are high default rates of the outstanding loans in scenarios with long duration and early starting point. Therefore, decreasing the exposure in cases of increased default rate in loans, the bank has chances to limit the expected losses. None of the applied policies could delay the increasing demand of deposits in many cases, but the bank appeared to have substantial buffer to meet all its liquidity needs without facing bankruptcy.

The aforementioned policies revealed that the bank can survive in a larger number of adverse scenarios, but still extreme cases need even more drastic measures, especially in decreasing the fear of bank runs. This should be the focus of regulatory authorities in an effort to secure the banking system of scenario. The capabilities of EMA workbench could provide even deeper insights in the analysis of those scenarios and assist in developing automated responses and policies for particular cases. Those scenarios will never be used for accurate prediction of the future, but their exploration can become an appealing tool to support the decision making and the risk management of a bank.

Finally, the end results are not surprising as they illustrate what we expected to as the model is stressed under heavy shocks. However, the objective of this project is not to identify extreme crises in a case of a hypothetical bank, but offer a model-based approach as a proof of concept. The model enables the identification of all possible influences that could affect the bank and the degree of their effect.

9. Reflections and Recommendations

After concluding this research study, it is crucial to reflect on the process, the design, the research methodology and the limitations that appeared. Reflecting can lead into recommendations for future research on this field.

9.1 Reflections on the process

A bank is a complex system and it is difficult to develop a generic model. Its structure and its functions differentiate in a high degree between various institutions. Regulatory framework that defines operations of banks differs across countries. Furthermore, each bank is able to offer different products and services if those meet regulatory restrictions. This complexity was the main obstacle in the development of the model. The problem lies on the decision to build a generic model and not specific for a real European bank. This decision posed problems regarding the input of accurate data from a bank's balance sheet, but also the choice of the operations of a bank that should be described.

The knowledge about internal bank's operations was limited making difficult to capture decisions of the management of the bank in each case. This knowledge could have been acquired from experts working in a bank environment which would improve the validity and the importance of this research. The knowledge and the insights provided by those experts could have made this model more bank-specific increasing its possible use for immediate incorporation in a bank's risk management practices. The initial data used could have been from a detailed balance sheet of a bank with confidentiality issues taken into consideration.

For the purpose of this study, one extensive SD model was developed representing a bank. However, in the starting point of this research, the intention was to keep the model relatively simple or develop multiple smaller models. During the process, the researcher focused on better developing this model and included more structures rather than developing more models. Although, the outcomes of the analysis of this model were extremely thought-provoking, developing a multi-model approach with multiple smaller models could as well offer different insights. Multi-model approach could give the chance to explore different perspectives as they refer to different situations and capture different dynamics in each case.

9.2 Limitations of the research method

The chosen research methodology framework is not only innovative and promising, but also has its own limitations. First of all, the main limitation lies on the fact that performing more runs and experiments requires high calculation power, especially for extensive simulation models like the aforementioned bank model. Exploring an extensive uncertainty space by defining more parameters in one model increases exponentially needs data storage and calculation power. A possible solution for this problem could have been the development of multiple smaller models focusing on particular stress events with fewer parameters to be explored. This implementation could have decreased substantially the calculation time needed for the experiments.

A major issue during the whole process was the contribution of this model based approach compared to the existing stress testing approaches. Of course exploring the dynamics of the system and identify possible disruptive relations and links that could affect the bank is an important issue. Providing an overall view of the system with all possible behavioural modes and delivering a high level message to the analyst is even more important in view of designing robust policies. However, economists and managers focus on numbers and numerical outcomes that they need to know for their decisions. They just need numerical predictions and estimations. Changing the way of how the existing stress testing approaches are developed is tough, but this approach could offer a step further, if not using System Dynamics modelling but Excel or other types of modelling with EMA workbench.

9.3 Future research

This research intends to address the research questions discussed in the first section, but also creates space for further discussion and ideas for future research. The use of ESDMA methodology framework enables the exploration of an extensive ensemble of future worlds and the investigation of dynamic behavioural modes. As a method which is still under development, ESDMA has its limitations but it can be a promising method for future research studies. In this research, not all the tools provided by EMA workbench were used, leaving space for further research regarding the bank model and plausible future worlds.

This research could serve a starting point for more advanced and detailed studies inside the context of a bank's risk management sector. Working next to senior bank management of the bank would support the development of a more accurate model with actual data including structures and mechanisms that are not in the scope of the current model, providing a more valid picture of the system and its behavioural modes. Current analysis could be the first step, but opportunities for improved and more advanced stress test tool exist.

Regarding the outcomes, the large amount of data produced during the experiments could be further used for more analysis. Clustering techniques provided by EMA workbench could improve the view of undesirable behaviours and allow further exploration by focusing on them and sampling more on the parametric space which is responsible for those outcomes.

One step further could be the design of robust more advanced policies. Depending on the outcomes, adaptive policies could improve the behaviour of the bank. Identifying the parametric space that created particular undesired outcomes and behaviours could enable the proposal and design of preventive actions in each case, based on particular early warning indicators. This could assist the management of the bank to simulate and test actions under certain adverse scenarios improving its position before crises occur. The outcomes would never be used to predict the future, but a view of what could happen in the future could be provided.

This research provides a major opportunity for future research in developing a stress test tool for assessing the performance of the overall banking system and not only focusing on one banking institution. This could be implemented by replicating the same model with minor changes for multiple other banks that compose the entire country's banking system. Developing various bank models with different data regarding the initial financial state of each bank and connecting them using EMA workbench would allow us to gain deeper insights of the banking system but also exploring in detail contagion effects in each stress event scenario. Simulating different players (banks) in the banking system exercising different management decisions with their own market power would provide us with significant outcomes and behaviours that it is not possible to capture in this research. For this multi-player perspective, agent- based modelling could be another interesting methodology to be used.

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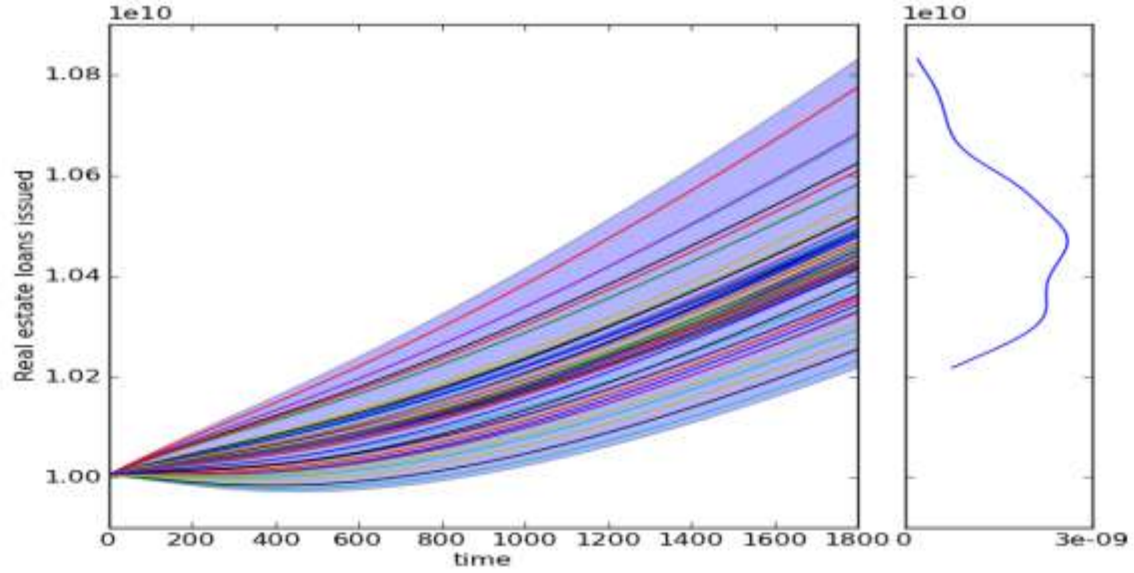
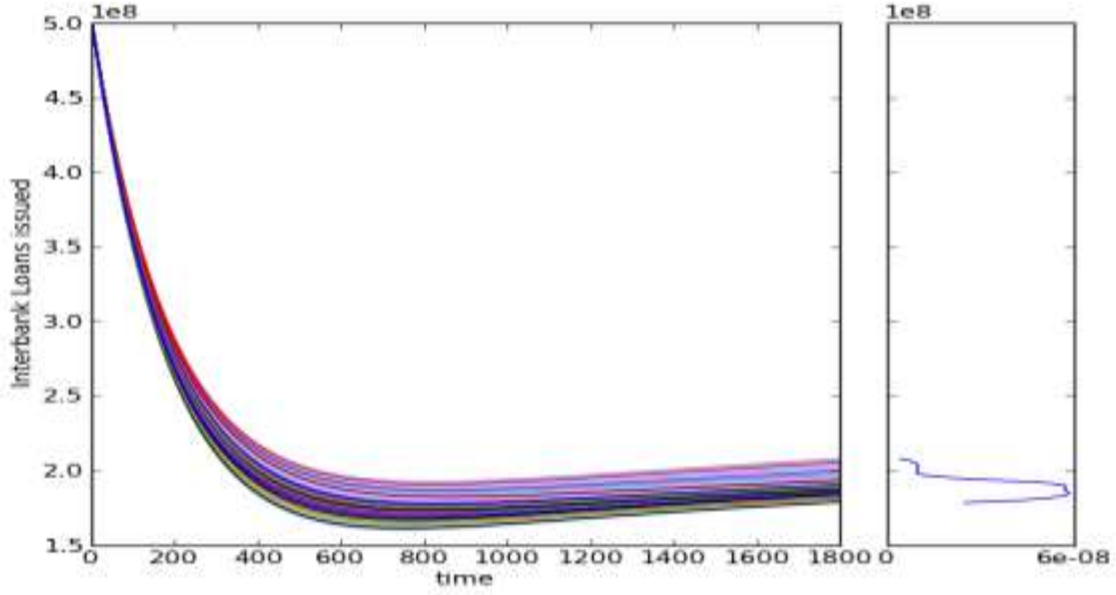
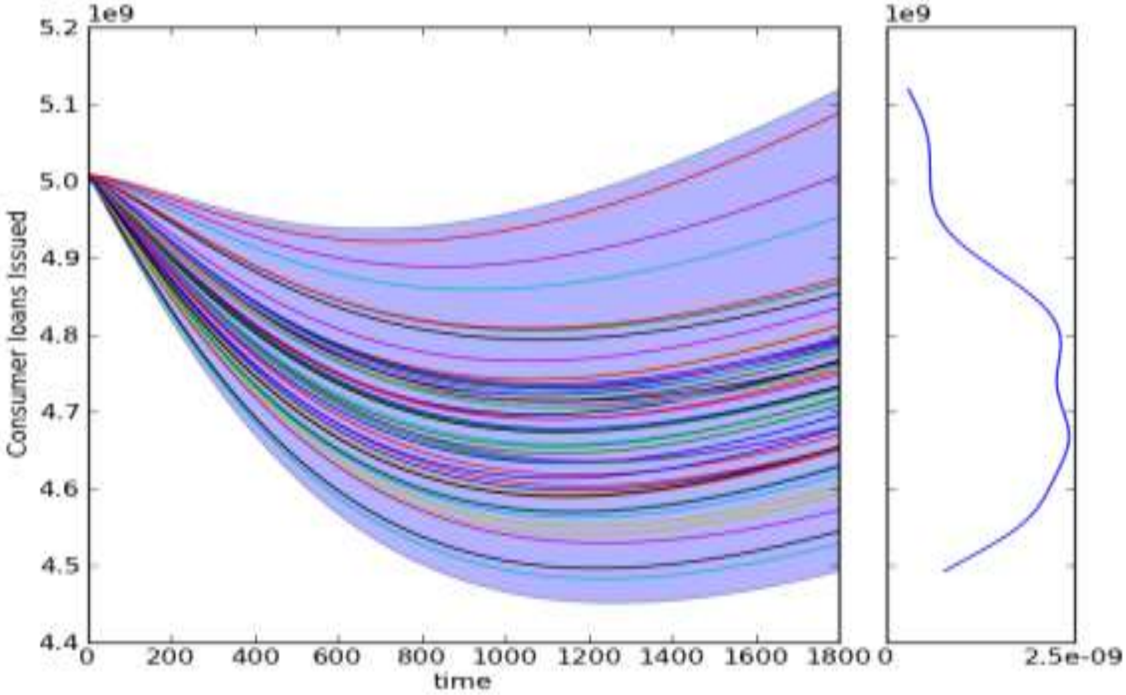
Appendix 1

Sensitivity runs of various indicators






1e9
5.2
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4.6
4.5
4.4
Consumer loans Issued
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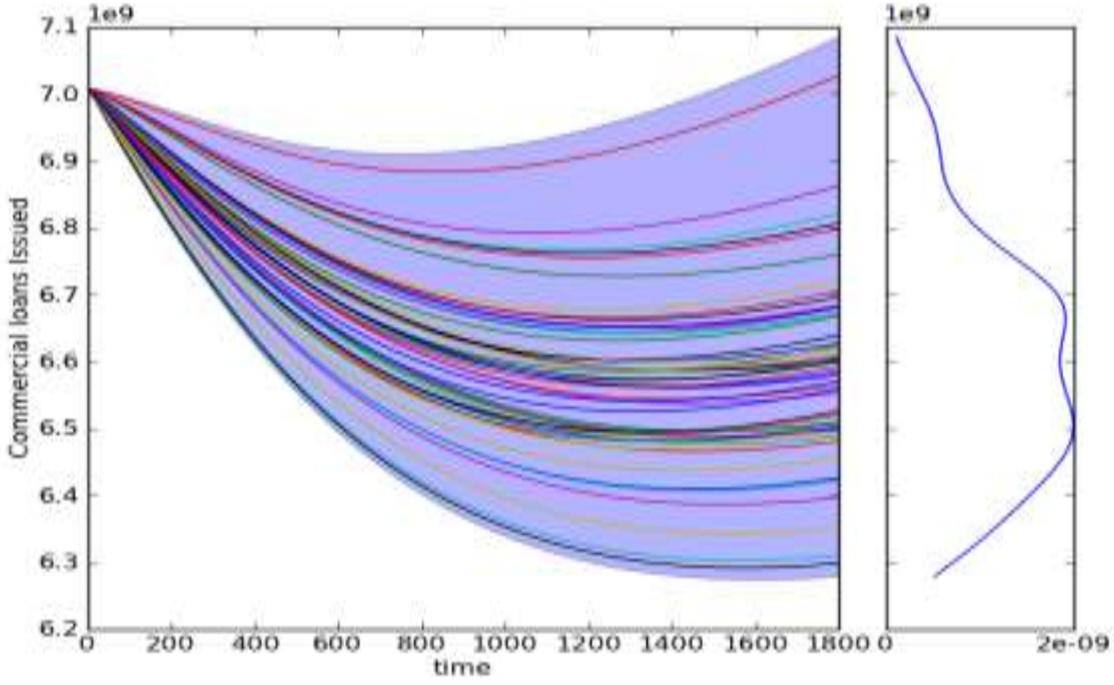
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
2.5e-09


1e9
7.1
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Commercial loans Issued
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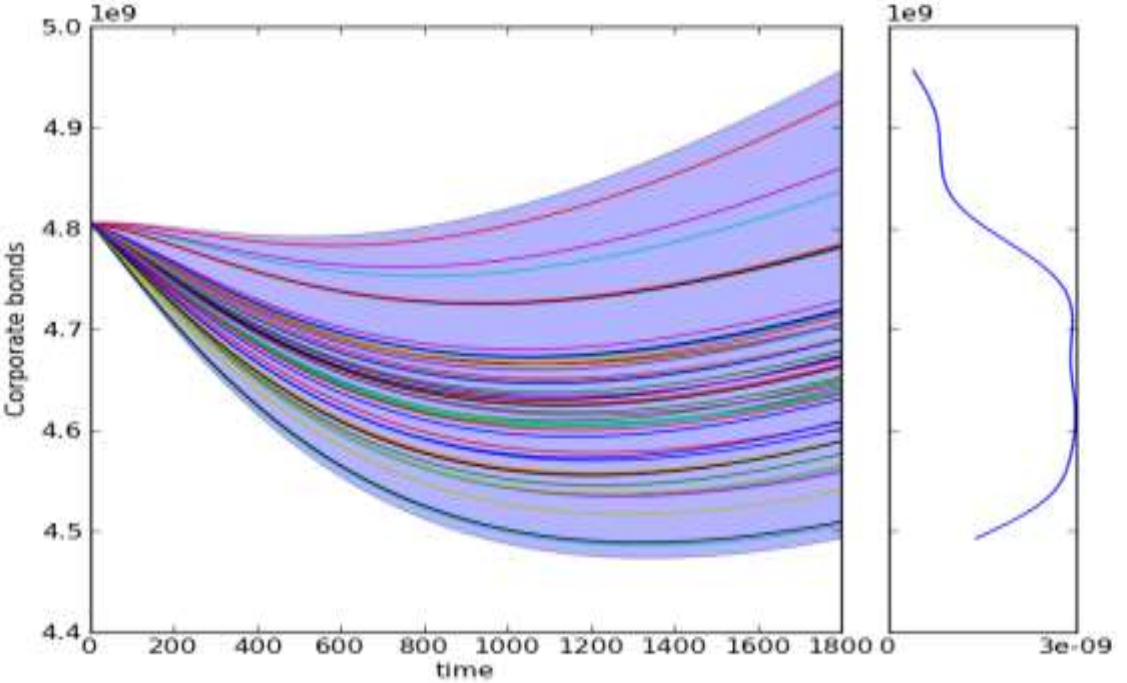
1e9
Corporate bonds
5.0
4.9
4.8
4.7
4.6
4.5
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0
200
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600
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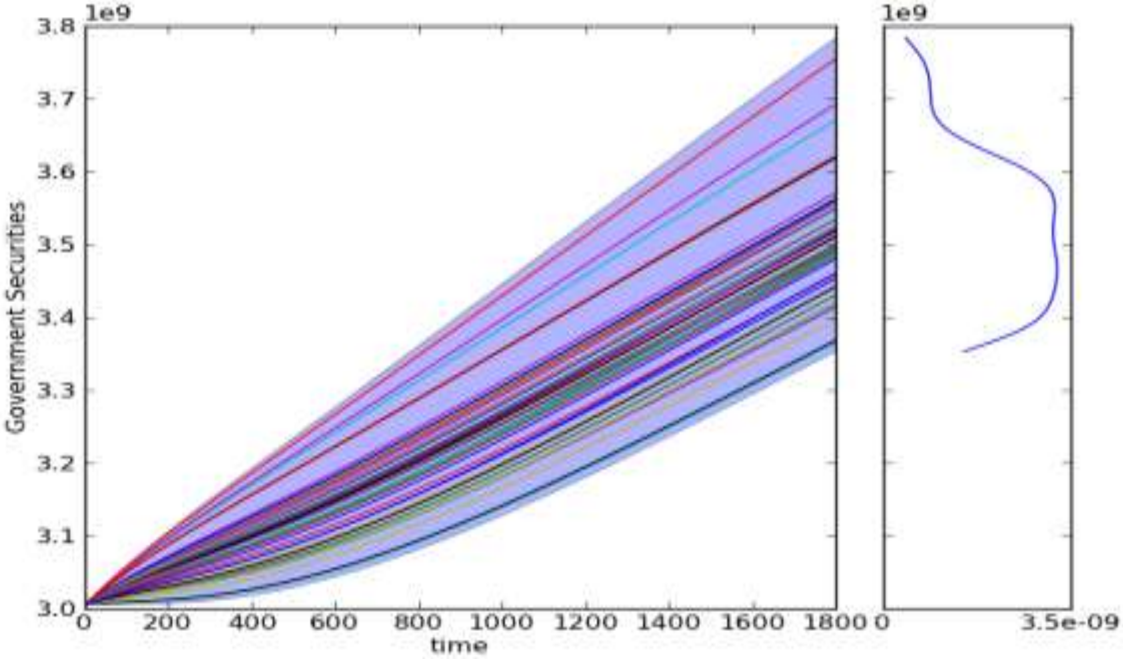
1e9
Government Securities
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
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1600
1800
time
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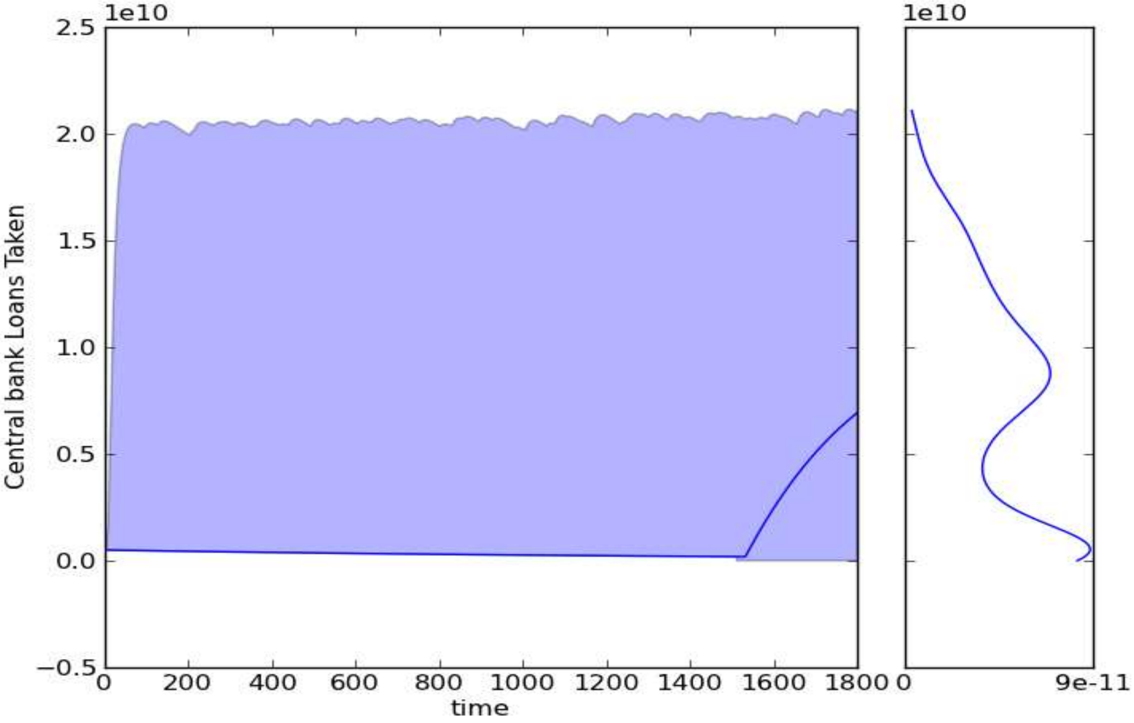
Behaviours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1600
1800
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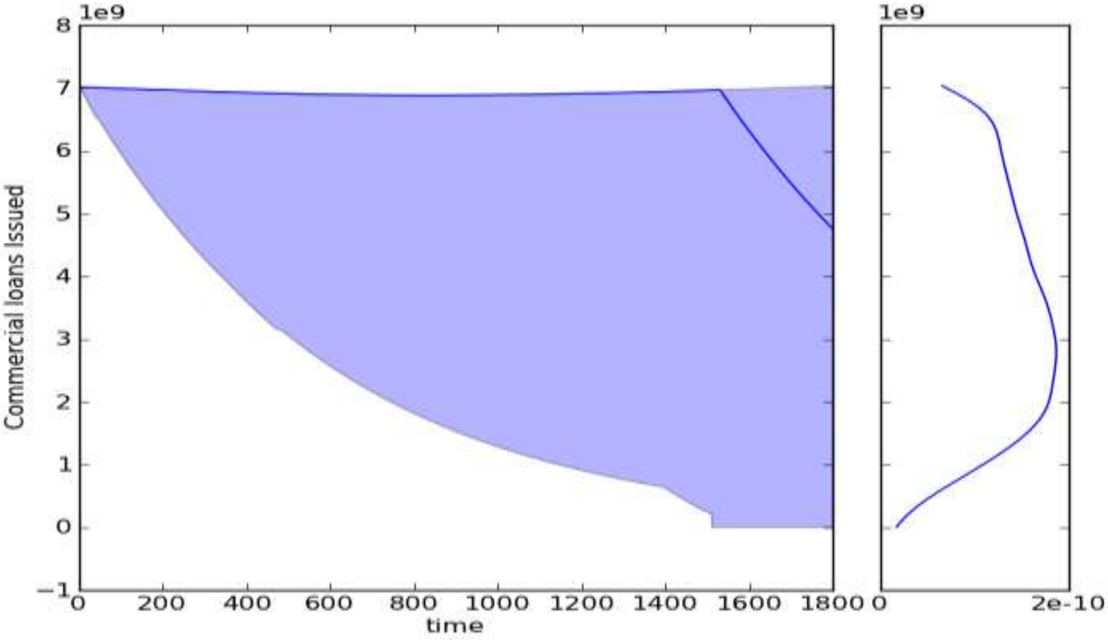
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Commercial loans Issued
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1600
1800
time
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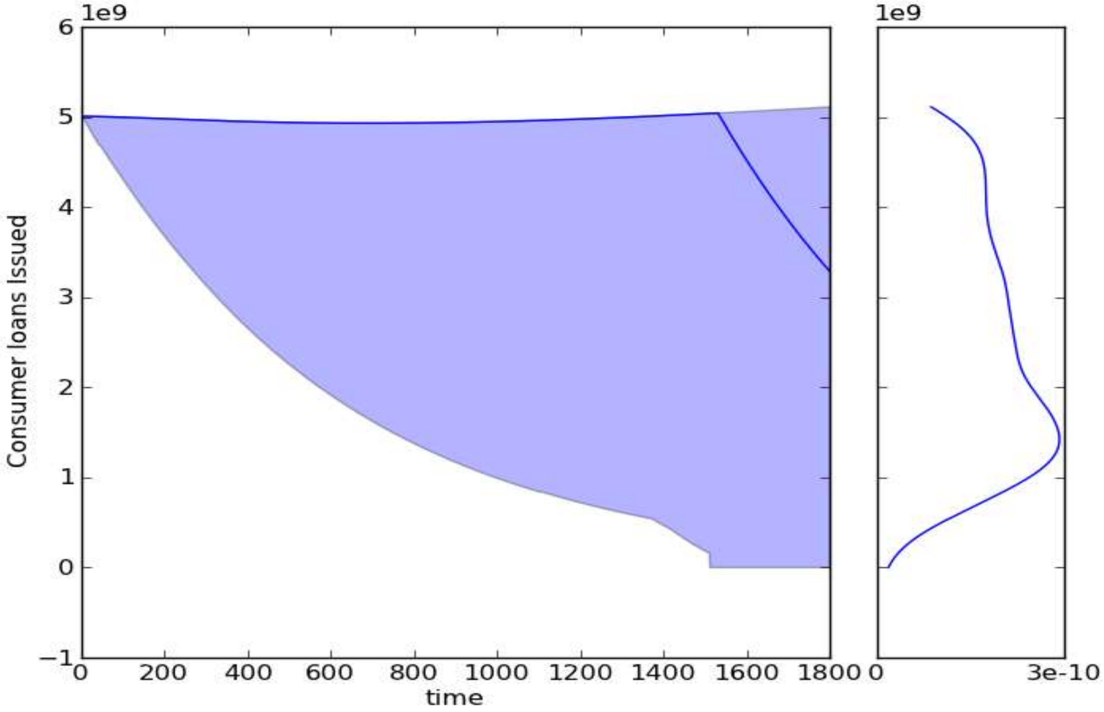
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5
4
3
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1
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Consumer loans Issued
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1600
1800
time
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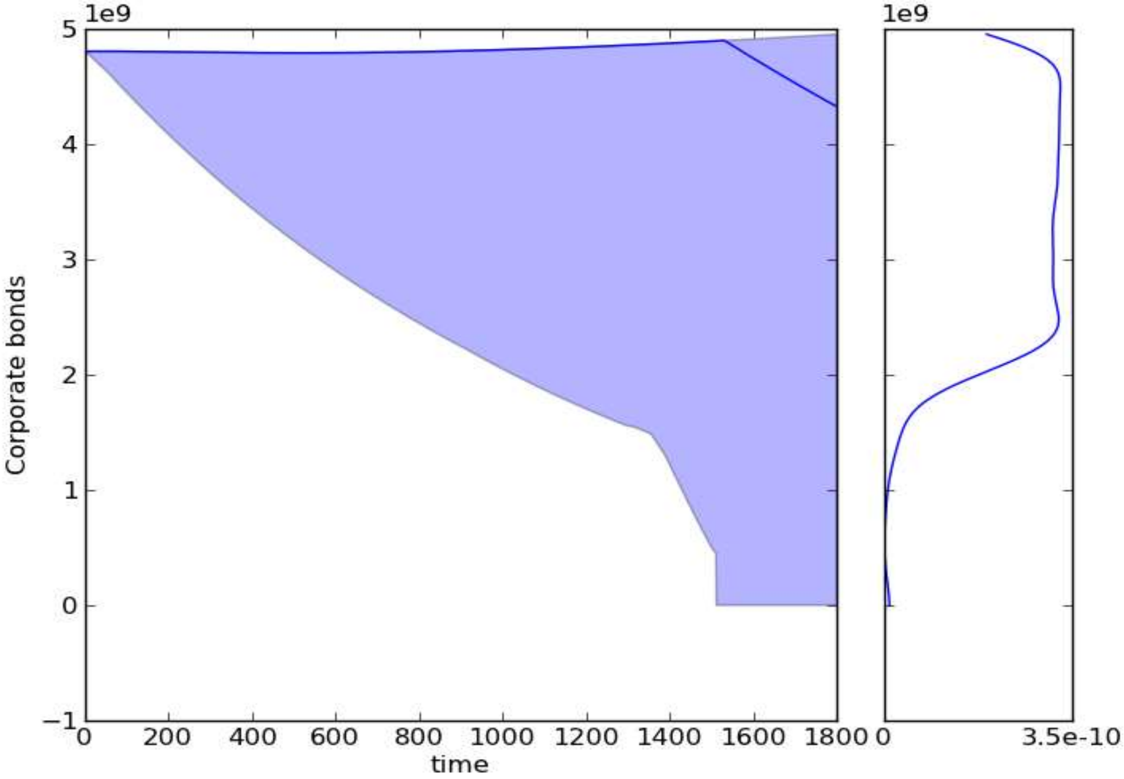
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5
4
3
2
1
0
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Corporate bonds
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200
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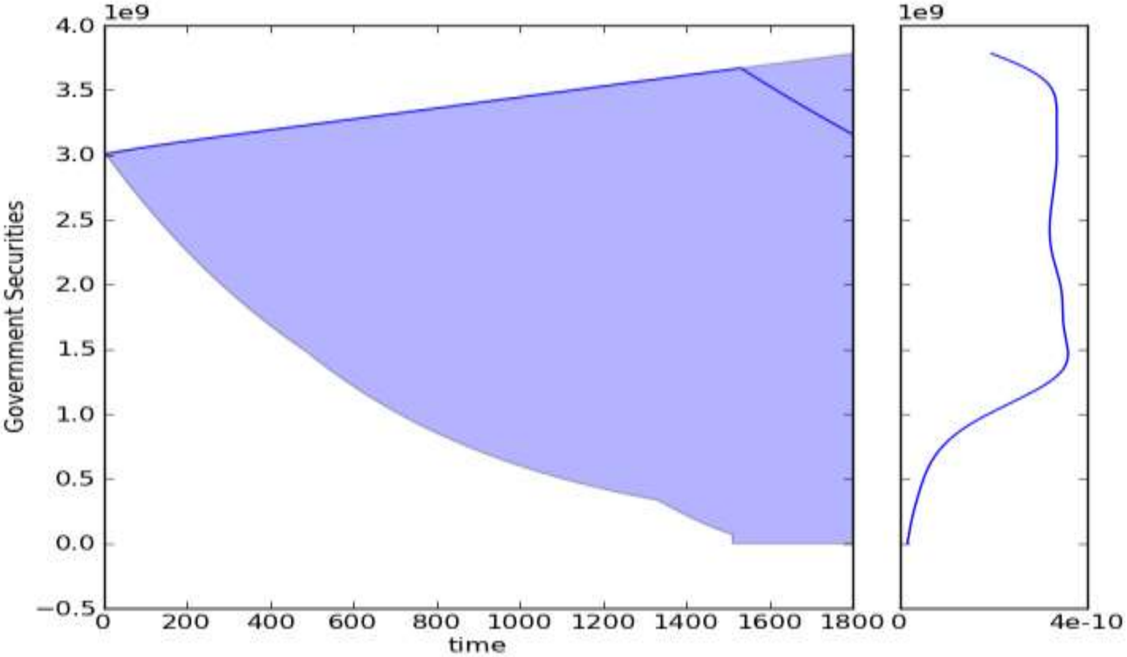
800
1000
1200
1400
1600
1800
time
1e9
0
3.5e-10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4.0
3.5
3.0
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2.0
1.5
1.0
0.5
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0
200
400
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800
1000
1200
1400
1600
1800
time
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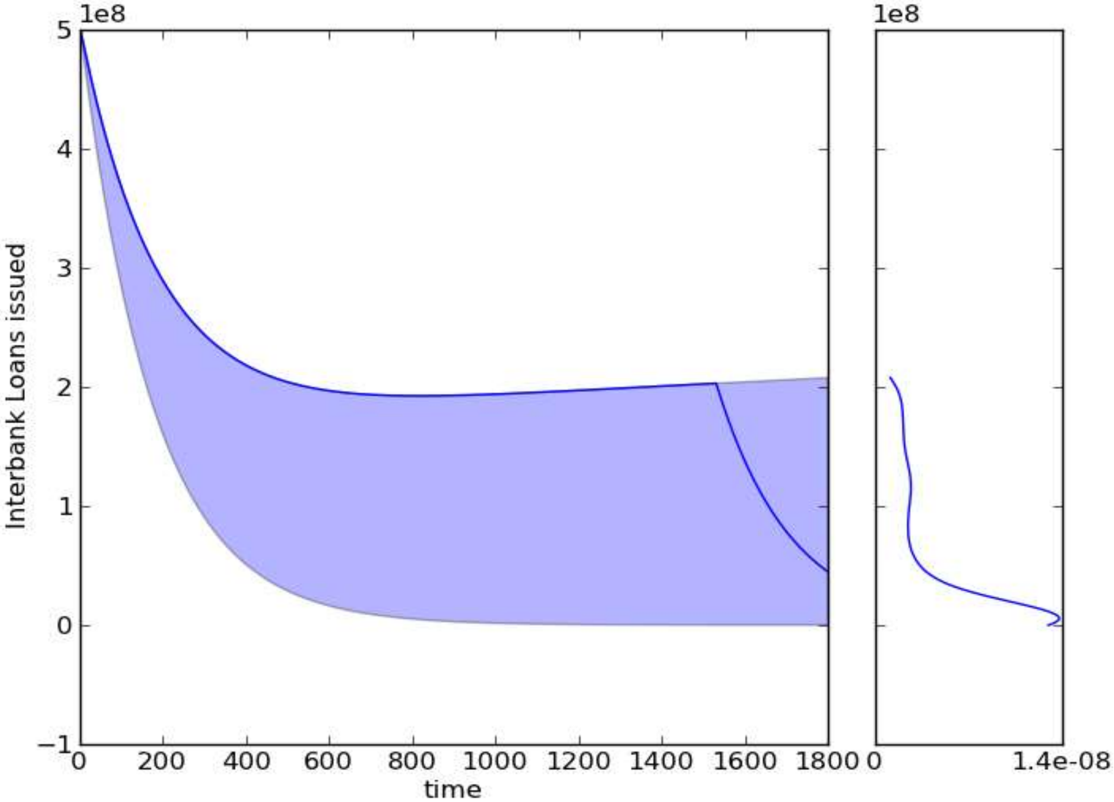
4e-10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5
4
3
2
1
0
−1
Interbank Loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e8
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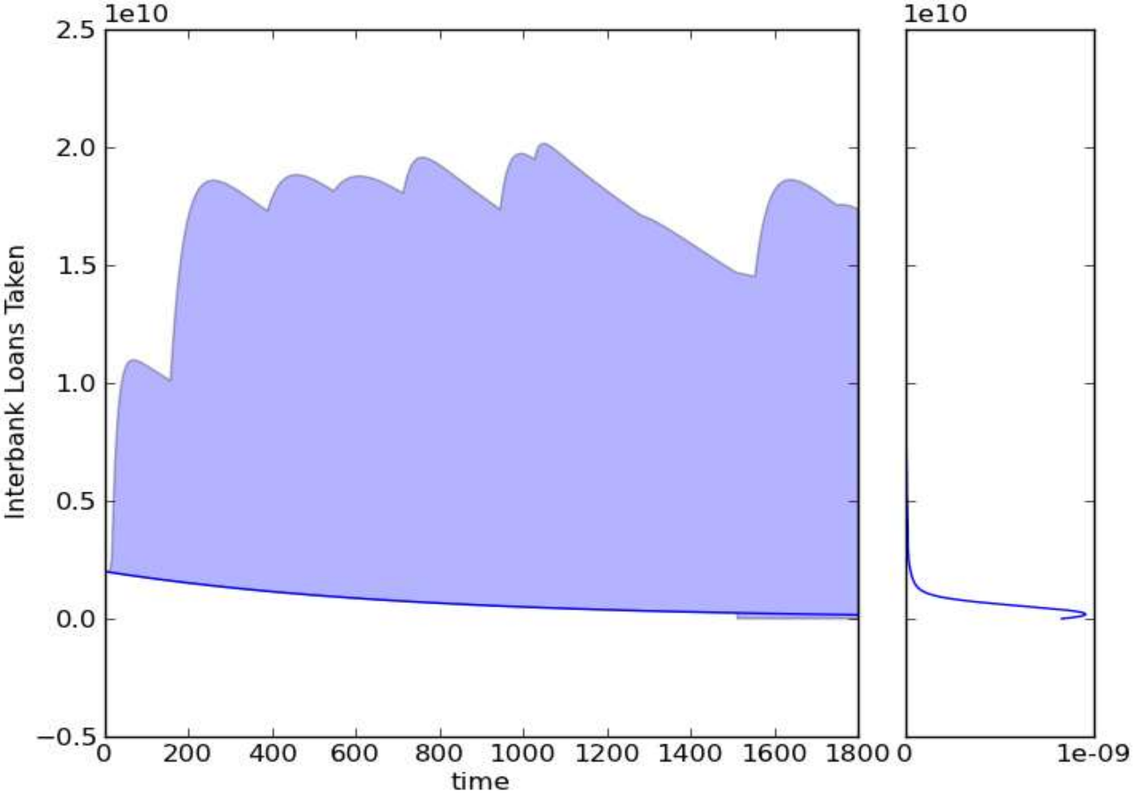
1.4e-08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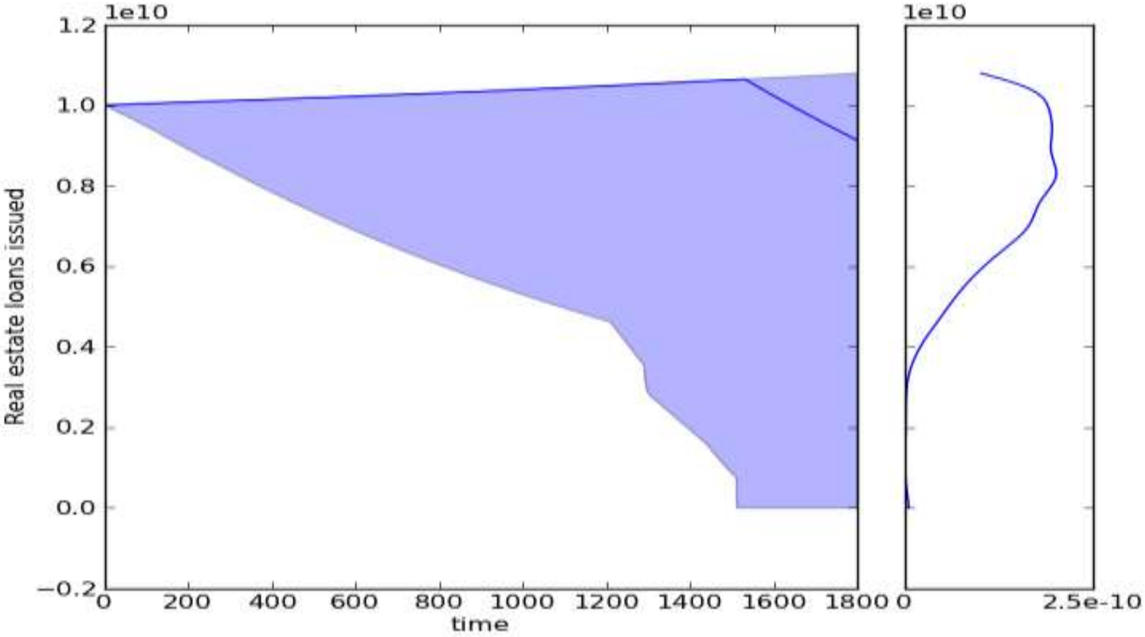
1e10
Interbank Loans Taken
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0
200
400
600
800
1000
1200
1400
1600
1800
time
0
1e-09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1e10
Real estate loans issued
1.2
1.0
0.8
0.6
0.4
0.2
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0
200
400
600
800
1000
1200
1400
1600
1800
time
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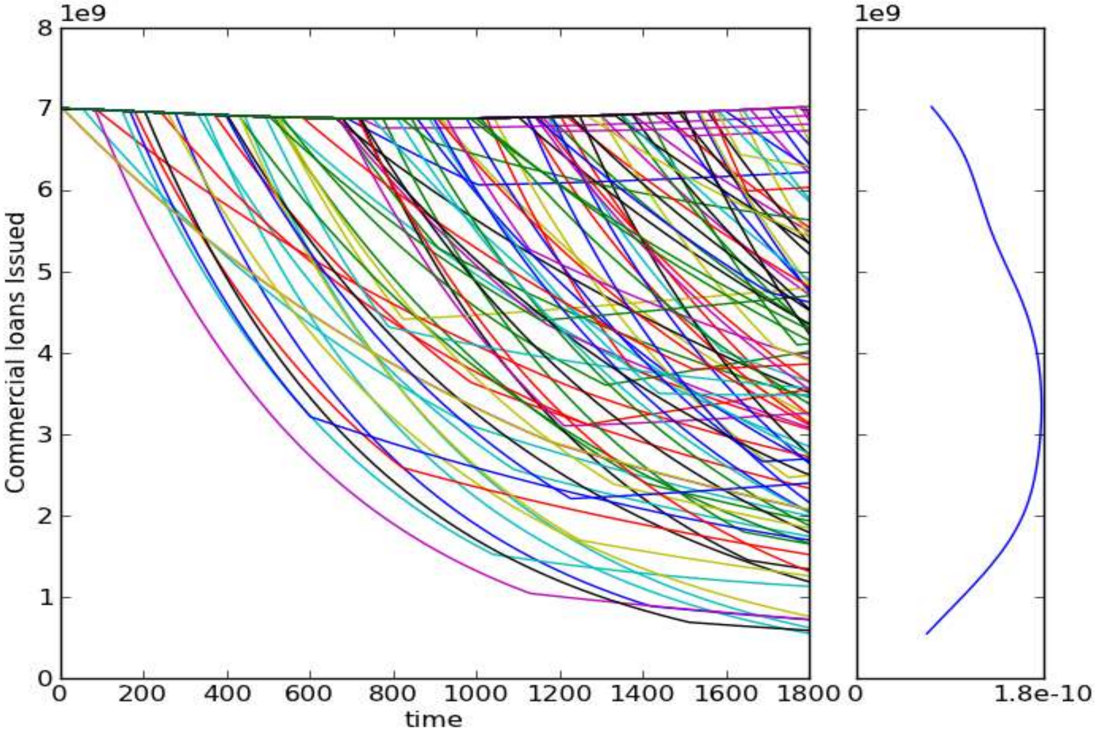
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Commercial loans Issued
0
1
2
3
4
5
6
7
8
time
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200
400
600
800
1000
1200
1400
1600
1800
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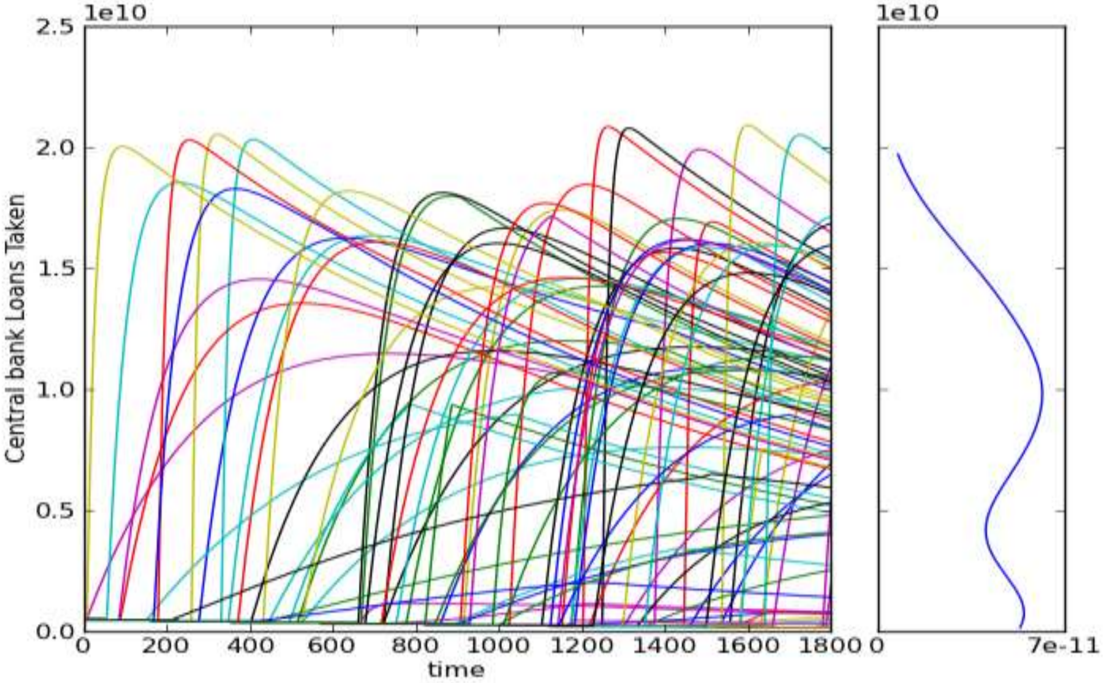
1.8e-10


1e10
Central bank Loans Taken
0.0
0.5
1.0
1.5
2.0
2.5
time
0
200
400
600
800
1000
1200
1400
1600
1800
1e10
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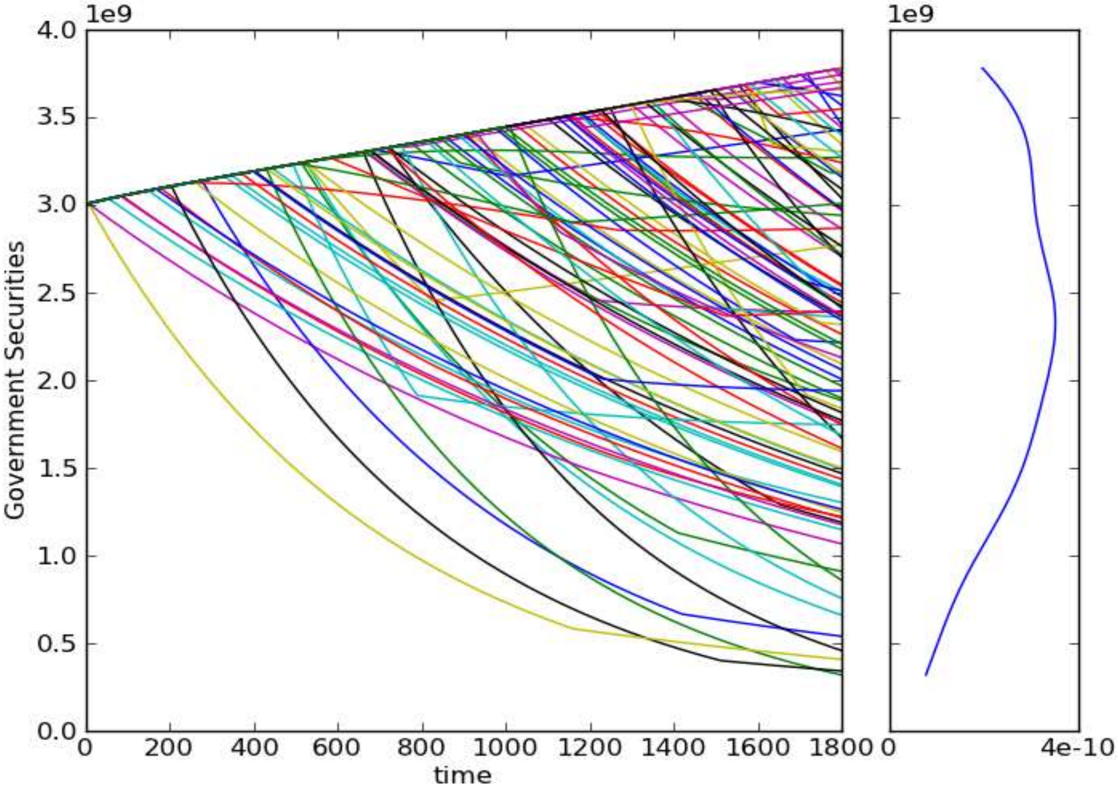
7e-11


1e9
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Government Securities
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
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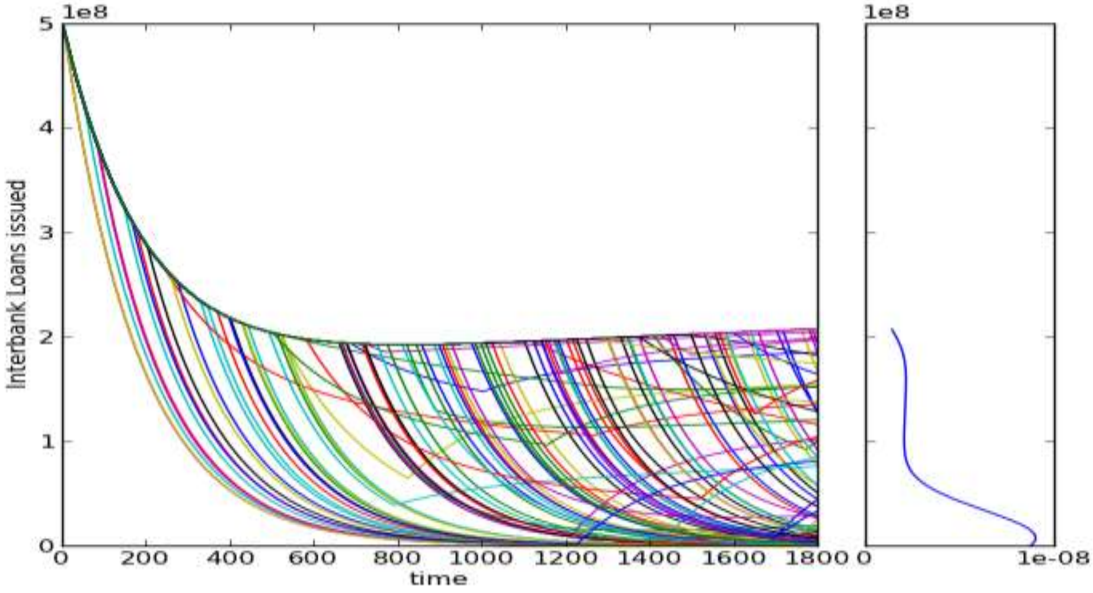
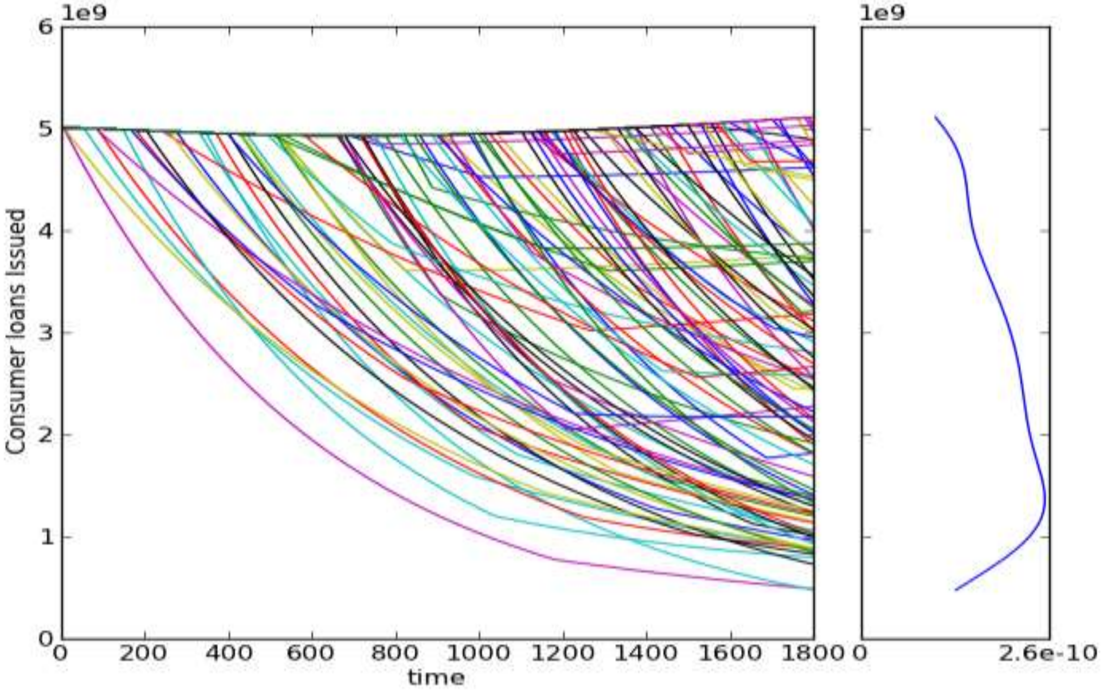
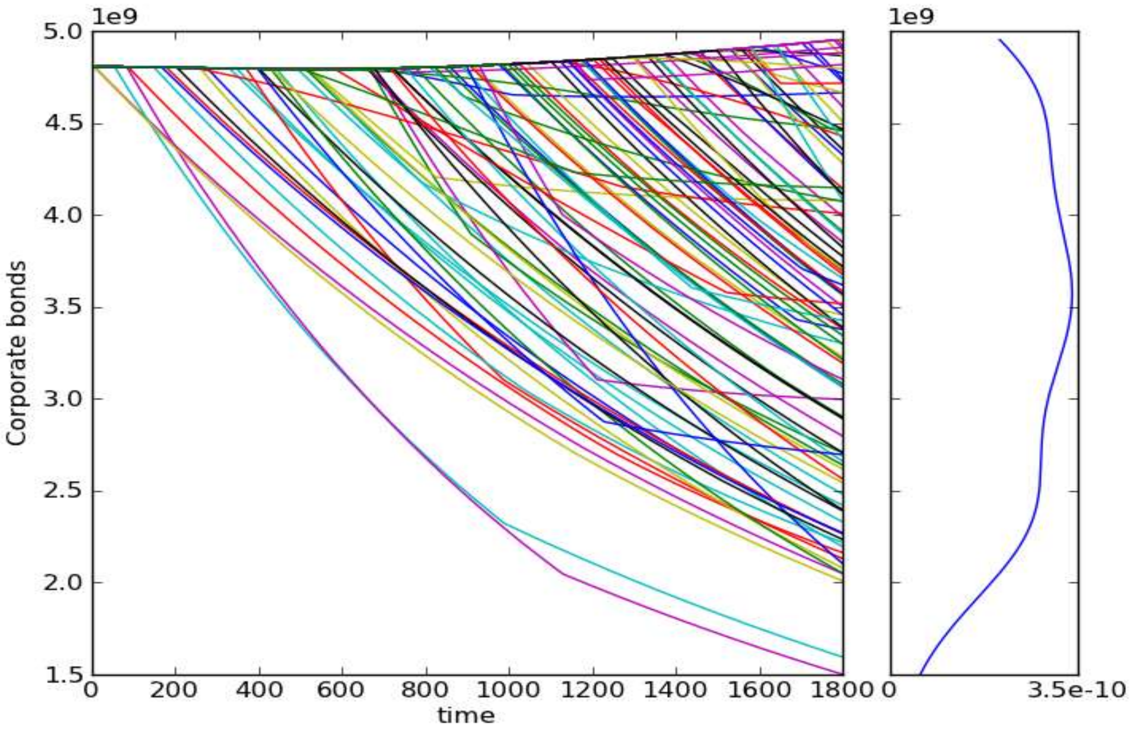
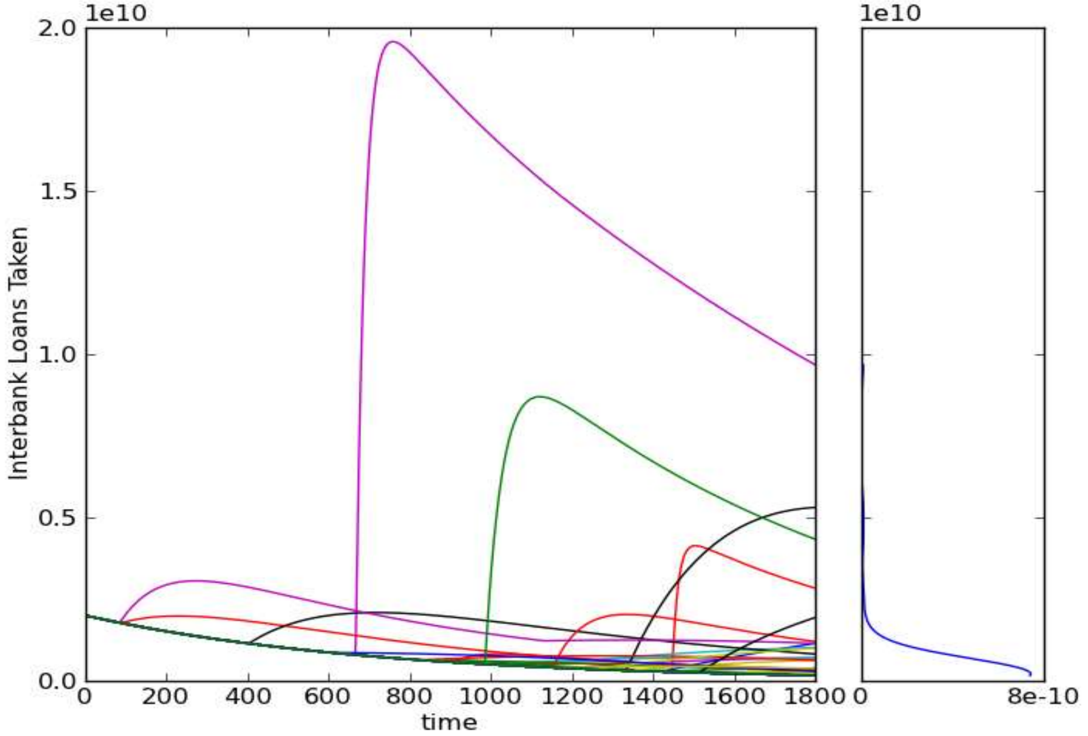
4e-10


1e8
5
4
3
2
1
0
Interbank Loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e8
0
1e-08


1e9
6
5
4
3
2
1
0
Consumer loans Issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
2.6e-10


1e9
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
Corporate bonds
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
3.5e-10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2.0
1.5
1.0
0.5
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Interbank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
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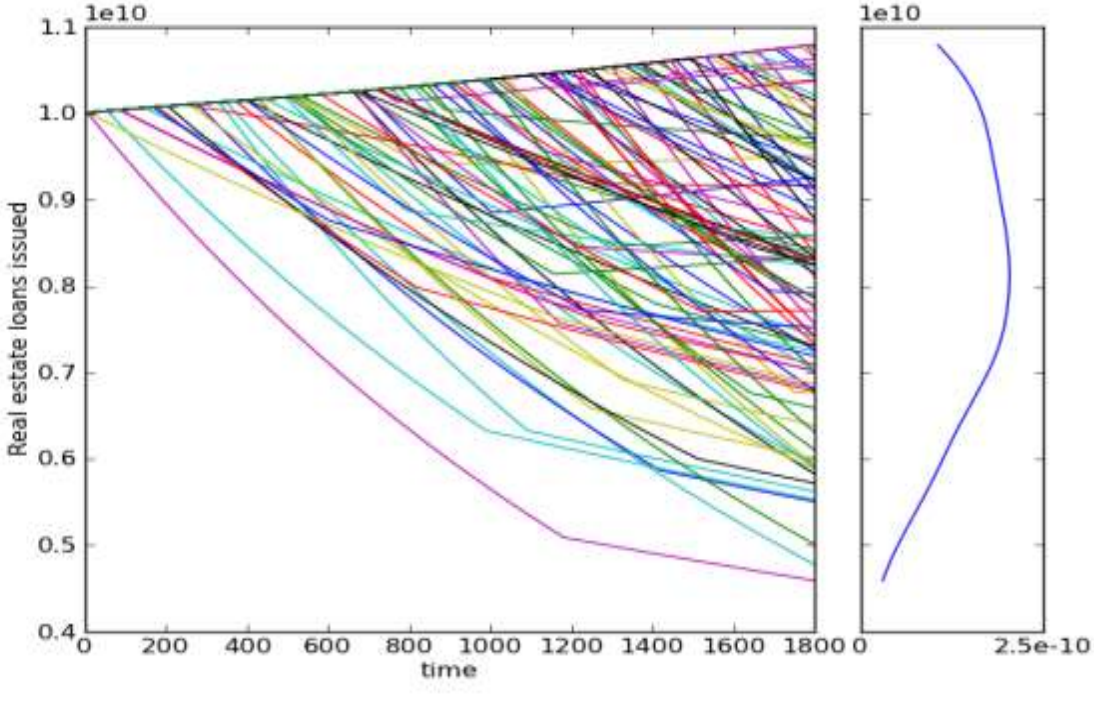
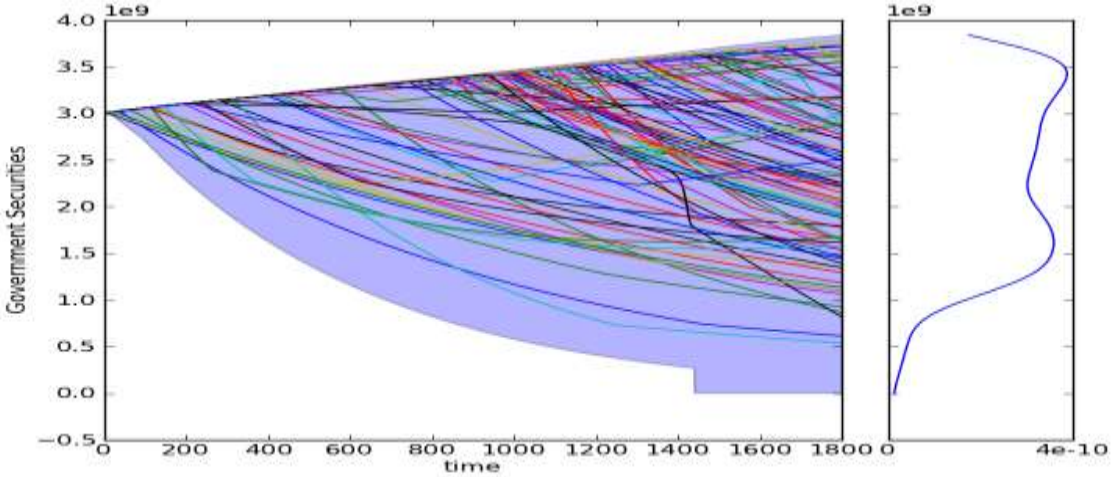
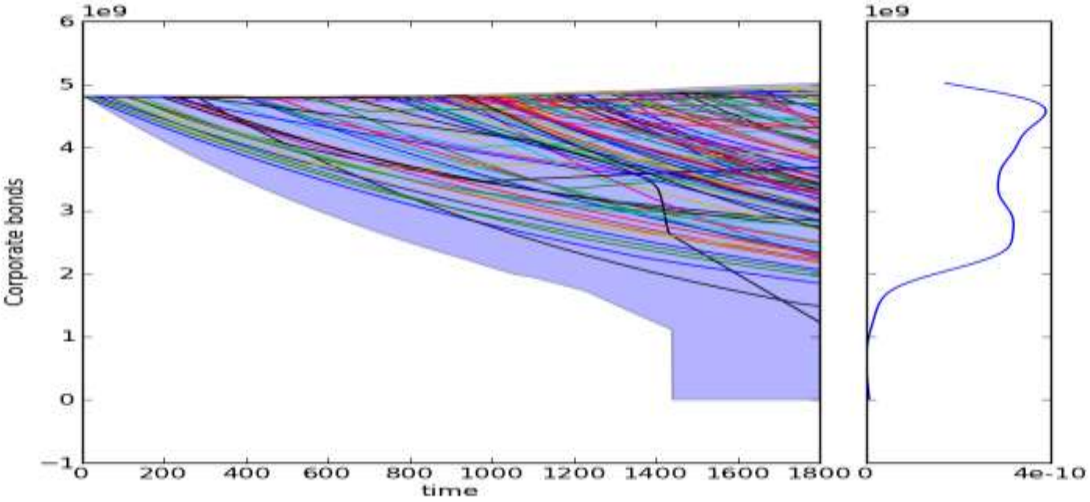
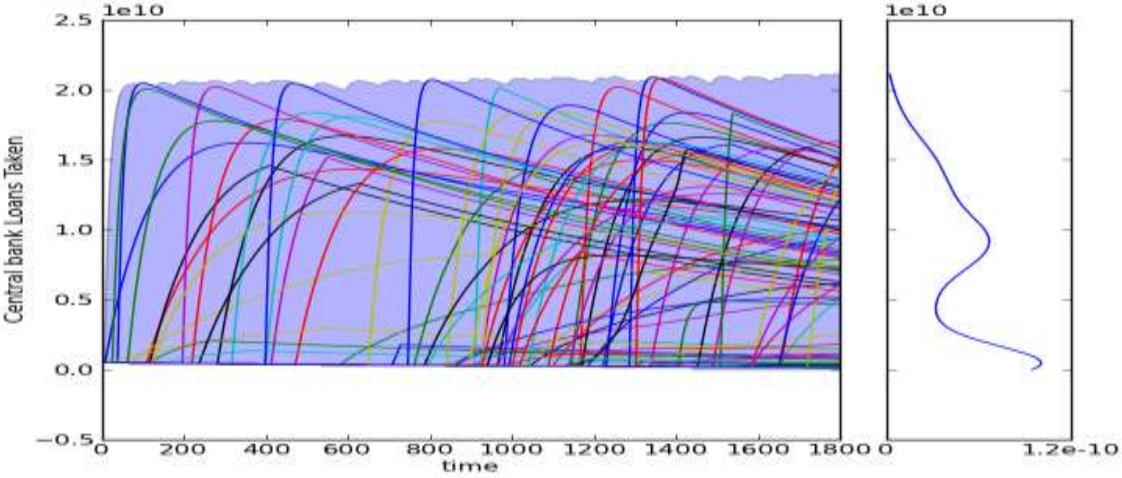
8e-10

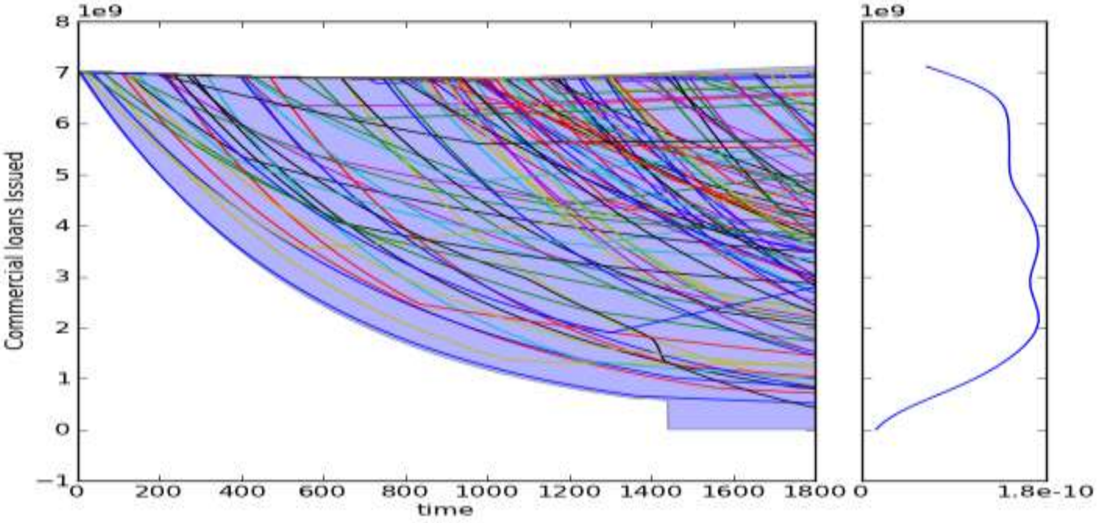

1e10
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Real estate loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
2.5e-10

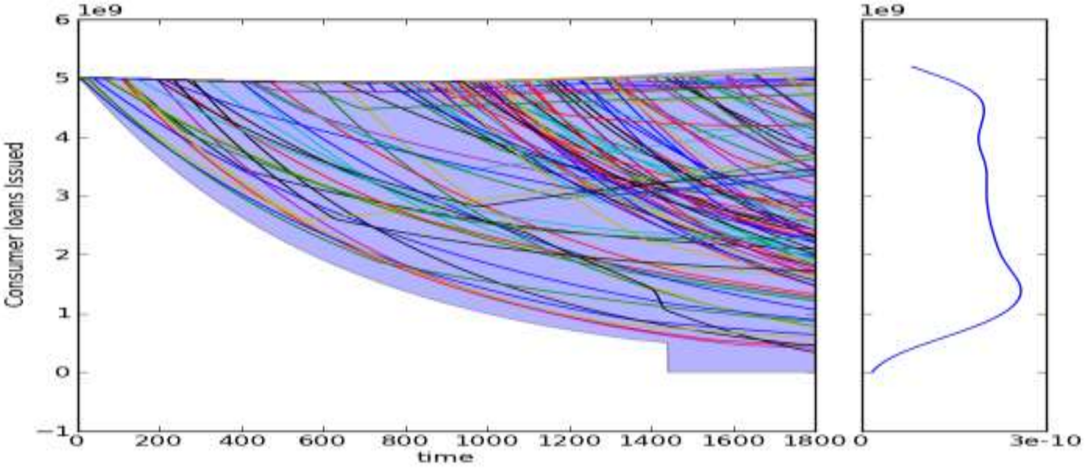
Policy 1

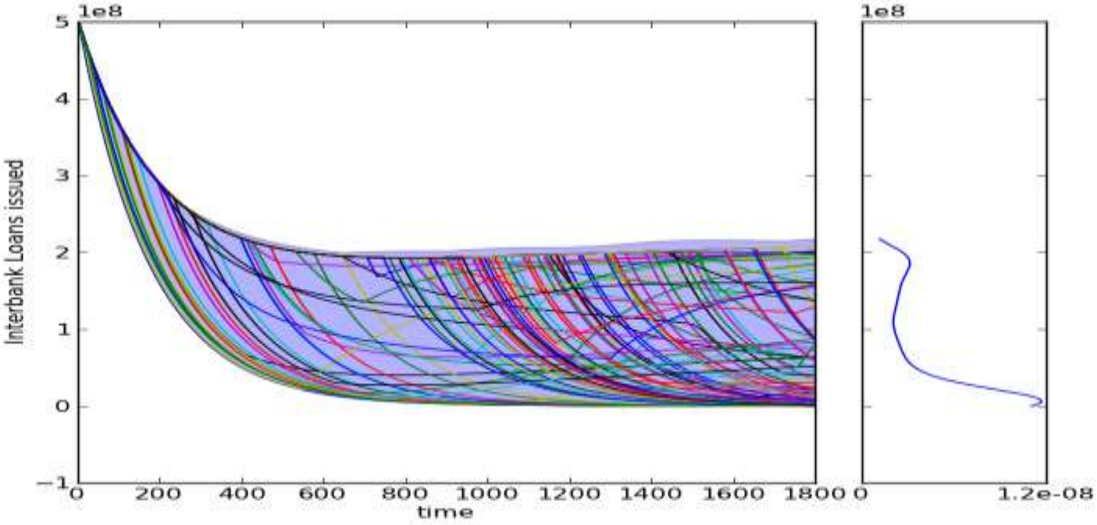

1e9
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Government Securities
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
4e-10

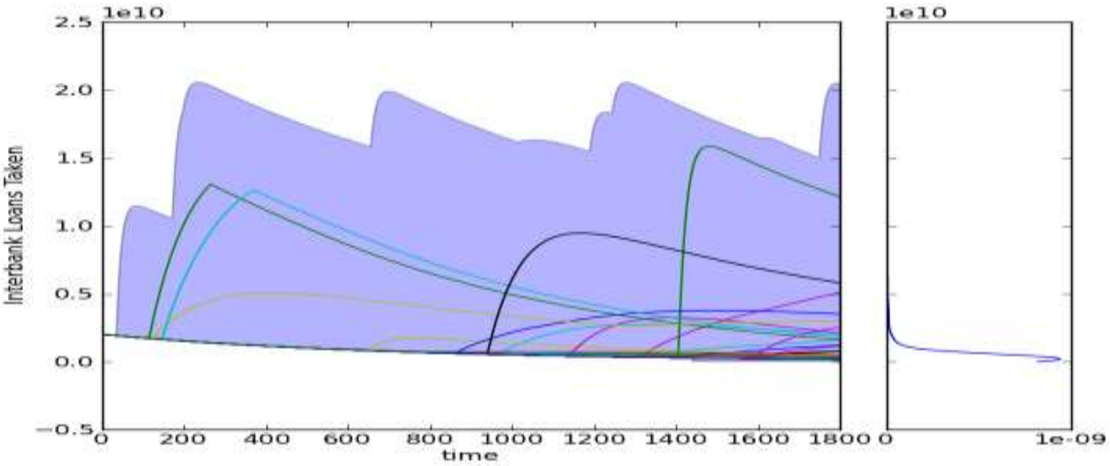

1e9
6
5
4
3
2
1
0
−1
Corporate bonds
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
4e-10


1e10
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Central bank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
1.2e-10

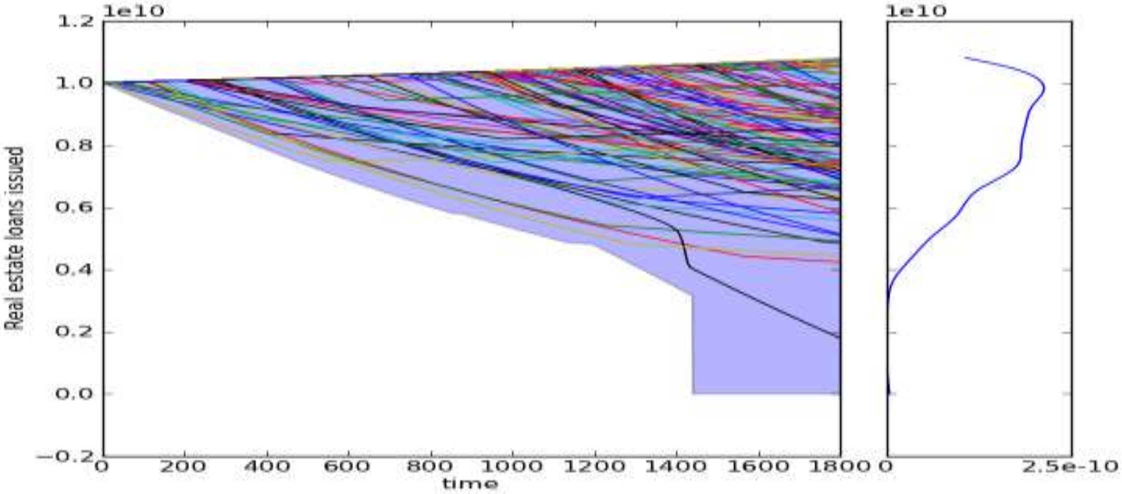

1e9
8
7
6
5
4
3
2
1
0
−1
0
200
400
600
800
1000
1200
1400
1600
1800
time
Commercial loans Issued
1e9
0
1.8e-10


1e9
6
5
4
3
2
1
0
−1
0
200
400
600
800
1000
1200
1400
1600
1800
time
Consumer loans Issued
1e9
0
3e-10


1e8
5
4
3
2
1
0
−1
0
200
400
600
800
1000
1200
1400
1600
1800
time
Interbank Loans issued
1e8
0
1.2e-08

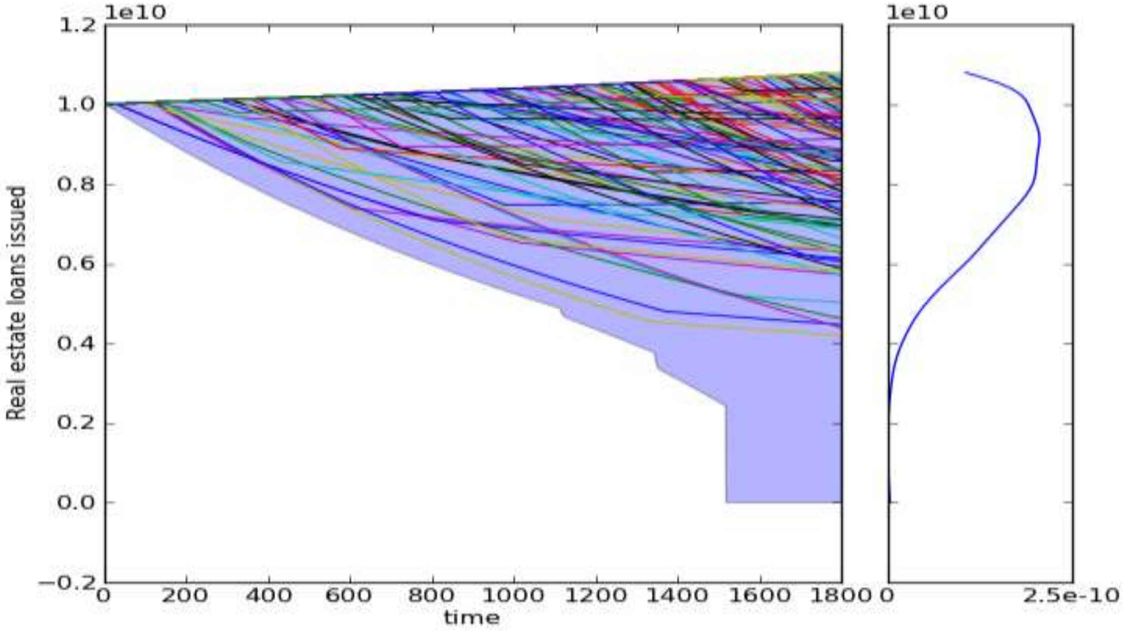


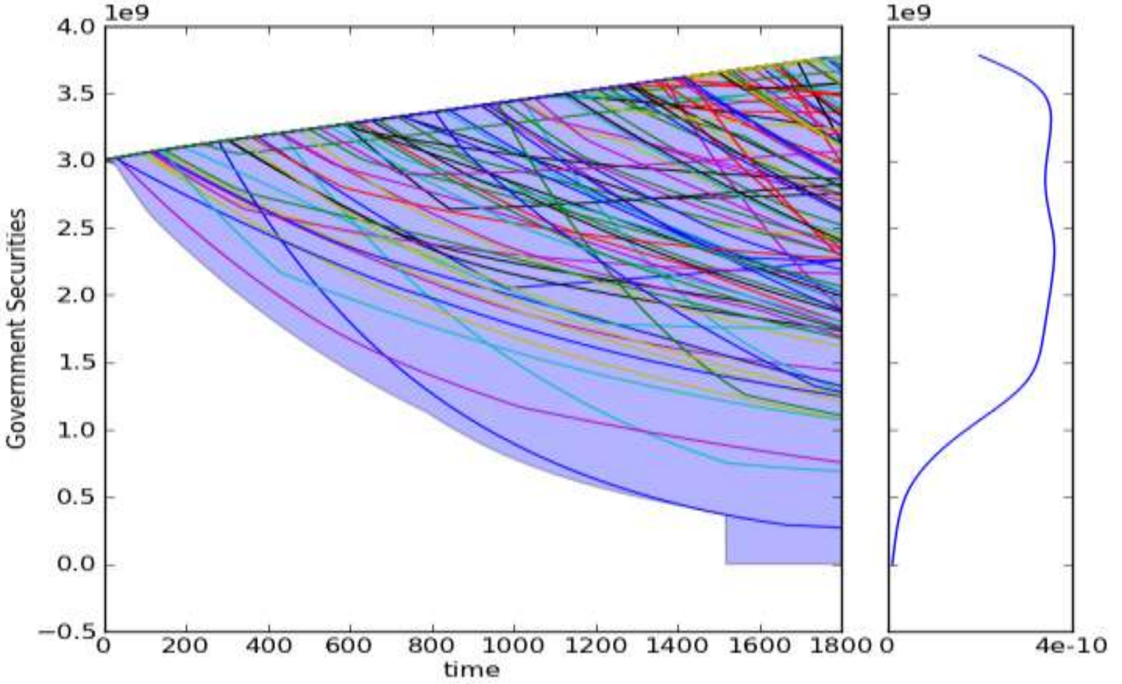
1e10
Interbank Loans Taken
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
1e-09

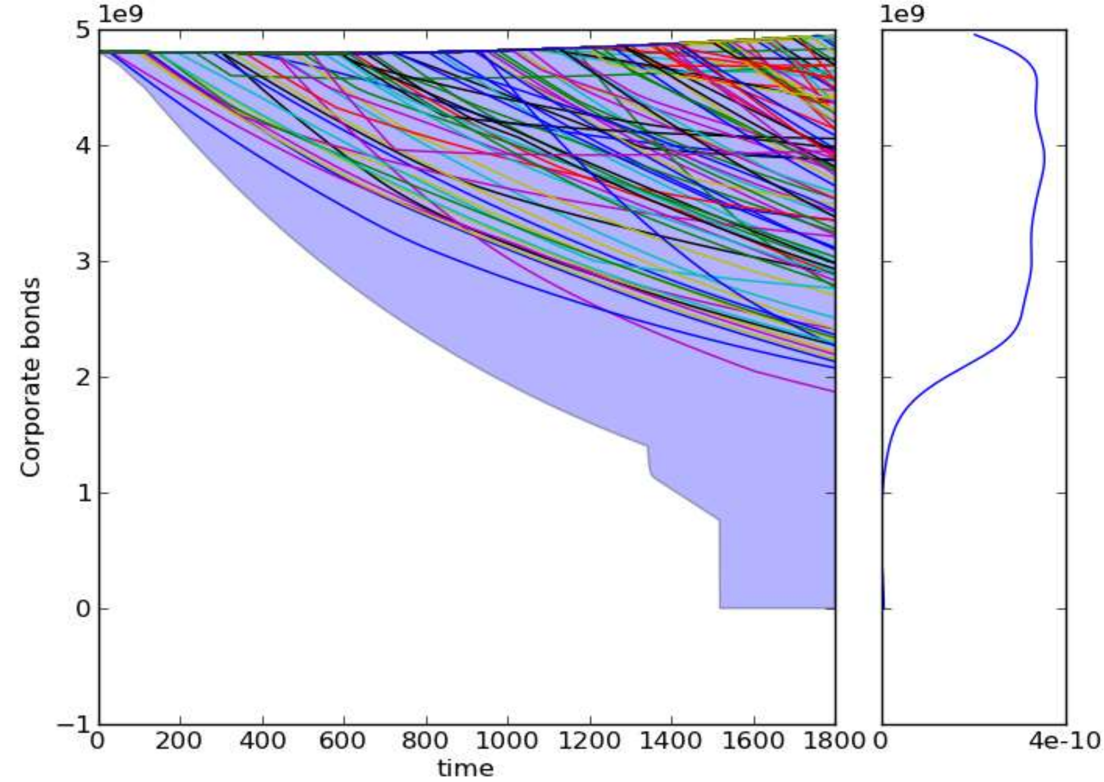


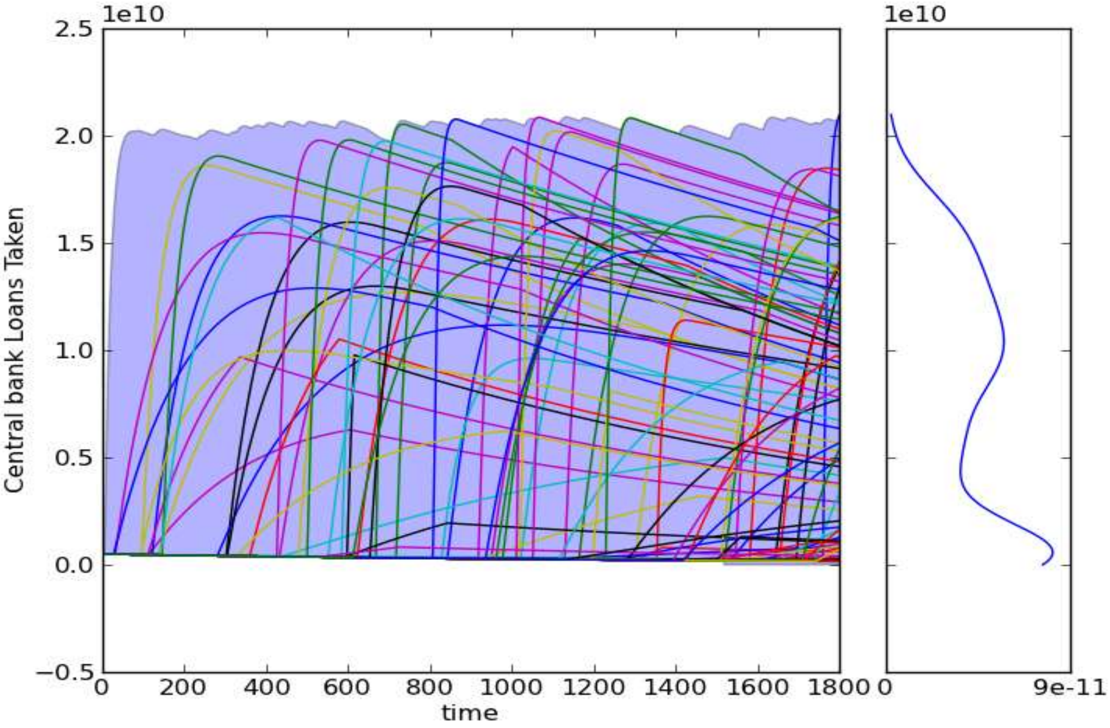
1e10
Real estate loans issued
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
2.5e-10

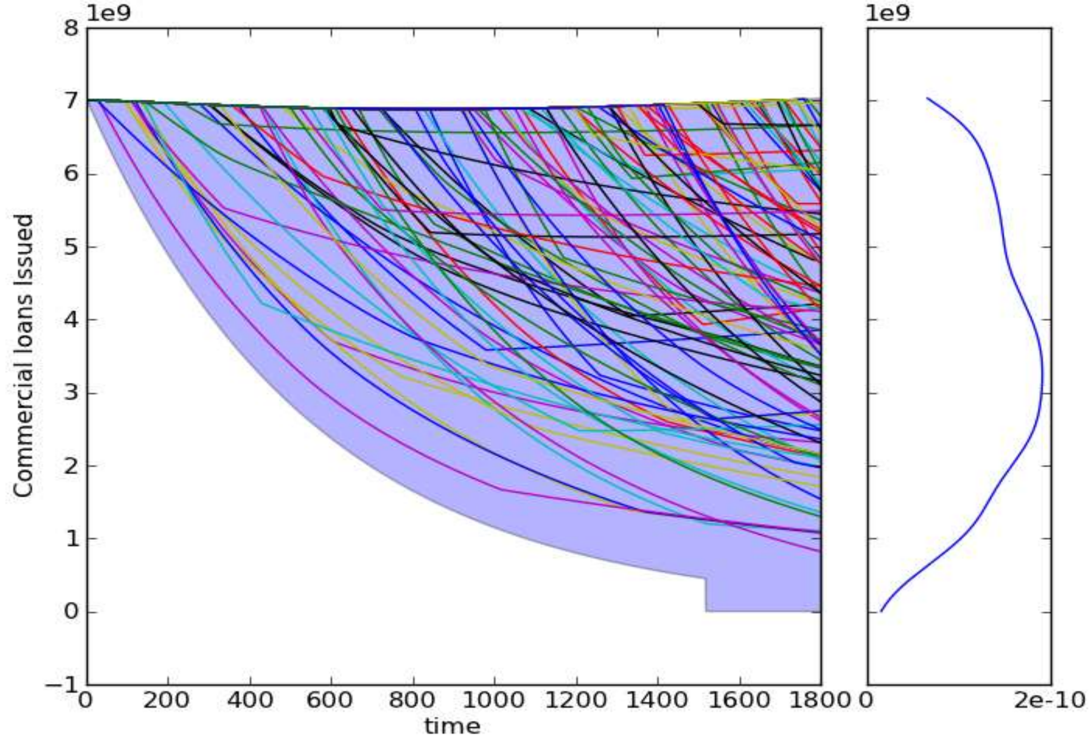
Policy 2

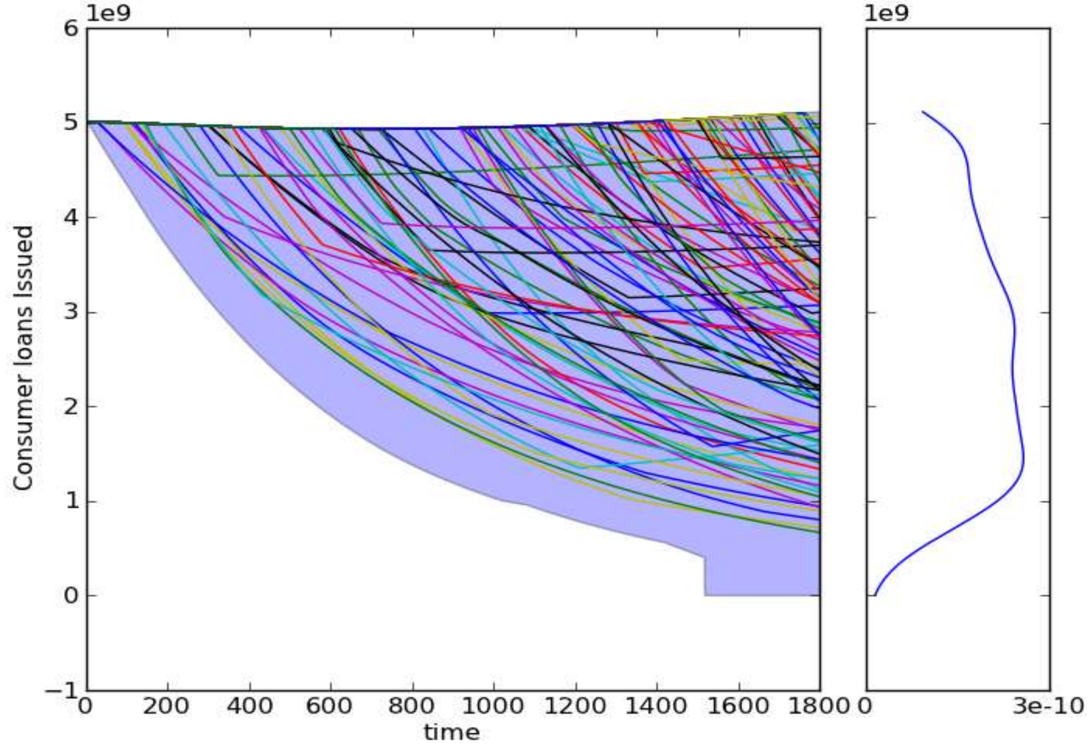

1e10
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
Real estate loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
2.5e-10

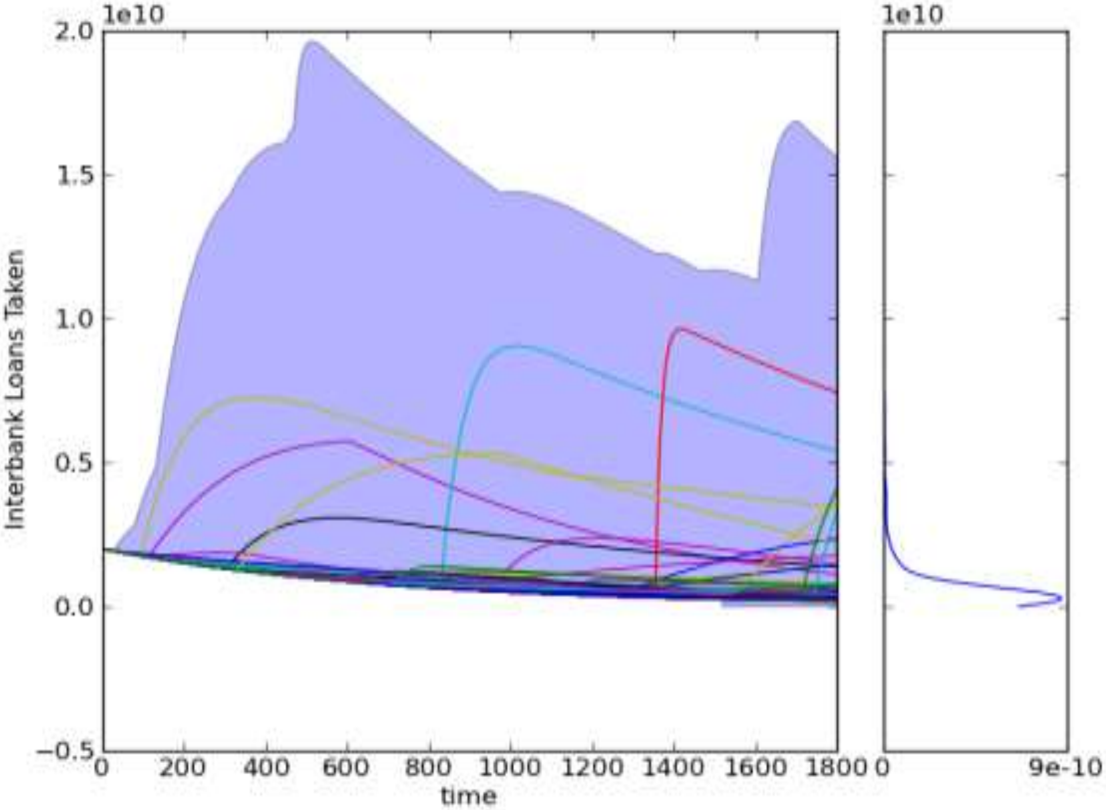

1e9
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Government Securities
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
4e-10

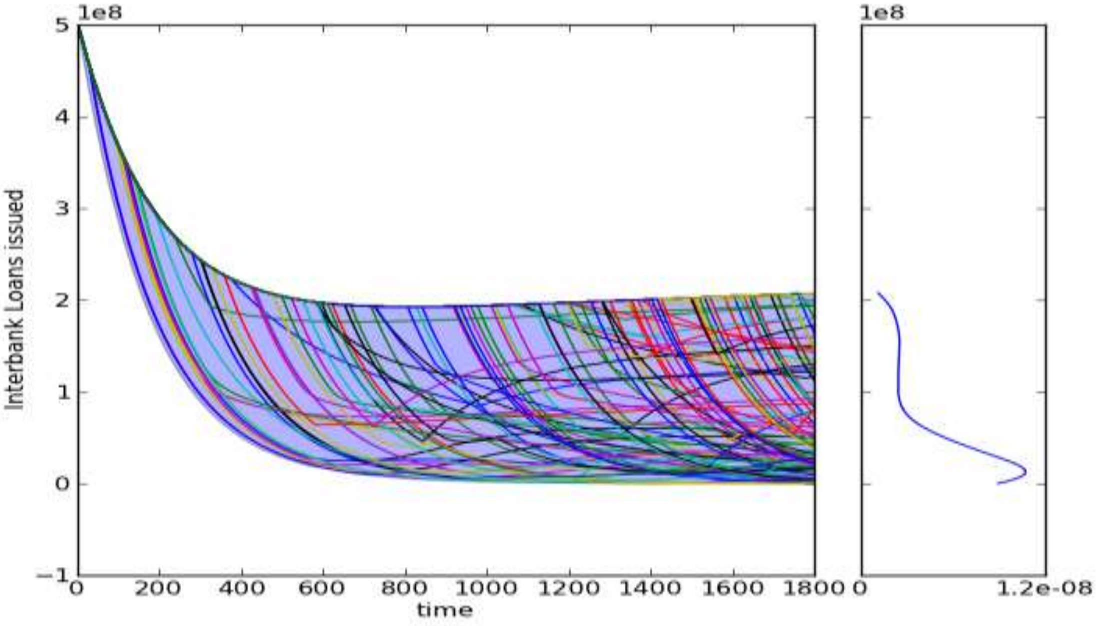

1e9
5
4
3
2
1
0
−1
Corporate bonds
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
4e-10


1e10
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Central bank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
9e-11

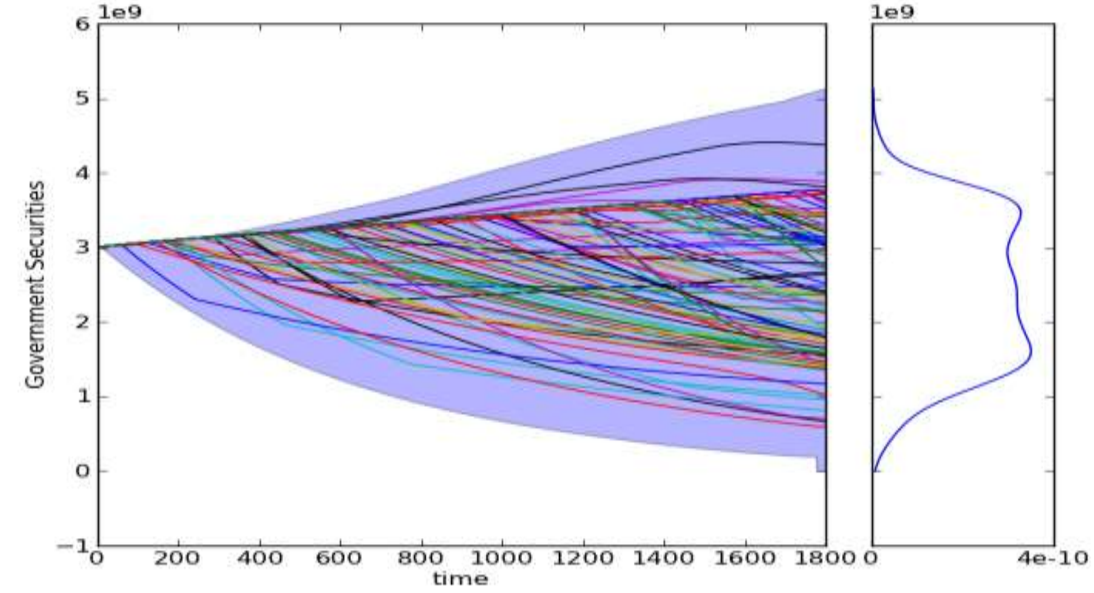

1e9
8
7
6
5
4
3
2
1
0
−1
Commercial loans Issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
2e-10


1e9
6
5
4
3
2
1
0
−1
Consumer loans Issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
3e-10

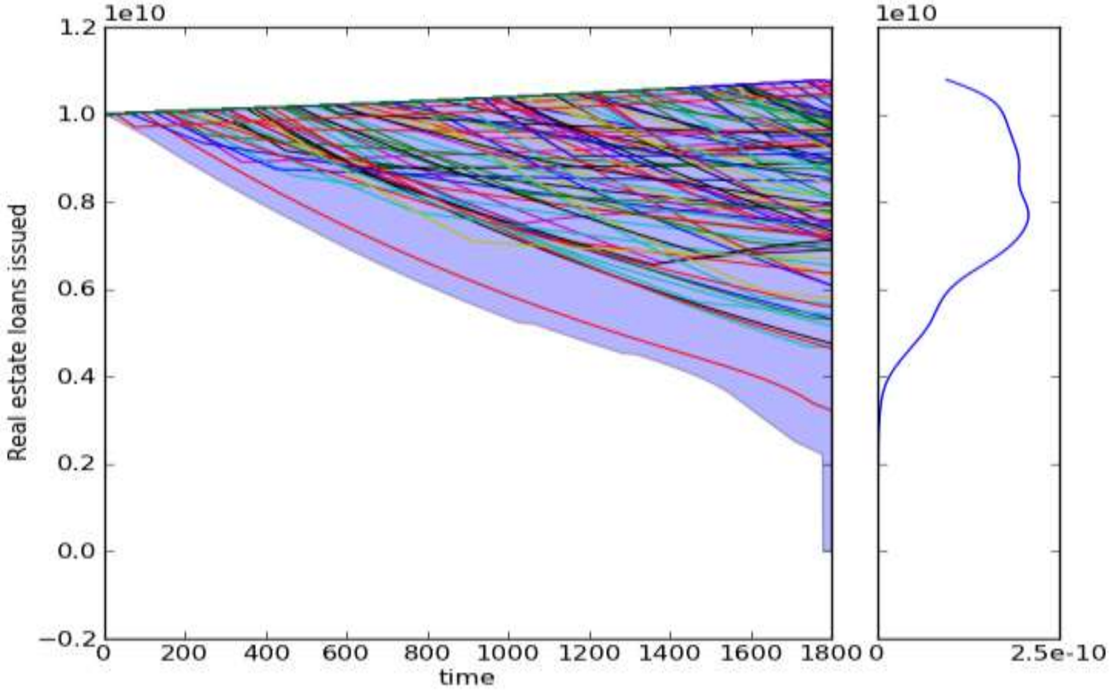

1e10
2.0
1.5
1.0
0.5
0.0
−0.5
Interbank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
9e-10


1e8
5
4
3
2
1
0
−1
Interbank Loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e8
0
1.2e-08

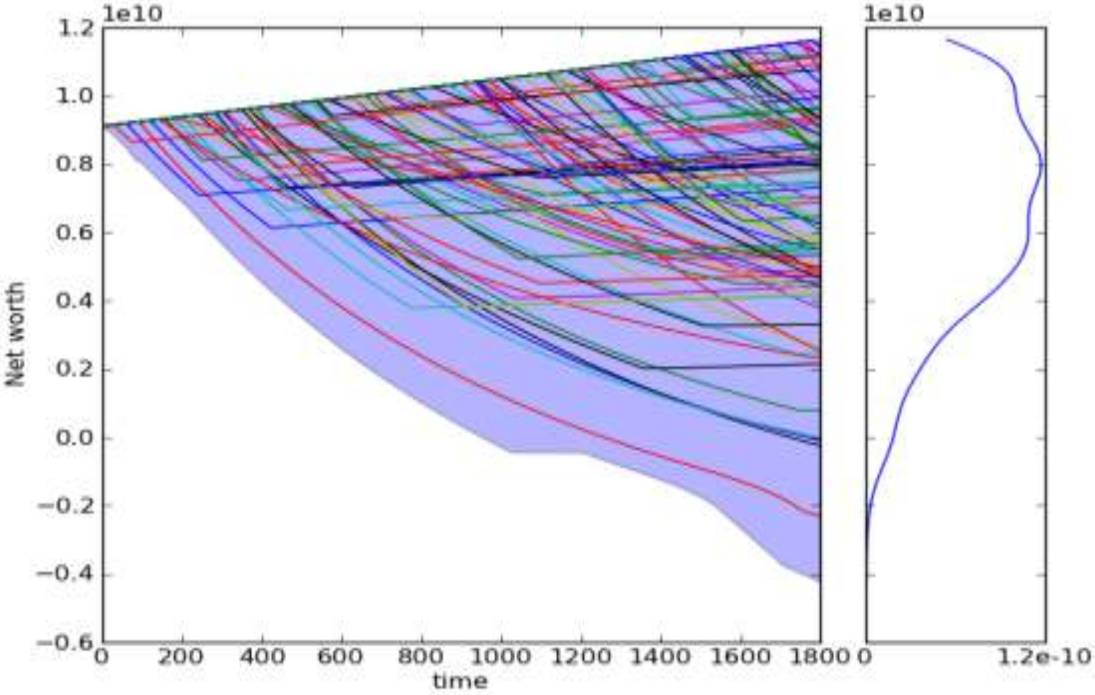
Policy 3

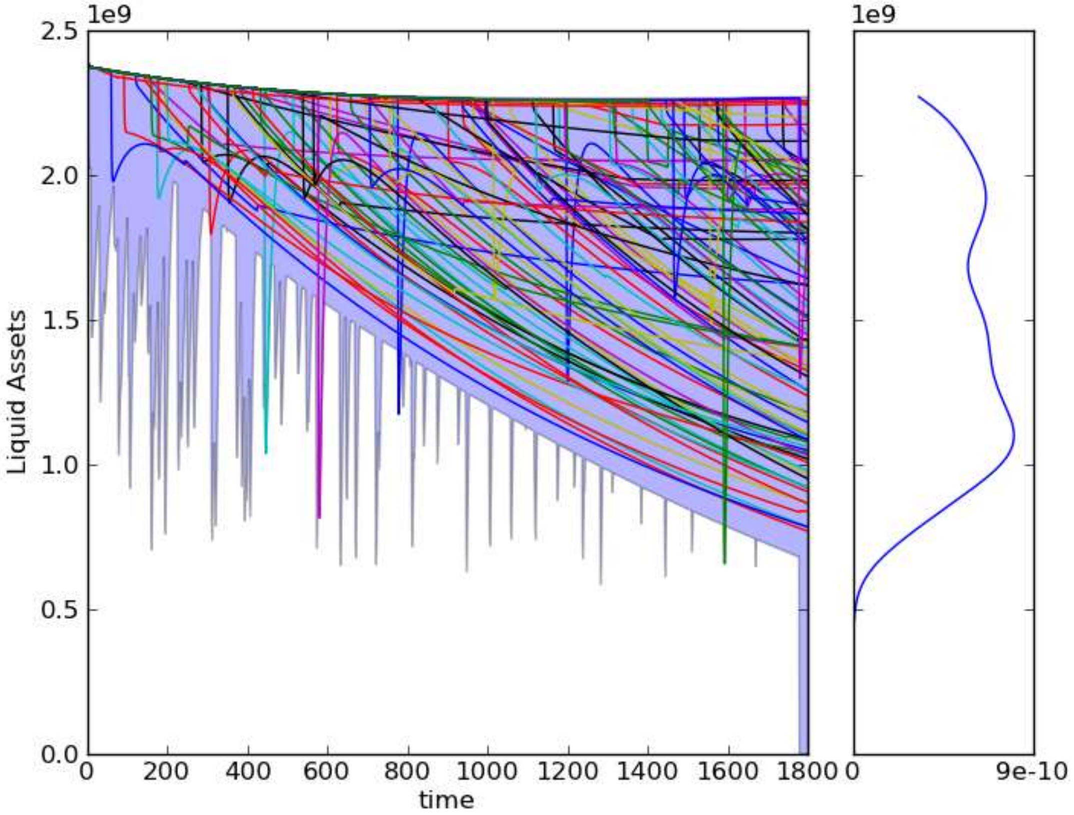


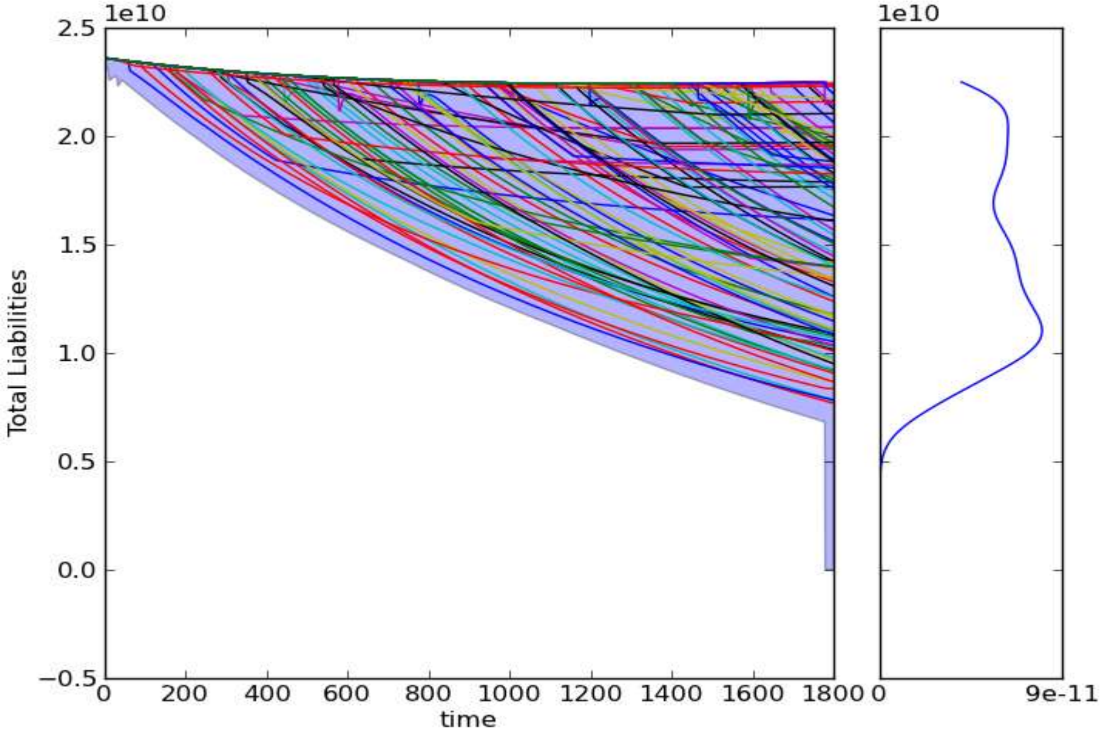
1e9
Government Securities
6
5
4
3
2
1
0
−1
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
4e-10

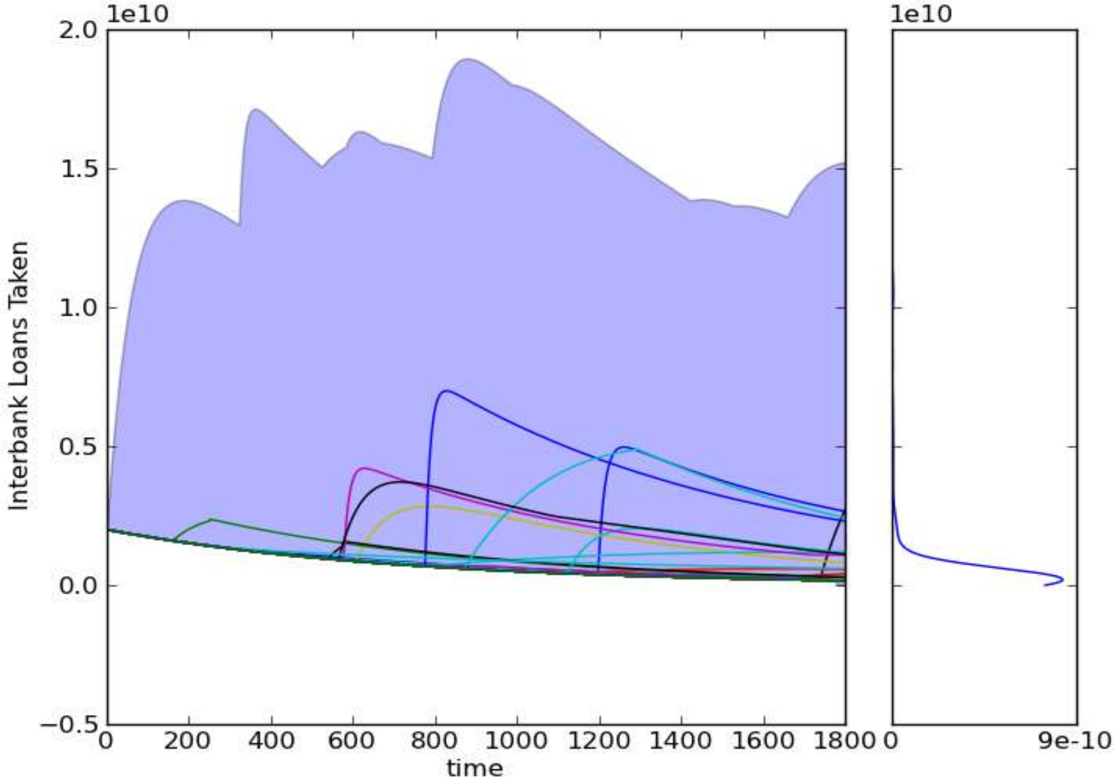


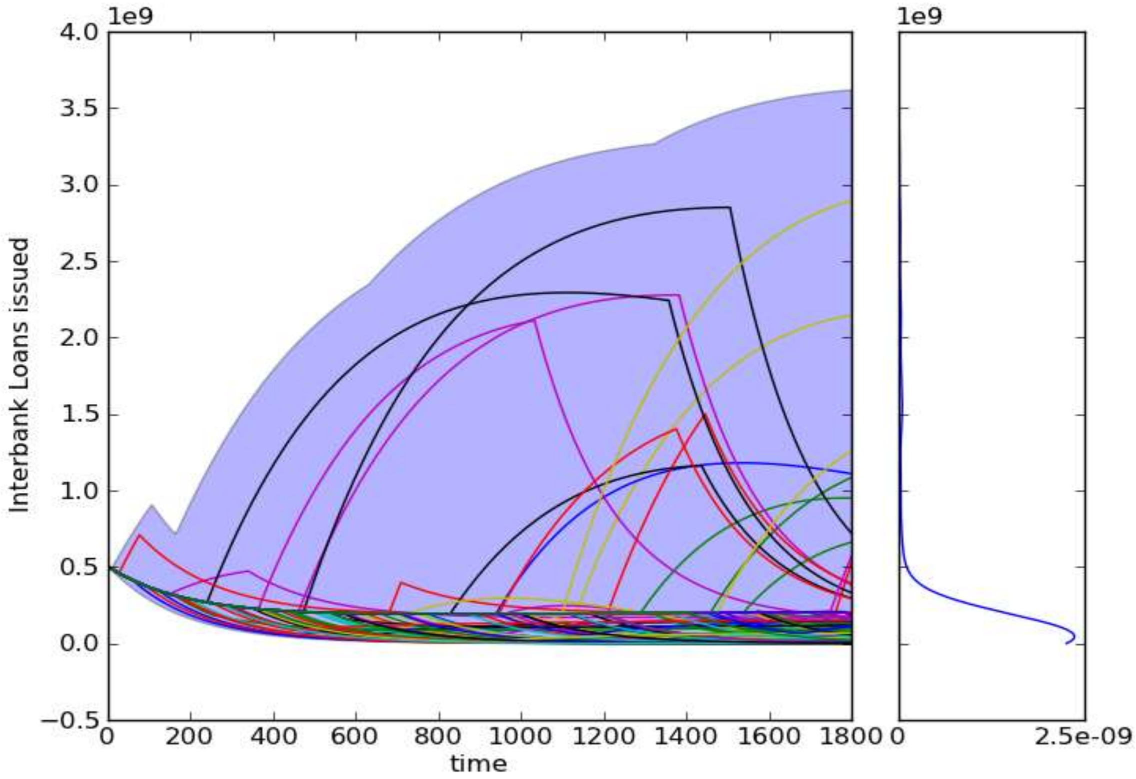
1e10
Real estate loans issued
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
2.5e-10

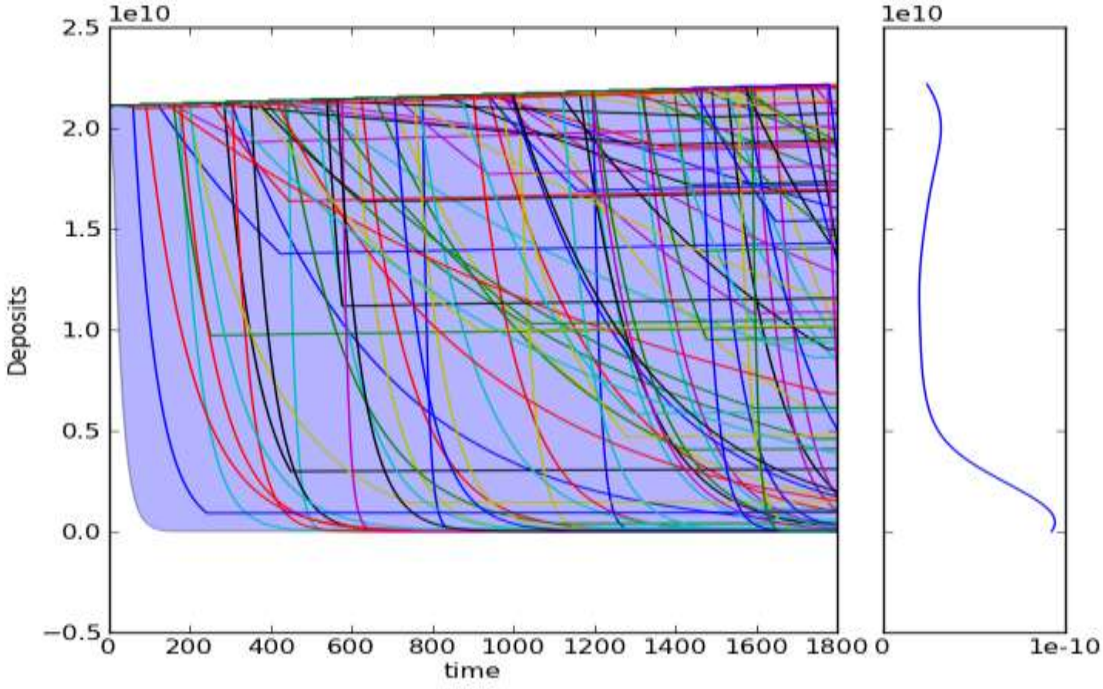

1e10
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Net worth
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
1.2e-10

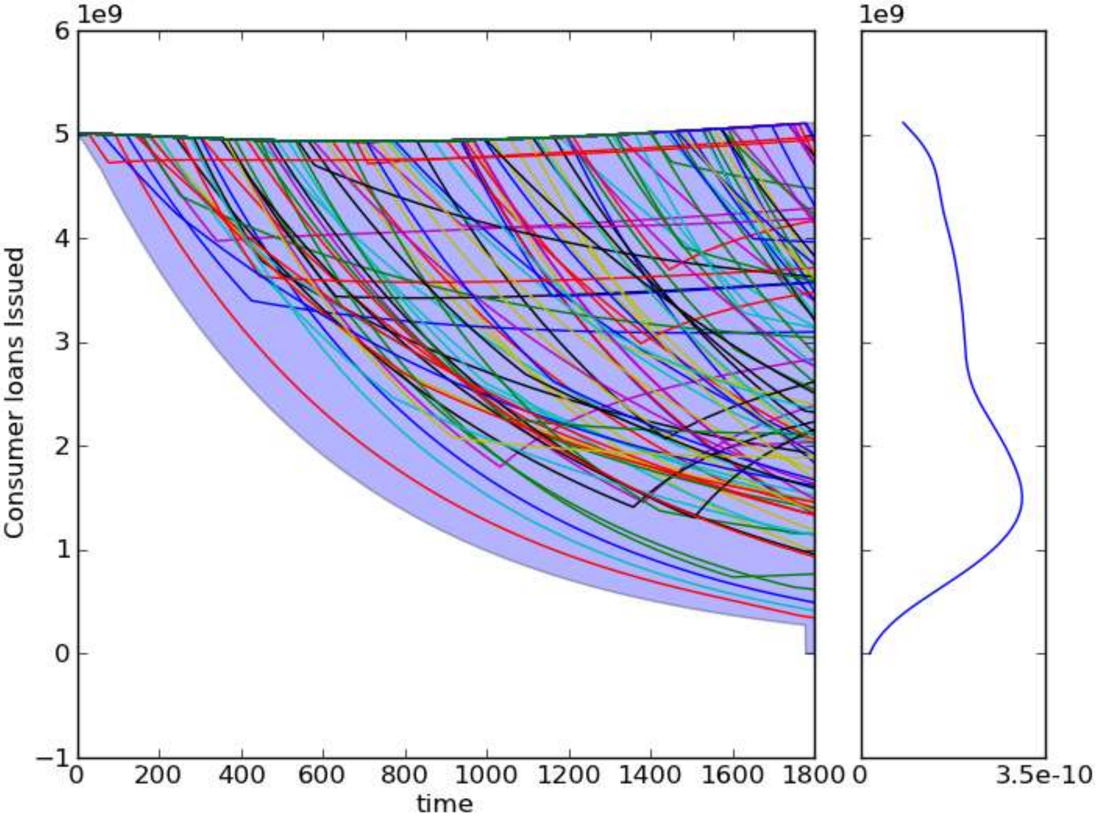

1e9
2.5
2.0
1.5
1.0
0.5
0.0
Liquid Assets
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
9e-10

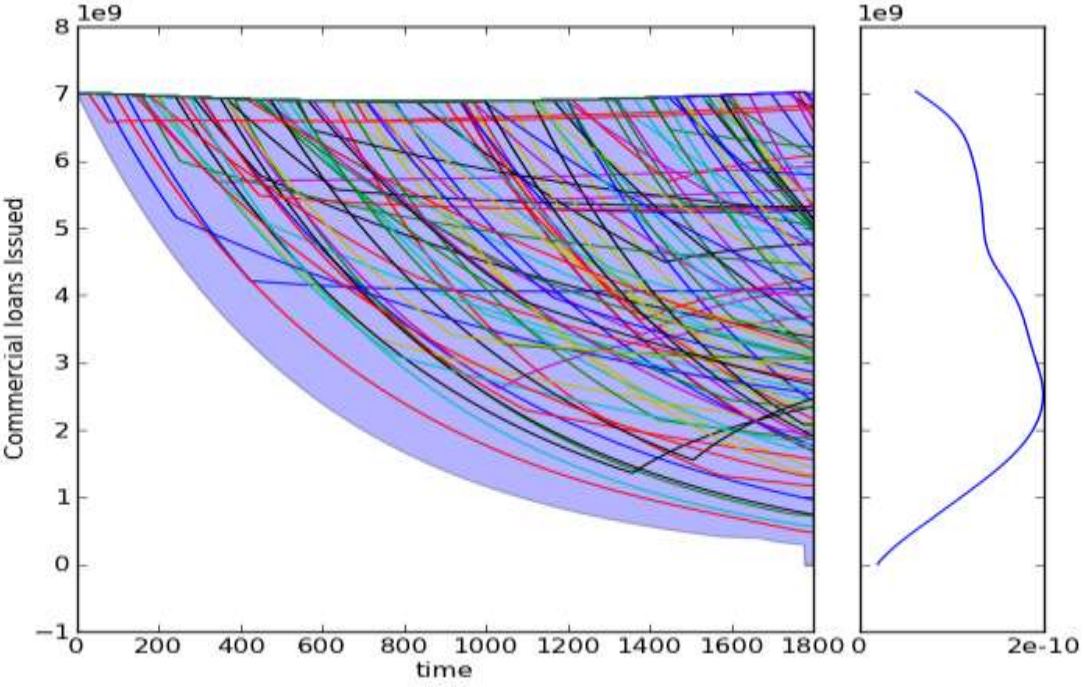

1e10
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Total Liabilities
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
9e-11

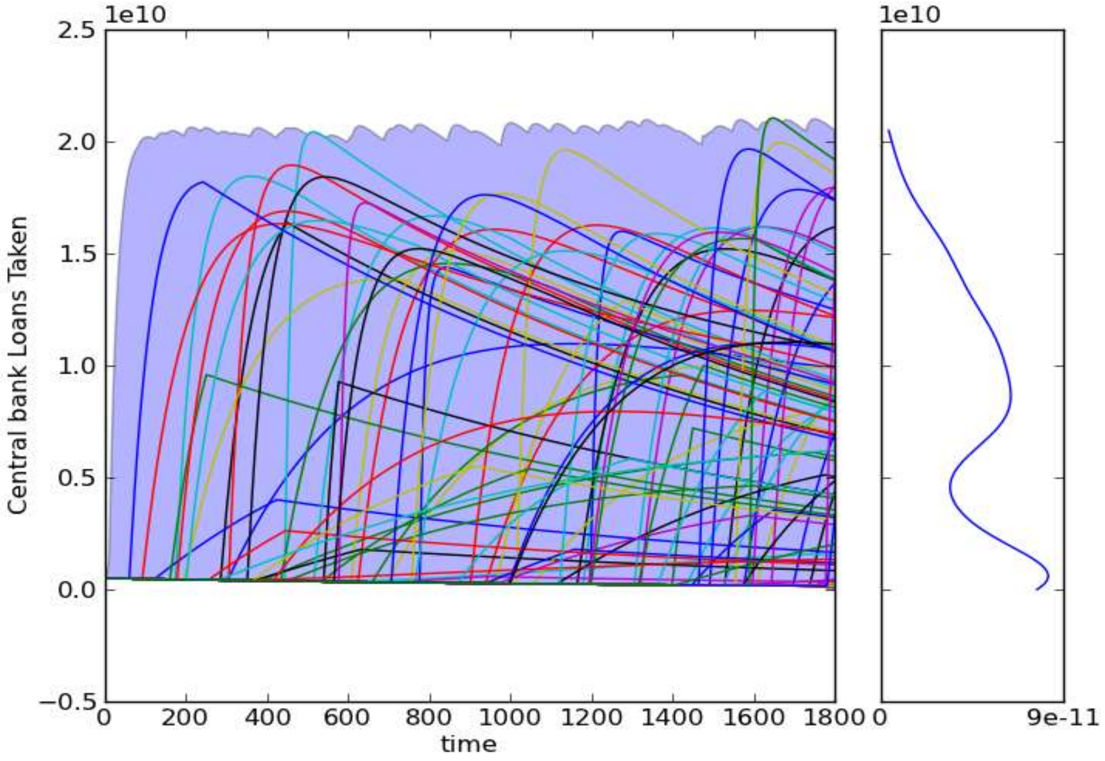

1e10
2.0
1.5
1.0
0.5
0.0
−0.5
Interbank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
9e-10

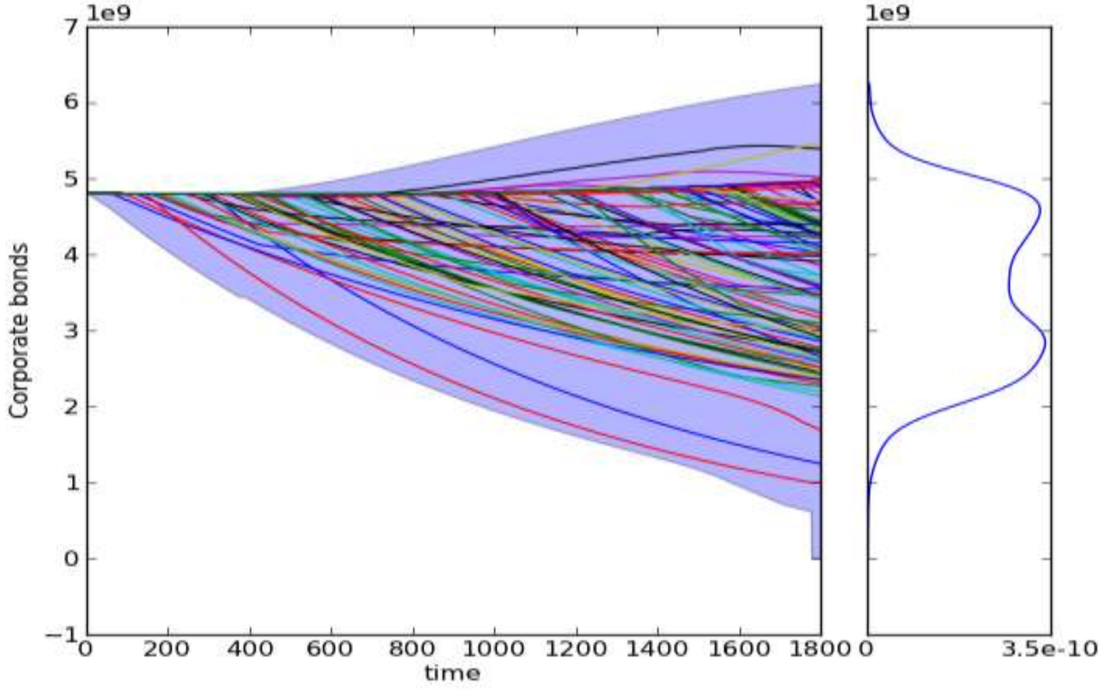

1e9
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Interbank Loans issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
2.5e-09

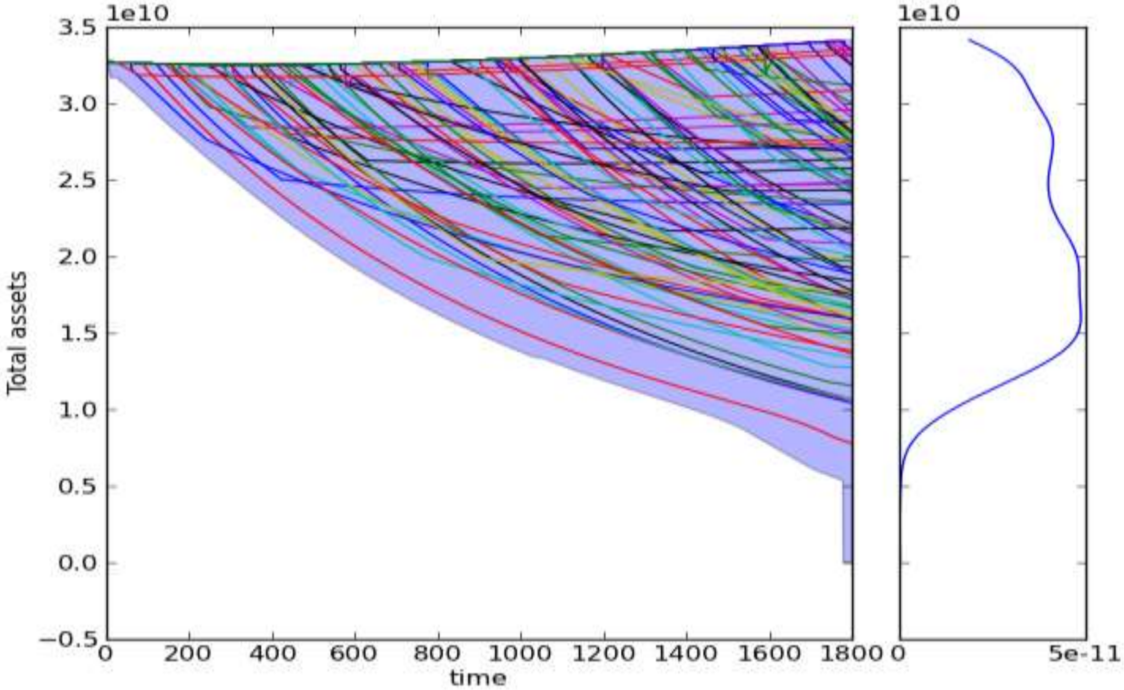

1e10
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Deposits
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
1e-10


1e9
6
5
4
3
2
1
0
−1
Consumer loans Issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
3.5e-10


1e9
8
7
6
5
4
3
2
1
0
−1
Commercial loans Issued
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
2e-10


1e10
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Central bank Loans Taken
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
9e-11


1e9
7
6
5
4
3
2
1
0
−1
Corporate bonds
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e9
0
3.5e-10


1e10
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Total assets
0
200
400
600
800
1000
1200
1400
1600
1800
time
1e10
0
5e-11

Appendix 2

Equations

Amount needed after looking for interbank loans= Amount of money needed-Total amount of money from interbank loans

Amount of money needed= IF THEN ELSE(Liquid Assets<Required reserves, Required reserves-Liquid Assets, 0)

Annual bond default rating= WITH LOOKUP (Bond rating, ([(0,0)-(10,10)],(0,0.5),(0.1,0.1),(0.2,0.06),(0.3,0.03),(0.4,0.01),(0.5,0.005),(0.6,0.001),(0.7,0.0005),(0.8,0.0001),(0.9,1e-005),(1,0)))

Annual commercial loans issued default rate=0.004*Crisis on Commercial loans default rate

Annual consumer loans issued default rate= 0.002*Crisis on Consumer loans default rate

Annual interbank loans issued default rate= 0.0001*Crisis on interbank loans issued default rate

Annual interest rate for commercial loans issued= 0.06

Annual interest rate for consumer loans issued= 0.09

Annual interest rate for corporate bonds= 0.09

Annual interest rate for interbank loans= 0.003*Crisis on interbank interest rates

Annual interest rate for real estate loans issued= 0.04

Annual interest rate for securities= 0.02

Annual real estate loans issued default rate= 0.003*Crisis on Real estate default rate

Annual securities default rate= WITH LOOKUP (Government rating,([(0,0)-(1,10)],(0,0.9),(0.2,0.3),(0.3,0.06),(0.4,0.02),(0.5,0.006),(0.6,0.004),(0.7,0.0015),(0.8,0.001),(0.9,0),(1,0)))

Average duration of Consumer loans issued= 1440

Average duration of Interbank Loans issued= 180

Average duration of Commercial loans issued= 2160

Average duration of Real estate loans issued= 7200

Average maturing time for securities =1800

Average maturing time for corporate bonds= 2160

Bank credibility= WITH LOOKUP (MAX(Perceived bank failure, Crisis on bank credibility), ([(0,0)-(1,1)],(0,1),(0.2,1),(0.5,0.8),(0.7,0.5),(0.9,0.2),(1,0.1)))

Bond rating= 1-Crisis on corporate bonds

Central bank Loans Taken repaid= Central bank Loans Taken/Average time to repay a Central bank Loans taken

Commercial loan default rate per day= ((1+Annual commercial loans issued default rate)^(1/360))-1

Commercial loans default= Commercial loan default rate per day*Commercial loans Issued

Commercial loans Issued= INTEG (New Commercial Loans-Commercial loans default-Commercial loans repaid-Commercial Loans to be securitized, Initial Commercial loans issued)

Commercial loans repaid= Commercial loans Issued/Average duration of Commercial loans issued

Commercial Loans to be securitised= (Percentage of commercial loans to be securitised)*Commercial loans Issued

Consumer Loan default rate per day= ((1+Annual consumer loans issued default rate)^(1/360))-1

Consumer loans default= Consumer Loan default rate per day*Consumer loans Issued

Consumer loans Issued= INTEG (New Consumer Loans-Consumer loans default-Consumer loans repaid-Consumer loans to be securitized, Initial Consumer loans issued)

Consumer loans repaid= Consumer loans Issued/Average duration of Consumer loans issued

Consumer loans to be securitized=Percentage of consumer loans to be securitised*Consumer loans Issued

Corporate bond's percentage of loss= WITH LOOKUP (Bond rating, ([(0,0)-(10,10)], (0,1),(0.1,0.8),(0.2,0.6),(0.5,0.4),(0.7,0.2),(0.8,0.1), (0.9,0.05),(1,0)))

Corporate bonds= INTEG (New corporate bonds purchased-Corporate bonds maturing-Corporate bonds default-Corporate bonds sold earnings-Corporate bonds sold losses, Initial corporate bonds)

Corporate bonds default= Corporate bonds*Corporate bonds'Daily Default rate

Corporate bonds maturing=Corporate bonds/Average maturing time for corporate bonds

Corporate bonds sold earnings= Corporate bonds*(1-Corporate bond's percentage of loss)*Need for Selling corporate bonds

Corporate bonds sold losses= Corporate bond's percentage of loss*Corporate bonds*Need for Selling corporate bonds

Corporate bonds'Daily Default rate= ((1+Annual bond default rating)^(1/360))-1

Crisis on bank credibility= Effect on bank rating*Crisis

Crisis on Commercial loans default rate= Crisis*Effect on commercial loans

Crisis on Consumer loans default rate=Crisis*Effect on consumer loans

Crisis on corporate bonds= Crisis*Effect on corporate bonds rating

Crisis on interbank loans issued default rate= Crisis*Effect on interbank loans issued default rate

Crisis on Real estate default rate= Crisis*Effect on Real estate loans

Daily interest Earnings on commercial loans= Commercial loans Issued*Daily interest rate for Commercial loans issued

Daily interest Earnings on Consumer loans= Consumer loans Issued*Daily interest rate for Consumer loans Issued

Daily interest earnings on corporate bonds=Corporate bonds*Daily interest rate on corporate bonds

Daily interest Earnings on Interbank Loans Issued=Interbank Loans issued*Daily interest rate for Interbank Loans issued

Daily interest Earnings on Real estate loans=Daily interest rate for Real estate loans Issued*Real estate loans issued

Daily interest earnings on securities= Daily Interest rate for securities*Government Securities

Daily interest Payments on Central bank Loans Taken= Central bank Loans Taken*Daily interest rate for Central bank Loans Taken

Daily interest Payments on Interbank Loans Taken=Interbank Loans Taken*Daily interest rate for Interbank Loans Taken

Daily interest rate for Commercial loans issued= ((1+Annual interest rate for commercial loans issued)^(1/360))-1

Daily interest rate for Consumer loans Issued= ((1+Annual interest rate for consumer loans issued)^(1/360))-1

Daily interest rate for Interbank Loans issued= ((1+Annual interest rate for interbank loans)^(1/360))-1

Daily interest rate for Real estate loans Issued= ((1+Annual interest rate for real estate loans issued)^(1/360))-1

Daily Interest rate for securities= ((1+Annual interest rate for securities)^(1/360))-1

Daily interest rate on corporate bonds= ((1+Annual interest rate for corporate bonds)^(1/360))-1

endogenous increase of deposits= Daily Interest Payments on Deposits

Funds to buy new securities and corporate bonds= IF THEN ELSE(Liquid Assets>Required reserves, Percentage of available funds to buy securities *(Liquid Assets-Required reserves), 0)

Funds to new loans issued= IF THEN ELSE(Liquid Assets>Required reserves, Percentage of available funds to issue new loans*(Liquid Assets-Required reserves), 0)

Government crisis=Crisis*Effect on government rating

Government rating=1-Government crisis

Government Securities= INTEG (New securities Purchased-Securities default-Securities maturing-Securities Sold Earnings-Securities sold losses, Initial Government Securities)

Increase in available funds=Loans Repaid+New deposits+Securities payments+Total daily Loan interest Earnings+Liquidation earnings of securitised loans+New loans taken+endogenous increase of deposits+Corporate bonds sold earnings

Initial Assets= Initial Government Securities+Initial Securitized loans+Initial Commercial loans issued+Initial Consumer loans issued+Initial Interbank Loans Issued+Initial Real estate loans issued+Initial Cash+Initial corporate bonds

Initial bank reserves= Initial Liabilities*Initial percentage of required reserves

Initial Cash= 5e+008

Initial Central bank Loans Taken=2e+009

Initial Commercial loans issued=1.1e+010

Initial Consumer loans issued= 5e+009

Initial corporate bonds=5.8e+009

Initial Deposits= 3.1e+010

Initial Government Securities=2.5e+009

Initial Interbank Loans Issued= 5e+008

Initial Interbank Loans Taken=1e+010

Initial Liabilities=Initial Central bank Loans Taken+ Initial Deposits+ Initial Interbank Loans Taken

Initial Liquid Assets=Initial bank reserves+ Initial Cash

Initial percentage of required reserves= 0.1

Initial Real estate loans issued=2.5e+010

Initial Securitized loans=0

Interbank Loans default rate per day=((1+Annual interbank loans issued default rate)^(1/360))-1

Interbank Loans issued= INTEG (-Interbank Loans Issued repaid-Interbank Loans Issued Default+ New Interbank Loans issued, Initial Interbank Loans Issued)

Interbank Loans Issued Default=Interbank Loans default rate per day*Interbank Loans issued

Interbank Loans Issued repaid= Interbank Loans issued/Average duration of Interbank Loans issued

Interbank Loans Taken repaid=Interbank Loans Taken/Average time to repay an Interbank loan taken

Liquid Assets= INTEG (Increase in available funds-Funds to buy new securities and corporate bonds-Money withdrawn-Money for interest payments-Money for loan payments-Funds to new loans issued, Initial Liquid Assets)

Liquidation earnings of securitised loans=(1-Liquidation premium)*Securitised loans

IF THEN ELSE (Securitised loans < (Amount of money needed from liquidation of securitised loans/(1-Liquidation premium)), Amount of money needed from liquidation of securitised loans, Securitised loans*(1-Liquidation premium))/Time to liquidate securitised loans

Liquidation Losses of securitised loans= Liquidation premium*Securitised loans

Liquidation premium= Percentage of Value loss because of Bank's credibility

Loans Repaid= Commercial loans repaid+ Consumer loans repaid+ Interbank Loans Issued repaid+ Real estate loans repaid

Money for interest payments= Daily interest Payments on Central bank Loans Taken+ Daily interest Payments on Interbank Loans Taken

Money for loan payments=Interbank Loans Taken repaid+ Central bank Loans Taken repaid

Money withdrawn=Withdrawals

Need for Selling corporate bonds= WITH LOOKUP (Ratio of amount needed after looking for interbank loans to perceived value of assets,([(0,0)-(1000,10)],(0,0),(0.5,0.2),(0.7,0.4),(1,0.5),(2,0.7),(10,1),(1000,1)))

New Central bank Loans Taken= Money finally got from Central Bank loans/Time for Central bank loans to be taken

New Commercial Loans=Funds to new loans issued*Percentage of funds to new Commercial loans

New Consumer Loans=Funds to new loans issued*Percentage of funds to new consumer loans

New corporate bonds purchased=Funds to buy new securities and corporate bonds*Percentage of funds to new corporate bonds

New deposits= Average amount of new deposits

New Interbank Loans issued=Funds to new loans issued*Percentage of funds to new Interbank loans

New Interbank Loans Taken=Money finally got from interbank loans/Time for domestic Interbank loans to be taken

New loans taken=New Central bank Loans Taken+New Interbank Loans Taken

New Real estate Loans=Funds to new loans issued*Percentage of funds to new Real estate loans

New securities Purchased=Funds to buy new securities and corporate bonds*Percentage of funds to new securities

Perceived bank failure= MAX(perceived likelihood liquidity failure,perceived likelihood solvency failure)

Perceived likelihood liquidity failure= WITH LOOKUP (Liquidity ratio, ([(-1,0)-(1,1)],(-1,1),(0,1),(0.1,1),(0.2,1),(0.3,0.7),(0.4,0.6), (0.5,0.5),(1,0))

Perceived likelihood solvency failure= WITH LOOKUP (Total assets to Total liabilities Ratio,((-1e+016,1),(0,1),(0.8,1),(0.9,0.8),(1,0.5),(1.1,0.1),(1.2,0),(2,0),(1000,0),(1e+013,0)))

Perceived value of total assets=(1-Percentage of Value loss because of Bank's credibility)*Total assets

Percentage of available funds to buy securities and bonds=0.3

Percentage of available funds to issue new loans=0.7

Percentage of commercial loans to be securitised= WITH LOOKUP (Ratio of amount needed after looking for interbank loans to perceived value of assets, ([(0,0)-(1000,10)],(0,0),(0.5,0.2),(0.7,0.4),(1,0.5),(2,0.7),(10,1),(1000,1)))

Percentage of consumer loans to be securitised= WITH LOOKUP (Ratio of amount needed after looking for interbank loans to perceived value of assets, ([(0,0)-(1000,10)],(0,0),(0.5,0.2),(0.7,0.4),(1,0.5),(2,0.7),(10,1),(1000,1)))

Percentage of funds to new Commercial loans=0.35

Percentage of funds to new consumer loans=0.35

Percentage of funds to new corporate bonds=0.5

Percentage of funds to new Interbank loans=0.1

Percentage of funds to new Real estate loans=0.2

Percentage of funds to new securities=0.5

Percentage of real estate loans to be securitised= WITH LOOKUP (Ratio of amount needed after looking for interbank loans to perceived value of assets, ([(0,0)-(1000,10)],(0,0),(0.5,0.2),(0.7,0.4),(1,0.5),(2,0.7),(10,1),(1000,1)))

Percentage of securities to be sold= WITH LOOKUP (Ratio of amount needed after looking for interbank loans to perceived value of assets,([(0,0)-(1000,10)],(0,0),(0.5,0.2),(0.7,0.4),(1,0.5),(2,0.7),(10,1),(1000,1)))

Percentage of Value loss because of Bank's credibility= WITH LOOKUP (Bank credibility,([(0,0)-(1,1)],(0,0.98),(0.1,0.95),(0.2,0.85),(0.3,0.75),(0.4,0.6),(0.5,0.45),(0.6,0.35),(0.7,0.15),(0.75,0.1),(0.8,0.05),(0.9,0.01),(1,0.001)))

Ratio Initial Assets to Inital liabilities= Initial Assets/Initial Liabilities

Ratio of amount needed after looking for interbank loans to perceived value of assets=Amount needed after looking for interbank loans/Perceived value of total assets

Real Estate loans default=Real Estate Loans Default Rate per day*Real estate loans issued

Real Estate Loans Default Rate per day=((1+Annual real estate loans issued default rate)^(1/360))-1

Real estate loans issued= INTEG (New Real estate Loans-Real Estate loans default-Real estate loans repaid-Real estate loans to be securitized ,Initial Real estate loans issued)

Real estate loans repaid=Real estate loans issued/Average duration of Real estate loans issued

Real estate loans to be securitised=(Percentage of real estate loans to be securitised)*Real estate loans issued

Required reserves=Percentage of required reserves*Total Liabilities

Securities default=Securities Default Rate per day*Government Securities

Securities Default Rate per day=((1+Annual securities default rate)^(1/360))-1

Securities maturing= Government Securities/Average maturing time for securities

Securities payments=Securities maturing+ Securities Sold Earnings

Securities Sold Earnings=Percentage of securities to be sold*Government Securities*Government rating

Securities sold losses=IF THEN ELSE (Government Securities>0 , (1-Government rating)*Government Securities*Percentage of securities to be sold , 0)

Securitised loans= INTEG (Commercial Loans to be securitised+ Consumer loans to be securitized+ Real estate loans to be securitised-Liquidation earnings of securitised loans-Liquidation Losses of securitised loans, Initial Securitized loans)

Total amount of money from interbank loans=Money finally got from Central Bank loans+Money finally got from interbank loans

Total assets=Commercial loans Issued+ Consumer loans Issued+ Interbank Loans issued+ Real estate loans issued +Government Securities+ Securitised loans+ Liquid Assets+ Corporate bonds

Total daily Loan interest Earnings=Daily interest Earnings on commercial loans+ Daily interest Earnings on Consumer loans+ Daily interest Earnings on Interbank Loans Issued+ Daily interest Earnings on Real estate loans+ Daily interest earnings on securities+ Daily interest earnings on corporate bonds

Total Liabilities=Central bank Loans Taken+ Deposits+ Interbank Loans Taken

Withdrawals= Deposits* Withdrawals percentage per day

Appendix 3

```
PRIM CATASTROPHIC

         mass           mean                  coverage              density

box 1:   0.008          0.875                 0.237288135593        0.875

box 2:   0.008          0.8125                0.220338983051        0.8125

box 3:   0.007          0.857142857143        0.203389830508        0.857142857143

rest box:0.977          0.0102354145343       0.338983050847        0.0102354145343

box limits

Crisis Duration  Crisis Starting time    Stress Commercial loans      Stress Consumer loans   Stress
Corporate bonds rating   Stress Government rating        Stress Interbank interest rates      Stress Interbank
loans issued      Stress Real estate loans  Stress bank rating Stress interbank lending

box 1:

         min:     1464.20972782 43.9668924046 6.81542069446 3.93083815768 0.224713933126
         0.0501655193101        0.00227232203023       20.432307506   7.07494369235
         0.0241634643395        3.64782271074e-05

         max:     1748.86009364 433.436320919 19.9014215296 18.6887784815 0.899651136867
         0.899912737073         19.4455034269 96.1676156462 19.9914471268 0.499814578355
         0.999992553342

box 2:

         min:     1344.42580351 2.95608649428 9.44814234413 6.16316638328 0.115661536747
         0.0482305185219        0.00227232203023       0.0355018358117        8.62258012652
         0.0133738762282        3.64782271074e-05

         max:     1734.03475613 606.666275903 19.4336190627 19.1119110588 0.899651136867
         0.899912737073         19.4517346434 96.5140904897 19.9914471268 0.499814578355
         0.999992553342

box 3:
```

min: 1300.62242073 61.4990365566 5.76565045153 2.80046684462 0.0479922287414 0.049059804574 0.528960560707 14.2907973859 8.66790487348 0.00010898301244 3.64782271074e-05

max: 1531.68022922 571.15430744 19.991424958 19.9927658148 0.899651136867 0.899912737073 19.4221363647 94.7130626477 19.9914471268 0.499747412794 0.938874978726

box 4:

min: 0.724498089495 0.596624384827 0.00840639749931 0.00205628840054 0.000208013070598 0.000215130712749 0.00227232203023 0.0355018358117 0.00794016766666 0.00010898301244 3.64782271074e-05

max: 1799.9278359 1799.98267118 19.991424958 19.9927658148 0.899651136867 0.899912737073 19.9928616687 99.9723991899 19.9800492505 0.499747412794 0.999992553342

Prim High losses

	mass	mean	coverage	density
box 1:	0.0255	1.0	0.147398843931	1.0
box 2:	0.023	1.0	0.132947976879	1.0
box 3:	0.0265	0.88679245283	0.135838150289	0.88679245283
box 4:	0.021	0.809523809524	0.0982658959538	0.809523809524
rest box :	0.904	0.0929203539823	0.485549132948	0.0929203539823

box limits

Crisis Duration Crisis Starting time Stress Commercial loans Stress Consumer loans Stress Corporate bonds rating Stress Government rating Stress Interbank interest rates Stress Interbank loans issued Stress Real estate loans Stress bank rating Stress interbank lending Stress withdrawals

box 1:

```
min:    1253.42625942 37.5062254088 7.45785336552 1.91469596203 0.0557340897039
0.000215130712749       0.1743583435   0.0355018358117         2.68688347299
0.0624247045712         0.0917627464563         0.0766599266618

max:    1759.84134319 905.573752644 18.9980136169 19.9927658148 0.804323948601
0.744692006812          19.4786184241 99.9723991899 17.9252335558 0.499814578355
0.999992553342          0.699969565957

box 2:

min:    1025.67346383 0.596624384827          5.56943516795 1.39548013085
0.000208013070598       0.000215130712749       1.9141404245   2.67450116306 6.33653822866
0.00010898301244        0.0807394092805         0.139798659865

max:    1678.18272595 873.386652965 17.8067349732 19.0465540622 0.875729492253
0.881370052528          19.7698629271 95.4162366087 19.3808926631 0.499814578355
0.999992553342          0.684148813669

box 3:

min:    865.00339579   273.429885581 7.86837829483 0.342717960369
0.000208013070598       0.000215130712749       1.56622210267 2.46120214465 3.12779838184
0.102476812788          0.0183957818268         0.000318871968028

max:    1799.9278359   881.191393994 19.2274629506 19.9927658148 0.874532628622
0.86338094875 19.9928616687 96.9785594814 19.9914471268 0.473839481358
0.999992553342          0.618476613611

box 4:

min:    844.171482065 90.3418931679 4.99540442363 0.00205628840054
0.266603314897          0.000215130712749       2.03475567354 4.21008326194 4.24769279898
0.0177659024558         0.0275097198893         0.0508972781505

max:    1667.2367927   994.268204577 17.3383255764 15.7936293105 0.899651136867
0.889028317506          19.1623859899 99.9723991899 19.9914471268 0.483375229732
0.96428310097 0.699969565957

box 5:

min:    0.724498089495          1.27835526103 0.00840639749931        0.00205628840054
0.000208013070598       0.000215130712749       0.00227232203023        0.0355018358117
0.00794016766666        0.00010898301244        3.64782271074e-05       0.000318871968028
```

```
max:      1799.9278359   1799.98267118 19.991424958   19.9927658148 0.899651136867
0.899912737073           19.9928616687 99.9723991899 19.9914471268 0.499814578355
0.999992553342           0.699969565957
```

Prim Moderate Losses

```
          mass           mean                 coverage            density

 box 1:   0.101          0.806930693069       0.203495630462      0.806930693069

 box 2:   0.1055         0.805687203791       0.212234706617      0.805687203791

rest box: 0.7935         0.294896030246       0.584269662921      0.294896030246

box limits

                  Crisis Duration           Crisis Starting time       Stress Commercial loans          Stress
Consumer loans              Stress Corporate bonds rating     Stress Government rating          Stress Interbank
interest rates      Stress Interbank loans issued      Stress Real estate loans  Stress interbank lending Stress
withdrawals

box 1:

min:      466.418146342 363.901645937 2.92261367673 0.00205628840054
0.031499705811 0.0747509635813        1.45348478883 0.0355018358117
0.00794016766666        0.0477356204492          0.0305983494659

max:      1799.9278359   1295.34025314 16.2397477363 17.9660510591 0.856351209634
0.7817946704   17.6795722652 92.5902758584 18.9484722087 0.999992553342
0.699969565957

box 2:

min:      331.155069425 15.6174908968 2.44904951201 0.00205628840054
0.000208013070598       0.0626412933696          0.00227232203023        0.0355018358117
2.25693721843 3.64782271074e-05       0.000318871968028

max:      856.581937374 1390.69900011 19.2914187871 19.9927658148 0.86922725449
0.815520532273           19.9928616687 99.9723991899 19.0447922587 0.999992553342
0.699969565957

box 3:
```

```
min:    0.724498089495          0.596624384827          0.00840639749931
0.0135550199061         0.000208013070598       0.000215130712749       0.00227232203023
0.0355018358117         0.00794016766666        3.64782271074e-05       0.000941974333636

max:    1798.67981172 1799.98267118 19.991424958    19.9927658148 0.899651136867
0.899912737073          19.9928616687 99.9723991899 19.9914471268 0.999992553342
0.699969565957
```

Prim Minor losses

```
        mass            mean                    coverage                density

 box 1: 0.1445          1.0                     0.363979848866          1.0

 box 2: 0.098           1.0                     0.24685138539           1.0

 box 3: 0.022           0.886363636364          0.0491183879093         0.886363636364

 box 4: 0.024           0.875                   0.0528967254408         0.875

 box 5: 0.0265          0.849056603774          0.0566750629723         0.849056603774

rest box :0.685         0.133576642336          0.230478589421          0.133576642336

box limits

                Crisis Duration         Crisis Starting time    Stress Commercial loans         Stress
Consumer loans          Stress Corporate bonds rating   Stress Government rating        Stress Interbank
interest rates  Stress Interbank loans issued   Stress Real estate loans Stress bank rating     Stress
interbank lending       Stress withdrawals

box 1:

min:    9.85347592201 1497.91606061 0.00840639749931        0.00205628840054
0.0188255164245         0.000215130712749       0.00227232203023        0.0355018358117
0.00794016766666        0.00010898301244        3.64782271074e-05       0.000318871968028

max:    1799.9278359    1799.98267118 16.8419953286 19.7505043885 0.899651136867
0.899912737073          19.9928616687 99.9723991899 19.9914471268 0.499814578355
0.999992553342          0.699969565957

box 2:
```

```
min:    0.958855128875          0.596624384827          0.00840639749931
0.00205628840054        0.000208013070598       0.000215130712749       0.00227232203023
0.0355018358117         0.00794016766666        0.00010898301244        3.64782271074e-05
0.000318871968028

max:    227.053240243 1799.98267118 19.991424958    19.9927658148 0.899651136867
0.899912737073          19.9928616687 99.9723991899 18.9161462972 0.499814578355
0.988028309047          0.699969565957

box 3:

min:    717.19736033    1342.01364722 0.00840639749931        0.00205628840054
0.000208013070598       0.000215130712749       0.855675224031          5.73614747867
0.00794016766666        0.0002831633513         3.64782271074e-05       0.000318871968028

max:    1732.2321345    1799.98267118 17.5074508223 18.9792030891 0.576091663543
0.822180395906          19.2033419779 99.9723991899 18.6543845551 0.499814578355
0.999260664151          0.63765282432

box 4:

min:    0.724498089495          1292.79882379 0.00840639749931        0.722999325496
0.000491383030784       0.000215130712749       0.00227232203023        3.99982961169
0.387926107713          0.0275691686838         0.0349434330476         0.0277024970563

max:    1743.65165536 1798.12367962 18.26115886     13.924077438    0.81575041111
0.824690709556          19.9883172967 99.9723991899 19.9914471268 0.475414869073
0.999260664151          0.639783514284

box 5:

min:    227.632151257 360.430842063 0.00840639749931        0.00205628840054
0.0254486778567         0.000215130712749       0.00227232203023        0.0722635214279
0.00794016766666        0.0228804553484         0.000995636044374       0.000318871968028

max:    389.996370423 1798.12367962 19.991424958    19.5098840542 0.822336221548
0.732924716501          19.9883172967 99.9723991899 18.8366630384 0.473822649063
0.950473365894          0.699389071205

box 6:

min:    0.724498089495          0.596624384827          0.00840639749931
0.00205628840054        0.000491383030784       0.000215130712749       0.00227232203023
0.0722635214279         0.00794016766666        0.0002831633513         0.000995636044374
0.000318871968028
```

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max:      1799.9278359   1790.49143638 19.991424958   19.9805409232 0.899651136867
0.899912737073           19.9883172967 99.9723991899 19.9914471268 0.499814578355
0.999260664151           0.699389071205
```