

Stress-Testing Banks under Deep Uncertainty

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Abstract

Years of turmoil in the banking sector have revealed the need to assess bank performance under deep uncertainty and identify vulnerabilities to different types of risks. Banks are not the safe houses of old. 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, internal design and policies can, and hence, offer opportunities for robust redesign. This paper illustrates a System Dynamics approach towards financial stress testing in view of making banks more robust, i.e. performing more appropriately in all plausible futures, especially in the most stressful futures. A System Dynamics model is used to represent the core operation of a bank. A variety of risks and shocks are applied to the model in order to generate insights into the plausible system behaviour under stress. The clustering of the different behaviours in turn aid in the understating and explaining the variety of bank runs exhibited by the model.

Keywords: Banking, Stress test, Exploratory Modelling and Analysis, System Dynamics, ESDMA, Deep Uncertainty, Bank risk

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 and highlighted the dynamic complexity and deep uncertainty of banking institutions. Multiple factors played a role and had a significant contribution to the severity of the crisis that affected extensively the banking sector. An unforeseen number of bank failures or last minute bailouts after regulatory authorities' intervention occur, as multiple banks globally have been "in distress".

The impacts of the financial crisis clearly showed that banks are not the safe houses that everyone believed them to be. 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 test techniques, utilized to gain a deeper insight of the banking environment and provide an in-depth exploration of possible vulnerabilities. Supervisory authorities are prompt to include stress testing tools in their monitoring and surveillance activities. Furthermore, for a bank, as it is critical to deal with shocks and vulnerabilities, stress testing could be a part of its risk management practises in order to assess its financial performance in plausible stressing scenarios.

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 what can be defined as "plausible" and stressor events are subjectively chosen in each analysis (Quagliariello, 2009).

System Dynamics modelling could offer a novel model-based technique providing a deeper understanding of the banking environment and an in-depth exploration of all possible vulnerabilities. The uncertainties and the dynamic complexity of the financial system call for an alternative approach instead of conventional forecasting, planning, and analysis methods. In this paper a model-based exploration is investigated as a tool to assist banks identify weaknesses under all sorts of uncertainties.

This paper is organised as follows. In the next section, the approach is discussed, followed by the description of the model and the stress events that are explored. The model and the analysis of the behaviours is presented in section 4. The adaptive sampling method and its results are described in section 5. Conclusions and future work are discussed in section 6.

2. Previous works

The last decades there is an on-going evolution 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, Stolz, & Moretti, 2008). Their Financial Sector

Assessment Program (FSAP) includes stress tests as part of their practices to assess a country's banking sector.

Common techniques can be summarised in simple sensitivity tests and historical or hypothetical scenario analysis. Sensitivity tests explore the impact of a single market risk factor on bank's portfolio, while scenario analysis focuses on multiple simultaneous changes in risk factors that influence bank's position in different ways. To this direction, focusing on an approach that could explore multiple future hypothetical scenarios, exploratory System Dynamics modelling could offer another tool for a model based exploration in order to support monitoring of bank's financial state.

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).

3. Approach

The aim of our work is to illustrate a pilot System Dynamics approach towards financial stress testing in view of making banks more robust by identifying possible weaknesses. The methodological approach applied is Exploratory System Dynamics Modelling and Analysis (ESDMA) (Pruyt & Kwakkel, 2011; Pruyt, 2010) in an effort to explore all sort of deep uncertainties that influence a bank's system behaviour. ESDMA is a combination of Exploratory Modelling and Analysis (EMA) (Agusdinata, 2008; Bankes, 1993; Lempert et al., 2003) and System Dynamics (SD) Modelling (Forrester, 1961, 1968; Sterman, 2000). Exploratory Modelling and Analysis (EMA) allows generating insights and understanding about the functioning of systems and the effectiveness and robustness of policies, while taking uncertainties into account. 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' (Pruyt & Kwakkel, 2011; Pruyt, 2010). Despite the existence of System Dynamic models that deal with banking system or specific banks (Lansink, 2011; MacDonald, 2002; Pruyt & Hamarat, 2010; Pruyt, 2009; Rafferty, 2008), approaching the uncertainties and risks of a bank's system with ESDMA is innovative.

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. 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 are focused on for the purpose of this study.

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 bank under stressful events and their severity. All plausible future scenarios that a bank could face can be included in all those experiment runs.

For performing EMA on the SD model, the EMA workbench is used. EMA workbench is a software toolbox, 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.

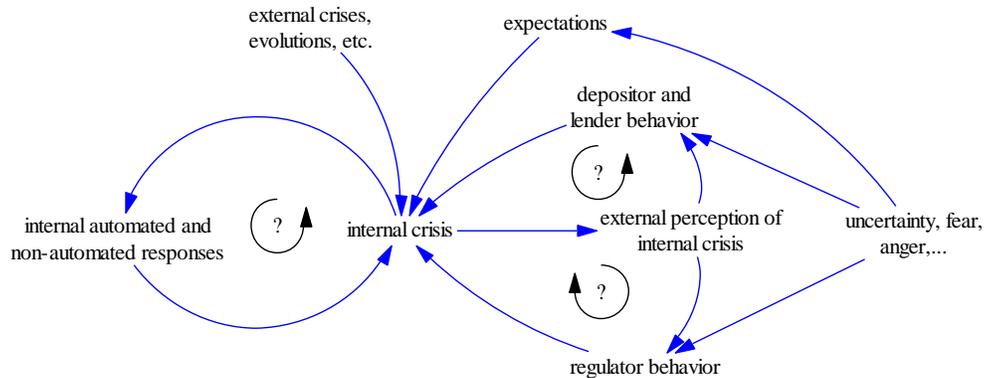


Figure 2. High level representation for Dynamic Stress Testing

4. Model description

In this section the description of the simple model built for exploratory purposes is provided

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. 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 well-known bank institution. 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.

The time horizon of the model one year and the unit time is one day, meaning that the model provides data regarding the behaviour of the system per day calculated. The unit 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.

Figure 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.

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.

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. 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.

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 2.

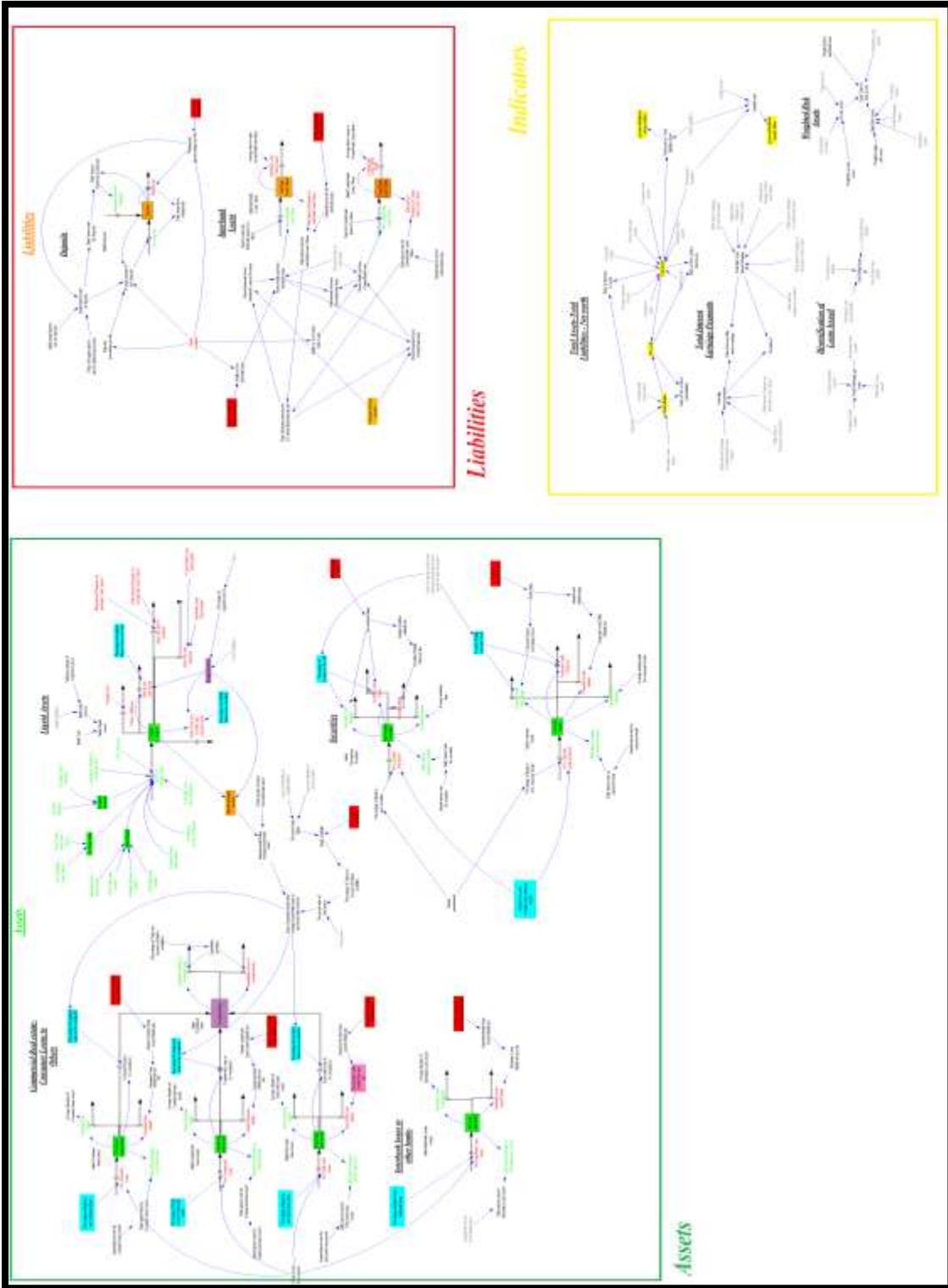


Figure 1 Overview of Bank SD model

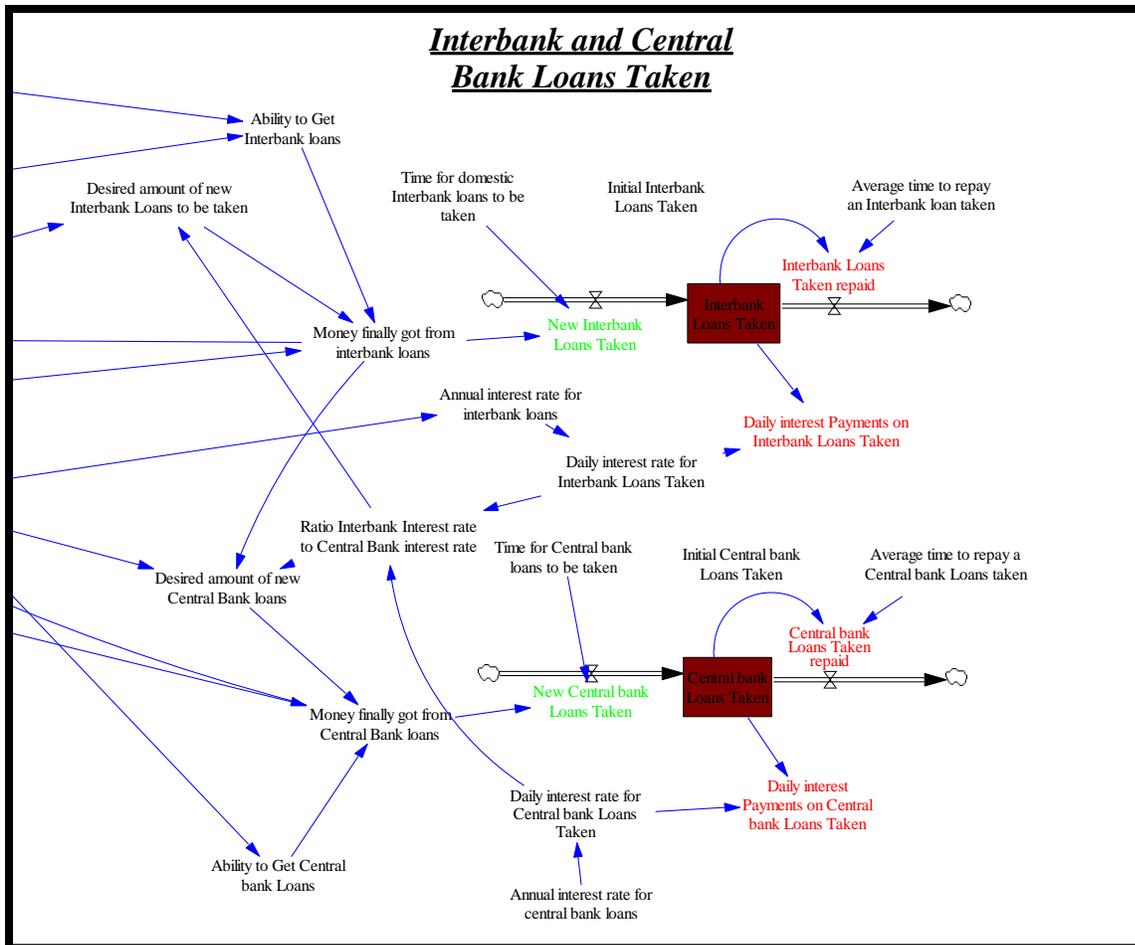


Figure 2. Interbank and Central bank loans taken structures

Deposits

The sub-system (Figure 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. 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.

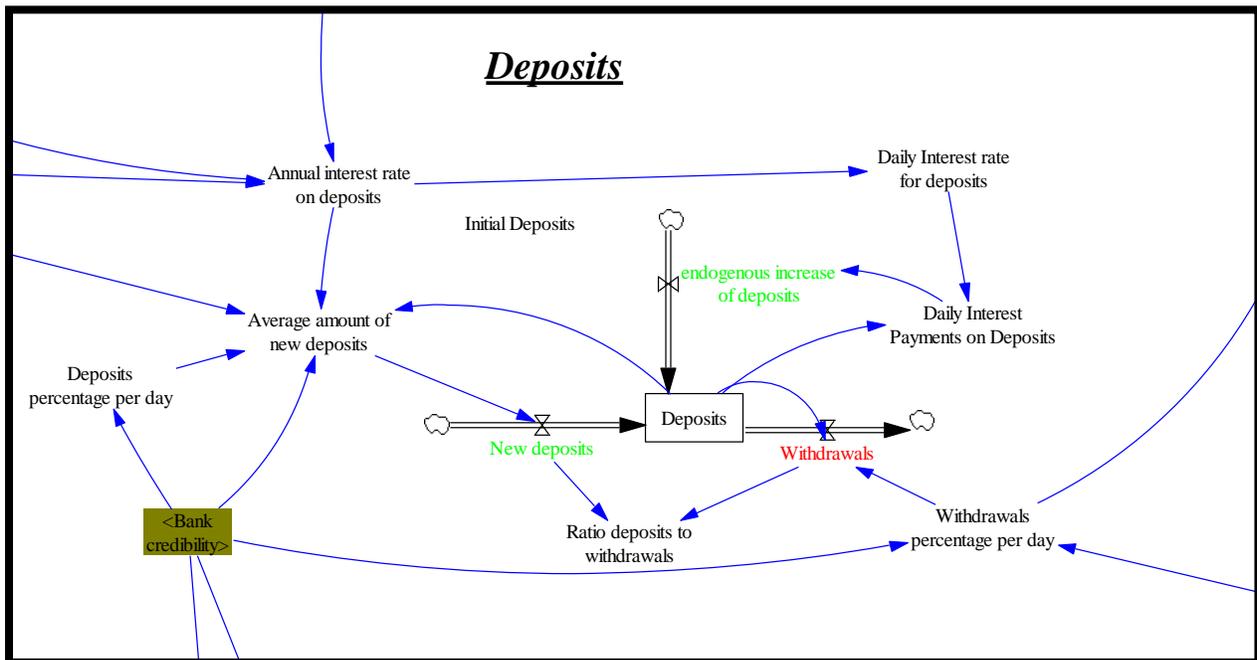


Figure3. Deposits structure

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.

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 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.

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). 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. If the bank faces liquidity issues because of large withdrawals, it is forced to liquidate (sell) securitised loans, possibly suffering losses depending on bank's rating. The percentages of loans which are to be securitised are defined with lookup functions (Appendix) and they increase when the bank is not able to receive loans from interbank market or Central Bank, because its credibility suffers. 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. Liquidation earnings are added to the sum of new liquid assets.

Interbank loans issued

When the bank's liquid assets exceed 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 6 shows the detailed structure of interbank loans issued.

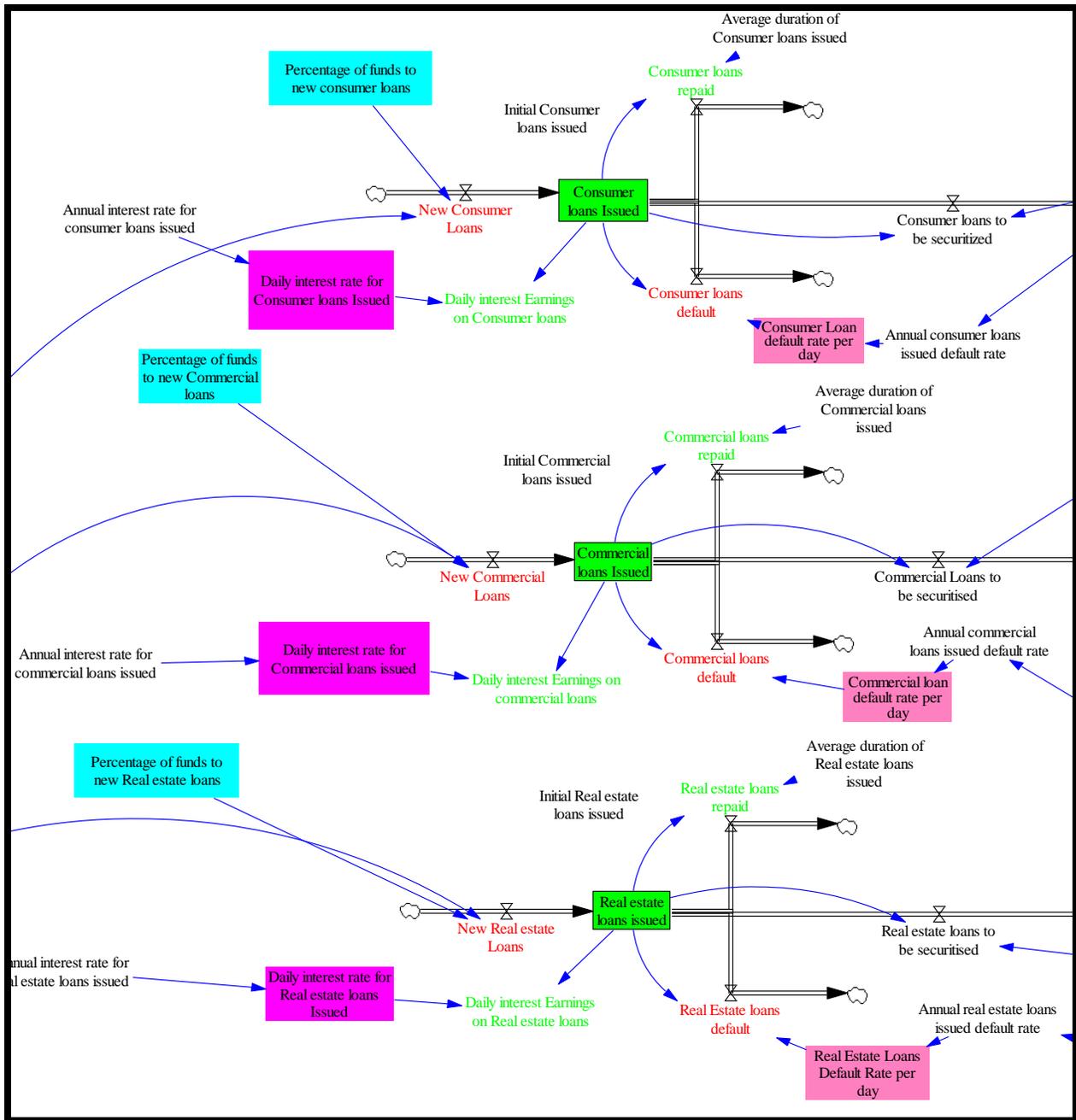


Figure 4. Consumer, commercial and real estate loans issued structures

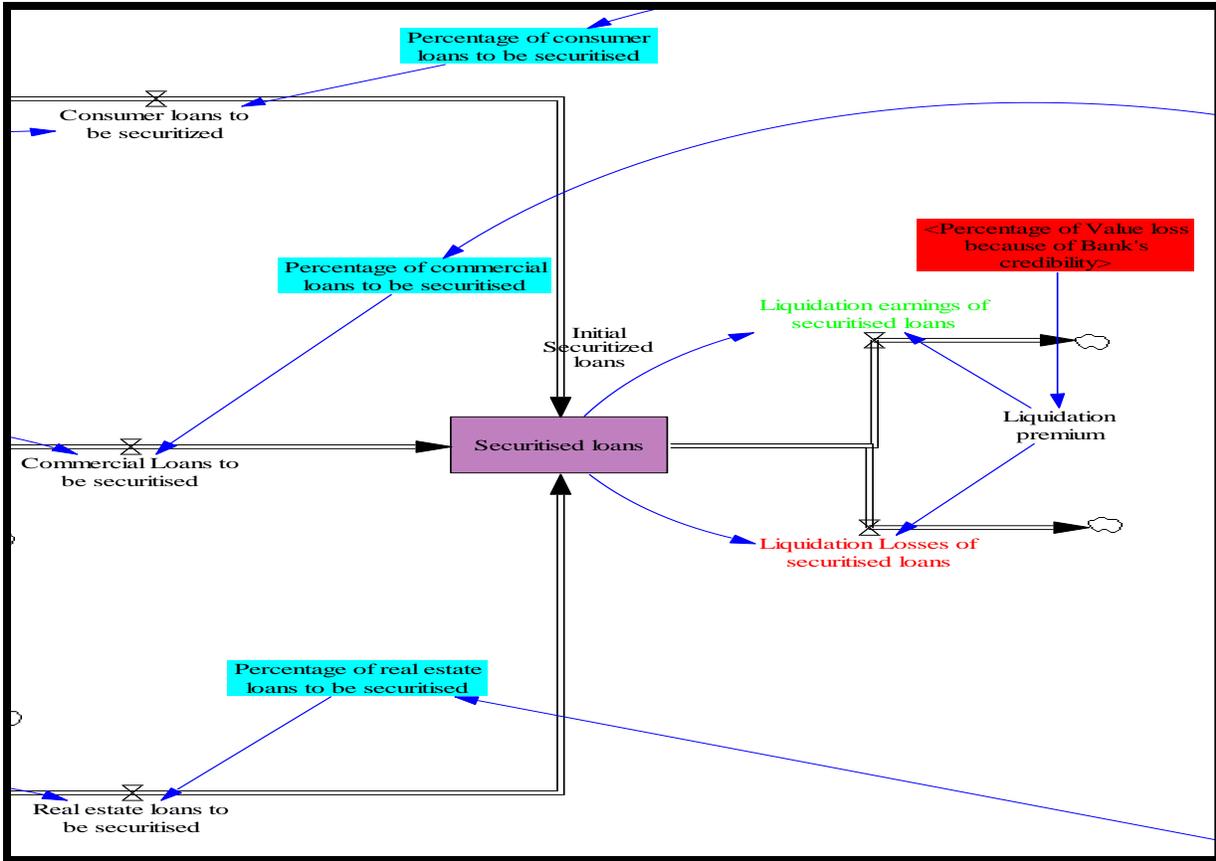


Figure 5. Securitization structure

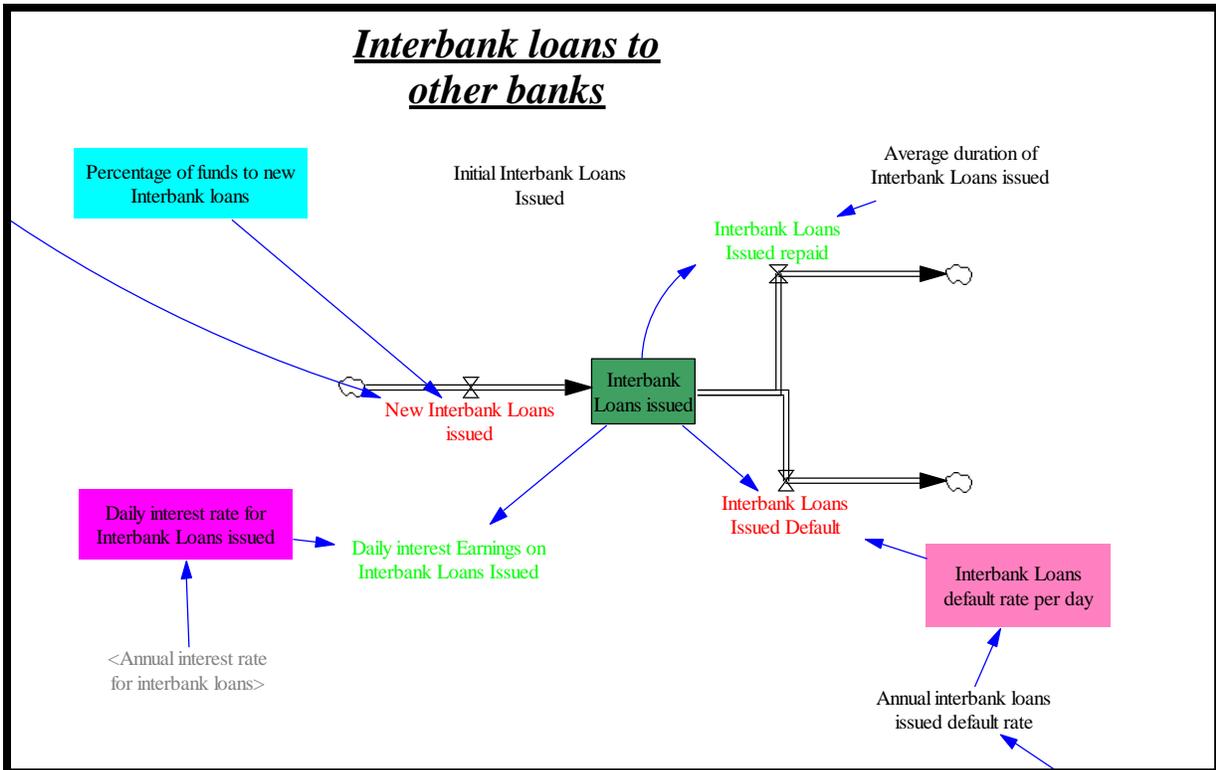


Figure 6. Interbank loans issued structure

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.¹

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 rating², 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. 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. In Figure 7, the securities' structure is demonstrated.

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

¹ 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. (Cline, 2011; Kalfaoglou, 2012)

² 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.

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. 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 8, the structure of corporate bonds is illustrated.

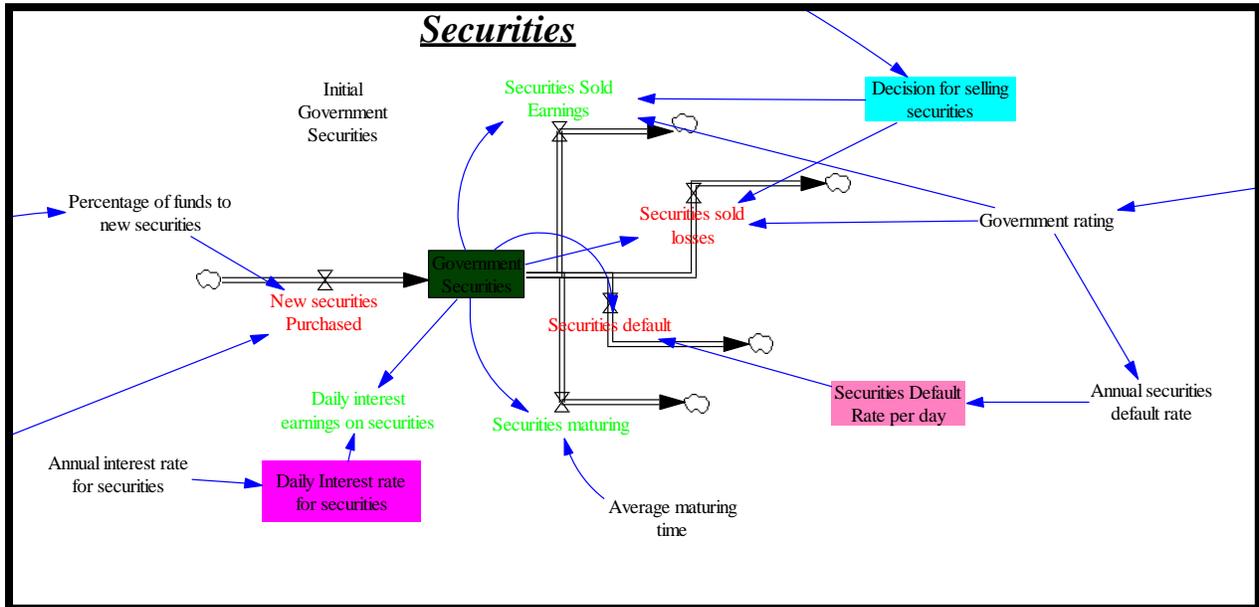


Figure 7. Government securities structure

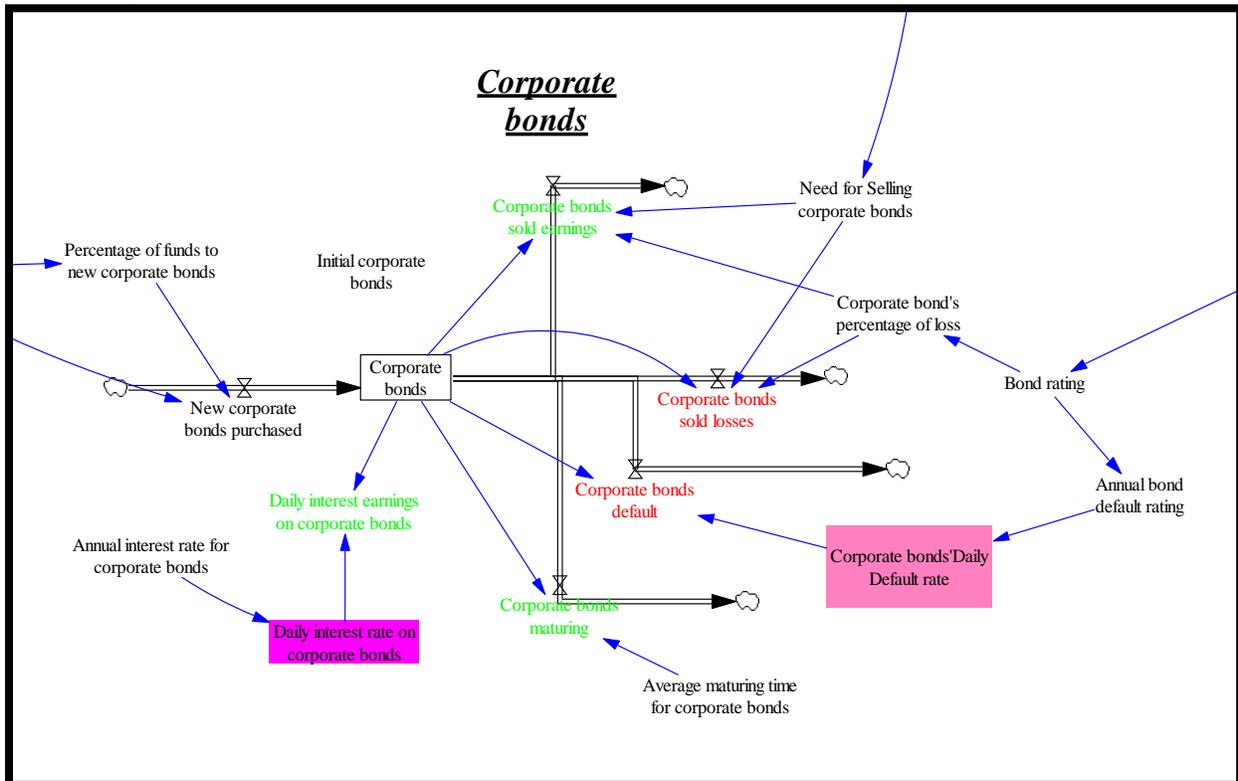


Figure 8. Corporate Bonds structure

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 reserves³ 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. 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 new loans to be issued, new securities or corporate bonds to be purchased.

In the model, in order to capture, in an abstract way, the new regulations included in Basel Accords demanding higher liquidity and capital ratios, the percentage of required reserves changes over time. At the starting point of the simulation, it is defined as 10% of the total liabilities and after 10 years has to be 30% of the total liabilities. This simple mechanism explores possible behaviours of the bank in an effort to be stable by increasing its ratios but also be profitable enough.

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 9, the structure of the liquid assets is illustrated.

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. However, the bank is stressed under extremely severe scenarios also that the banks is not able to recover.

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.

³ 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)

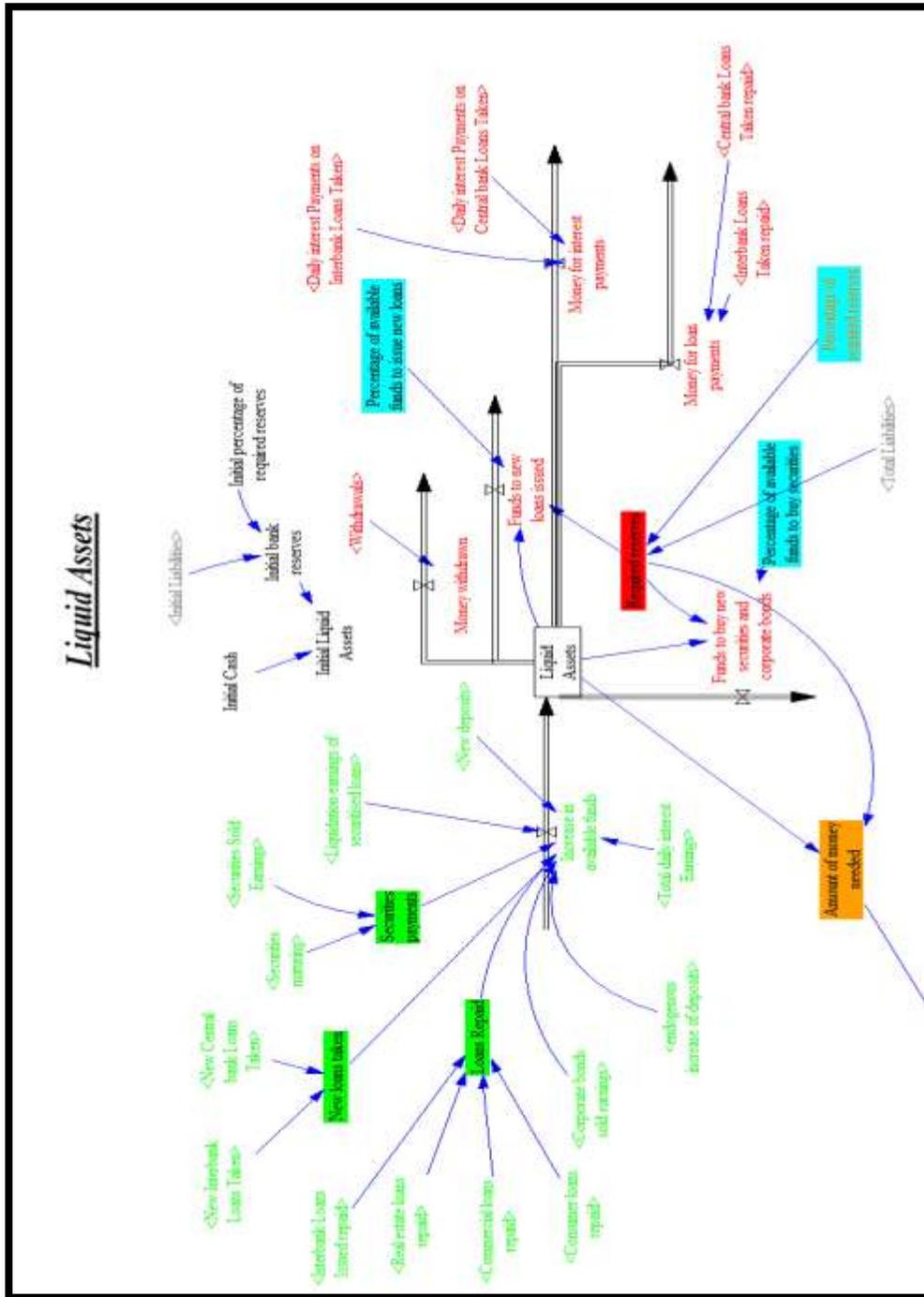


Figure 9. Liquid Assets Structure

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 depending on the time that the stress events occur.

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 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 round 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 default rate”, “Crisis on Commercial loans default rate” and “Crisis on Consumer loans default rate” 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.

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 default rate”. Because of initial low value for interbank loans issued default rate, the uncertainty of possible future values range is up to 1000 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 market, stock market crash or recession that could affect firms and corporations, would cause down-grading the corporate bonds hold 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 1 shows all the uncertainties and stress events explored in the model. Their ranges and the influenced parameters of each shock are illustrated. High values are considered extreme conditions especially in cases that lead to bank runs (extreme values of withdrawal rates)

Table 1 Uncertainties

Crisis	Parameter	Range	Influenced Parameter	Range of influenced Parameter
-	Crisis Starting time	100-1600	-	
-	Crisis Duration	1-720	-	
Crisis on corporate bonds	Effect on corporate bonds rating	0-1	Bond rating	0-1
Crisis on interbank loans issued default rate	Effect on interbank loans issued default rate	1-1000	Annual interbank loans issued default rate	0.0001-0.1
Government crisis	Effect on government rating	0-1	Government rating	0-1
Crisis on bank credibility	Effect on bank rating	0-1	Bank's credibility	0-1
Crisis on interbank interest rates	Effect on interbank interest rates	1-50	Annual interest rate for interbank loans	0.003-0.15
Crisis on Commercial loans default rate	Effect on commercial loans	1-100	Annual commercial loans issued default rate	0.004-0.4
Crisis on Consumer loans default rate	Effect on consumer loans	1-100	Annual consumer loans issued default rate	0.002-0.2
Crisis on Real estate default rate	Effect on Real estate loans	1-100	Annual real estate loans issued default rate	0.003-0.3
Crisis on withdrawals	Effect on withdrawals	0-1	Withdrawals percentage per day	0-0.98
Crisis on ability for interbank lending	Effect on ability for interbank lending	0-1	Ability to Get Interbank loans	0-1

5. Adaptive Sampling

To create a comprehensive picture of the different types of behaviours experience by the bank, a modified adaptive sampling method (Bucher 1988) is used. Due to the large search space associated with the model, it is not possible to exhaustively search for all behaviours. However, the developed mythology attempts to find gaps in the behaviour spectrum and then fill them.

To differentiate between the behaviours, the concept of scenario roughness is used. Roughness measures are used in road condition monitoring (ASTM 1996; Garmo et al. 2011), to describe the state of distress of a length of road. There exist a variety of measuring metrics, and for this paper, the length of the scenario is used. As opposed to using other forms of geometric or statistical descriptions of each simulation run, the measure indicates the “roughness” of the experienced scenario. For comparative purposes, a relative roughness scale is used, which requires all the lengths to be divided by the shortest sampled simulation length. In this paper, a singular output variable, the net worth, will be the object of study.

When visualizing the previously described transformation, a second curve attribute is shown on the second axis of the scatter plot. Figure 10 shows the curve roughness on the x-axis, and the minimum net worth of experienced during the simulation run is shown on the y-axis. The figure shows the result of a 1000 runs using Monte-Carlo method, applied to the model. In the figure, with increasing roughness of simulations the lowest net worth experienced by the model decreases proportionally. Furthermore, there appear to be gaps in the roughness spectrum, indicating that either such futures either do not exist, or that they have not been sampled

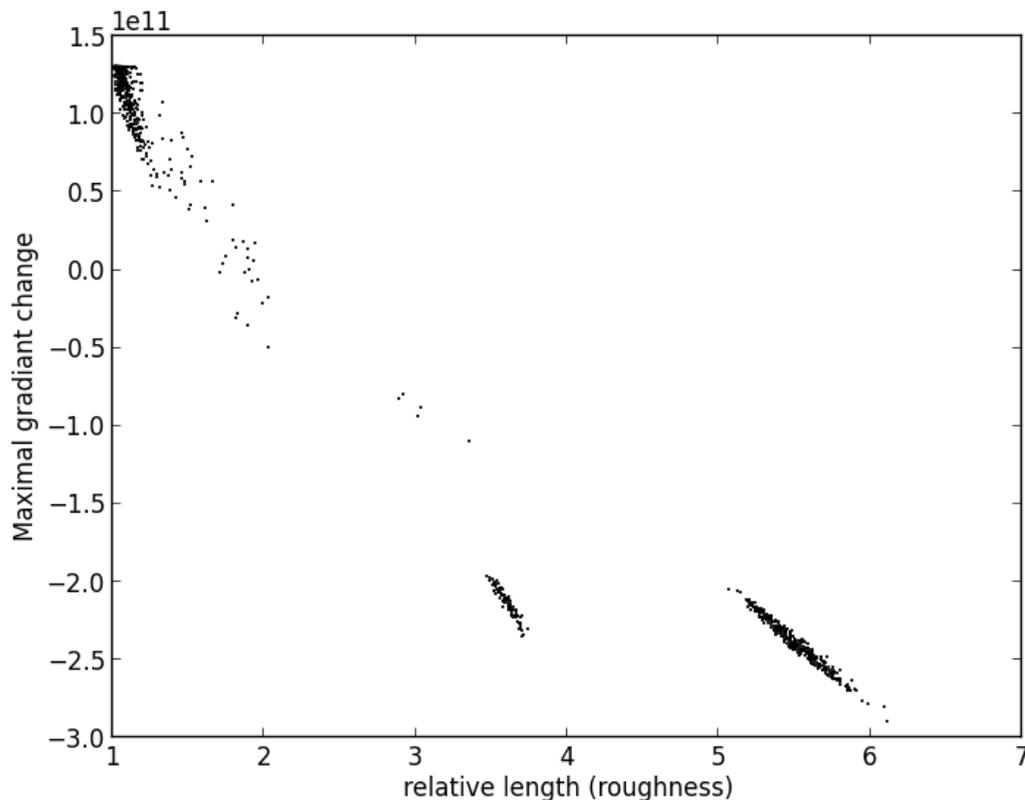


Figure 10. Curve attributes of 1000 runs

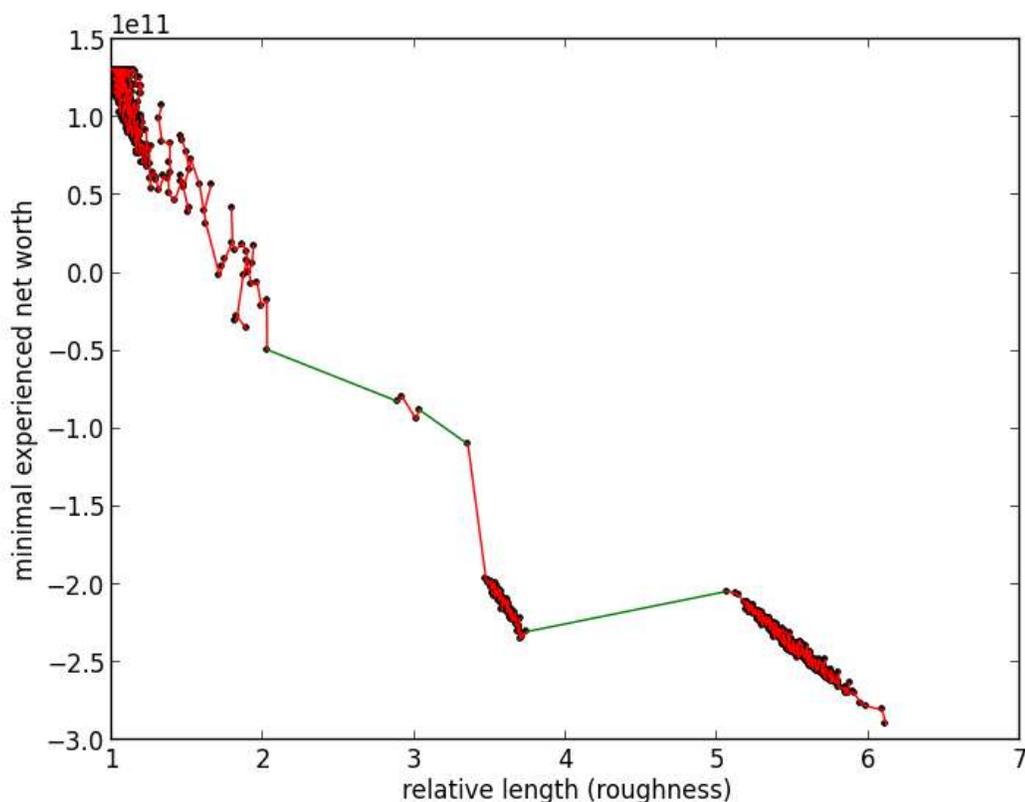


Figure 11. Curve attributes of 1000 runs and overlaid minimal spanning tree

Next, a minimal spanning tree is applied to the scatter plot data, and the three largest gaps are identified. The parameters associated with the runs linked with the two end points of each gap are taken as extents for running further a 1000 runs using the Monte-Carlo method. This gap filling process is applied a second time, to result in a total to 7000 runs. The transformed data of these runs are shown in figure 12. Two observations can be made from this figure. A first note, the points on the left side of the figure shown in blue are points that were filtered out before the data was fed into the minimal spanning tree, to reduce the processing time (in region I). The first area to focus on is the gap on the right side of the plot that remains empty, even after attempts to fill (in region IV). Secondly, there appears to be a point of bifurcation, where for the same roughness, there happens to be two possible values of net worth (in region II & III). As this methodology has not been used in any other study previously, it is not known if this is a common phenomenon. However, it indicates that the model has a degree of non-linear behaviour beyond a certain roughness. If the curves associated with each of the four regions in figure 12, are plotted further insight can be found. It can be seen in Figure 13, that Region I shows all the curves where the bank experiences a small crisis and Region II shows the medium scale crisis and recovery by interbank loans. Region IV show the curves with large scale crisis, followed by central bank loan. Region III is similar to Region IV in regards to the scale of the crisis, however different as the crisis hits late and a central bank loan did not follow. Region III is therefore, an artefact of the sampling window, a “drifting continent”, and if the model were to be run for a longer time horizon, these runs would fill the gaps seen in Region IV.

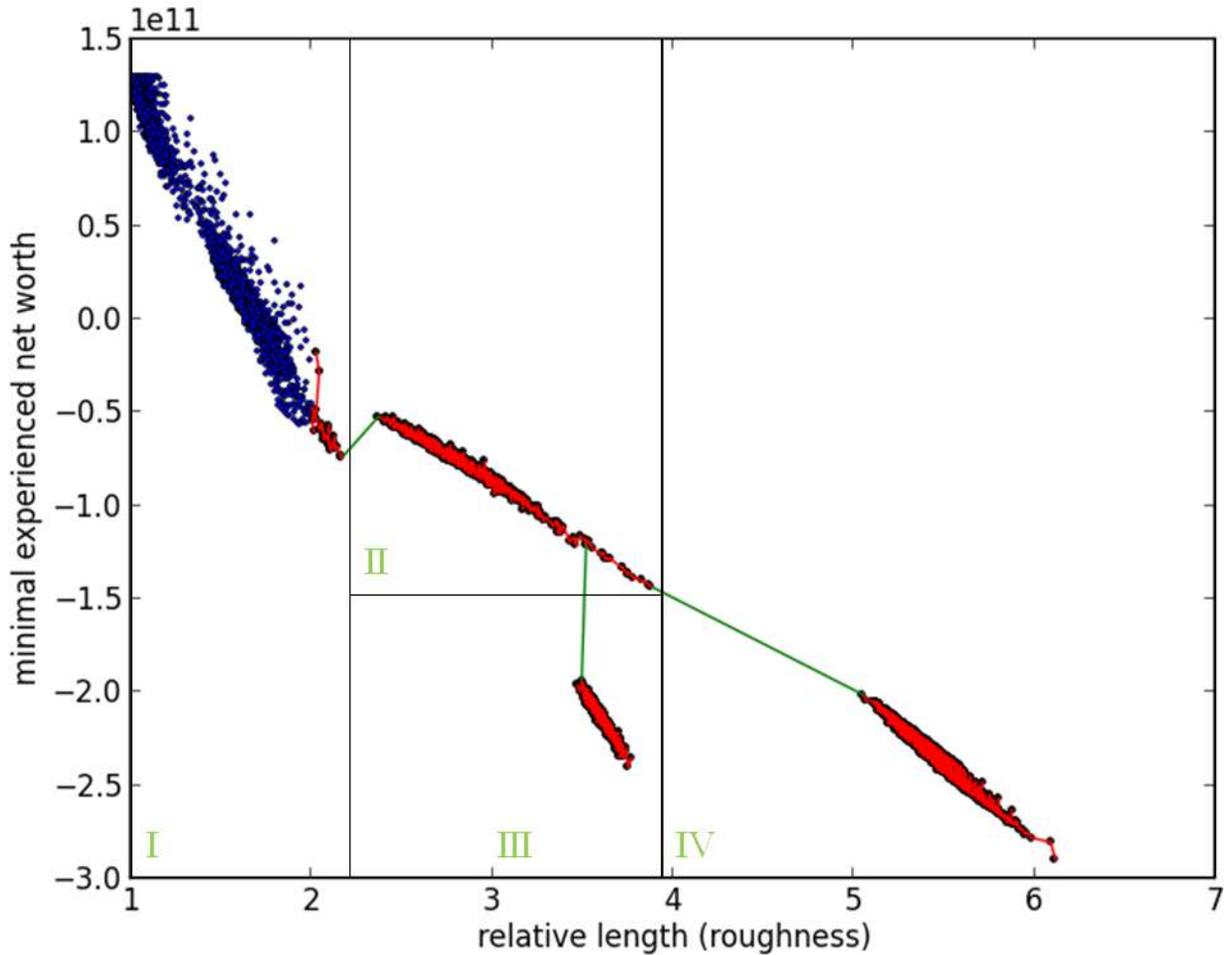


Figure 12. Curve attributes of 7000 runs overlaid by minimal spanning tree

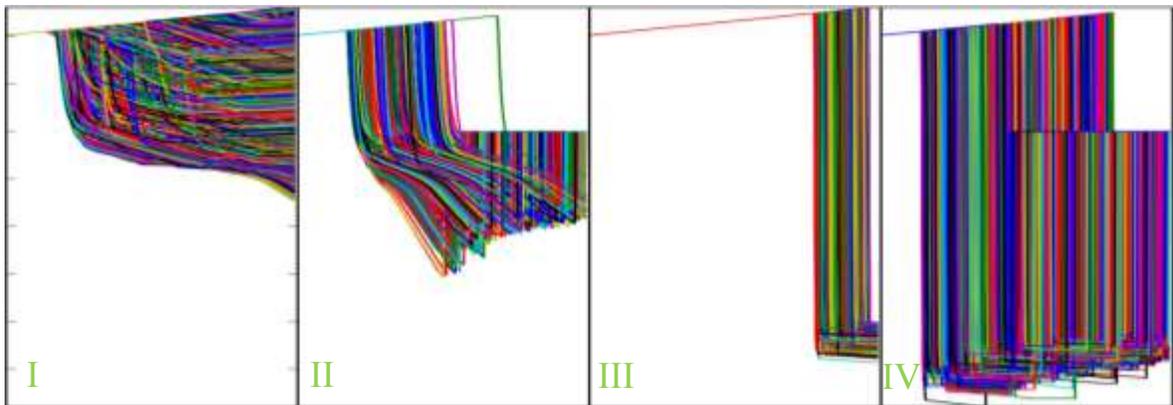


Figure 13. Runs associate with each of the identified regions

Scenarios of the model reveal various behavioural patterns regarding the performance of each part of the system. In severe crisis scenarios, the bank faces bankruptcy because of unavailable liquid assets or depletion of its total assets. Extremely sharp decreases in liquid assets are observed, mainly because of cases of extreme withdrawal rates as a result of severe stress events. In a high number of scenarios the bank is bankrupt due to liquidity problems. 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-round effect, leading to the depletion of liquid assets. The model demonstrates such an extreme behaviour in many scenarios because the bank has not applied any preventive action and based on the modelling process the entire amount of deposits is available to the customers to be withdrawn. However, this is not the case in the real world as banks use notice savings accounts in which the depositor is not able to withdraw their savings at all times, and if so, with added fees. Nevertheless, this extreme behaviour is present in the real world when bank runs are taking place and the bank is not able to meet its liquidity needs.

6. Current and Future work

The current research focus is on model-based Bank Stress testing and a more extensive use of ESDMA in financial issues. In the future, our goal is to improve the stress test tool with the use of one or multiple System Dynamics models so as to assist a bank to identify efficiently and sufficiently possible risk factors and stress events that could cause financial instability. By identifying the regions of behaviour, control mechanisms can be crafted to uniquely respond to each of the different regions. This paper is a preliminary research and the intention is to explore further and broaden the abilities of the specific stress test tool.

This paper illustrates how a simple bank SD models could be used to identify behaviour groups with the application of ESDMA. However, the model included in this approach is just indicative as more SD models could be additionally simulated and explored. Another future attempt could focus on a more advanced System Dynamics model that could capture more types of crises or stress events. The model would then need to contain structures to simulate different uncertainties, risks, and knock-on effects. The ensemble generated with the model should, if done well, be as rich as possible and allow the investigation of effects of policies, strategies, scenarios, all sorts of risks and exogenous effects.

Moreover, further scenario analysis needs to be conducted in order to deal with more and more uncertainties. Thousands of runs generated with model(s) representing the core of a particular bank could be used to identify root causes, uncertainties that require monitoring, and appropriate strategies. Finally, using curve characteristics, such as roughness, for clustering and non-brute force sampling strategies, will aid analysts in comprehending complex models.

7. Conclusions

Multiple banks faced problematic conditions during the crisis of 2008 and most of them needed to be rescued from collapsing, in order to keep the whole banking system stable. Therefore, there is a great need to explore uncertainties and identify key factors that could reduce the risk of a bank run. This paper illustrated an experimental model-based study that explores multiple uncertainties of a dynamic and complex bank's system and assists us to identify possible dynamic mechanisms in a bank that could cause undesired state and explore policies to prevent a collapse from happening.

From a methodological view, application of ESDMA is an innovative approach for financial issues. To date, SD models related to financial issues have been developed, but they have never been explored under all those uncertainties. The combination of SD and EMA in our ESDMA research enables us to explore multiple different scenarios for bank models. The identification of uncertainties that could cause instability on a bank's status is important for strategic decision making. The applied side of the project is especially relevant for financial market authorities, central banks, and banks interested in dynamic risk management under deep uncertainty by developing insights about underlying mechanisms, (inter)actions, and conditions, and their power to generate potentially disruptive dynamics.

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