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Designing scalable and stock-flow-consistent agent-based models: Policy scenarios and experiments on housing markets, monetary unions and interbank networks

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To my compatriot scholars and friends; those who opted to stand in solidarity against the breach of academic rights and liberties that are barred from us due to our petition for peace to stop the government's violence and crime on its own citizens.

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List of Abbreviations

ABM: Agent-based modelling

ARM: Adjusted-rate-mortgaging

CGE: General equilibrium framework

CGP: Consumption goods producer

CPI: Consumer price index

DSTI: Debt-service-to-income ratio

ETA: Equity to asset ratio

FRM: Fixed-rate-mortgaging

IIM: Inflation-indexed-mortgaging

LTV: Loan-to-value

LTI: Loan-to-income

KGP Capital goods producer

M.A.S: Multi-agent systems

OCA: Optimal currency areas

SFC: Stock-flow consistent

Abstract The recent debates in economics, following the 2008 crisis, have pointed out a necessity for micro-founded macroeconomic modelling approaches for policy analyses. Agent-based models (ABM) have been adopted to address two underlining aspects of a micro-founded macroeconomic approach. On the one hand, this methodology enables to accommodate heterogeneous agents with limited perception of market information that corresponds to bounded rationality concept in economics. The essence of its micro foundations is established by conceiving economic phenomena as the emergent results of these interactions in a bottom-up manner. On the other hand, ABMs have proven to be able to accommodate top-down policy experimentations such as fiscal and monetary interventions. However, ABM practices are criticized at lacking a methodological maturity that clearly offers such bidirectional value towards scalable and re-usable models.

This dissertation as a whole is an effort at fulfilling this necessity. It is composed of a number of interrelated studies. Specific research questions are raised around the debates on **monetary unions, housing markets** and **interbank networks**. The overall objective in these works is to be able to address policy questions while employing sound and reusable stock-flow-consistent models. A common methodological practice is elicited at reaching this objective: delineating the design of a top-down policy experimentation set-up from the design of individual agent behaviors for a bottom up emergence first, and then coupling them back to reach a conceptual coherence between the policy issue and the assumptions on agents' behavioral choices.

The research on **monetary unions** has led us to re-factor an advanced yet closed single country macroeconomic model in such a way that the model sub components and certain agent behaviors can be selectively added for a desired multi-country policy experimentation. From a methodological point of view, the work introduces a novel approach on both vertical scalability (flexibility as of markets, mechanisms and behaviors) and horizontal scalability (flexibility in population design and configuration). The set-up enables us, for instance, to analyze the impact of a fiscal pool within a monetary union under varying labor mobility constraints and technological differences.

Our multiple studies on **housing markets** demonstrate prospects of a model re-usability. Different subsets of behaviors and mechanisms selected from the same model library on hous-

ing markets serve for different policy experiments: (i) examining stylized relation between mortgage credits and business cycles, (ii) experimenting with alternative and prudent mortgage regulating instruments, (iii) examining macroeconomic impacts of different mortgage types, and (iv) investigating impact of policies towards *green finance* when speculative lending channel via housing market is prevalent in the system.

The work on **interbank markets** introduces a novel ABM simulation set-up in order to study the role of balance sheet structures and network topologies at interbank markets with respect to their resilience against systemic risks. Its parsimonious set of configuration parameters can create different interbank network models and balance-sheet configurations with varying degree of concentration, connectivity and capitalization without violating stock-flow consistency (SFC) of its constituents.

In this dissertation, results of these studies are summarized and discussed briefly along with methodological novelties that have been introduced or applied at each one of them. Relatively more space is dedicated to major individual contributions: (i) design, analyses and discussion on mortgaging regulations, (ii) design and development of a scalable multi-country experiment set-up, (iii) design and development of a financial contagion model, (iv) and an outline of a methodological guideline that has been consolidated through the studies within this dissertation.

Results on housing markets: *First*, our models confirm that the dynamics of mortgages are supporting the theory of endogenous nature of credit money giving a contribution to a debate that has grown stronger over the last two decades. In general, regulations allowing a high leverage of the banking tend to inflate asset bubbles and boost the economy in the short run, while tend to result in bubble bursts and economic depression in the medium and long run. *Second*, we suggest that the stimulating impact of mortgage credits can sustain a long term growth and stability when regulated via complementary instruments: a stock control regulation that targets households net wealth combined with a flow control regulation that targets households debt service. Besides, we demonstrate that stock control regulation exhibits the interesting property to directly affect mortgage distribution among households. *Third*, we suggest that inflation-indexed mortgages can mislead households' expectations of risk encouraging them to buy more housing due to their low initial amortizations which, in turn, increases housing prices. The results further hint that in long-run inflation-indexed mortgages create relatively more uneven housing wealth distribution among households. *Last*, we examine macro-prudential policies that may help to stimulate the banking sector to shift from speculative lending to an energy efficient production technology. As of the regulatory instrument, we introduce a differentiation of capital requirements according to the destination of lending, demanding higher bank capital in the case of speculative lending via mortgages. Results suggest that the proposed regulation is able to foster investments and capital accumulation in the short term, improving the energy efficiency of firms. However, reducing mortgages with a restrictive banking regulation has a negative impact on total private credit, and thus on endogenous money supply, weakening consumption and aggregate demand. In the long term, the contraction of total credit becomes stronger, and the negative outcomes on aggregate demand also affect investment making the energy efficiency become negligible.

Results on monetary unions: The work on a scalable multi-country experiment set-up enables us address the conditions under which two or more countries can benefit from becoming part of a monetary union. Our results suggest that for similar countries, it is always beneficial to join in a union, although a lack of mobility frictions can weaken its performance. Even if countries have different productivities, the performance of the union is in general better than the performance of the isolated countries. The exception is when the productivity gap between member countries and labor mobility across borders are both too high. In this case, the union can even exacerbate the gap between the member states. We devise and test a fiscal pool policy to measure to what extent it could alleviate the effects of structural differences, such as high tech and productive member versus a low tech and underdeveloped member. Our findings suggests that stronger fiscal integration via transfers from surplus countries to deficit countries helps reducing inequality between such members, supporting a sustainability of the monetary union.

Results on interbank networks: Our initial results suggest that a medium density of connections in regular networks is already sufficient to induce a '*robust-yet-fragile*' response to insolvency shocks, while the same occurs in star networks only when the centralization is very high. From a policy perspective, we suggest that the resilience of interbank networks can be increased by a complementarity between concentration and connectivity. Our findings suggest that a sustainable resilience to external shocks can be achieved if there is more interbank trade among peripheral nodes of the second tier banks while there is less debt exposure among the money centers of the first-tier core banks. This implies a moderation towards reducing the connectivity within the core while increasing the connectivity between the peripheral nodes.

Resumen Los recientes debates en economía tras la crisis de 2008, han señalado la necesidad de utilizar modelos macroeconómicos micro fundados para el análisis de políticas. Se han utilizado modelos basados en agentes (ABM, en en inglés) para abordar dos aspectos destacados dentro de los modelos macroeconómicos micro fundados. Por un lado, esta metodología permite acomodar agentes heterogéneos con una percepción limitada de la información de mercado que corresponde al concepto de racionalidad limitada en economía. La esencia de su micro fundamentación se establece al interpretar los fenómenos económicos como los resultados emergentes de estas interacciones de abajo a arriba. Por otro lado, los ABM han demostrado ser capaces de acomodar experimentaciones de políticas de arriba hacia abajo, como las intervenciones fiscales y monetarias. Sin embargo, las pr acticas de ABM son criticadas por carecer de una madurez metodológica que ofrece claramente ese valor bidireccional hacia modelos escalables y reutilizables.

Esta tesis es un esfuerzo para satisfacer esta necesidad. Se compone de una serie de estudios interrelacionados. En ella se plantean cuestiones específicas en torno a los debates sobre **uniones monetarias, mercados de vivienda** y **redes interbancarias**. El objetivo general de estos trabajos es poder abordar diferentes cuestiones de política económica, a la vez que se utilizan modelos sólidos y stock-flujo consistentes reutilizables. Se utiliza una misma metodología para lograr este objetivo: primero, delinear un entorno de experimentación de políticas de arriba hacia abajo a partir del diseño de comportamientos de agentes individuales para una emergencia ascendente, para luego unirlos de nuevo para alcanzar una coherencia conceptual entre la cuestión de política introducida y los supuestos sobre las elecciones de comportamiento de los agentes.

La investigación sobre **las uniones monetarias** nos ha llevado a reformular un modelo macroeconómico avanzado pero cerrado de un solo país, de tal manera que los subcomponentes del modelo y ciertos comportamientos de los agentes se pueden agregar de forma selectiva para una experimentación política deseada en varios países. Desde un punto de vista metodológico, el trabajo introduce un enfoque novedoso sobre la escalabilidad vertical (flexibilidad en cuanto a mercados, mecanismos y comportamientos) y la escalabilidad horizontal (flexibilidad en el diseño y configuración de la población). La configuración nos permite, por ejemplo, analizar

el impacto de un grupo fiscal dentro de una unión monetaria bajo diversas restricciones de movilidad laboral y diferencias tecnológicas.

Nuestros numerosos trabajos sobre **el mercado de la vivienda** demuestran las perspectivas de una reutilización del modelo. Diferentes subconjuntos de comportamientos y mecanismos seleccionados de la misma biblioteca de modelos en los mercados de vivienda sirven para diferentes experimentos de políticas: (i) analizar la relación estilizada entre los créditos hipotecarios y los ciclos económicos, (ii) experimentar con instrumentos reguladores de hipotecas alternativos y prudentes, (iii) analizar los impactos macroeconómicos de diferentes tipos de hipotecas, e (iv) investigar el impacto de las políticas hacia las *finanzas verdes* cuando el canal de préstamos especulativos a través del mercado de la vivienda prevalece en el sistema.

El trabajo sobre **los mercados interbancarios** introduce una nueva configuración de simulación ABM para estudiar el papel de las estructuras de balance y las topologías de red en los mercados interbancarios, respecto a su resistencia frente a los riesgos sistémicos. Su parsimonioso conjunto de parámetros de configuración puede crear diferentes modelos de red interbancaria y configuraciones de balance con diversos grados de concentración, conectividad y capitalización sin violar la consistencia stock-flujo (SFC, en inglés) de sus constituyentes.

En esta tesis, los resultados de estos trabajos se resumen y discuten brevemente junto con las novedades metodológicas que se han introducido o aplicado en cada uno de ellos. Se dedica relativamente más espacio a las principales contribuciones individuales: (i) diseño, análisis y discusión sobre regulaciones de hipotecas, (ii) diseño y desarrollo de una configuración escalable de experimentos multinacionales, (iii) diseño y desarrollo de un modelo de contagio financiero, (iv) y un resumen de una guía metodológica que se ha consolidado a través de los trabajos incluidos en esta tesis.

Resultados sobre los mercados de vivienda: *en primer lugar*, nuestros modelos confirman que la dinámica de las hipotecas respalda la teoría de la naturaleza endógena del dinero de crédito, lo que contribuye a un debate que se ha fortalecido en las últimas dos décadas. En general, las regulaciones que permiten un alto apalancamiento de la banca tienden a inflar las burbujas de activos e impulsar la economía en el corto plazo, mientras que tienden a generar estallidos de burbujas y depresión económica en el medio y largo plazo. *En segundo lugar*, sugerimos que el impacto estimulante de los créditos hipotecarios puede sostener un crecimiento y estabilidad a largo plazo cuando se regula a través de instrumentos complementarios: una regulación de control de stock que se dirige a la riqueza neta de los hogares combinada con una regulación de control de flujo que se dirige al servicio de la deuda de las familias. Además, demostramos que la regulación de control de stock exhibe una propiedad interesante que afecta directamente a la distribución de hipotecas entre los hogares. *En tercer lugar*, sugerimos que las hipotecas indexadas a la inflación pueden confundir las expectativas de riesgo de los hogares, alentándolos a comprar más viviendas debido a sus bajas amortizaciones iniciales que, a su vez, aumentan los precios de la vivienda. Los resultados sugieren que, en el largo plazo, las hipotecas indexadas a la inflación crean una distribución de la riqueza de vivienda relativamente más desigual entre los hogares. *Por último*, examinamos políticas macro-prudenciales que puedan ayudar a estimular al sector bancario al pasar de los préstamos especulativos a una tecnología de producción con mayor eficiencia energética. A partir del instrumento regulatorio, introducimos una diferenciación de los requisitos de capital según el destino de los préstamos, exigiendo un mayor capital bancario en el caso de los préstamos especulativos a través de hipotecas. Los resultados sugieren que las medidas propuestas pueden fomentar las inversiones y la acumulación de capital a corto plazo, mejorando la eficiencia energética de las empresas. Sin embargo, reducir las hipotecas con una regulación bancaria restrictiva tiene un impacto negativo en el crédito privado total y, por lo tanto, en la oferta de dinero endógeno, debilitando el consumo y la demanda agregada. A largo plazo, la contracción del crédito total se vuelve más fuerte y los resultados negativos sobre la demanda agregada también afectan a la inversión, lo que hace que la eficiencia energética sea insignificante.

Resultados sobre las uniones monetarias: el trabajo en una configuración de experimentos escalable en varios países nos permite abordar las condiciones bajo las cuales dos o más países pueden beneficiarse de formar parte de una unión monetaria. Nuestros resultados sugieren que, para países similares, siempre es beneficioso crear una unión monetaria, aunque la falta de fricciones de movilidad puede debilitar su desempeño. Incluso si los países tienen diferentes productividades, el funcionamiento de la unión es en general mejor que el funcionamiento de los países aislados. Encontramos una excepción cuando la brecha de productividad entre los países miembros y la movilidad laboral a través de las fronteras son demasiado altas. En este caso, la unión puede incluso exacerbar la brecha entre los estados miembros. Diseñamos y probamos una política fiscal para evaluar en qué medida podría aliviar los efectos de las diferencias estructurales, como la alta tecnología y el miembro productivo frente a la baja tecnología y el miembro subdesarrollado. Nuestros hallazgos sugieren que una mayor integración fiscal a través de las transferencias de los países con superávit a los países con déficit ayuda a reducir la desigualdad entre dichos miembros, apoyando la sostenibilidad de la unión monetaria.

Resultados sobre redes interbancarias: nuestros resultados iniciales sugieren que una densidad media de conexiones en redes regulares ya es suficiente para inducir una respuesta "*robusta pero frágil*" a los shocks de insolvencia, mientras que lo mismo ocurre en redes estelares solo cuando la centralización es muy alta. Desde una perspectiva política, sugerimos que la resistencia de las redes interbancarias se puede aumentar mediante una complementariedad entre la concentración y la conectividad. Nuestros resultados sugieren que se puede lograr una resistencia sostenible a los shocks externos si hay más comercio interbancario entre los nodos periféricos de los bancos de segundo nivel, mientras que hay menos exposición de deuda entre los centros monetarios de los bancos centrales de primer nivel. Esto implica una moderación hacia la reducción de la conectividad dentro del núcleo, al tiempo que aumenta la conectividad entre los nodos periféricos.

Chapter 1

Introduction

1.1 Overview

This dissertation is composed of a number of interrelated studies. The common objective is addressing policy questions in macroeconomics or finance while employing sound and reusable agent based models (ABM). Specific research questions have been raised around the debates on monetary unions, mortgage markets and interbank networks.

I have carried out the work collaborating with different teams. An enlisted summary of publication outcomes is below in Section 1.3. My contributions within the teams are two sided: conceptual and methodological. At the macro economic theory side, I have lead our discussion on housing market regulations; at the economic network theory side, I have lead our conceptualization of network formations at Interbank markets. On the other side, primarily, I have lead the research methodology in design and implementation of our agent based models and analysis of their simulation outcomes.

More specifically, I have lead the design and implementation of housing markets within two ABM models: Eurace[1] and Iceace[2]. The housing market in Eurace has served us to examine (i) a stylized relation between mortgage credits and business cycles (Raberto et al., 2017), (ii) investigate policies on green finance (Raberto et al., 2018), and (iii) experiment with alternative and prudent mortgage regulating instruments (Ozel et al., 2016). The housing market in Iceace model enabled us to examine macroeconomic impacts of different mortgage types within a stylized context of Icelandic economy (Bjarnason et al., 2015).

The most prevalent methodological contribution that I have lead is within the multi-country simulation set-up that we have created for the analysis of monetary union models (Petrovic et al., 2018). The flexible and modular set-up enables us to conduct very complex yet controlled policy experiments. With the help of novel computational methodology, we are able to create a variety of economic systems from an isolated national economy to a global economic system with various heterogeneous unions and union types, isolated or trading national economies. It is an ABM framework where we are able to study circulation of labor, goods and financial capital under various political, technological and later possibly cultural configurations.

Another methodological novelty that I have lead is in our work (Ozel et al., 2018) where we have addressed the resilience to financial contagion under varying interbank network structures. We have developed an ABM simulation set-up where not only stylized network models such as star, fully-collected, or circular topologies but also random core-periphery graph models of interbank networks can be studied. Its parsimonious set of configuration parameters can create different interbank network models with varying degree of concentration, connectivity and capitalization without violating stock-flow consistency of its constituents. At a follow up work (Gencer and Ozel, 2018), we have developed a computational model on interaction and integration of multiple interbank networks.

[1]Eurace is a stock-flow consistent (SFC) computational model, grounded on the agent-based methodology, which has been used for studying a range of macroeconomic issues by researchers from various institutes. Its initial design and development has taken place during a EC funded projects: EURACE project between 2006 and 2008: `https://cordis.europa.eu/project/rcn/79429_en.html`. Further enhancements on the model have taken place during another consortium, namely the SYMPHONY project between 2013 - 2016: `https://cordis.europa.eu/project/rcn/110002_en.html`. I have taken part in both consortium as one of its researchers. Gencer and Ozel (2011) disseminates our modelling experience within the first consortium.

[2]Iceace is another SFC macroeconomic model that is inspired by Eurace model. For the project details, its documents and source codes, please see `http://iceace.github.io/home/`.

1.2 A brief on agent based modelling

An agent based model, in very general sense, is one of the simulation techniques on complex systems. Its adoption in the analysis of macroeconomic phenomena goes back to the early years of the availability of digital computers (Dawid and Delli Gatti, 2018). ABM is specifically used for simulating the actions and interactions of autonomous agents. The ABM models or systems are decentralized. That is, there is no centralized and hierarchical control on agents' actions and interactions. These autonomous agents usually don't have a full global view of the system. The systems for which ABM models are employed are too complex for an agent to make practical use of such global level complete knowledge. This limited perception of global information corresponds to bounded rationality concept in economics. Agents are not expected to take globally optimal decisions. Besides, agents in such systems may have different characteristics and behave differently from one another. In ABM terms they are heterogeneous with respect to their attributes and their actions or behaviors.

These foundations of ABM models reflect reality of human behaviors within complex social-economic systems (Secchi, 2017). For instance, consumer choices at buying smartphones are personal yet are influenced by their social circles. In ABM terms, consumers are autonomous but yet they interact and are influenced by their local social environments. In addition, the odds that one collects full information of all smartphones and maximizes the universal utility of a smartphone is extremely low. And utility of a smartphone by itself is subjective. Again in ABM terms, there is also heterogeneity in tastes and limited (bounded) view of the full picture of smartphone market. Besides, agents use simple heuristics and computations in their decision making processes. This simplicity in behaviors or decisions is what differs ABMs from multi-agent systems (M.A.S). Agents in ABMs don't necessarily need to be "intelligent" compared to agents in M.A.S models that are mainly used to solve difficult engineering problems using methodical, functional, procedural approach, algorithmic search or reinforcement learning. In other words, agents in ABMs are not necessarily computationally complex implementations. For instance, in Schelling (1978)'s social segregation model, which is one of the first known agent model, autonomous and adaptive behavior rules are quite simple, yet patterns of interaction and the overall emerging outcome is very powerful at explaining a range of social phenomena. The model shows that a simple preference rule of an agent may result in an interesting and a complex outcome. In the original model, the colored agents move to an empty space on a grid when they observe that more than a certain ratio of their neighbors have a different color than themselves. This simple rule leads to a total segregation at the community level. Likewise, agents in a model on macroeconomics are not expected to have a full understanding of the highly complex outcomes and processes of the entire economy (Branch and McGough, 2018). Like in reality, the agents have limited information on the entire economy and they may not necessarily take optimal decisions.

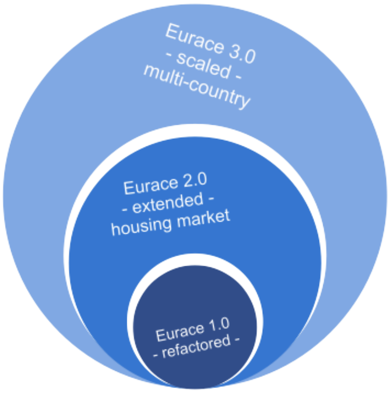
An agent based model designer aims to understand the decision rules of individual agents in certain environments at certain actions. However, extracting simple and sound decision rules is not an easy task. Understanding behaviors of agents in an economy may require the collection of survey data, investigations on market transactions, the analysis of large set of balance sheets and income statements, the conduct of controlled social experiments in the labs, etc.

Depending to context agents can be individual entity or a collective entity such as an organization or a group. The main motivation of employing ABM is to observe and assess effects of simultaneous agent-agent interactions on the system as a whole. ABMs are typically implemented as computer simulations to create a virtual laboratory and test how changes in individual behaviors will affect the system's emerging overall behavior. ABM simulations attempt to re-generate a complex phenomena first to justify validity of the computer model and later use the simulator to predict other appearances of a complex phenomena. The process is called emergence from the lower (micro) level agent-agent interactions to a higher (macro) system level outcome. This notion that simple behavioral rules generate complex behavior is extensively adopted in the modelling community. It combines elements of game theory, complex systems, emergence, computational sociology, multi-agent systems, and evolutionary programming. Monte Carlo methods (Metropolis and Ulam, 1949) are used to introduce randomness. ABMs are used in scientific domains including biology, ecology and social science, and relatively more recently in economics.

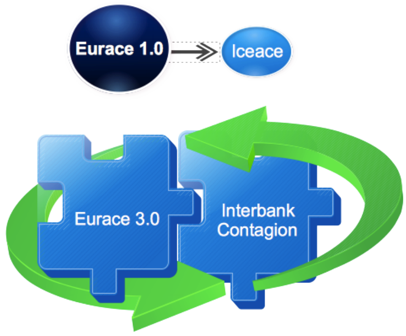
ABMs of macro economy are generally developed to be able to run certain policy scenarios (Nikiforos and Zezza, 2017; Dawid and Delli Gatti, 2018). Conceiving economic phenomena as the emergent results of agents interactions in complex socio-economic and ecological environments, agent-based simulations may improve the understanding of the individual and joint impacts of environmental policies, fiscal policies, monetary policies, banking and financial markets regulation augmenting their capacity of dealing with the profound effects of the financial crisis in an increasing interconnected world, and allowing the policy maker to compare different strategies (Farmer and Foley, 2009). In particular, agents' expectations may considerably reduce or amplify the effects of policy interventions. Economic agents' decision processes are also characterized by bounded rationality and limited information gathering and computational capabilities (Tesfatsion and Judd, 2006). Agents's behavior follows adaptive rules derived from the management literature about firms and banks, and from experimental and behavioral economics of consumers and financial investors.

ABMs, in general, have shown to be able to investigate very important real world features of our economies, such as the link between the real economy and the financial aspects. For example Riccetti et al. (2013) embody both the credit network and the firms' leverage cycle. Delli Gatti et al. (2010) represent characteristics like the networks of credit and ownership relationship among economic agents. In the studies via Eurace model credit networks are formed by the balance-sheet inter-linkages among firms and banks Cincotti et al. (2010a); Teglio et al. (2012b). The Eurace experiments are able to capture rationing, the non-equilibrium outcomes, in markets, in particular the credit rationing. These features have demonstrated the capacity to be able to explain bubbles and crashes in financial markets as well as credit rationing and bankruptcy waves in the real economy.

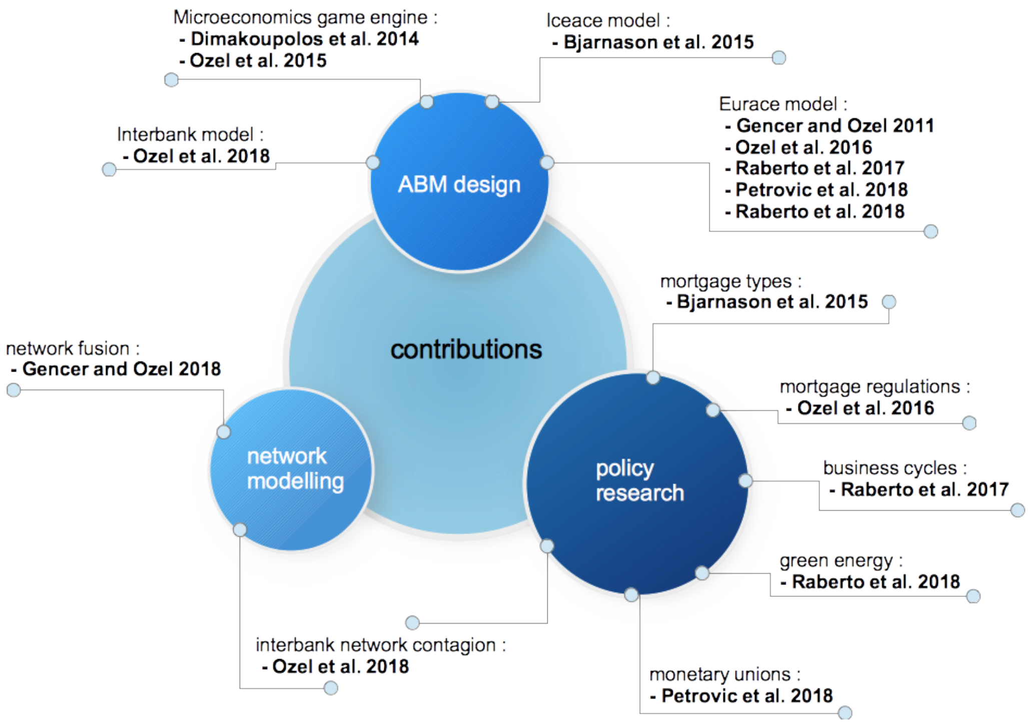
ABMs can be used to test how different economic policies or regulations could impact the economy. For instance, Cincotti et al. (2010a) investigate the implications of the monetary policy on the dynamics of output and prices, while Russo et al. (2007) analyze the role of fiscal policy in promoting R&D investments that may increase economic growth, Dosi et al. (2010) study the influence of economy policies on business cycles fluctuations and long-term growth, and Neuberger and Rissi (2012) analyze the effects of macro-prudential banking regulation on financial stability. ABMs are further adopted to examine information asymmetry and herding in financial markets (Todd et al., 2016; Chen et al., 2017).



(a) Contributions to Eurace model.



(b) Relations across models.



(c) Co-authored papers.

Figure 1.1: Co-authored articles and contributions to the designs and developments of agent-based models in economics. Fig. 1.1a displays contributions to Eurace model from a refactoring work on the base model until creation of a scalable multi-country setup. As upper panel in Fig. 1.1b implies, Iceace model is inspired by the base version of Eurace model. Lower panel in Fig. 1.1b refers to a future research direction where interactions between interbank networks and macroeconomic systems are to be examined. The work reported in Gencer and Ozel (2011) is relevant to the design and development of the very first version of Eurace model which took place prior to this dissertation study. Eurace and Iceace models are implemented in C using FLAME framework; Interbank networks' contagion models is implemented in R adopting and extending its native 'sna', 'network' packages; Interbank networks' fusion model is implemented in Python using 'NetworkX' module. Monte Carlo simulations are run on super or cluster computers.

1.3 Relevant publications

This section lists the contributions in the area during the study that has lead to this dissertation. Figure 1.1 is a graphical summary of the contributions and their relevance to each other.

1.3.1 Housing market regulation

Reference: Bulent Ozel, Reynold Christian Nathanael, Marco Raberto, AndreaTeglio, Silvano Cincotti, 2016. Macroeconomic implications of mortgage loans requirements: an agent based approach. Working Papers 2016/05, Economics Department, Universitat Jaume I, Castellon (Spain).

Summary: In this work we have extended the Eurace agent-based model by designing a housing market with a related mortgage lending device. Our results show that mortgage credits generally helps to increase and stabilize aggregated demand in consumption goods market, thus improving the main economic indicators. However, if the mortgage lending regulation is relaxed too much, by raising the debt-service-to-income ratio (DSTI), then the additional supply of mortgages does not increase the macroeconomic performance any more, and undermines the stability of the economic system. Following some recent discussion, a stock control regulation that targets households net wealth (a stock), instead of income (a flow), is designed and analyzed. Results show that stock control regulation can be effectively combined with DSTI in order to increase the stability of the housing market and of the whole economy. Moreover, stock control regulation exhibits the interesting property to directly affect mortgage distribution among households.

Publication status: The work was submitted to Journal of Evolutionary Economics within 2017. The paper is accepted with minor revisions. It's under a final revision round.

Role and contributions: In this work, my primary role has been designing, implementing and integrating the housing market model within the Eurace model; doing primary research on the literature; and laying out policy experiments. For the written form of the work, I have created the first drafts on motivations, discussions of relevant studies, description and calibration of housing market model, introduction of stock-flow control policy instruments and conclusion sections. Analyses and revisions of the results have been conducted with other co-authors.

1.3.2 A multi-country simulation setup

Reference: Marko Petrovic, Bulent Ozel, Andrea Teglio, Marco Raberto, Silvano Cincotti. "Should I stay or should I go: an agent-based setup for a Monetary Union" Working Papers 2017/09, Economics Department, Universitat Jaume I, Castellon (Spain).

Summary: In this work, our primary objective has been to create a simulation set-up in order to be able to study, for instance, the conditions under which two or more countries can benefit from becoming part of a union. Combining state-of-the art software engineering methodologies and agent-based computational economics, we have designed a complexity-wise scalable and flexible multi-country model, which is able to consider a wide variety of union configurations. In other words, the model enables us to create and control the economic characteristics of the countries joining a union, i.e., the level of integration of its markets, regulations, and institutional bodies. In this first paper, specifically, we have focused on a monetary union structure inspired from the Eurozone. Our results suggest that for similar countries, it is always beneficial to join in a union, although a lack of mobility frictions can weaken its performance. Even if countries have different productivities, the performance of the union is in general better than the performance of the isolated countries. The exception is when the productivity gap between member countries and labor mobility across borders are both too high. In this case, the union can even exacerbate the gap between the member states. We have devised and tested a fiscal pool body to measure to what extend it could alleviate causes of a structural difference, such as high tech and productive North versus a low tech and underdeveloped South, between member states. Our findings suggests that stronger fiscal integration via transfers from surplus countries to deficit countries helps reducing inequality between countries, supporting a sustainability of the monetary union.

Publication status: The first paper out of this work has been submitted to the Journal of Economic Dynamics and Control.

Role and contributions: In this work, my primary role has been leading the design and implementation of a modular and scalable agent based model. An extended version of the closed economy Eurace model has been used as the base model. However, a significant amount of initial effort has been dedicated to re-factor, re-design and re-implement a large part of the base model aiming a theoretically and computationally modular core model. Thus we are able to decouple markets or replace, for example, fiscal policies without a necessity of model re-implementation from scratch. The resulting architecture enables us to configure and initialize a large spectrum of economies. We are able to instantiate economies from a closed economy with or without housing markets, energy sector or financial markets to a global economy of multiple unions, trading or isolated economies where each union or country may have its own housing markets, energy sectors or financial markets. In the first research paper, for instance, we have limited the model to two isolated control-state economies and a two-country monetary union where housing sector and energy sector are turned off and secondary financial markets of securities are excluded.

1.3.3 Housing sector and green finance

Reference: Marco Raberto, Bulent Ozel, Linda Ponta, Andrea Teglio, Silvano Cincotti, 2018. From financial instability to green finance: the role of banking and monetary policies in the Eurace model. Journal of Evolutionary Economics, pp. 1-37, Springer[3].

Summary: In this work, we study macro-prudential policies that may help to stimulate banking sector to shift from speculative lending, the cause of asset bubbles and economic crises, to an energy efficient production technology. Housing market in the adopted model functions as an important destination of speculative credit in the economy. Eurace model in Ozel et al. (2016) is further enhanced for the work. A stylized energy sector is added to the model and

[3] See `https://doi.org/10.1007/s00191-018-0568-2`.

energy efficient capital investment is made possible. In other words, the enhanced model has heterogeneous capital goods, allowing for different degrees of energy efficiency in the production technology. Credit money is endogenous and limited by Basel capital adequacy regulation on the supply side, while on the demand side it is determined by firms' loan requests for investments and households' mortgage requests for house purchasing. As of the regulatory instrument, we have introduced a differentiation of capital requirements according to the destination of lending, demanding higher bank capital in the case of speculative lending via mortgages, thus encouraging banks to finance firm investment. As up-to-date capital goods have better energy efficiency in the model design, a higher pace of investment implies also a positive environmental effect. Results suggest that the proposed regulation is able to foster investments and capital accumulation in the short term, improving the energy efficiency of firms. However, reducing mortgages with a restrictive banking regulation has a negative impact on total private credit, and thus on endogenous money supply, weakening consumption and aggregate demand. In the long term, the contraction of total credit becomes stronger, and the negative outcomes on aggregate demand also affect investment making the energy efficiency become negligible.

Publication status: The paper is accepted and published by Journal of Evolutionary Economics, see Raberto et al. (2018).

Role and contributions: In this work, my primary role has been adopting, calibrating and validating the housing market model that I have lead the design and implementation within the Eurace model (Ozel et al., 2016). In this work, mortgage debt for house purchase is served as a proxy for speculative investments that diverts the credits from productive investments.

1.3.4 Money creation via mortgage credits and business cycles

Reference: Marco Raberto, R.C. Nathanael, Bulent Ozel, Andrea Teglio, Silvano Cincotti. 2017. "Credit-driven business cycles in an agent-based macro model", in H. Hanappi, S.s Katsikides, M. Scholz-Wäckerle (Eds) “Theory and method of evolutionary political economy”, pp. 182-192. Routledge[4].

Summary: In this work, we have particularly focused on the interaction between credit and business cycles. A part of the features of the model that is described in Chapter 2.1 is employed. Here we primarily address importance of mortgage credits from the real estate market on the economy and business cycles. The dynamics of credit money is endogenous and depends on the supply side by the banking system, which is constrained by Basel capital adequacy regulatory provisions, while on the demand side depends on firms financing production activity and households indebtedness for housing needs and speculation. Results point out a non-trivial dependence of real economic variables such as gross domestic product, unemployment rate and aggregate capital stock on banks’ capital adequacy ratios; this dependence is in place due to the credit channel and varies significantly according to the chosen evaluation horizon. In general, regulations allowing for a high leverage of the banking tend to inflate asset bubbles and boost the economy in the short run, while result in bubble bursts and economic depression in the medium and long run. Results also point out that the stock of money is driven by the demand for loans, therefore supporting the theory of endogenous nature of credit money. The study then also clarify the nature of endogenous money, giving a contribution to a debate that has grown stronger over the last two decades.

Publication status: The work is accepted and published as a book chapter, see Raberto et al. (2017).

Role and contributions: In this work, my primary role has been designing and adopting the model to be able to examine the interplay between mortgage credits and business cycles. In collaboration with the co-authors I have contributed to the discussions, analysis of the simulation outputs and initial drafts and further revisions of the written material.

[4]See `https://doi.org/10.4324/9781315470214`

1.3.5 Impact of mortgage instruments on wealth and regulations

Reference: Thorir Bjarnason, Einar Jón Erlingsson, Bulent Ozel, Hlynur Stefánsson, Jón Thor Sturluson, Marco Raberto, 2017. "Macroeconomic effects of varied mortgage instruments studied using agent-based model simulations". Working Papers 2017/10, Economics Department, Universitat Jaume I, Castellon (Spain)[5].

Summary: In this paper, employing Iceace[6] model of a credit network economy we have examined macroeconomic implications of three mortgage instruments. They are (i) an adjusted-rate-mortgaging (ARM) where interest rate follows the rate of the Central Bank plus a constant 2% spread; (ii) an inflation-indexed-mortgaging (IIM) where interest rate is fixed throughout the term and principal indexed to consumer price index (CPI); and (iii) a fixed-rate-mortgaging (FRM) where interest rate is fixed. The Central Bank rate at the moment plus a constant 3% spread is used. Our results suggest that inflation-indexed mortgages can mislead households' expectations of risk, encouraging them to buy more housing due to their low initial amortizations which, in turn, stimulates housing prices. The results further hint that in long-run inflation-indexed mortgages create relatively more uneven housing wealth distribution among households. We also find that the effectiveness of standard monetary policy tools is diminished when inflation-indexed mortgages are used. Banks partake in the interest rate risk with fixed rate mortgages but bear little or no risk with adjustable rate or inflation-indexed mortgages.

Publication status: Working paper. Disseminated via UJI, Economics Department, Working Paper Series. To be submitted to JEIC.

Role and contributions: Iceace is an agent-based computational macroeconomic model that utilizes the balance sheet accounting of economic agents (Erlingsson et al., 2014). The model was inspired by Eurace model however it differs in a number of ways such as firms' production decision schemes and replacement of financial markets with a generic Equity Fund agency. For

[5]See `https://ideas.repec.org/p/jau/wpaper/2017-10.html`.

[6]The FLAME implementation of the model is used. See model description, documentation and implementation at `http://iceace.github.io/home/`.

this work I have designed and implemented the model from scratch adding new mortgaging features that forms the basis of this work. The modelling and implementation details and the source is made available at the project Web site[7]. The first draft of the work was lead by first and the second authors. I have contributed to the later revisions and discussions around the outputs from the simulations.

1.3.6 A simulation model and setup on financial contagions

Reference: Bulent Ozel, Mario Eboli, Andrea Teglio, Andrea Toto. 2018. "Robust-yet-fragile: A simulation model on exposure and concentration at interbank networks" Working Papers 2018/??, Economics Department, Universitat Jaume I, Castellon (Spain).

Summary: For this work, we have developed a layered financial contagion simulator that provides a modular and flexible simulation set-up. It decouples the steps of a research on financial contagion where a cascaded procedure from the network creation to the data analysis is made possible. The current version enables researchers (i) to create an interbank system of a desired network structure, (ii) to initialize bank balance sheets where the network in previous step can optionally be used as an input, (iii) to configure a controlled or randomized sequence of exogenous shock vectors, (iv) to simulate and inspect detailed process of a single contagion process via tables, graphs and plots generated by the simulator, (v) to design and run automated Monte Carlo simulations, (vi) to analyze results of Monte Carlo simulations via tools from the simulation analysis library. We have created a range of stylized and complex network models, such as, star-networks or core-periphery structures with certain network level connectivity and centralization. The simulation results confirm the theoretical conjectures that a medium density of connections in regular networks is already sufficient to induce a 'robust-yet-fragile' response to insolvency shocks, while the same occurs in star networks only when the centralization is very high.

Publication status: Working paper is in second revision by the co-authors.

[7] `http://iceace.github.io/home/`.

Role and contributions: My primary contribution in this work has been designing, implementing and documenting the entire simulation set-up based on the discussions with co-authors and personal desktop research on similar studies in the field. Besides, I have lead the controlled experiment design and analysis which yielded current results. I have also lead the draft of the first complete version of the working paper.

1.3.7 Fusion of economic and financial networks

Reference: Mehmet Gencer and Bulent Ozel. 2018. "Multi-level Fusion of Random Networks". Working Papers 2018/??, Economics Department, Universitat Jaume I, Castellon (Spain).

Summary: This paper concerns the problem of creating random network structures as one of the essential requirements for realistic simulations of complex networks. While the study of random networks is a long standing area of research available methods have significant shortcomings in terms of producing structures that correspond to real networks. Real networks tend to have a 'multi-level' structure which does not lend itself to modeling with a single algebraic scheme. Computational, rather than algebraic, approaches have been explored to address this problem more recently. Our study adds on to this emerging research thread by addressing the problem of abridging multiple levels in random network creation. We focus on the problem of interconnecting two micro level random networks to create a larger network at the macro level. In approaching this problem we develop a method which is driven by certain parameters which represents the characteristics of the final network that results from fusion of lower level networks.

Publication status: Working paper is in final revision by the co-authors.

Role and contributions: My primary contribution has been at problem definition and research design. My collaborator has taken the initiative at its initial implementation and generation of the first draft.

1.3.8 Other published technical reports

- Bulent Ozel, Marko Petrovic, Andrea Teglio, Linda Ponta, Marco Raberto, Andrea Mazzoccheti, Silvano Cincotti, Mauro Gallegati, Ruggero Grilli, Annarita Colasante, Antonio Palestrini, 2015. "Final version of large-scale multi-country agent-based model of the macroeconomy", SYMPHONY Deliverable D3.3: Orchestrating Information Technologies and Global Systems Science for Policy Design and Regulation of a Resilient and Sustainable Global Economy. Contract no.: 611875[8].

  Relevance and role: Conceptual model of a multi-country set-up has been discussed in this project deliverable (Ozel et al., 2015). A major part of the multi-country modelling features from this work has been realized in the work that is presented in Chapter 3. As part of this work, individually, I have lead the conceptualizations of labor mobility dynamics and integration which is to be added to the future versions of the Eurace multi-country set-up.

- Nikos Dimakopoulos, Anna Triantafillou, Panagiotis Kokkinakis, Kostas Giannakakis, Richard Mark Brown, Miha Papler, Luis Rei, Bulent Ozel, Efthimios Bothos, Lex Robinson, Linda Ponta. 2014. "Definition of System Architecture" SYMPHONY Delieverble D52: Orchestrating Information Technologies and Global Systems Science for Policy Design and Regulation of a Resilient and Sustainable Global Economy. Contract no.: 611875[9].

  Relevance and role: The relevant part of my contribution to this system architecture of the SYMPHONY game platform (Dimakopoulos et al., 2014) is the novelty that is presented in Section 3.3.2. In brief, the novelty has enabled us to accommodate real agents' decisions, for instance policy decisions of a human player of the platform, to take over

[8] Earlier versions D3.2 and D3.1 are available at https://cordis.europa.eu/docs/projects/cnect/5/611875/080/deliverables/001-SYMPHONYD31.pdf, https://cordis.europa.eu/docs/projects/cnect/5/611875/080/deliverables/001-SYMPHONYD32.pdf

[9] https://cordis.europa.eu/docs/projects/cnect/5/611875/080/deliverables/001-SYMPHONYD52.pdf

the role of an artificial agent such as one of the centralbank agent from a multi-country set-up. An early version of the multi-country model has been developed and integrated to the platform serving as a turn-based game engine. Another novelty that is introduced in this work has been combining big-data analytics and agent based modelling. Large sets of publicly available social media data has been analyzed by consortium members where a proxy measure for central bank credibility is measured. The measurement is used while calibrating the trading behaviors of households in financial markets.

1.4 Organization of the dissertation

The next Chapter 2 initially discusses details of the primary work as part of this dissertation which is a complete research on the role of housing market in economy at large and its regulation from an ABM approach. It mainly highlights the computational methodology while giving a summary of findings from that first study where we have employed the methodology. Research findings and methodological novelties from the other housing market related works are reported in the rest of the chapter. The second primary work is presented in subsequent Chapter 3. The chapter mainly focuses on the novel modelling design approach for large scale ABMs. Nevertheless, the research findings from the very first study where we have employed the methodology are discussed briefly. The third major contribution is presented in Section 4.1 where a novel model of interbank networks is presented. The results from its initial employment is discussed. Chapter 4, in general, introduces a novel approach with parsimonious modeling parameters to study risk and contagion at interbank networks. Novelties and state-of-the-art methodological experiences from all research activities that are presented in detail or in brief within this dissertation are summarized within Chapter 5. More specifically, the chapter aims to outline design patterns and validation practices for complex, large-scale and reusable ABM models. I conclude summarizing the findings and pointing out a research direction beyond this dissertation.

Chapter 2

Housing market linkages: business cycles, mortgage regulations and types, and green finance

This chapter primarily discusses the role of housing market in economy at large and its regulation from an ABM approach. Details of the base housing market model within Eurace model are presented in Section 2.1. The subsequent sections within the chapter presents summary of results from our other housing market related studies where the base model is employed or adopted. We have specifically examined impact of mortgage credits on business cycles, summarized in Section 2.2. We have investigated macro-prudential policies that may help to stimulate banking sector to shift from speculative lending, the cause of asset bubbles and economic crises, to an energy efficient production technology, summarized in Section 2.3. Finally, we have examined impacts of mortgage types on housing bursts and booms, summarized in Section 2.4. Unlike the other studies in this chapter, the study in this final section adopts a housing market mechanism within Iceace model.

2.1 Design and integration of an housing market within Eurace artificial economy

2.1.1 Motivation

It is well-known that the housing market, with the related mortgage securities, has a crucial role in modern economies. The crisis of 2007 - 2009, triggered by the U.S. real-estate bubble, reconfirms this crucial role and suggests the importance of a mortgage lending regulation. It is now universally recognized that monitoring systemic risk can be misleading if the housing market sector is not properly considered.

We have designed and implemented a housing market within a larger agent-based model along with two complementary mortgage lending instruments. More specifically, we address the role of the housing market in the economy (Muellbauer and Murphy, 2008), by designing a housing sector and a mortgaging mechanism in the Eurace agent-based macroeconomic simulator (Dawid et al., 2008; Cincotti et al., 2010a; Raberto et al., 2012b; Teglio et al., 2012a). The model enables us investigate money injection role of mortgage credits; examine its impacts on real economy; and be able to raise regulatory policy questions under a broader and more realistic simulation setting.

This extended Eurace model includes all major agents of an economy: households, firms, banks, central bank and government. Households may take over the roles of consumers, workers, financial investors, share-holders and house owners. There are two types of firms which are consumption goods producers and capital goods producers. Agents interact in different types of markets, namely, consumption goods market, capital goods market, housing market, labor market, credit market and financial market for stocks and government bonds. Except for the financial market, all markets are characterized by decentralized exchange with price setting behavior on the supply side. Agents' decision processes are characterized by bounded rationality and limited information gathering and computational capabilities (Tesfatsion, 2003; Tesfatsion and Judd, 2006); thus, agents's behavior follows adaptive rules derived from the management literature about firms and banks, and from experimental and behavioral economics of consumers and financial investors.

The extended model enables us to address the crucial issue of the interplay between mortgages to households, loans to firms and business cycles in the economy (Catte et al., 2005; Muellbauer and Murphy, 2008). In this new context, in addition to banks' loans to firms, banks' mortgages to households are considered among the factors connecting the banking sector to the real economy (Gallegati et al., 2008). The dynamics of credit money is endogenous and its supply depends on the banking system, which is constrained by Basel capital adequacy regulatory provisions (Blum and Hellwig, 1995; Santos, 2001), while on the demand side it depends on firms' necessity to finance the production activity and from households' requirements for housing purchase.

Our results show that the presence of an housing market in the model has relevant macroeconomic implications, mainly driven by the additional amount of endogenous money injected into the economy by new mortgages. This additional money generally helps to support and stabilize aggregated demand at consumption goods market, thus improving the main economic indicators. However, if the mortgage lending regulation is relaxed too much, by raising the debt-service-to-income ratio (DSTI), then the additional supply of mortgages does not increase the macroeconomic performance any more, and undermines the stability of economic system. Following some recent discussions, a stock control regulation that targets households net wealth (a stock), instead of income (a flow), is designed and analyzed. Results show that stock control regulation can be effectively combined with DSTI in order to increase the stability of the housing market and of the whole economy. It also exhibits the interesting property to directly affect mortgage distribution among households, avoiding excessive concentration. From a policy perspective, our results suggest that using a mild flow control regulation, when coupled with a stricter stock control measure, fosters a sustainable growth and eases the access to housing for first time buyers, therefore promoting house ownership.

In this chapter, after discussing the motivations behind the work, description of mortgage market model and summary of results will be presented. Before concluding, the methodological novelty of the work will be discussed where an incremental model extension and calibration are practiced without disrupting the existing large-scale base model.

2.1.2 Background and relevant studies

A relatively recent article in Science (Battiston et al., 2016) highlights promising potentials of ABM as an experimental macroeconomic approach. The article also points out its under-utilization. A relevant overview by Richiardi (2015) on the state-of-the-art of agent-based models in economics reports that a major problem that current models suffer is due to the fact that they are not modular or scalable for adding new features or for deactivating an existing component. In this respect, the housing market model within Eurace artificial economy represents a seamless extension to an already highly advanced ABM model, designed as a new module that can be easily switched off. The calibration of the housing market within the Eurace base model is driven by recent surveys (Dubecq and Ghattassi, 2009; Borsch-Supan, 1994; Gharaie et al., 2012; European Central Bank, 2013; Anderson et al., 2014; Deloitte Real Estate, 2014; FinansInspektionen Mortgage Survey, 2014).

In contrast to its acknowledged importance, there are only a few number of other ABM models on housing markets: Gilbert et al. (2009), Ge (2014), Axtell et al. (2014) and Baptista et al. (2016). All of these housing market models are standalone, i.e., they don't interact with the rest of the economy. Their common and main focus is on the mechanisms of housing prices. The simple model by Gilbert et al. (2009) consists of sellers, buyers and real-estate agents. The income of households and any other variables are provided exogenously. A relatively more advanced model by Ge (2014) demonstrates that a loose debt-to-income (DTI) constraint for households leads to a high volatility of housing prices. However, unlike to our model, shocks to the model are applied externally. The model by Axtell et al. (2014) is specifically tailored for the housing market in the city of Washington, D.C. The model is able to generate a housing bubble of approximately the same size as occurred earlier in Washington. The model has a micro level focus on households' real estate purchasing behaviours. The study by Baptista et al. (2016) examines price dynamics given the ratio of renters as well as speculators in a housing market. Their results suggest that a growing size of the renters and speculators increase the price volatility while a regulated market decreases the volatility. They consider a DTI type macro-prudential regulation.

Other than ABM approaches, there are a few relatively recent stock-flow consistent (hereafter SFC) simulation models that analyses macroeconomic implications of the housing markets, such as Zezza (2007, 2008), Nikolaidi (2014), Meijers et al. (2015), and Nikiforos (2016). The SFC approach (Lavoie and Godley, 2012), in these studies and in general, enables an integrated framework for treating the linkages between the real and financial sectors. Zezza (2007, 2008) builds models to explore implications of the housing market boom on wealth distributions among households. The aim is to lay down a growth model, grounded in the postkeynesian SFC approach of Lavoie and Godley (2012) to analyze the links between consumption and saving behaviour at financial markets and at the housing market. There are two classes of households, namely, capitalists and non-capitalists. Each type is modelled by a respective representative agent. Households buy real estate from firms and receive loans from banks. In the version of the model in Zezza (2007), houses produced by firms are valued and sold at the general price level, which is given exogenously, but bought at the real estate price level that differs from the former. Zezza (2008) extends this model to include the interaction with the housing market. In both version, there is theoretically unlimited supply of housing units and mortgage regulation is not addressed. At another relevant study by Nikolaidi (2014), houses are also produced by firms at the general price level but sold and bought at the real estate price level. Meijers et al. (2015), instead, improve these aforementioned models by including relevant open economy characteristics and modelling the financial sector in a more elaborate way. The work extends the model of the banking sector and including housing and mortgages. They model the housing market differently making house prices endogenous, yet they still assume an unlimited stock of exogenous housing units. They show that the more elaborate modelling of the financial sector, also in an open economy context, is a necessary ingredient to explain the vulnerability of the financial sector.

Housing markets in most of the real economies are prone to strong government regulations. The government interferences are generally in the form (i) direct subsidies such as public housing, (ii) tax incentives typically by deduction on mortgage interests, (iii) market regulations via policy instruments (Borsch-Supan, 1994). The claimed objectives of government interventions are threefold. First, governments are aiming at increasing the efficiency of the market and reducing housing driven crises in the economy. Second, their intervention is based on the belief that everybody merits reasonable housing and that society ought to provide a house to an individual who cannot afford it. Third, housing consumption and investment serve as a convenient mechanism to redistribute income and wealth (Case et al., 2009; Bubb and Krishnamurthy, 2015).

Motivational framework for our investigation on mortgage regulation policies are based on the following observations: (i) Historically, housing has been the single largest asset in the economy (Dagher and Fu, 2011; FinansInspektionen Mortgage Survey, 2014). Keeping to be a leading source of financial crises and economic fluctuations, it poses a big regulatory challenge; (ii) Mortgage regulation should operate in a prudential mode rather than as a response to a bubble after it bursts (The Financial Services Authority, 2011); (iii) Regulatory measure should act at the mortgage level. In other words, regulations that are targeting only banks or other financial institutions may not be sufficiently effective. For instance, mortgage risk can move from regulated banks to unregulated shadow banking institutes (Dagher and Fu, 2011); (iv) Access to mortgage should not be too restrictive. A very strict regulation may inhibit the stimulative effect of mortgage credits on the business cycles (Kydland et al., 2012).

Two common ways to assess credit worthiness of individual mortgage requests are the loan-to-value (LTV) or loan-to-income (LTI) measures (The Financial Services Authority, 2011). LTV is the ratio of the requested mortgage to the present value of the house. A LTV value of 1 would mean the purchase is fully covered by credit. Commonly adopted LTI related measures are Debt-To-Income ratio (DTI) and Debt-Service-To-Income-ratio[1] (DSTI). Following the mortgage lead financial crisis of 2007 - 2009, these ratios have been probed extensively by surveys conducted by regulatory institutions such as, among others, the Bank of England (Gareth et al., 2014; Anderson et al., 2014), the Swedish financial supervisory board Finansinspektionen (FinansInspektionen Mortgage Survey, 2014), and the Bank of Canada (Meh et al., 2009).

[1]DSTI is often defined simply as Debt-Service-Ratio (DSR)

The main policy conclusion of these studies is that the mortgage crediting is one of the main factors inflating housing prices. This is often followed by shocks in financial markets and real economy, amplifying feedback loops which may cause the collapse of the economy. The multi-country study by Muellbauer (2012) highlights that "credit supply conditions in the mortgage market are the 'elephant in the room'. Without taking them into account, one simply cannot understand the behaviour of house prices, household debt and consumption." (p. 36).

These survey-based studies are also raising questions regarding the appropriateness of LTV and LTI measures as enforced policy instruments[2]. For instance, one of the key observation of the paper by the Financial Service Authority of UK (The Financial Services Authority, 2011) is that loan-to-value (LTV) and loan-to-income (LTI), when they are the only measures employed, are not very useful to detect and prevent mortgage crises. Anderson et al. (2014) state that allowing mortgage contracts with high debt service ratios (DSTI) would not always trigger mortgage arrears (p. 422). Gareth et al. (2014) points out that the use of DSTI alone may not be reliable in long term, especially when there is a high volatility in the interest rates and housing prices.

Like other researchers, Bubb and Krishnamurthy (2015) point out that a strict LTV as a single regulatory measure may prevent mortgage crisis to a large extent, however, they pinpoint one of the major drawbacks of a strict LTV ratio: "An important objection to a leverage limit is that it might reduce access to homeownership by less wealthy households in contravention of a long standing policy commitment to expanding homeownership" (p. 67). They discuss how a strict LTV would create a barrier to homeownership for the first-time homebuyers who have limited resources to make a downpayment on a house. The book by Case et al. (2009) dedicates two chapters in this line on the access to mortgages for the poor social classes. They point out the necessity for a generic regulatory criteria in order to let lower income households access to mortgages.

Meh et al. (2009) raise a rather more technical concern about the use of LTI type measures. The authors use micro data to identify changes in household debt, and discuss their potential

[2] British parliament approved regulations granting powers to the Financial Policy Committee over housing tools, and specifically regulating residential mortgage lending using loan-to-value LTV and debt-to-income ratio DTI on 25 March 2015. These measures came into force on 6 April 2015.

implications for monetary policy and financial stability. They examine sub-components of assets and liabilities of households' balance sheets. The rationale of their criticism is due to mixture of stock and flow variables within an LTI type measure, where in general households' total mortgage debt, a 'stock' entry on their balance sheet, is related to households' disposable income, a 'flow' entry in their monthly income statement (Skingsley, 2007).

The concerns around LTV and LTI measures have been leading to new discussions for identifying relevant measures in order to evaluate the risk of individual household's mortgage debts[3]. Earlier, Meh et al. (2009) suggested to compare a stock entry to another stock entry of households' balance sheet (e.g., debt-to-asset ratio) to assess the long-term vulnerability. Other authorities (The Financial Services Authority, 2011) conclude that there is no simple quantitative rule, proposing to look into other measures where for instance consumption expenditures and current payments of households are considered. Svensson (2014b) proposes to use the net-worth ratio on a household's balance sheet in order to assess his credibility. This is qualitatively the same measure as the one suggested by Meh et al. (2009).

Why LTV measure is not considered in our study? (1) In long term, it increases inequality in housing wealth and hence social inequality which is against the principals of a welfare approach. (2) It has a less stimulative impact on the overall consumption. It is seen that at an individual level accumulation of housing wealth doesn't have a very strong impact on the consumption level (Muellbauer, 2012). A strict LTV policy may cause allocation of housing stocks in the hands of a minority, which in return indirectly could reduce overall consumption level that would inhibit stimulating impact of mortgage credit on GDP growth. (3) It creates a barrier for the first time buyers and low-income level households. (4) From a simulation research point it is not interesting.

Why a standard LTI or DTI measure is not considered in our study? (1) Empirical studies show that DTI does not explain the occurrence of crises (2) It is a short-sighted evaluation. It disregards (a) drop in housing prices, where a fire sell case may even not be able to cover the

[3] See the speech "The household debt ratio is an unsuitable risk measure - there are much better ones" delivered by Lars E.O. Svensson, a Resident Scholar at IMF (https://larseosvensson.se/2014/05/19/the-household-debt-ratio-is-an-unsuitable-risk-measure-there-are-much-better-ones/).

remaining unpaid principal debt; (b) it is susceptible to interest rates fluctuations; (3) it is a mixture of flow vs stock control.

2.1.3 Eurace: The base ABM model

At this part of the work, we have employed the large-scale agent-based model and simulator Eurace, which represents a fully integrated economy consisting of a real sector, a credit sector, a financial sector and a public sector. The model is a stock-flow consistent model since its initial design, and the stock-flow consistency (Lavoie and Godley, 2012; Nikiforos and Zezza, 2017) is ensured at all stages: design, update, initialization and run-time. The Eurace model includes different types of agents: households, consumption good producers (hereafter CGPs), banks, a capital goods producer (hereafter KGP), a government and a central bank. Agents interact through several markets, i.e. consumption and capital goods markets, labor market, credit market, and a financial market where households exchange stocks (i.e. the claims on firms/banks net worth and future dividends) and government bonds in a centralized Walrasian financial market. A detailed description of the base model, –its theoretical and methodological assumptions, behavioral rules, market mechanisms etc,– has been given in Teglio et al. (2018). In this study, we have enriched the base Eurace model by introducing housing assets, mortgage lending and a housing market. Households are endowed with equal number of homogeneous housing units that they can trade in the housing market. Households can also take mortgages from banks to buy new housing units from other households that creates –heterogeneity in house ownership–. Details are available below in Section 2.1.4.

We outline the complex set of interactions in the model by reporting two key matrices in Tables 2.1 and 2.2. The first one is the balance sheet matrix and describes all assets and liabilities for each class of agents. The second one, Table 2.2, represents the transaction flow matrix, showing all the monetary flows among agents. This approach allows to check the consistency at any time step between stocks and flows in the model, both at the level of the single agent and at the aggregate one. This is in line also with post-Keynesian stock-flow-consistent modelling approach, see e.g. Caverzas and Godin (2015). We believe that this is a critical feature, in particular in a model where the creation/destruction of the endogenous money stock plays a crucial role in determining economic activity.

In the following sections we describe some of the main behavioral rules and decision making mechanisms which are more relevant to this work. The dynamical change of balance sheet variables depends on agents' individual decisions and on the result of agents interaction within the different markets.

The scheduling of agents' decisions and events

The elementary simulation time step is the calendar day, but most of agents' decisions and economic events happen with different periodicity and are generally asynchronous. For instance, the financial market is active daily, the housing market is active monthly[4], consumption budget decisions are made monthly but purchases are made weekly, firms' decisions about production planning, new hirings, pricing, investments and financing are monthly. Finally, decisions by policy makers can be monthly, quarterly or yearly. In particular, the policy rate is set monthly and tax rates are adjusted yearly.

Consumption goods producers

We provide here a compact sequential list of the more relevant decisions made by the firms in the model. More details can be found in Teglio et al. (2018). Expected values are denoted with the superscript e, while desired values will be marked by a hat, e.g. $\widehat{x}$, on a variable symbol. Each firm, indicated with the subscript f, makes its decision asynchronously, according to its activation day, on the following list of variables:

- the expected demand of consumption goods $q^e_{C_f}$ based on a linear interpolation of past T_C monthly sales;
- the desired level of inventories $\widehat{I_f}$ to meet expected demand $q^e_{C_f}$;

[4] A calendar month is defined as a set of 20 days where a calendar week is 5 days.

- the production $\bar{q}_{C_f}$ that is needed to accumulate the desired level of inventories $\widehat{I}_f$, i.e., $\bar{q}_{C_f} = \max[0, \widehat{I}_f - I_f]$;
- the production plan $\widehat{q}_{C_f}$ as a linear combination[5] of production needs $\bar{q}_{C_f}$ and previous month production q_{C_f}, i.e., $\widehat{q}_{C_f} = \lambda \bar{q}_{C_f} + (1-\lambda) q_{C_f}$;
- the labor force $\widehat{N}_f$ needed and the amount of physical capital $\widehat{K}_f$ needed to meet the desired production plan, given the present endowment of capital goods K_f, the present number of employees N_f, and a Cobb-Douglas production technology[6];
- the myopic labor demand N_f^d given by the difference, if not negative, between the needed labor force $\widehat{N}_f$ and the present number of employees N_f; labor demand fully depends on the one-step forward expected demand of consumption goods, considering the current level of capital as given;
- the planned investment in new capital goods $\widehat{\Delta K}_f$, bounded by the difference $\widehat{K}_f - K_f$, comparing the price of capital goods p_K and the present value of the foreseen additional revenues generated by the investment; firms adjust investment demand, according to the discounted long-term expected cash flows;
- the total financial needs $\widehat{M}_f$ given by the foreseen cost of planned capital goods investments $p_K \widehat{\Delta K}_f$, planned labor costs $w_f \widehat{N}_f$, debt interests $\mathscr{I}_f$ and repayment $\delta_D D_f$, taxes $\mathscr{T}_f$ and the foreseen dividend payout $n_{E_f} d_f$, i.e.,

$$\widehat{M}_f = p_K \widehat{\Delta K}_f + w \widehat{N}_f + \mathscr{I}_f + \mathscr{T}_f + n_{E_f} d_f \, ; \tag{2.1}$$

  where δ_D is the monthly fraction of debt repayment and, considering the yearly interest rate r_{f,b_i} paid by firm f on its i-th debt of amount D_{f,b_i} to bank b, monthly debt interests payments are given by $\mathscr{I}_f = \sum_{b,i} \frac{r_{f,b_i}}{12} D_{f,b_i}$;

[5]This provision is aimed to smooth the production plan over time and then reduce oscillations of input demand.

[6]Cobb-Douglas production function is widely used in economics literature. However, Leontief is more often adopted in ABM models including our Iceace model, e.g., see Section 2.4 where we have examined impact of mortgage types. As it is pointed out in Section 5.2.2, replacing Cobb-Douglas production function with Leontief or another production function according to an underlying conceptual design would be quite simple.

- the amount of new loan $\widehat{\ell}_f$ requested to the banking system, given by the difference between $\widehat{M_f}$ and present liquidity M_f;
- the amount of new shares Δn_{E_f} to issue in the stock market if the firm is rationed in the credit market, i.e., the new loan ℓ_f received is lower than $\widehat{\ell}_f$;
- (in the case of rationing in the stock market) the reduction up to zero, in priority order, of the total dividend payout, the investment plan and, eventually, the production plan, in order to make the total financial needs consistent with available liquidity[7].

Finally, firms complete the production process that, following a Cobb-Douglas technology, delivers an amount of new consumption goods q_{C_f} given by the new levels of labor N_f and capital K_f. The new produced goods are summed to present inventories and made available for sale to households during the 20 business days following firms' activation days. Finally, the new sale price p_{C_f} is set based on a fixed mark-up μ_C on the overall unit costs c_{u_f}. At the end of the 20-th day, the day before the activation day of the new calendar month, each firm compute the income statement of the month and updates its balance sheet[8].

Banks

Banks are always active on a daily basis being ready to receive loans requests from firms and mortgage demands from households. In this section we describe the interaction between banks and firms, while the novel part concerning mortgages to households for house purchase will be described in more detail in Section 2.1.4. As outlined in the previous paragraph, each firm sends a loan request at its activation day and firms' activation days are uniformly distributed during the calendar month. Whenever a bank receive a loan request $\widehat{\ell}_f$ by a firm f, the request is evaluated and a loan eventually offered according to the following steps:

[7]If the available liquidity is not even sufficient to meet compulsory payments, i.e. debt service and taxes, then the firm enters a process called illiquidity bankruptcy, where the firm fire all workers and stay inactive till it is able to raise the necessary funds in the stock market.

[8]In particular, each firm updates the value of its net worth and if the equity becomes negative the firm is declared insolvent. In that case, it enters a special process termed insolvency bankruptcy, where the firm fires all workers, undergoes a restructuring of its debt with a related loan write-off and a corresponding equity loss on creditor banks' balance sheets, and stays inactive for a period of time after which it enters again the market with a healthy balance sheet. Physical capital of insolvent firms is therefore not lost but remains inactive for a while.

- the bank assesses the risk of the new loan, first, by estimating the default probability π_{D_f} of the prospective borrower, based on firm' leverage along the lines of the Moody's KMV model (Saunders and Allen, 2010), then by assessing the risk weight $\omega_{\widehat{\ell}_f}$ of the new loan through an ad-hoc cubic function that approximates the so-called Basel II internal ratings approach, after considering its graphical representation, as in Yeh et al. (2005), i.e.,

$$\pi_{D_f} = \frac{D_f + \widehat{\ell}_f}{D_f + \widehat{\ell}_f + E_f} \qquad \omega_{\widehat{\ell}_f} = 2.5\big(\pi_{D_f}\big)^3 . \tag{2.2}$$

  The rationale is that the lower is the capital base of the borrower with respect to its debt, the higher is the likelihood of default, and then the loan's risk, because of possible equity losses due to negative earnings;

- the bank b checks if its risk-weighted portfolio of total loans (including mortgages) plus the new prospective loan, weighted by its risk, still fulfills regulatory capital requirements, i.e. if the following condition holds:

$$E_b \geq \Psi\Big(\sum_i \omega_{\ell_i} \ell_i + \omega_{\widehat{\ell}_f} \widehat{\ell}_f\Big) ; \tag{2.3}$$

  where Ψ is a policy parameter, ranging from 0 to 1, set by the regulatory provisions of the banking system;

- the bank b rejects the loan requests or otherwise it offers to firm f a loan amount $\ell_{b,f} \leq \widehat{\ell}_f$ to the extent the capital requirement condition of Eq. 2.3 is satisfied. In any case, the new loan is offered for a duration of T_ℓ months at a yearly interest rate $r_{b,f}$, given by central bank rate plus a risk premium depending on the estimated loan risk ω_{ℓ_f}.

The firm sending the loan request ranks the loan offers received according to their interest rates, and accept the loan offers characterized by the lowest rates up to the amount of money requested.

At the end of any calendar month, each bank computes its income statement along with income taxes and net earnings, then decides the dividends payout to be paid each first day of the calendar month, and updates its balance sheet. All net earnings, if positive, are paid out as dividends, unless the bank had to decline loan requests because of the regulatory capital requirements constraint. In this case, the bank retains all net earnings to increase its equity base.

Households

Households are potentially active on a daily basis in the financial market, accessing the market according to a given participation probability. If unemployed, they also look for new jobs on a daily basis. Their activity in the housing market, instead, is on a monthly basis, and more details are provided in Section 2.1.4.

In particular, at any daily simulation step, each household decides to change the allocation of its financial asset portfolio with given exogenously probability π_H. If selected, the household forms beliefs about the expected returns of all financial assets (firms' share and government bond) according a weighted average of fundamentalist, random and chartist prototype expected return formation, compute the new "optimal" asset allocation according to preference structure based on myopic loss aversion hypothesis taken from prospect theory (see Raberto et al. (2008); Benartzi and Thaler (1995) for further details), and then issue buy and sell orders to get its desired optimal allocation.

After financial market transactions are closed, unemployed households enter the labor market, where each household evaluates job offers and applies to the set of jobs characterized by the highest wages provided that they are higher than its reservation wage[9]. If the household is not successful in getting a new job, it decreases its reservation wage by a constant rate δ_w and then starts a new cycle of job offers evaluation/application. If the job search is again unsuccessful, the household decreases again its reservation wage by the same rate δ_w and stays

[9]The reservation wage is set to the latest received wage and then is heterogeneous among households

unemployed till next day when it will start a new cycle.

Employed households receive their salary from their employers on a monthly basis but at different days which coincide with firms' activation days, which are the times when they are hired. Salaries w_f are equal among the employees of the same firm f but differentiate among firms, according to the labor market outcome, as firms raise their wage offer if unable to find the needed employees. Households employed in the public sector receive from the government a public wage w_g, which is set equal to the average wage in the private sector in the last 12 months. Unemployed households receive on a monthly basis from the government an unemployed benefit[10] which is paid the same day of the month the household is fired. The day of the month a households receive the salary or the unemployment benefit, it gets also a transfer payment[11] y_{T_h} from the government and computes and pays taxes on both labor/unemployment benefits income y_{L_h} and capital income (stocks' dividends y_{E_h} and bonds' coupons y_{B_h} received during the previous 20 business days). The same day the household receives its labor/unemployment benefit income, it also determines its monthly consumption budget $\mathscr{C}_h$, which is modelled according to the theory of buffer-stock saving behavior (Carroll, 2001; Deaton, 1992), which states that households consumption depends on a precautionary saving motive, determined by a target ratio ω_C of liquid wealth[12] W_h to total net income before mortgage related payments $y_{h,\text{net}}$. In particular, the total net income is given by:

$$y_{h,\text{net}} = (1-\tau_L)\, y_{L_h} + (1-\tau_K)\left(y_{B_h} + y_{B_h}\right); \tag{2.4}$$

where τ_L and τ_K are the tax rates on labor and capital income, respectively. The monthly consumption budget then is determined by:

$$\mathscr{C}_h = y_{h,\text{net}} - m_{U,h} + \xi_C\Big(W_h - \omega_C\, y_{h,\text{net}}\Big), \tag{2.5}$$

[10]The unemployment benefit is set at a fraction ξ_U of the latest salary received by the households

[11]The transfer payment is set to a fraction ξ_T of the average wage among households

[12]The liquid wealth is given liquidity plus the market value of the stocks and government bonds portfolio.

where $m_{U,h}$ is the household's mortgage related payments, and ξ_C gives the speed of adjustment of consumption to meet the desired wealth to income target ratio.

Centralbank

The central bank is in charge of monetary policy and, on a monthly basis, it sets the policy rate, which is the cost of liquidity provided to banks. In particular, at the beginning of each month, the central bank collects the information about the latest values of inflation and unemployment in the Eurace economy and sets the interest rate r_{CB} for the incoming month as follows:

$$r_{CB} = \pi_C + r^* + \omega_\pi \left(\pi_C - \widehat{\pi}_C \right) + \omega_\upsilon \left(\widehat{\upsilon}_N - \upsilon_N \right), \qquad (2.6)$$

where π_C is the yearly-to-date inflation rate, r^* is the assumed real interest rate, $\widehat{\pi}_C$ is the inflation target, $\widehat{\upsilon}_N$ is the unemployment target, and υ_N is the previous month unemployment rate.

It is worth noting that Eq. 2.6 resembles the well known Taylor rule (Taylor, 1993), but departs from the standard one for the use of the unemployment rate, and then of a sort of unemployment gap, instead of the output gap. The reason of this choice is practical as it is not obvious, in particular in an agent-based model, how the output gap could be measured. However, the two measures are clearly strongly interconnected and the unemployment gap used in Eq. 2.6 is certainly a satisfactory indicator of economic recession.

Another role of the central bank is the provision of a standing facility to grant liquidity in infinite supply to commercial banks, when they are in short supply.

Government

The government is in charge of fiscal and welfare policies. The revenues of the government come from taxes that are applied to four sources: corporate earnings, consumption, capital income (dividends and bond coupons) and labour income (wages and unemployment benefits).

Taxes are collected on a monthly basis, while the four related tax rates are usually revised yearly, depending on the particular fiscal policy adopted.

Governments expenditures include the labor cost of public sector employees[13], unemployment benefits, transfers and government bond coupons. On a monthly basis, if in short of liquidity, the government decides to issue new bonds, which are directly sold in the bond market at a discounted price with respect to the market price p_G, and then purchased by households. In case of a budget surplus, the government can repurchase its bonds entering the market by offering a higher price with respect to the market price p_G. The government determines the quantity of bonds to issue or to repurchase on a monthly basis, but there is a smoothing across the month. Government enters the bond market on a daily basis. Government bonds are perpetuities that pay a monthly fixed coupon that depends on the bond nominal value $\widehat{p}_G$ and the fixed nominal yearly interest rate r_G. Government bonds are traded in a centralized Walrasian financial market. The clearing mechanism determines the market price of the bonds. Government bond market price depends on the trading behavior of households, which discount future bond coupons with the central bank policy rate.

[13]The number of public employees is set at a fixed percentage ξ_G of the total household population.

	Non-Financial Private Agents (NFPAs)				Policy Makers		
Sectors / Agents	**Hous (H)**	**CGPs (F)**	**KGP (K)**	**Banks (B)**	**Gov(G)**	**Central Bank (CB)**	Σ
Tangible Capital	$+X_H\ p_X$	$+K_F\ p_K$					$+X_h\ p_X$ $+K_F\ p_K$
Inventories		$+I_F\ p_c$					$+I_F\ p_c$
Debt(-) / Credit(+)	–Mortgages	–Loans		+Loans +Mortgages $-\text{Loans}_{CB}$		$+\text{Loans}_{CB}$	0
Liquidity:							
NFPA	$+M_H$	$+M_F$	$+M_K$	$-D_B$			0
Banks/Gov				$+M_B$	$+M_G$	$-\ D_{CB}$	0
Central Bank						$+\text{M}_{CB}$ $-\text{Fiat}_{CB}$	$+\text{M}_{CB,0}$
Gov Bonds	$+n_G^H\ p_G$				$-n_G\ p_G$	$+n_G^{CB}\ p_G$	0
Equity Shares (+) / Net worth (-)	$+\Sigma_f n_{E_f} p_{E_f}$ $+n_{E_k} p_{E_k}$ $+\Sigma_b n_{E_b} p_{E_b}$ $-E_H$	$-E_F$	$-E_K$	$-E_B$	$-E_G$	$-E_C B$	$+\Sigma_f n_{E_f} p_{E_f} - E_F$ $+n_{E_k} p_{E_k} - E_K$ $+\Sigma_b n_{E_b} p_{E_b} - E_B$ $-E_H - E_G - E_{CB}$
Σ	0	0	0	0	0	0	0

*Table 2.1: **Sectorial balance sheet matrix**. A plus (minus) sign corresponds to agents' assets (liabilities) and each column can be read as the aggregated balance sheet of a specific sector (e.g. households). Rows show assets and claims of assets among sectors, thus generally adding up to zero. Exceptions are the value of capital ($K_F\ p_K$), housing units ($X_H\ p_X$) and inventories ($K_F\ p_K$), and households' equity shares, which are issued by CGPs, KGP and banks and do not add up to zero because of the difference between market price and book value. Note that CGP stands for Consumption Goods Producer and KGP stands for Capital Goods Producer.*

		Households (H)	**CGPs (F)**	**KGP (K)**	**Banks (B)**	**Government (G)**	**Central Bank (CB)**	**Σ**
Current Account	Consumption	–	+					0
	Wages	+	–	–		–		0
	Transfers	+				–		0
	Investment		–	+				0
	Taxes	–	–	–	–	+		0
	Dividends	+	–	–	–			0
	Coupons	+				–	+	0
	CB coupons payback					+	–	0
	Banks loan interests		–		+			0
	Banks mortgage interests	–			+			0
	Banks mortgage principal payments	–			+			0
	CB loans interests				–		+	0
	CB interests payback				+		–	0
		=	=	=	=	=	=	
	Net cash flow	Savings	Profits	Profits	Profits	Surplus	Seignoirage	0
Capital Account	Net cash flow	+Savings	+Profits	+Profits	+Profits	+Surplus	+Seignoirage	0
	Δ Capital		$+\Sigma_f \Delta K_f p_K$	$-\Delta K_K p_K$				0
	Δ Loans	+Δ Mortgages	+Δ Loans		–Δ Mortgages –Δ Loans +Δ Loans_{CB}		–Δ Loans_{CB}	0
	Δ Issue of new shares / bonds	$-\Sigma_f p_{E_f} \Delta n_{E_f}$ $-p_{E_G} \Delta n_{E_G}$	$+\Sigma_f p_{E_f} \Delta n_{E_f}$			$+p_{E_G} \Delta n_{E_G}$		0
	Δ Quantitative easing	$+p_{E_G} \Delta n_{E_G}^{QE}$					$-p_{E_G} \Delta n_{E_G}^{QE}$	0
	Δ Private Liquidity & Δ Banks' deposits	$-\Delta M_H$	$-\Delta M_F$	$-\Delta M_K$	$+\Delta D_B$			0
	Δ Banks / Public Liquidity & Δ Central bank deposits				$-\Delta M_B$	$-\Delta M_G$	$+\Delta D_{CB}$	0
	Δ CB Liquidity / Δ Fiat Money						$+\Delta M_{CB} - \Delta \text{Fiat}_{CB}$	0
	Σ	0	0	0	0	0	0	

Table 2.2: ***Sectorial transaction flow matrix****. The current account describes the flows of revenues (plus sign) and payments (minus sign) that agents get and make. Agents are reported in the columns and monetary flows are reported in the rows. The result of agents' sector transactions is the net cash flow. The capital account section describes the balance sheets changes related to each sector. Subscripts represent the index of the agent to which the stock refers. Uppercase subscripts are used when the stock refers to a whole sector, whereas lowercase subscripts are used when it refers to a single agent (for instance in the case of sums). Finally, superscript characters are introduced when the balance sheet counterpart is more than one single sector. The households column, for example, shows the generation of households' savings in the current account part. Then, in the capital account part, it is shown that savings plus the received mortgages, plus the money received by the central bank for QE ($+p_{E_G}\Delta n_{E_G}^{QE}$) are used to buy a higher bond/stock endowment ($-\Sigma_f p_{E_f}\Delta n_{E_f} - \Sigma_f p_{E_f}\Delta n_{E_f}$) or to "buy" new deposits ($-\Delta M_H$).*

2.1.4 Housing market extension

This extended version of the model integrates a housing market into the Eurace artificial economy. It designs and implements a mortgaging mechanism, which enables us to explore the role of the housing market in the economy and its impact on business cycles. Besides, this extended model enables us to conduct and analyze various housing market regulatory policies. The extension covers (i) households' seller and buyer behaviors at the housing market, (ii) a house pricing mechanism, (iii) households' mortgage requests and banks' mortgage lending behavior, (iv) and households' mortgage default conditions and their consequences.

The housing market is active on the first day of every calendar month. Households are activated in the market with an exogenous probability Φ_H, to assume randomly the role of buyer or seller with equal likelihood. The reason of this random selection is that we are more interested in the credit aspects of housing market, and its impact on the economy as a whole. However, we allow also for a special case, called fire sale case, where households enter the housing market because they are financially distressed and are forced to sell their houses at a discounted price with respect to the last average market price p_H. In any case, households are allowed to sell a housing unit only if they own at least two of them, i.e., households cannot become homeless.

The market is a posted price market with decentralized exchange, and households can sell or buy one housing unit at a time. If a household h is randomly picked to enter the housing market with a seller role, she/he posts one of her/his housing units for sale at price p_{H_h} given by:

$$p_{H_h} = p_H(1 + \xi\, \varphi_H)\,, \tag{2.7}$$

where ξ is a random draw from uniform distribution between 0 and 1 and φ_H is the maximum percentage price increase of housing price with respect to the previous month average price p_H. Conversely, if a household h is financially distressed, she/he posts one of her/his housing unit for sale at price p_{H_h} given by:

$$p_{H_h} = p_H(1 - \xi \, \varphi_S), \tag{2.8}$$

where ξ is a random draw from uniform distribution between 0 and 1 and φ_S is the maximum fire sale price reduction. The rationale behind Eq. 2.8 is that financially distressed households post their housing units for sale at a discounted price to increase the likelihood of a transaction to be able to reduce their indebtedness and future mortgage payments. Conversely, we stipulate that normal seller households don't have any particular necessity to liquidate their housing units and therefore are willing to sell only if they can realize a small random gain with respect to the last housing market price p_H.

For the clearing, buyers are randomly queued. Each buyer in the queue takes turn one by one aiming the cheapest available housing unit. The housing units in the model are homogeneous. A transaction takes place only when the buyer has the necessary financial resources or is able to get a mortgage from a bank. Then the transaction takes place with the price posted by the seller. The housing market closes when all buyers have had their turn or there are no more houses for sale. The monthly housing price of the market p_H is the average of the realized transaction prices within the month.

Mortgage lending

We consider variable rate mortgages where the annualized rate r_H is determined at the beginning of each month as the central bank interest rate, r_{CB}, see Table 2.3, plus a fixed spread:

$$r_H^t = r_{CB}^t + r_H^0, \tag{2.9}$$

Mortgage payments are monthly and they spread over T_M years. Monthly mortgage payments R_n of each mortgage n include both the interests and the principal installment, where the latter is fixed for each mortgage and determined by the ratio between the initial mortgage amount and mortgage duration in months. Monthly interest payments are computed on the outstanding mortgage principal according to the mortgage rate r_H^t which follows the central bank interest rate, r_{CB}^t.

Regulation measures and policies

Buyers may use their cash to buy housing units or, if they do not have enough liquidity, they request mortgages from banks. However, in the experiments for this study, the households are financing the whole housing purchase by credit money, that is loan-to-value (LTV) ratio is set to 1. See the next section for more details. It should be noted that banks are able to provide mortgages only if they fulfill the capital adequacy conditions imposed by the regulator, as in equation 2.3. Banks evaluate mortgage requests according to the following two alternative criteria.

- **Flow Control - Constraints on housing debt payment ratio**: This measure is widely known as DSTI, the debt service to income (Svensson, 2014a). The ratio of mortgage payment of a household to her disposable income is used to check her credibility. In other words, banks evaluate applicants capability to face mortgage repayments before granting it. In particular, banks compare household's net income[1] (both labor and capital) earned in the last quarter with household's expected quarterly mortgage payments, including both old outstanding mortgages and the new requested mortgage. The measure primes the repayment performance of a household and enables us to relate a flow, the mortgage payment, to another flow, the disposable income. In the simulations, it is referred as β policy parameter. A household's quarterly mortgage payment, $m_{U,h}^q$, and her quarterly net income, $y_{net,h}^q$, is used to check her credibility. The credibility of a household is checked against a housing budget constraint parameter, β, as follows:

$$\frac{m_{U,h}^q}{y_{net,h}^q} \leq \beta. \tag{2.10}$$

[1]Table 2.1 and Table 2.2 in the Appendix reports a household's income and her/his wealth.

- **Stock Control - Constraints on household's net wealth ratio**: Household's net wealth (equity, E_h) over total wealth (assets, A_h) is used as a stock-control measure. If this ratio is high enough, the household is able to request the mortgage. In our current implementation, the stock control parameter is called equity to asset ratio (ETA) and it is labeled as γ. Under this regulation, households' net wealth is considered as an insurance in case of default or repayment difficulties. The wealth of the household is computed after the mortgage request, in order to keep into account the impact of the mortgage amount on household's balance sheet; wealth includes the value of housing units, financial assets, and bank deposits. To request the mortgage, households must satisfy this condition:

$$\frac{E_h}{A_h} \geq \gamma. \tag{2.11}$$

From the lending side, a bank's equity and volume of its risky assets is used to compute its leverage. The maximum leverage for the bank is regulated by central bank. In the model, a bank needs to satisfy Basel II accords as it has been the case in base Eurace artificial economy. It is typically a capital adequacy ratio of, i.e. 8%. That is, with that specific value, ratio of risk valued assets of a bank to equity of a bank should be less than 12.5. However, this value can be adjusted dynamically and endogenously by the central bank during a simulation run time. The adjustment can be tailored according to an experimentation policy. For instance, status of total private debt in the economy or unemployment level can be used to adjust the maximum allowed leverage. An additional safety buffer ratio such as 0.75% can be further added to have a tighter capital control.

Lending out mortgage is assumed to increase financial risk of a bank. Upon a mortgage request there are two criteria to be fulfilled before the requested mortgage is released. First, the household needs to pass credibility evaluation before placing the request. The criteria, depending on the policy in place, can be either via the stock control or via the flow control or both. Second, the bank should still be able to preserve its capital adequacy after delivery of the requested amount.

Mortgage defaults - Debt restructuring: A household is financially distressed if the ratio of quarterly mortgage payments to quarterly net labor plus capital income, that is the debt service to income ratio of the household h, is higher than a given threshold $\beta_h \geq \Psi_S$. A financial stressed household is forced to go to housing market as a fire seller as described above in Equation 2.8. If the total mortgage payments of a household exceeds a larger threshold $\beta_h \geq \Psi_W > \Psi_S$, then the household undergoes a mortgage restructuring with a consequent loss on the equity of the respective bank. Instead of a complete write-off, households' mortgage is restructured by a Ψ_R ratio:

$$\hat{L}_h = \Psi_R L_h \tag{2.12}$$

The restructuring mechanism allows a gradual burden on banking considering the probability that a household may recover from financial stress. For the sake of simplicity and control on model dynamics, in this study, mortgage restructuring does not imply a direct housing asset ownership from households to banks. From a balance-sheet stock consistency point, this implies a direct and corresponding reduction on the creditors' wealth (equity). For the calibrated values of these thresholds please refer to Table 2.3.

Calibration of the housing market within Eurace

A typical challenge of any agent based modelling is to be able calibrate model's parameters and to initialize model's population in a way that is theoretically and empirically acceptable and relevant to the focus of the study. In this work, parameters and variables of housing market mechanisms are incorporated into Eurace artificial economy staying within the domain of empirically observed patterns. Table 2.3 summarizes calibration of housing market parameters within Eurace model.

The population size in the Eurace model is constant and so it is the number of housing units in the model. Each housing unit is identical to others and can not be transacted partially. At the initialization phase of the model, each household is assigned a fixed and equal number of such housing units. The re-allocation of the housing units within the economy is governed endogenously via housing market. Households' are able to acquire a new housing unit one at a time only when they are active at housing market and if they are eligible to get a full mortgage that covers whole value of the housing unit to be bought. In other terms, loan-to-value (LTV) ratio is set to 1. From a behavioral modeling perspective, this simplification enables us to observe endogenous money creation in a clearer manner and to examine the direct impact of different mortgage eligibility criteria on the economy. It should be noted that in reality a household's decision to invest in housing assets is complex and multifaceted. It may involve complicated and diverse asset portfolios due to various saving and consumption decisions, expectations or speculations regarding returns on housing units, etc.

The repayment of bank loans has two components, i.e., a monthly principal payment and a monthly interest payment. The duration of a mortgage loan is fixed and calibrated as outlined below. Each monthly principal installment is constant and is spread over whole loan duration. The interest payment on remaining installments is adjusted to the latest central bank interest announcement plus a fixed cap of 1%.

We make a set of assumptions in order to determine the initial housing unit price and the initial ratio of housing assets to total assets of a household, as well as for determining the mortgage loan duration in the model. These assumptions are based on empirical facts. In order to set the initial housing price, we observe the ratio of housing prices to average yearly wage income in European urban areas. The majority of these ratios, until the end of 2013, lie in between 4 and 12 (Deloitte Real Estate, 2014; FinansInspektionen Mortgage Survey, 2014). Based on this observation, we have picked a median rate, which is equal to 8. In the Eurace artificial economy the initial average yearly wage is $12 \times w_f^0$, where w_f^0 is average start-up wage offered by firms. This allows us to set a housing value which is equivalent to $8 \times 12 \times w_f^0 = 96 w_f^0$. Recent surveys hint that a 'healthy' debt to income ratio should be around one third of disposable income (Meh et al., 2009; Anderson et al., 2014). This is also the most general rate which is used by banks at determining the allowable loan amount for a mortgage requests (Dubecq and Ghattassi, 2009; Borsch-Supan, 1994; Gharaie et al., 2012). Accordingly, we have estimated that households are able to use up to one third of their net disposable income

Symbol	Description	Value
β	Debt Service To Income (DSTI)	0.0 to 0.6
γ	Equity To Assets ratio (ETA)	0.6 to 0.8
φ_H	Maximum selling price increase	0.025
φ_S	Maximum fire sale price reduction	0.05
Ψ_S	DSTI threshold for fire sale triggering	0.6
Ψ_W	DSTI threshold for mortgage write-off triggering	0.7
Ψ_R	Mortgage re-structuring ratio	0.75
r_H^0	Mortgage spread on top of r_{CB}^t	0.01
Φ_H	Housing market entrance exogenous probability	0.5
w_f^0	Initial wage of firms	1
X_h^0	Initial amount of housing units per household	5
P_H^0	Initial price of one housing unit	$20w_f^0$
PtW^0	Initial ratio of housing prices to average yearly wage income	8
T_M	Mortgage duration in years	30
LTV	Ratio of housing value covered by mortgages	1

Table 2.3: Calibration of Housing Market parameters. The upper row block denotes the range of regulation parameters used during the policy experiments. The lower row block tabulates the calibrated initializations of housing market related parameters, where w_f^0 is the initial average yearly wage. The initial reference wage level of base Eurace model is used to set the values for the rest of housing market parameters. For details of calibration process see Section 2.1.4.

to serve their mortgage payments. Assuming that 80% of households' gross wage is disposable, we have identified $12 \times 0.8 \times 1/3 = 3.2w_f^0$ as a valid debt service level per year. This implies that in the Eurace artificial economy $96/3.2 = 30\,years$ is a reasonable loan duration. In a relatively stable economy, applying a 4% mortgage interest rate is acceptable. This rounds up to an initial housing value which is equivalent of $100w_f^0$. Looking at the components of household assets of several large survey data, it can be seen that real estate assets form around half of the total assets of households (Meh et al., 2009). This is also the composition of households' assets in the Eurace artificial economy: initial household's wealth in Eurace, excluding real estate, is approximately $100w_f^0$. Hence, a housing value allocation of $100w_f^0$, is in line with empirical patterns. The initial housing assets of the household are divided into 5 tradable units, and the market price of each unit is set to $20w_f^0$. An overall summary of the initialization of the relevant parameters of the housing market is reported in Table 2.3.

2.1.5 Results

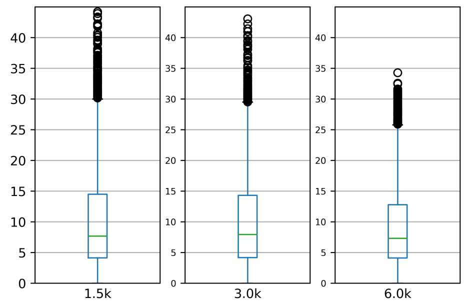
The artificial economy is populated by 3000 households, 50 consumption goods producers, 1 investment good producer, 1 government, 3 banks, and 1 central bank. For each combination of parameters that are under investigation the economy is simulated for 30 years. Each simulation run, corresponding to a different parameter set, is performed with 50 different seeds of a random number generator.

Sensitivity of the results to differing population size has been checked. An additional set of simulations are run where we have used double big and half small population sizes while keeping all other parameters constant. Figure 2.1 demonstrates the stability as of key exemplary variables. The statistical tests, reported in the figure, demonstrate that economic performance indicators are statistically stable against differing population sizes.

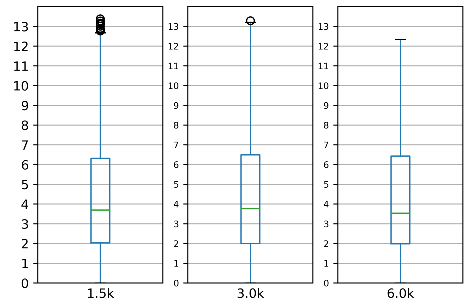
Results are presented in two steps. The first step, in Section 2.1.5, explains the macroeconomic effects of designing an housing market and a related mortgage market into the Eurace model. The second step, in Section 2.1.5, describes how regulation (or deregulation) of banks mortgages affects the housing market performance and, in general, the main economic indicators.

The housing market role in the economy

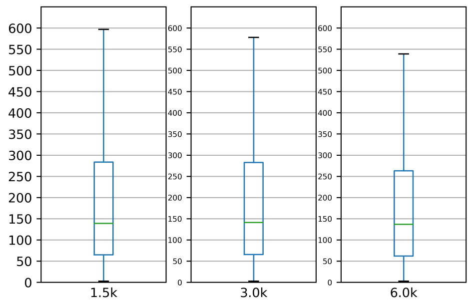
In the baseline version of the model, households are endowed with a fixed number of housing units but they have no possibility to buy new housing units or to sell them, meaning that the housing market is frozen, or nonexistent. This baseline version of the model corresponds to a required debt service to-income ratio (DSTI) equal to zero: households are never eligible for a mortgage and are therefore unable to enter the housing market (see Section 2.1.4). For values of the required DSTI higher than zero, households are able to obtain mortgages from banks, according to their expectation to be able to pay them back. Higher DSTI requirements mean a looser banking regulation and an easiest access to bank credit.



(a) GDP per capita. ANOVA: F-value = 0.27, p-value = 0.76.

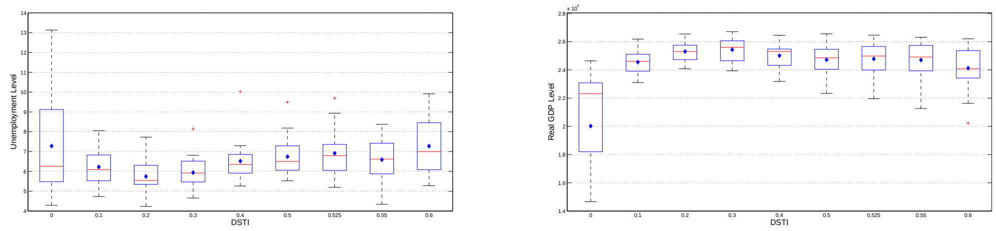


(b) Wages. ANOVA: F-value = 1.25, p-value = 0.29.



(c) Mortgage per capita. ANOVA: F-value = 0.014, p-value = 0.98.

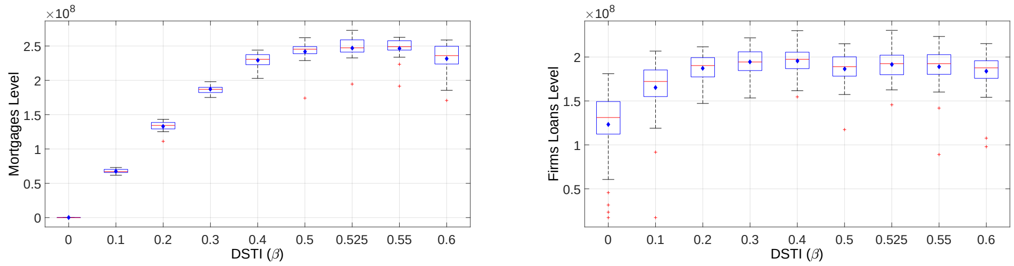
Figure 2.1: Sensitivity test to differing population sizes. The results presented in the paper are based on a population with 3000 households. We have run new simulations with double and half population sizes while keeping all other parameters constant (As of key policy parameters, ETA = 0.7 and DSTI = 0.3 are used in all of the seeds for this sensitivity analyses. In the actual experiments where we present results with 3000 households running using 50 different seeds for each parameter configuration, DSTI is varied from 0 to 0.6 and ETA is varied from 0.6 to 0.8). For each population we have run simulations with 10 different seeds. The plots are distributions from key exemplary variables. We have conducted ANOVA tests to compare outcomes. The box-plots and the test results demonstrate that results are statistical stable against differing population sizes. The same pattern has been observed in other variables that are not displayed here. Nevertheless, the box-plots hint observation of fewer outliers as we double the population sizes.



(a) Unemployment Level

(b) Real GDP Level

Figure 2.2: Unemployment and real GDP over different DSTI. The line that divides each box into two halves is the median value, where each half corresponds to a quartile of the underlining distribution. The diamond shaped point denotes the mean of the distribution. All observations from the entire run time of each simulation seed are used for the calculation of the values that determine the shape of the box-plot and hence the distribution of the observed variable. This applies to all of the box-plots in this paper.



(a) Mortgages Level

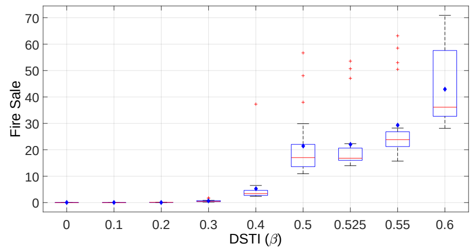
(b) Loans Level

Figure 2.3: Mortgages and firms'loans over different DSTI. Figure 2.3a is the level of the mortgage in the economy. Figure 2.3b is total loans level in the economy.

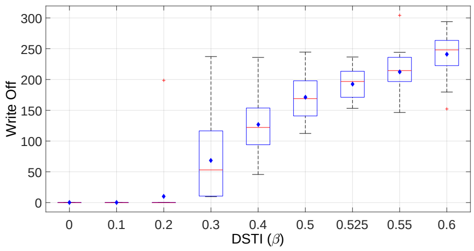
Figures from 2.2a to 2.6b summarize in box-plots[2] the effect of different DSTI requirements on the main indicators of the economy. In this section we focus on the first two values of DSTI$= 0$ and DSTI$= 0.1$, which highlight the transition from an economy without housing (and mortgage) market to an economy with housing (and mortgage) market. The economic impact of different regulation strategies, i.e., higher or lower DSTIs, will be discussed in the next section.

In order to understand the housing market role in the economy we show also some sample trajectories of several aggregated variables like loans, consumption and unemployment. Figures from 2.7 to 2.11 show these trajectories for three selected values of DSTI. Again, we will focus for the moment on the difference between an economy with or without housing market,

[2]Please note that on each box-plot displayed in this paper, the line that divides each box into two halves is the median value, where each half corresponds to a quartile of the underlining distribution. The diamond shaped point denotes the mean of the distribution. All observations from the entire run time of each simulation seed are used for the calculation of the values that determine the shape of the box-plot and hence the distribution of the observed variable.

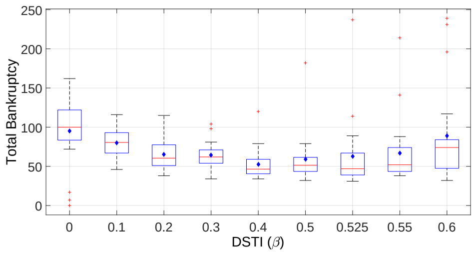


(a) Housing fire sales

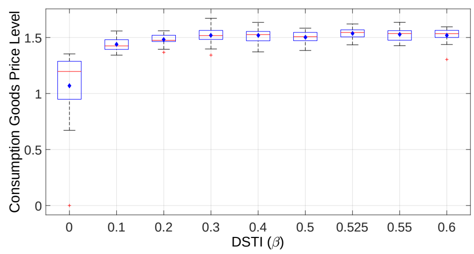


(b) Mortgage write-offs

Figure 2.4: Fire sales and debt write-off over different DSTI. Figure 2.4a is the the total fire sale cases in the housing market. Figure 2.4b is total mortgage write-offs in the economy.

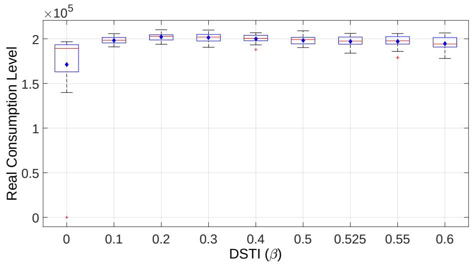


(a) Total Bankruptcies

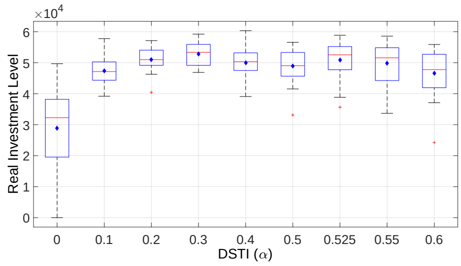


(b) Consumption goods price

Figure 2.5: Total firms' bankruptcies and price level over different DSTI. Figure 2.5a is the bankruptcies occurrences. Figure 2.5b is the consumption goods price level.



(a) Real consumption



(b) Real investment

Figure 2.6: Real consumption and investments over different DSTI. Figure 2.6a is the level of real consumption. Figure 2.6b is the level of real investments.

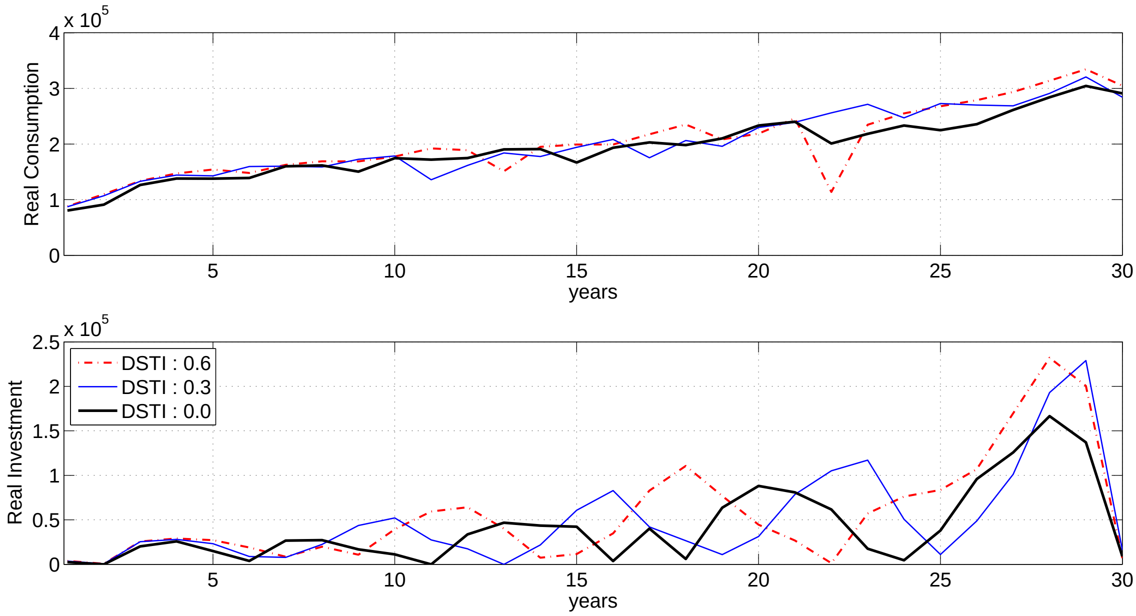


Figure 2.7: Time trajectories of real consumption (upper panel) and real investment (lower panel) over different DSTI(β) values. The figure demonstrates time trajectories for a specific random seed, i.e. a single simulation, presenting interaction between consumption and investment.

i.e., DSTI equal to zero or different from zero. The time series of these plots correspond to a specific random seed, whereas the aforementioned box-plots represent all the set of used seeds for the simulations.

By visually analyzing the sample time series, it clearly emerges that the presence of a mortgage market increases money supply. Figure 2.8 shows that for positive DSTIs banks start to grant mortgages and the total amount of credit in the economy raises. This higher credit amount affects on one side the money supply (bank deposits on Figure 2.9) and on the other side the housing price (Figure 2.10).

These results are still valid if we observe the whole set of simulations. Figure 2.3a shows that the mortgage level becomes positive when DSTI departs from zero (compare DSTI $= 0$ and $= 0.1$). In general, all features observed in the time series plot for one seed are confirmed in the box-plots for all seeds.

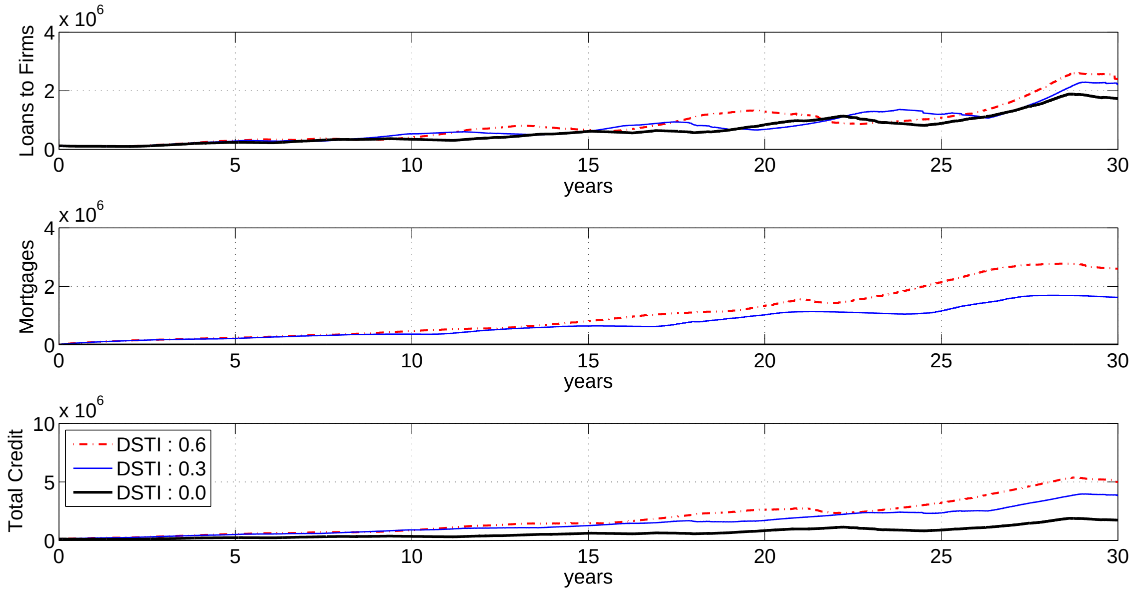


Figure 2.8: Time trajectories of firms loans (top panel), mortgages (middle panel), and total credit (bottom panel) over different DSTI(β) values.

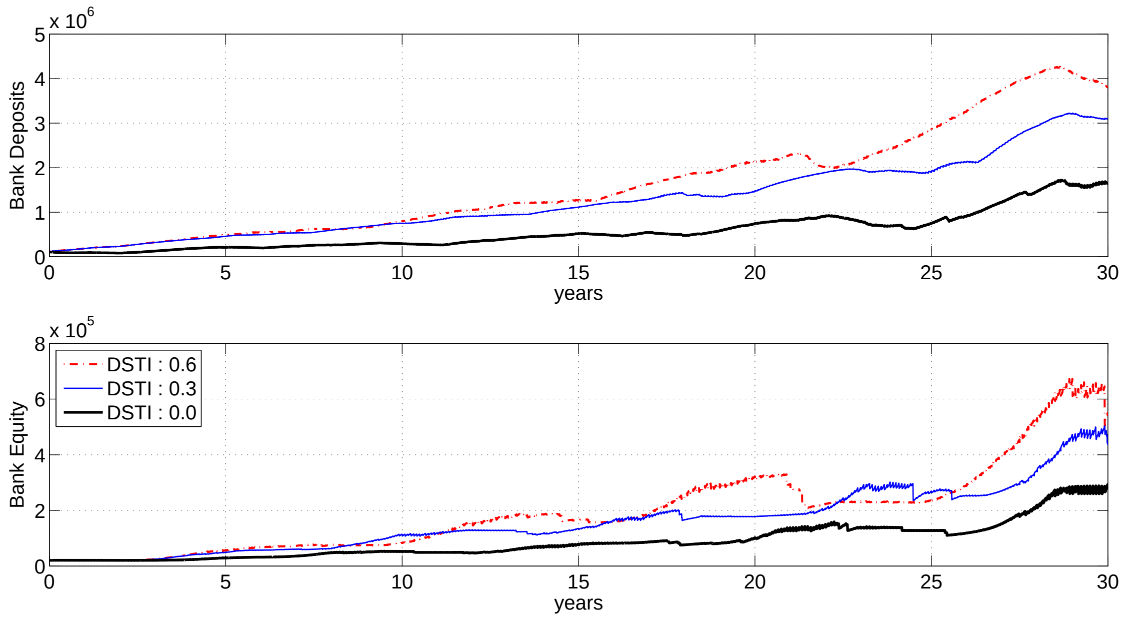


Figure 2.9: Time trajectories of bank deposits and bank equities over different DSTI(β) values.

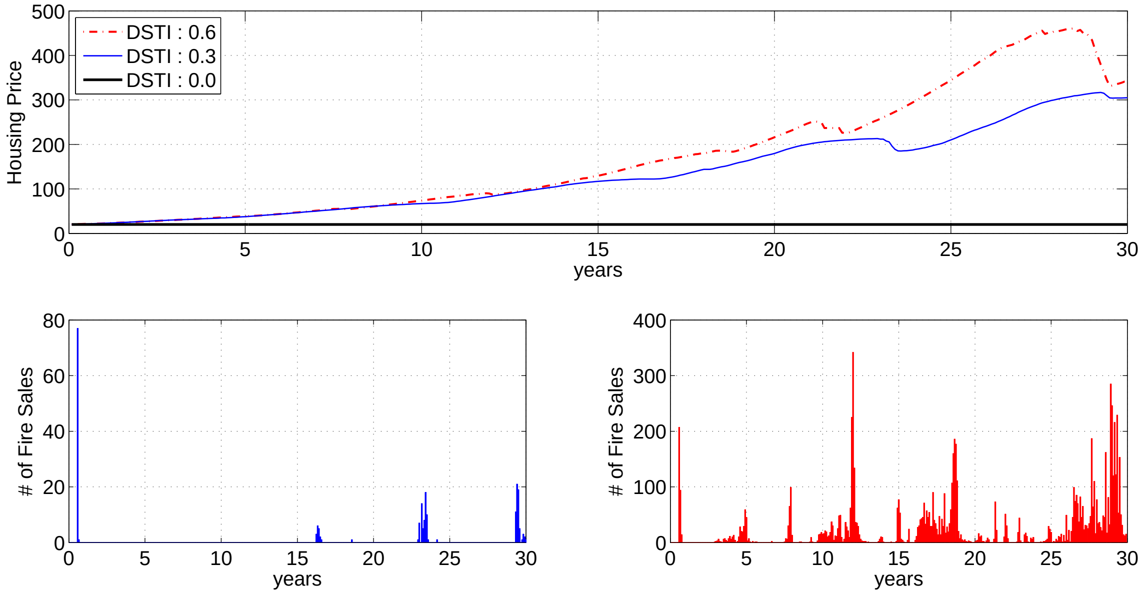


Figure 2.10: Housing unit prices and fire sales. The bottom left panel displays fire sale cases when DSTI(β) = 0.3. The bottom right panel reveals increased fire sale cases with DSTI (β) = 0.6.

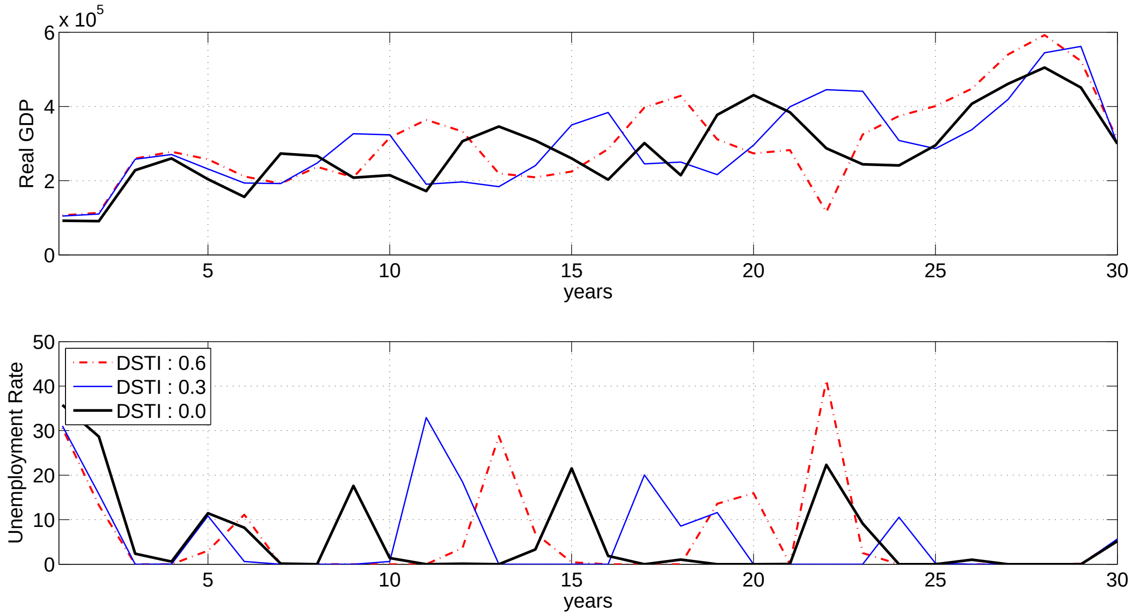


Figure 2.11: Time trajectories of real GDP and unemployment rates over different DSTI, β, values. The figure demonstrates time trajectories for a specific random seed, i.e. a single simulation, presenting interaction between the production capacity and the level of employment.

The mortgage-driven endogenous monetary expansion The mortgages granted by banks directly affect households deposits. As it is well known[3], whenever a bank gives a mortgage, it simultaneously creates a matching deposit in borrower's bank account, thereby creating new money, which is finally transfered to the deposit of the household who is selling the house. This endogenous money creation mechanism affects households aggregated demand, sustaining consumption. From Figure 2.6a we see that the level of real consumption is higher when the endogenous creation of money is reinforced by the existence of banks mortgages (DSTI ≥ 0.1).

In equation 2.5 we can see how the new endogenous money created by mortgages is channeled into the real economy through households consumption. Mortgage money ends into the payment accounts of the house sellers, raising their liquidity. Households' consumption in the model is not affected directly by housing ownership, i.e., the individual desired level of consumption does not depend explicitly on households housing assets[4]. However, the higher liquidity in households' deposits creates a buffer that helps households to achieve their desired consumption level, both in boom and recession periods [5]. This effect can be observed by comparing the higher stability of consumption across different simulation seeds in Figure 2.6a. The reduction in dispersion between DSTI$= 0$ and DSTI$= 0.1$ shows the role of endogenous money in stabilizing consumption, apart from increasing its average level.

Looking at Figure 2.5b we observe a similar situation for consumption price levels. The money injection, due to new mortgages (from DSTI$= 0$ to DSTI$= 0.1$), raises the level of prices but also increases the stability of prices, given a more stable consumption goods demand pattern.

Supporting aggregated demand improves firms sales, giving more resources for investments to firms. Comparing box-plots of real investments and firms loans between DSTI$= 0$ and DSTI$= 0.1$, it emerges that higher consumption (i.e., higher sales) affects firms investment

[3] See for instance the Bank of England Quarterly Bulletin 2014 Q1

[4] See (Muellbauer, 2012). It demonstrates that housing wealth does not have a very strong impact on the consumption level. The study is based on data from developed countries.

[5] Households consumption depends on a precautionary saving motive, determined by a target ratio ω_C of liquid wealth W_h to total net income y_h^{net} (see equation 2.5)

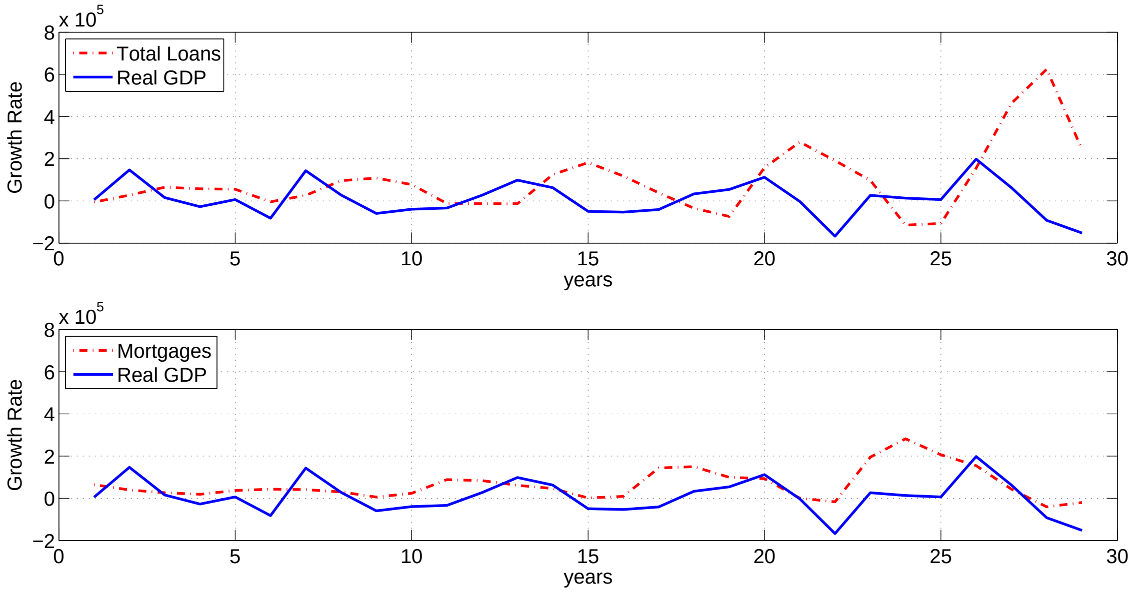


Figure 2.12: Time trajectories of the growth in GDP, loans to firms, and mortgages to households within Eurace Artificial Economy. Sample time trajectories hints that GDP growth leads the growth in loans to consumption goods producers (upper panel) while it lags the growth in mortgages to the households (lower panel). For the cross correlation of the dynamics see Figure 2.13.

decision and, consequently, raises the level of loans requested by firms and granted by banks. See Figure 2.6b for investments and Figure 2.3b for firm loans.

Therefore, real GDP is positively affected by the presence of an housing market in the Eurace economy, both in terms of total production and of economic stability, measured here by the dispersion level around the median. Observing the unemployment rate we draw similar conclusion. The average rate of unemployment (the diamond in Figure 2.2a) decreases from DSTI$= 0$ to DSTI$= 0.1$, as it does the variability across different simulations seeds. This, again, suggests that the additional amount of endogenous money created by mortgages tends to stabilize the main economic indicators, including the employment rate.

Stylized facts on credit and GDP We have shown that the presence of mortgages affects consumption and sales, which in turn stimulate investments and firms loans demand. This propagation mechanism is actually confirmed by empirical evidence. In the past three decades, within the Eurozone, growth rates of loans to firms revealed a relatively stable relationships with the business cycle (European Central Bank, 2013). The growth rate of loans to non-

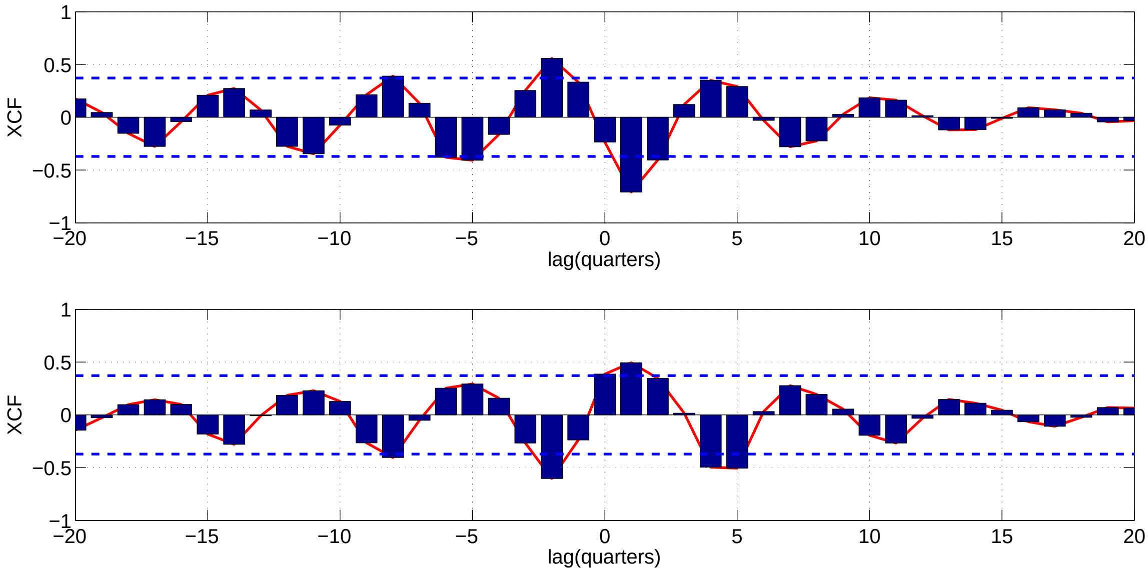


Figure 2.13: The dynamic relationship between loans, mortgages and the business cycle in the model. The upper panel denotes the cross correlation between total Loan and Real GDP, while the lower panel displays the cross correlation between Mortgages and Real GDP. Note that GDP growth leads when lags have − signs and it lags when they have + signs.

financial corporations tend to lag real GDP fluctuations. On the other side, mortgages to households exhibit a correlation with real GDP growth and lead the cycle slightly [6]. Our computational results in Figure 2.13 show similar patterns. The figure demonstrates the dynamic relationship between loans, mortgages and the business cycle in the model.

The upper plot in Figure 2.12 and 2.13 suggests that loans to the private sector lag GDP growth. The phase difference is observed to be around 2 quarters. This phase difference we observe in the Eurace model is somewhat shorter than the differences that have been observed in empirical data, where it can go up to one year. This difference may be explained by the modeling simplifications where firm agents' responses to aggregate demand variation are shorter. The lower panel in the same figure displays a clear lead of mortgages to business cycles. This lead of mortgages can partly be explained by the already mentioned mechanism where any housing transaction causes injection of money in the economy whose size is proportional to the value of the housing unit.

[6]For a recent overview, see the box "Stylized Facts of Money" in European Central Bank (2013)

The lagging pattern of loans to firms over the business cycle may suggest that during recoveries firms can first finance investment expenditure using their internal funds, as cash flows improve during a recovery, and only later they seek for external financing (as suggested by European Central Bank (2013)). On the other way around, it may also indicate that during recessions the reduction of banks equity capital caused by firms defaults prevents further loan issuing, due to Basel II restrictions.

The lead of mortgages confirms that mortgages produce an injection of liquidity to households and hence an increase in demand, production, and GDP growth. This, in turn, increases demand for investment at producers' side, which leads them to request more loans from the banking sector. Overall, what we observe is a pattern of systematic responses, where money creation via mortgages is responded by a growth in GDP and later an increase in loan requests for further investment in productions. A comparison of upper and lower panels in Figures 2.12 and 2.13 clearly reveals this dynamics.

Mortgage lending regulations

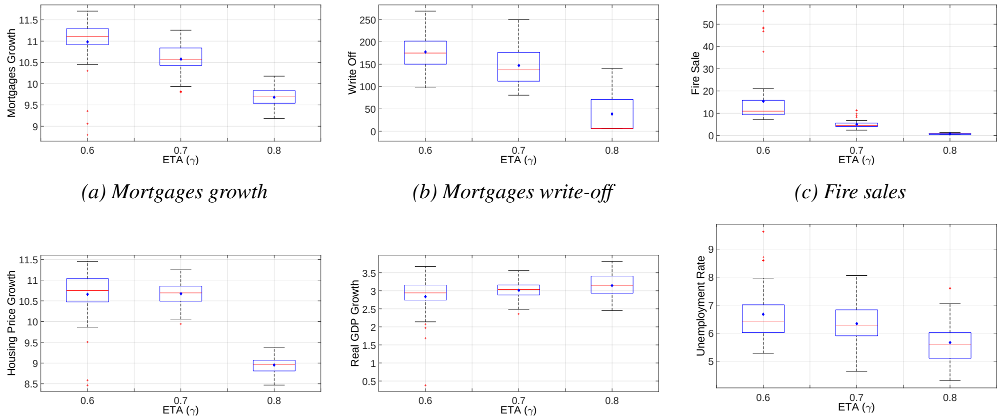
In previous sections, the impact of housing market in the Eurace model has been described, showing the central role of endogenous money creation triggered by the mortgage market activation. However, a legitimate question arises: to what extent an increasing amount of mortgages, corresponding to an easier and less regulated access to credit, improves the economic performance and stabilizes the economy? In order to answer this question, we gradually relax the financial constraints of the mortgage lending regulation, allowing households with higher debt-to-income ratios (DSTI) to receive credit from banks. This relaxation of credit constraints is associated with the increase of DSTI threshold, i.e, when DSTI is high enough also citizens with low income with respect to the debt service are eligible for a mortgage. A high value of DSTI could also be labeled as sub-prime lending, recalling the recent housing market crisis in the U.S.

Looking at the box-plot figures, resuming results for all seeds, we can try to give an answer to the question. Figure 2.3a shows that the total amount of mortgages in the economy is sharply raising up to a certain level of DSTI (around 0.4), but it tends to stabilize or to even decline afterward. Mortgages overtake total loans from DSTI = 0.4, but at the same time they boost the level of loans in the economy for low DSTI, as shown in Figure 2.3b. The same pattern is confirmed for bank deposits in Figure 2.9, which do not increase any more when regulation becomes too loose. On the other hand, the stability of the housing market is seriously undermined by a loose regulation, as shown in Figure 2.4a and Figure 2.4b. When credit is given to fragile, or sub-prime borrowers, the number of housing units fire-sales increases, driving down the housing price and triggering many debt write-off, that in turn damage banks equity capital.

This propagation mechanism can be observed both in the box-plots and in the time trajectories. Looking at the loosest regulation case (See DSTI = 0.6 on box-plots in Figures 2.4a, 2.4b, 2.5a, and time series in Figure 2.9 and Figure 2.10), a clear time structure can be observed. Fire sales tend to increase in the last part of a boom, causing a crash of the housing price and, afterwards, a strong reduction in banks equity and therefore in banks financial stability. Through the channel of the reduced lending capacity of banks, also real economy can be affected, as the two crisis around year 21 and year 29 clearly show.

We can summarize that the benefit of additional endogenous money creation is no more relevant after a certain DSTI threshold, i.e., bank deposits grow quickly up to DSTI = 0.3, and then stabilize. On the other hand for higher DSTI the economy becomes more unstable; the average number of total firms defaults in Figure 2.5a has a parabolic shape with a minimum value around DSTI = 0.4. In particular, the considerable difference between mean and median for high DSTI values suggests the presence of simulation seeds with disastrous outcomes in terms of firms defaults chains.

Looking at real GDP in Figure 2.2b a slight decreasing trend can be observed from DSTI = 0.3 onward. A similar pattern is followed, i.e., by the unemployment rate and by the GDP components, consumption and investments, etc. Figures 2.11 and 2.7, respectively, demonstrate the patterns as of exemplary single runs . Therefore, our results suggest that the positive



(a) Mortgages growth *(b) Mortgages write-off* *(c) Fire sales*

(d) House price growth *(e) Real GDP growth* *(f) Unemployment rate*

Figure 2.14: Stock control, ETA(γ), regulations when coupled with a flow control regulation of DSTI(β) $= 0.5$. For a detailed comparison as of different combinations of γ and β see Table 2.4 and Table 2.5

effects related to the introduction of an housing market mechanism in the economy become weaker when the regulation of mortgage loans becomes too loose.

Stock Flow Control Role in Housing Market We finally consider in our analysis the impact of banking regulation on mortgages based on stock control rather than flow control. We already introduced the recent debate on this subject, and we present here some results obtained with the Eurace model. We recall that, according to the stock control regulation, a household will get a mortgage if its net wealth over total wealth ratio (ETA, i.e., Equity over Total Assets) is higher than a threshold γ. Therefore, if γ is high the regulation is tighter, and households with high debt with respect to their total wealth are less likely to get a new loan.

We explore three stock control policies, tightening for increasing γ values (from 0.6 to 0.8) combined with three flow control policy, i.e., DSTI, tightening for decreasing β values (from 0.5 to 0.3), for a total of nine different policies. Table 2.5 shows the values of the main economic indicators for each policy combination, while Table 2.4 focuses on indicators strictly related to the housing/mortgage market. Figures 2.14 shows a set of box-plots comparing the impact of the three stock control policies in the case of a threshold $\beta = 0.5$ for flow control

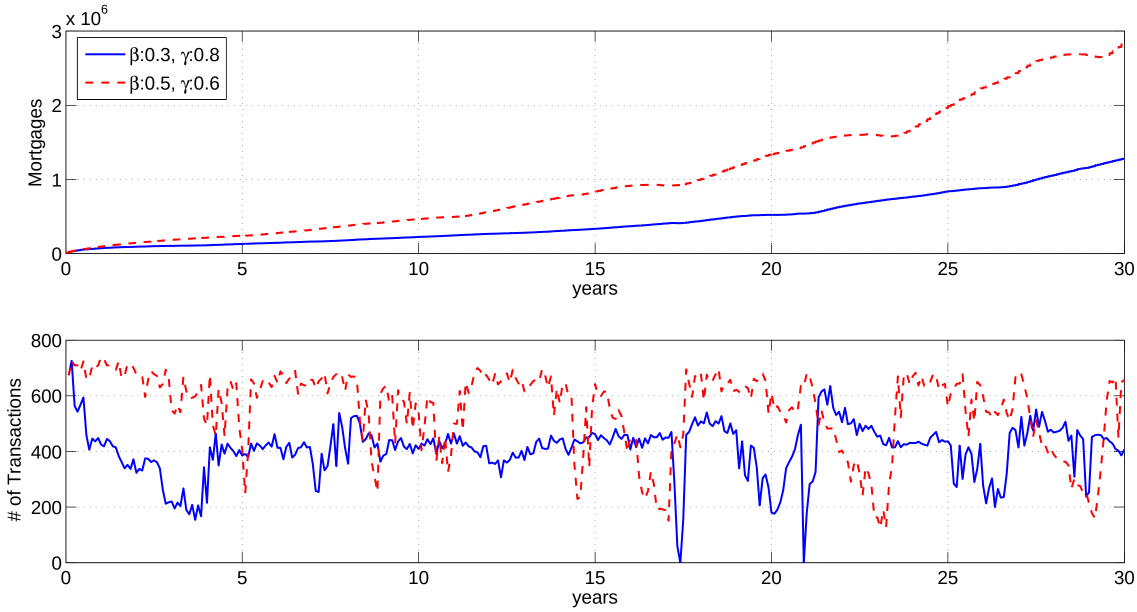


Figure 2.15: A sample time trajectory, i.e., from a single seed, comparing impacts of combined loose vs strict regulatory policies on Mortgage Levels and Number of Transactions in housing market. Strict policy control is denoted by the solid line (—) and loose policy control is denoted by strip line (- -)

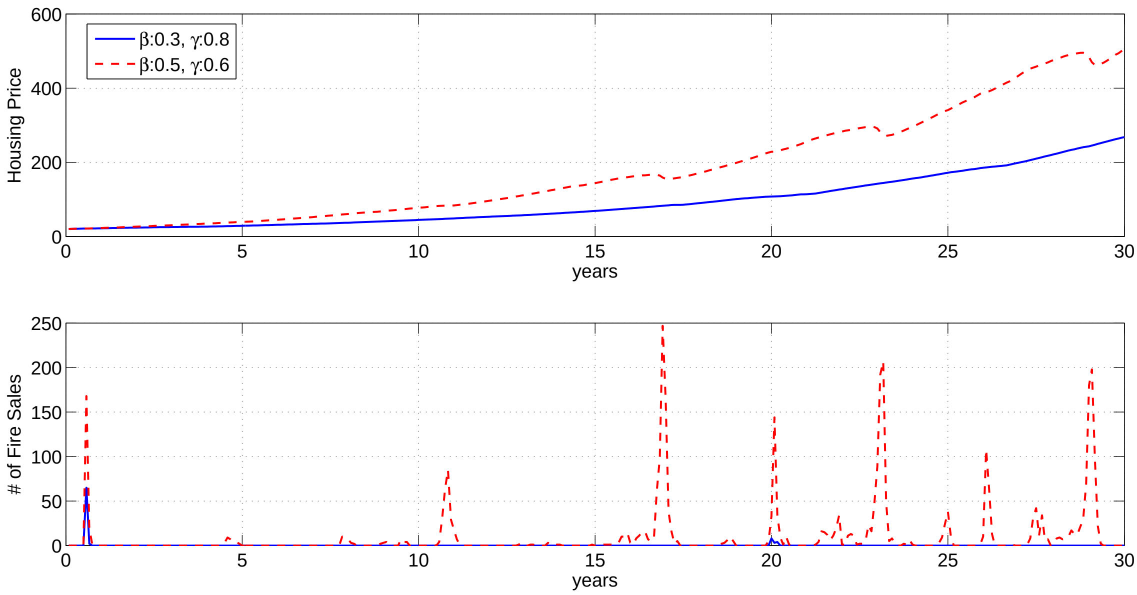


Figure 2.16: A sample time trajectory, i.e., from a single seed, comparing impacts of combined loose vs strict regulatory policies on average House Price and number of Fire Sale cases. Strict policy control is denoted by the solid line (—) and loose policy control is denoted by strip line (- -).

	β	γ=0.6	γ=0.7	γ=0.8
Average House Price	0.3	142 (1)	137 (1)	95 (0)
	0.4	172 (1)	158 (1)	96 (0)
	0.5	178 (2)	166 (1)	97 (0)
Average Transaction Volume	0.3	5613 (18)	5481 (18)	4857 (14)
	0.4	6169 (23)	5837 (15)	4912 (17)
	0.5	6555 (33)	6098 (17)	4974 (14)
Household Mortgage growth	0.3	9.79 (0.05)	9.67 (0.04)	9.52 (0.03)
	0.4	10.73 (0.06)	10.28 (0.04)	9.62 (0.03)
	0.5	10.98 (0.08)	10.58 (0.05)	9.68 (0.03)
Average Fire-Sale	0.3	0.50 (0.06)	0.27 (0.02)	0.13 (0.01)
	0.4	4.01 (0.65)	1.68 (0.10)	0.43 (0.02)
	0.5	15.37 (1.63)	4.99 (0.23)	0.73 (0.04)
Average Write Off	0.3	52.77 (7.95)	35.54 (6.34)	9.86 (0.29)
	0.4	120.03 (7.50)	89.48 (7.47)	11.12 (2.68)
	0.5	177.26 (5.70)	146.96 (6.23)	38.31 (6.29)

Table 2.4: Simulation results on housing market indicators with 3 different flow control measures DSTI (β) and 3 different stock control measures ETA(γ). It tabulates the results obtained by running Monte Carlo simulations using 50 different seeds of random number generator. Standard errors are shown in parenthesis.

regulation.

Results clearly indicate that tighter stock control stabilizes both the mortgage market and the housing market, especially in the case of looser flow control regulation. Results also show that a tighter stock control regulation improve slightly the indicators of growth and unemployment.

In particular, the first two plots of Figure 2.14, which are related to mortgages, show a slowdown of mortgage growth and a significant decrease in write-offs when stock control is stricter. This effect is mainly due to the risk-averse nature of the stock control regulation that penalizes debt holders. When γ is high, households who hold too much debt are not allowed to borrow more. The aggregate effect is reducing risk on mortgages and allowing for a more stable path. The fire sales and the housing price growth plots confirm that the housing market is more stable when the regulation based on households stocks (ETA) is tighter. Finally, the last two plots show a positive effect also on two fundamental economic indicators, i.e., GDP growth and unemployment rate. In general, stock control regulation has a stronger effect in

	β	γ=0.6	γ=0.7	γ=0.8
Firm Loans	0.3	$1.91 \cdot 10^8$ ($2.24 \cdot 10^6$)	$1.89 \cdot 10^8$ ($2.31 \cdot 10^6$)	$1.88 \cdot 10^8$ ($2.16 \cdot 10^6$)
	0.4	$1.97 \cdot 10^8$ ($2.01 \cdot 10^6$)	$1.92 \cdot 10^8$ ($2.02 \cdot 10^6$)	$1.88 \cdot 10^8$ ($2.64 \cdot 10^6$)
	0.5	$1.93 \cdot 10^8$ ($2.49 \cdot 10^6$)	$1.91 \cdot 10^8$ ($2.29 \cdot 10^6$)	$1.89 \cdot 10^8$ ($2.37 \cdot 10^6$)
Total Credit	0.3	$3.75 \cdot 10^8$ ($3.25 \cdot 10^6$)	$3.55 \cdot 10^8$ ($3.25 \cdot 10^6$)	$2.94 \cdot 10^8$ ($2.47 \cdot 10^6$)
	0.4	$4.25 \cdot 10^8$ ($3.34 \cdot 10^6$)	$3.82 \cdot 10^8$ ($2.99 \cdot 10^6$)	$2.96 \cdot 10^8$ ($3.04 \cdot 10^6$)
	0.5	$4.36 \cdot 10^8$ ($4.59 \cdot 10^6$)	$3.91 \cdot 10^8$ ($3.45 \cdot 10^6$)	$2.98 \cdot 10^8$ ($2.67 \cdot 10^6$)
Bank Equity	0.3	$3.98 \cdot 10^7$ ($6.19 \cdot 10^5$)	$3.86 \cdot 10^7$ ($5.91 \cdot 10^5$)	$3.52 \cdot 10^7$ ($5.45 \cdot 10^5$)
	0.4	$4.39 \cdot 10^7$ ($6.41 \cdot 10^5$)	$4.06 \cdot 10^7$ ($5.21 \cdot 10^5$)	$3.51 \cdot 10^7$ ($6.67 \cdot 10^5$)
	0.5	$4.35 \cdot 10^7$ ($8.39 \cdot 10^5$)	$4.15 \cdot 10^7$ ($5.89 \cdot 10^5$)	$3.61 \cdot 10^7$ ($6.21 \cdot 10^5$)
Bank Deposits growth	0.3	8.51 (0.08)	8.50 (0.11)	9.09 (0.05)
	0.4	9.01 (0.09)	8.86 (0.09)	9.12 (0.06)
	0.5	8.96 (0.11)	9.03 (0.10)	9.14 (0.06)
Consumer Goods Price Growth	0.3	5.58 (0.04)	5.49 (0.05)	5.68 (0.04)
	0.4	5.61 (0.05)	5.61 (0.04)	5.68 (0.04)
	0.5	5.57 (0.04)	5.59 (0.04)	5.71 (0.04)
Money Wage growth	0.3	7.35 (0.04)	7.34 (0.05)	7.68 (0.03)
	0.4	7.36 (0.04)	7.40 (0.04)	7.70 (0.04)
	0.5	7.29 (0.04)	7.34 (0.04)	7.64 (0.04)
Real Consumption	0.3	$2 \cdot 10^5$ (671)	$1.99 \cdot 10^5$ (682)	$2.01 \cdot 10^5$ (551)
	0.4	$2.01 \cdot 10^5$ (633)	$2 \cdot 10^5$ (657)	$2.01 \cdot 10^5$ (548)
	0.5	$1.99 \cdot 10^5$ (830)	$1.99 \cdot 10^5$ (601)	$2 \cdot 10^5$ (591)
Real Consumption growth	0.3	3.15 (0.02)	3.15 (0.03)	3.20 (0.02)
	0.4	3.11 (0.03)	3.14 (0.03)	3.20 (0.03)
	0.5	3.01 (0.05)	3.10 (0.02)	3.20 (0.03)
Real Investment	0.3	49,924 (667)	49,622 (815)	51,212 (674)
	0.4	51,421 (743)	50,260 (623)	50,906 (812)
	0.5	49,638 (795)	50,641 (714)	51,012 (831)
Real Investment growth	0.3	9.43 (0.23)	9.74 (0.27)	9.58 (0.21)
	0.4	9.68 (0.23)	9.81 (0.21)	9.48 (0.23)
	0.5	9.22 (0.35)	9.65 (0.24)	9.51 (0.23)
Real GDP	0.3	$2.5 \cdot 10^5$ (1157)	$2.49 \cdot 10^5$ (1353)	$2.52 \cdot 10^5$ (971)
	0.4	$2.52 \cdot 10^5$ (1251)	$2.5 \cdot 10^5$ (1157)	$2.52 \cdot 10^5$ (1149)
	0.5	$2.49 \cdot 10^5$ (1457)	$2.5 \cdot 10^5$ (1143)	$2.51 \cdot 10^5$ (1210)
Real GDP growth	0.3	3.96 (0.03)	3.97 (0.04)	4.08 (0.04)
	0.4	3.93 (0.05)	3.97 (0.03)	4.06 (0.04)
	0.5	3.77 (0.07)	3.94 (0.04)	4.08 (0.05)
Unemployment (%)	0.3	6.21 (0)	6.20 (0)	5.48 (0)
	0.4	6.36 (0)	6.20 (0)	5.55 (0)
	0.5	6.68 (0)	6.34 (0)	5.67 (0)

Table 2.5: Simulation results on general macroeconomic indicators with 3 different flow control measures DSTI (β) and 3 different stock control measures ETA(γ). The results are from Monte Carlo simulations using 50 different seeds of random number generator. Standard errors are shown in parenthesis.

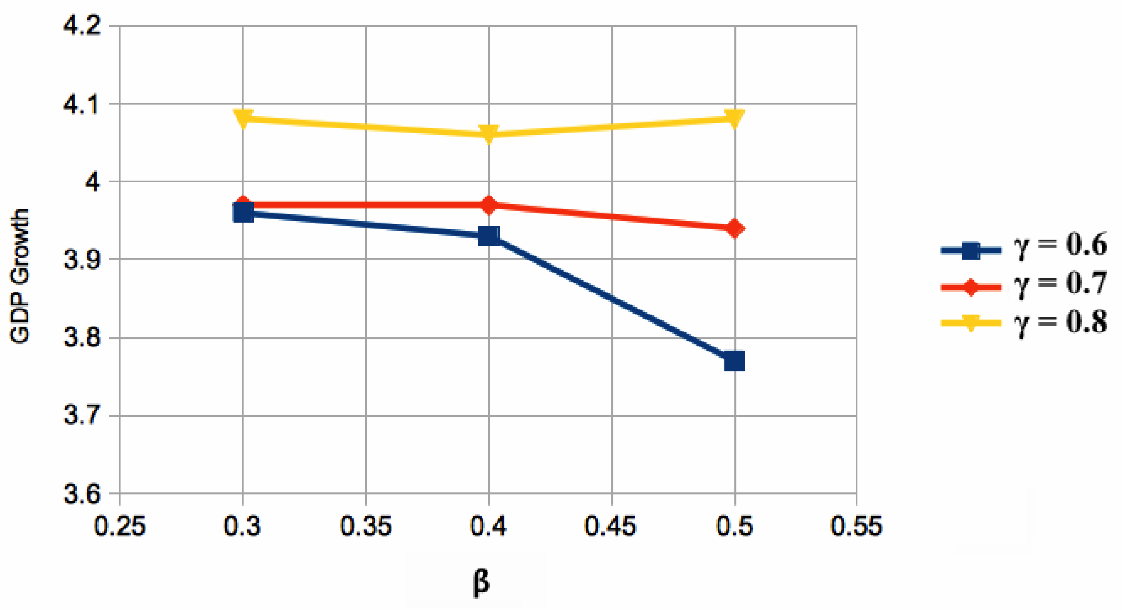


Figure 2.17: Complementary impact of stock-flow regulation. The figure is a depiction of tabulated results on real GDP growth of Table 2.5. The degrading impact of a loose flow control on GDP growth is reverted when it is combined with stricter stock control measures.

the case of a loose flow control. This can be better seen in Figure 2.17, suggesting that the degrading impact of a loose flow control on GDP growth is reverted when it is combined with stricter stock control measures. The two policies can be considered complementary and can be both used in order to regulate (and stabilize) our credit driven economy.

Finally, the stock control regulation has a relevant implication in terms of mortgage debt distribution. Figure 2.18 shows the Gini index of households mortgages for different stock control policies. As already noted, households who are not holding any debt are clearly favorite for getting a new mortgage. Thus, when there is a tight stock control regulation along with a mild flow control, the combined policy works as an equalizing mechanism that has two main effects. The first one is to bring about a more homogeneous distribution of housing wealth, in this case represented by the housing units that households buy with the mortgage. In other words, access to housing units for the first time buyers is eased and hence house ownership is promoted. The second effect is to reduce the risk of mortgage default and fire sales, preventing

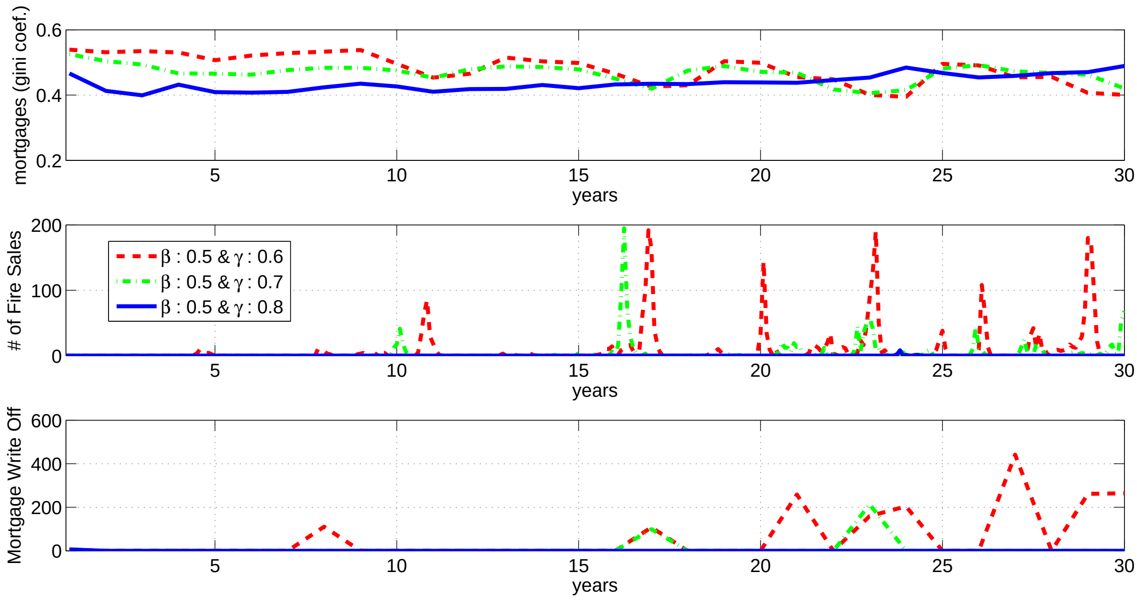


Figure 2.18: Comparison of distributions of mortgage acquisitions under a loose flow control $\beta = 0.5$ w.r.t different stock cases: $\gamma = 0.6$, $\gamma = 0.7$ & $\gamma = 0.8$. The top panel traces mortgage distributions among households by computed gini-coefficient. Homogenizing impacts of mortgage write-offs and fire sales are hinted by the bottom panel and the middle panel respectively.

the accumulation of debt that could become unsustainable. Looking at the loose stock control policies in Figure 2.18, it emerges that the unequal distribution of debt among households is reduced whenever a crisis in the housing market occurs. In this case, households holding more debt, thus more financially fragile, are punished by debt write off, leading the economy towards a more homogeneous distribution of debt. This can be detected in Figure 2.18 by observing the correspondence between fire sales (and write-off) and the decreasing trend of the Gini index when stock control is loose. On the other hand, when the housing market is booming, the distribution becomes more unequal again. When stock control is high enough we do not observe any fire sales (or write-off) and the Gini index does not fluctuate.

2.1.6 Modelling assumptions and limitations

There are a couple of limitations in the current version of housing market. First, in the current model the number of housing units is constant. At the beginning of each simulation households are endowed 5 housing units and they can sell their housing units down to the last remaining one as there is no rental market. There is no construction sector that adds new housing units to the economy. Hence any type of boom in construction sector and its impact on real economy and on total private sector debt can not be addressed. A relaxation of this constraint would require design and implementation of construction firms, their access to capital and financial networks. Such an extension could be used to address role of government investment in infrastructures and hence on the economy at large (Stiglitz, 1997). The extension could be further exploited to discuss and experiment with various policies which may stimulate or inhibit activities of building sector. Last but not least, having relaxed this constraints would enable us to discuss the role of growing number of housing units per person in an economy or vice versa (Baffoe-Bonnie, 1998; Tibaijuka, 2013). One may expect that existence of a construction sector, depending on its relative size in the artificial economy, may amplify amplitude of business cycles. It may deepen and enlengthen burst phases that are specifically driven by mortgage led crises while it may lead the booms led by housing construction and speculative activities in the real estate market.

Second, in the current version, when a fire-sale is not possible or is not a remedy for the financially stressed household, a debt-write-off occurs. The bank is covering the whole burden. That is, the debt of the household is restructured without a transfer of a partial or full ownership of the housing assets to the bank. This simplifications saves us from a modelling complexity on the banks' balance sheets and behaviors, while it might hinder us observing severity at uneven housing ownership distributions due to recurring endogenous crises. Nevertheless, we would like to point out that it is an enforced fire-sale mechanism that serves a reduction in the number of debt re-structuring occurrences. In case of an active market the mechanism may fully or partially reduce the burden on the banks. A stressed household may end up selling all of her housing units but the last one. Since there is no rental market the households in the model are not allowed to sell all of their housing units for speculative purposes or due to an enforced fire-sale condition. However, in case of a system wide crisis, it is possible that there are not enough buyers. This would cause the burden transferred to the banking sector and let the household keep the unsold housing units. A modelling update in that direction along with addition of a rental market, indeed, would enrich our insights. We would be able address possible uneven household wealth distributions triggered by economy wide mortgage crises.

Third, banks apply a flat risk rate to total mortgages they have provided. There is no risk adjustment associated to each single mortgage. Banks' risk associated with mortgages they give out to households can be tailored to financial stress a household does have. The measure can be interpreted and used as a micro-level prudence and the current results can be contrasted against it.

Last but not least, in the current model, other than a speculation on housing market prices (Levin and Wright, 1997), households are not engaged in an asset management behavior where they aim to improve their returns from their housing ownership. The current model has focused on impacts of credit money creation via a relatively simplified mortgaging mechanisms. In the current implementation, households are not managing a saving account where they build up a budget to cover a part of housing value that they will attempt to buy in 'advantageous' market conditions. They rather need to improve their financial state to be able to acquire a loan which covers whole value of the housing unit they attempt to buy. This modeling simplifications can be later relaxed to study various saving as well as investment decisions, for instance, where impact of a rental market on housing value as well as on expectations on returns at investments in real estate ownership is addressed.

2.1.7 Summary

In this chapter we have investigated the macroeconomic implications of the presence of an housing market and its related mortgage device in the Eurace model. The aim is twofold, from the one hand we want to understand the economic impact of having an housing market in the model, and from the other hand we want to explore the effect of different mortgage regulations on the economic performance.

We observe that the main effects of the housing market are delivered through the endogenous money creation mechanism, due to the new mortgage loans that banks grant to households. These new loans increase money supply and stimulate the aggregate demand of goods. Our computational experiment shows that the inflow of endogenous money affects both the financial variables of the economy and, to a minor extent, the real ones, including real GDP and unemployment rate.

The second part of the experiment studies impact of mortgage requirements on the artificial economy. In particular, we use the debt-service to income (DSTI) ratio as a mortgage qualification measure (high DSTI means lower requirements to get a loan). Our study shows that increasing DSTI has non linear effects on the economy. While raising DSTI, we observe an expansion for low values of DSTI both for the monetary and the real side of the economy. However, after a threshold, the economic performance deteriorates, due to a higher instability of the mortgage market when sub-prime borrowers have access to credit, thus increasing the number of housing units fire sales, bank write offs and, finally, firms bankruptcies.

We also consider an alternative mortgage qualification measure, called "stock control" because it observes the equity over total assets (ETA) of the potential borrowers. A tight "stock control" regulation is able to stabilize the mortgage and housing markets in the case of loose DSTI regulation.

Finally, our study indicates from the one hand the importance of the housing market in the economy, due to its role of regulating endogenous money creation and thus accommodating aggregate demand. From the other hand, results warn us that excessively loose mortgage requirements can lead to financial instability and economic crises. Our results further suggest that stock control regulation can be effectively combined with DSTI in order to increase the stability of the housing market and of the whole economy. The results from experiments on stock control regulation exhibit the interesting property to directly affect mortgage distribution among households and avoid excessive fluctuations in households' debt (and asset) distribution. From a policy stand point, our results suggest that using a mild and even a loose flow control along with a strict stock control leads to sustainable growth and eases the access to housing for first time buyers, therefore promoting house ownership.

2.1.8 Methodological Novelty: Incremental calibration

In this particular work, we have introduced a methodological novelty by introducing and incremental calibration. The housing market model in this work has been added to a complex model that has been already calibrated and validated during numerous works. Within the particularity of this work, we examine two economic phenomenon: money creation via a mortgage lending mechanism and policy experimentation on regulation of housing markets towards a steered credit growth and stability. While examining impact of a new component on top of a complex system the challenge is to be able to extend the model in a modular and controlled manner so we would be able to compare and contrast the artificial economy with or without the new component. A seamless integration is needed for the kind of controlled experiment set up we aim for. Along with model design and implementation a careful calibration exercise is necessary while introducing new model parameters. We have used a key and relevant variable of the base model: Eurace model's initial wage offer. Using the initial wage offer of firms as the measurement unit and referring to empirical findings from the literature we calibrated the housing market parameters and we set the initialization values of the new agent variables. For the details please refer to Section 2.1.4 and Table 2.3

2.2 Mortgage credits and business cycles

2.2.1 Motivation

In this work, we primarily address importance of real estate markets on the economy (Muellbauer and Murphy, 2008). We have used the extended version of Eurace model by accommodating a real estate market and a mortgaging mechanism. The work at one hand has enabled us to observe the impact of mortgages on business cycles in the extended artificial economy (Catte et al., 2005) on the other hand enabled us to examine validity of the extended Eurace artificial economy.

In this context, in addition to banks' leverage, their financial links to the other banks and firms, also, their mortgage loans are considered among the list of factors at observing reaction of banking sector to real economy (Gallegati et al., 2008). In the model, the dynamics of credit money is endogenous and depends on the supply side by the banking system, which is constrained by Basel capital adequacy regulatory provisions (Blum and Hellwig, 1995; Santos, 2001), while on the demand side depends on firms financing production activity and households indebtedness for housing needs and speculation.

2.2.2 Summary of results

Our results are in line with empirical evidences elsewhere (European Central Bank, 2013). That is, growth in loans to consumption goods producers tend to lag real GDP fluctuations while mortgages to households tend to either lead GDP growth slightly or occasionally follow a coincident pattern relative to GDP growths. This dynamics is presented in Figures 2.19 and 2.20 and Table 2.6. In the experiments that has generated these results the model as detailed in Chapter 2.1 was employed where economic indicators with or without a housing market activity has been compared[7].

Housing purchases via mortgage credits cause injection of money in the economy. An increase in the amount of mortgage in the current model follows empirical patterns of increase in

[7] For further discussions see Section 2.1.5.

	Without Mortgage	With Mortgage
Real GDP Growth	3.38 (0.08)	3.85 (0.10)
Real Consumption Growth	2.93 (0.19)	3.07 (0.08)
Real Investment Growth	6.09 (1.29)	9.74 (0.29)
Total Credit Stock Growth	6.95 (1.22)	9.93 (0.08)
Unemployment Rate	7.07 (1.00)	6.52 (0.01)
Money Wage Growth	6.51 (0.44)	7.28 (0.06)
Bank Equity Growth	7.13 (0.67)	9.87 (0.17)

Table 2.6: Simulation results with the Eurace model with and without the real estate market with 20 different seeds of random number generator. Standard errors are shown in parenthesis. The economy model as detailed in Chapter 2.1 is used.

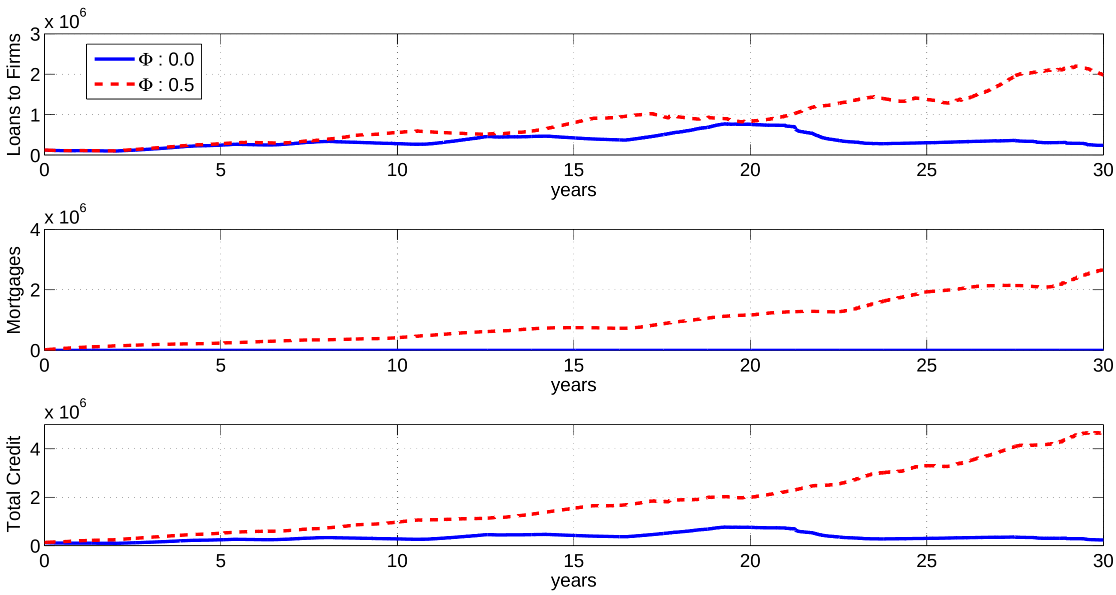


Figure 2.19: Time trajectories of firms loans (top panel), mortgages (middle panel), and total credit (bottom panel). Each panel compares trajectories with or without housing market. A model parameter ϕ is used, which determines the entry probability of a household to the housing market. A $\phi = 0$ implies a zero transaction.

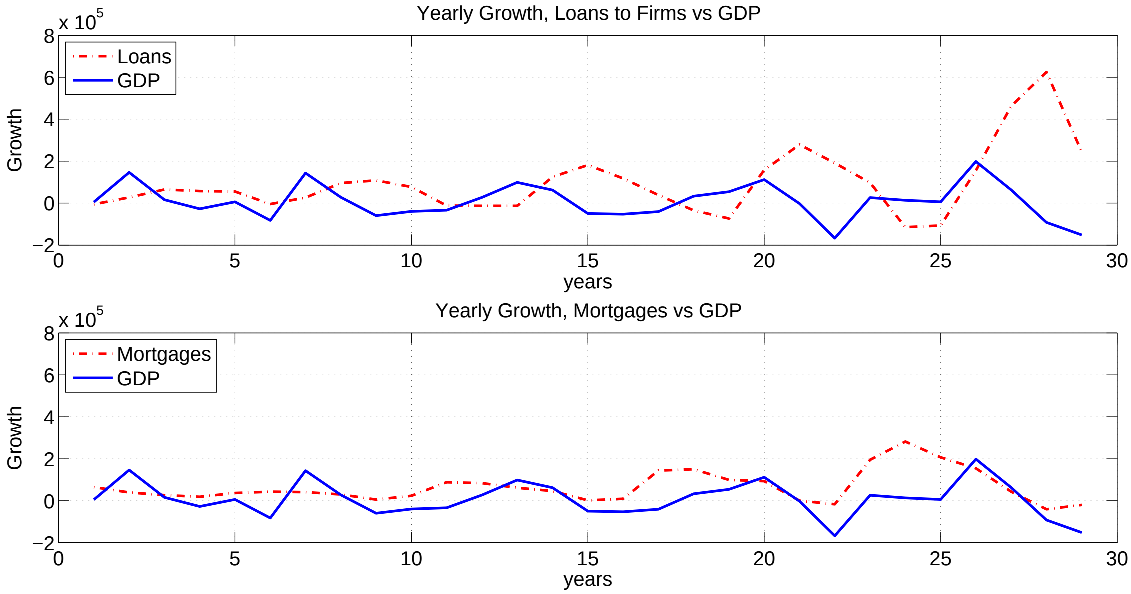


Figure 2.20: The figure displays a sample credit growth pattern over time in. GDP vs loan growths are on the upper panel and GDP vs mortgage growths are on the lower panel. The time series plots suggests the fact that growth in mortgages in the economy leads a growth in GDP which is followed by a growth in loans to firms.

M1 type of money in an economy. The lagging pattern of loans to firms over the business cycle may suggest that during recoveries firms can first finance investment expenditure using their internal funds, as cash flows improve during a recovery, and only later they seek for external financing. On the other way around, it may also suggest that during recessions the reduction of their equity capital prevents banks from granting credit to firms. The lead of mortgages suggest that mortgages function as injection of liquidity to households' consumption budget, and hence an increase in demand, production, and a GDP growth in the system. This, in return, increases demand for investment at producers' side, which leads them to request more loans from the banking sector. Overall, what we observe is a pattern of systematic responses, where money creation via mortgages is responded by a growth in GDP and later an increase in loan requests for further investment in productions.

In simulation scenarios where mortgaging is active, it is seen that the additional mortgages create new money, raise households' consumption and firms' investments. The impact of money creation via mortgages can be observed by higher growth rates at wages, bank deposits as well as at banks' equity. A clear increase in consumption as well as in investment is observed. These results can be attributed to the factors relevant to endogenous money creation via households' mortgages (See Figure 2.19). Furthermore, the model when mortgaging mechanism is activated produces a lower unemployment rate and higher money wage, as presented in Table 2.6.

The existence of mortgaging gives advantages to the banks through an increase of bank equity and bank deposits which in return eases the access to the credit for investment. Overall results suggest that existence of a regulated mortgaging contributes to macroeconomic system by increasing real consumption, real investment, money wage, bank equity, bank deposit, and reduce the unemployment rate. This result is relevant with empirical facts on global economy where real estate markets play a significance role to drive the booms (Catte et al., 2005). The results also point out that the stock of money is driven by the demand for loans, therefore supporting the theory of endogenous nature of credit money (Howells, 1995; Arestis and Howells, 1999). The study then also clarify the nature of endogenous money, giving a contribution to a debate that has grown stronger over the last two decades.

2.2.3 Methodological novelty: Time lagged cross correlation tests

In order to be able to present business cycle dynamics we have employed cross-correlation analysis on panel data of relevant parameters. Although cross correlation on lagged time series data is known in econometrics, the application of the methodology to the simulation data within ABM domain is one of the first. This validation approach has been further employed in our subsequent works, e.g. see Figure 2.13.

2.3 Housing sector and green finance

2.3.1 Motivation

In this work, we aim to investigate macro-prudential policies that may help to stimulate banking sector to shift from speculative lending, the cause of asset bubbles and economic crises, to an energy efficient production technology. The most well-known and discussed solution to the low-carbon investment challenge has been the introduction of a price on carbon (Nordhaus, 2013; WB, 2015), either through a carbon tax, i.e. a tax on the carbon content of goods and services, or through a cap-and-trade system of emissions allowances, with the aim to address the market failure related to the exclusion of environmental costs from the market pricing system. The rationale is that a carbon price would push private agents to internalize correctly environmental costs and therefore to perform the appropriate green investments aimed to reduce them. However, carbon price mechanisms still have strong political opposition on the grounds that they are harmful for business and can dampen economic growth.

Beside carbon pricing, a new idea that has gained recent attention concerns the design of appropriate banking regulation policies aimed to push banks to lend to low-carbon activities in order to ease the green investment gap (Rozenberg et al., 2013; Ferron and Morel, 2014; Aglietta et al., 2015; Campiglio, 2016). In this work, we aim to see to what extend a banking regulatory framework, where banks that lend to firms undertaking green investments are required to respect looser requirements could manage to direct credit toward the green sector and therefore reduce the green investment gap. However, in our work we differentiate on capital requirements depending on the destination of credits employing the Basel regulatory framework but not reserve requirements in terms of the quantity of supply.

Our design of banking regulation that follows a proposal by Campiglio (2016), which suggests the adoption of different capital adequacy ratios according to the type of lending that banking institutions provide. Accordingly, we have designed a set of computational experiments characterized by capital requirements for mortgages that can be higher or lower than a reference value, i.e. 10%, which is the basic capital requirement value adopted for firms' loans. The rationale behind this choice is the assumption that loosening credit access for house purchases may produce asset bubbles with destabilizing effects for the real economy, while loans to business firms are aimed at increasing and renewing their capital endowment with positive effects for the productive capacity of the economy and for environmental sustainability.

2.3.2 Summary of results

Inspired by some recent proposals, aimed at promoting green investments at the expense of speculative ones, we designed a set of computational experiments within Eurace. It should be noted that in the model, there is no construction of new housing units or renovation of existing ones.

First, housing market in the model functions as an important destination of speculative credit in the economy. Therefore, our main research question is about the effects of loose credit conditions, depending on the destination of the borrowed funds. In this respect, we should consider that over-lending to the business sector has downside risks due to increasing insolvency rates for firms' but also positive effects on productive capacity and energy efficiency (in our model) of the economy. By contrast, easy mortgage lending gives rise to price bubbles and incentives speculative house purchases.

The second relevant feature of our model design regards the heterogeneity of capital goods with respect to energy efficiency that we assume to be exogenously increasing over time. This new model provision implies that investments in capital goods provide an environmental benefit as the new vintages are characterized by higher energy efficiency and then allow the production of consumption goods at a lower energy intensity per unit of consumption good produced. Investment decision making is then updated accordingly to take into account the inter-temporal saving of energy per unit of consumption goods produced due to investment decisions.

The rationale behind this choice is the assumption that house purchases are made mostly for speculative purposes and may produce asset bubbles with destabilizing effects, while loans to business firms are aimed to increase their capital endowment with long-run positive effects for the productive capacity of the economy. Banking regulation should then favor lending to business firms with respect to lending for house purchases, e.g. through setting lower capital requirement in the former case. A similar proposal has been set out by Campiglio (2016) to spur green investments, at the expenses of speculative ones, as an alternative to carbon taxation.

We devised a simple regulation for banks in order to incentivize loans to firms with respect to real estate mortgage lending. The regulation consists in demanding higher capital requirements for banks in the case of mortgages, thus encouraging banks to give loans to firms. As up-to-date capital goods have better energy efficiency in the model design, a higher pace of investments implies lower energy intensity per unit of produced consumption goods, energy savings and a positive environmental externalities.

Simulation outcomes suggest that the regulation is successful in promoting investments and capital accumulation in the short term, and consequently in improving energy efficiency of firms. However, in long run, these results are achieved at some welfare costs for households, which can be summarized in lower consumption growth rates and purchasing power. The reason is that reducing mortgages with a restrictive regulation has a negative impact on the total private credit in the economy, and therefore on the endogenous money supply. This, in turn, reduces consumption and aggregate demand. In the long term, the contraction of total credit increases, and the negative outcomes on aggregate demand become more serious, reducing firm investments. Therefore, in the long run, the positive effects on capital and energy efficiency become negligible, while the main economic indicators show a period of recession.

2.3.3 Methodological novelty: Robustness test on exogenous modelling factors

We have applied robustness tests on the model dynamics and outcomes to measure the impact of fossil fuels. In the model fossil fuels are provided externally by a foreign sector. The price of the raw energy in the model is determined exogenously. The growth of the price is exponential given by $p_E(t+1) = p_0(1+\xi_0)^t$. We have tested the validity of the results to such exogenous factor. We have re-run simulations with fixed prices as well as declining oil prices. The statistical tests suggest the results are indifferent to external price dynamics. A detailed discussion on robustness test and empirical validation on the choices made for p_0 and ξ_0 are given in Section 3 of our relevant work Raberto et al. (2018).

2.4 Impact of mortgage instruments on wealth and regulations

2.4.1 Motivation

The objective of the study has been to examine macroeconomic implications of mortgage types. Iceace macroeconomic model of a credit network economy has been used. It is an agent-based computational macroeconomic model, see the model Web site[8], that utilizes the balance sheet accounting of economic agents, introduced by the Eurace model. The Iceace model was created in the likeness of the Icelandic economy and for this paper it was used to compare different mortgage instruments. Specifically, the housing market in the model was built up adhering to empirical facts from the Icelandic housing market and the behavior of Icelandic households, where an adjusted-rate-mortgaging (ARM) is more common. For this paper we have added two more mortgage types, namely, IIM and FRM:

- ARM: Interest rate follows the rate of the Central Bank plus a constant 2% spread.
- IIM: Interest rate is fixed throughout the term and principal indexed to CPI.
- FRM: Interest rate is fixed as the rate of the Central Bank at the moment of the request plus a constant 3% spread.

Although Iceace is inspired by Eurace that is described in Chapter 2.1, it differs from Eurace. Unlike Eurace it lacks a financial market. Instead, all equities are owned by an EquityFund agent which sends dividends to the households. If one or more firms have requested financing from the equity fund the equity fund may retain a part of the dividends for financing, given that two conditions pertaining to the financing are fulfilled. A firm must apply for financing and only do so when in need of financing and it must have exhausted every possibility to get a loan from the banking system. In the model, the government is responsible for the fiscal policy of the artificial economy, setting the level of income tax and general transfer benefits, always aiming at a zero deficit.

[8] http://iceace.github.io/home/

An exogenously set parameter is used to determine to what extent income tax versus benefits is to be used to reach zero deficit. In other words, unlike in Eurace model where the government can issue bonds and trade them in the financial markets to finance its deficit, in Iceace model the government is increasing tax or reducing the transfers to be able to balance its deficit. In Iceace instead of a Cobb-Douglas production, firms are characterized by a Leontief production technology. Lastly, in Iceace a construction sector is modeled via Constructor Firm agents which produce new housing units and trade them in the decentralized housing market. For the details see Bjarnason et al. (2015); Erlingsson et al. (2014).

2.4.2 Summary of results

Both the analytical analysis of total mortgages for different mortgaging instruments as well as the results from simulation confirm the fact that there are more mortgages in the system with IIM. However, the GDP levels with IIM mortgage type comparatively don't match this pattern. This can be explained mainly by circulation of money that is created by mortgages. Although, IIM creates more money which would increase level of demand for consumption in short-run followed by a growth in supply of consumption goods, the macro indicators of the artificial economy don't suggest this.

According to our analytical analyses that we have presented in the paper, in case of IIM amount of mortgage repayment by households is significantly higher, which decrease their consumption budget proportionally in mid to long-run. That is, short term inflow of money to households' consumption budget is reversed by large amount of mortgage payments neutralizing a possible and expected growth in GDP in long term. The collected mortgage payments via IIM, on the other side, increase earnings of the banking sector, the central bank and the tax income of the government yet it doesn't lead to a growth in production due to lack of an required growth in demand for consumption.

In summary, in this study we saw that inflation-indexed mortgages can mislead households' expectations of risk with the low initial monthly mortgage payments and encourage households to purchase more housing which stimulates housing prices. However, in long run it creates relatively more uneven housing wealth distribution amongst households. Further, IIMs seem to increase the profits and reduce the risk for banks and diminish the effectiveness of standard monetary policy tools, i.e. the policy rate, and seem to cause a decline in real GDP in the long-term. In other word, the effect of the policy rate, is diminished when inflation-indexed mortgages are used. Banks partake in the interest rate risk with fixed rate mortgages but bear little or no risk with adjustable rate or inflation-indexed mortgages.

2.4.3 Methodological novelty: combining simulation data and analytical analysis

In this work, model specification regarding households' mortgage debt repayment schemes and a set of sample simulated data are used to compare expected volume of principal payments in the economy under differing mortgage type enforcement regimes. Then consistency of simulation data from Monte-Carlo experiments is compared against analytical and numerical findings. Both analytical and simulation results foresee the additional mortgages that are injected into the economy in case of IIM. However, it should be noted that it has been the micro-level data from the simulations that enabled us to examine the impact of additional mortgage repayments on housing wealth distributions and hence its relevance to policy making.

Section 2.3[9] in Bjarnason et al. (2015) details and discusses the use of simulation data combined with empirically observed data in order to conduct an analytical comparison of mortgage payments under IIM, ARM, and FRM regimes. Averaged time series of interest and inflation rates of the simulation data are used to compute total, first, mean, and nominal mortgage payments for ARM and IIM cases respectively. Annuities for different loan terms are calculated analytically for a representative initial mortgage amount. In order to explore the role of path dependency as of inflation rates on cumulative mortgage payments at IIM annuities, empirical and simulated figures are compared to hypothetical fixed inflation rate cases with the same initial mortgage principal and annuity regime.

[9]For a direct access see `https://ideas.repec.org/p/jau/wpaper/2017-10.html`.

Chapter 3

A Multi-country simulation set-up for economic interactions and integrations

3.1 Policy motivations

The recent history of the European Union highlighted the critical importance of a proper political and economic architecture in order to take full advantage of the unification and to withstand exogenous negative shocks. The global financial crises of 2007 – 2008 had a pervasive impact on all the leading economies in the world, but the place where it might have been more disruptive is the European Union, which revealed structural fragility and inadequacy to tackle some of the main challenges ahead. The crisis in the Middle East and North African countries, exacerbating migration flows towards Europe, represents another shock that disclosed the lack of coordination among countries in the EU.

The geographical, cultural, and economic diversity among these countries has not been harmonized in a well-balanced and convincing project, thus exposing the union to frequent confrontations and conflicts at different levels, i.e., north versus south, core versus periphery, Germany versus Greece, U.K. versus continental Europe. Brexit and the recent elections of 2018 in Italy, bringing to power euro-skeptical parties, have shown both the vulnerability of the current project and the need to revise it. A rich debate flourished among scholars, politicians, and observers, about the needed steps to improve the prosperity and the stability of the European project.

The aim in this work has been to provide a computational model, which is flexible enough to address several of the main topics that are emerging within the European Union and beyond. The basic idea of this work is to convert the "current state of the art" Eurace model[1], which is a single country model, into a versatile compound of open economies interacting in many potentially different ways, including by joining unions. One of the advantages of this incremental approach is the generality of the resulting model, which is not conceived to study a particular problem but to mimic the main features of the agents that populate the economy, in order to reproduce the most important stylized facts. The single country Eurace model has been used for studying endogenous business cycles (Raberto et al., 2012a; Cincotti et al., 2010b), monetary policy and banking regulation (Teglio et al., 2012b; Cincotti et al., 2012), fiscal policy (Teglio et al., 2018), environmental sustainability (Raberto et al., 2018), housing market regulations (Ozel et al., 2016), among other topics, showing how the model can be applied to study very diverse economic issues. The work in this study starts from the generality of the original single country model and extends it by designing the main interactions that characterize open economies, like international goods and capital markets, workers mobility, and common international rules and policies. Therefore, the core simulation element evolves from a single closed economy to a multiplicity of open economies that are connected in different ways and with different strengths.

In the first work (Petrovic et al., 2018) where we have employed the model, summary of which has been given in Section 3.4, we study the macroeconomic implications of becoming part of a union, whose architecture is inspired from the EU, i.e, it includes international labor, goods and capital markets, along with a common currency. We start with a very simple and general case, where we compare the performance of two identical countries belonging to the union with two equivalent closed economies. We are particularly interested to study how the mobility of workers across borders affects the economy of the union. We extend the first experiment to the case of countries endowed with different productivity levels. The main goal, in this case,

[1] Eurace is a stock-flow consistent computational model, grounded on the agent-based methodology, which has been used for studying several macroeconomic issues. See the citations in this and previous chapter for more details.

is to understand the conditions under which two countries with different productivities benefit from becoming members of a union, and which are the main problems that might emerge. This setting can be related again to the European Union case, as countries are characterized by different productivities. We observe that in general, the union shows a better performance than the two isolated countries, however, when the productivity gap is high and mobility frictions are low, the union can even aggravate the inequality between the two countries because an excessive emigration impoverishes the country with low productivity. In order to tackle the problem of inequality, we design a last experiment where we test the possible mitigation effect of a re-distributive fiscal policy at the union level.

The stylized fiscal integration mechanism that we call "fiscal pool" in our last experiment of the first paper consists of a centralized deposit account where member countries of the union are obliged to put a part of their budget surplus (if any). On the other hand, countries that need to finance their budget deficit can ask (and obtain) money from the fiscal pool. Since the governments finance their budget deficits raising new public debt, the "fiscal pool" should enable a better use of the income surplus in the union consequently improving the budget balance and reducing the public debt of the union members. The governments should afford higher spendings providing also higher transfers to households which would increase their total income. In turn, this should decrease the likelihood of migration since households will be willing to stay in their home countries if they can earn competitive incomes. In addition, note that the outflow of workers may act as a sort of the accelerator mechanism. With a lower amount of production factors (workers) the economic activity declines, and so the tax revenue. If the public expenses (e.g. interest on the sovereign debt, public employees, etc.) are downward rigid in the short run, the government may be forced to raise new public debt and try to decrease some of the public expenditures (contractionary fiscal policy) which will further slow down the economic activity. On the contrary, expansionary fiscal policies generally improve the performance of the countries in the union. For instance, an increase in the maximum deficit-to-GDP ratio (expansionary policy) improves the dynamics of GDP, labor productivity, and employment, however, at the cost of a higher level of public debt and inflation (Caiani et al., 2018). In addition, diverse shocks that may hit the members of common currency areas can be mitigated through the fiscal integration among countries. The fiscal transfers between regions can absorb the impact of asymmetric shocks and improve the efficiency of the common monetary policy, as in Kenen (1969).

3.2 Relevant studies

There are a few works in the agent-based literature, dealing with multi-country or multi-regional settings. Dawid et al. (2014) present a two-region model to study the effects of policies which aim at fostering convergence, in the case of fully integrated or fully separated labor markets. In a later study, Dawid et al. (2017) use a similar model to test the effects of a set of interregional fiscal policies on the economic growth of the different regions. In particular, they find that fiscal transfers have a positive effect on the weaker (periphery) region, which is in line with our results. A conceptual difference between our work and the work by Dawid et al. (2017), besides the design issues concerning the multi-country model, is that we do not focus on convergence, but we aim at understanding the conditions under which two countries with a permanent productivity gap can coexist in a monetary union. The rationale for this choice can be found in the empirical literature casting doubt on the productivity convergence process in Europe. Many studies, from Tsionas (2000) and Boldrin and Canova (2001), to Aiello and Pupo (2012), Monfort et al. (2013), and Sondermann (2014), show from different perspectives a lack of significant convergence, therefore highlighting the relevance of studying if and when it is convenient for countries with different productivities to join in unions. There is also a more general standpoint, behind the choice of permanent productivity gaps, which questions the indisputable *desideratum* of economic convergence. Actually, non-convergence can stem from different economic traditions and cultural traits that might be important to acknowledge or even protect. In this perspective, the union should be the place allowing for the successful coexistence of countries with different economic strength and properties: Germany and Greece can serve as an example.

Another multi-country model has been proposed by Caiani et al. (2018), to perform fiscal policy experiments in a European-like economy, finding that fiscal austerity raises public debt-to-GDP ratio. They focus attention on the design of international trade, omitting the international labor market, which is, on the contrary, quite central in our work (details about the framing of labor mobility in our paper are provided further on). Furthermore, Wolf et al. (2013) designed a multi-regional model, especially focused on the study of climate policy. More in general, the model presented in this paper belongs to the recent tradition of macroeconomic agent-based models, which includes Dosi et al. (2015), Caiani et al. (2016), and Ashraf et al. (2017), as a non-exhaustive sample. This paper presents a methodological innovation, with respect to the state of the art, which is related to the very nature of the flexible multi-country structure of the model. As our setting allows for running as many countries as we like within the same simulation[2], we use isolated countries as exact replicas of the countries in the union, in order to have a control group to evaluate results. Indeed, this "control group" approach could be applied also for addressing research question related to single-country models[3].

The contribution of our work is not limited to the agent-based approach but extends to other fields of studies. One of them is the work on Optimal Currency Areas - *OCA* (see for instance Broz, 2005 for a review and Mélitz, 1995 for a critical analysis), which studies under which conditions countries would benefit from a common currency. In particular, Alesina et al. (2002) express the shared vision that the higher the association of shocks among the union countries, the lower the costs of losing independent monetary policy. Moreover, Frankel and Rose (1997) show that raising the trade volume among countries in a monetary union may generate a higher correlation among countries' business cycles resulting in common demand shocks. Our model is able to generate business cycles endogenously (see Raberto et al. (2012a) for more details), and we show that becoming part of a currency union significantly smooths the cycle asymmetries, which is in line with the empirical findings of Frankel and Rose (2001). In any case, we are cautious in the very first paper about drawing conclusions on a common monetary policy in the union, and we postpone this delicate topic to a more specific subsequent work.

The effects of labor mobility on the macroeconomic aggregates have been widely examined in the theoretical literature, mainly using the computable general equilibrium (CGE) framework, for instance in the context of the EU Eastern enlargement. This type of studies allows

[2]See the Appendix of our work Petrovic et al. (2018) for more details on the extensive range of configurations envisaged by the model.

[3]We could, for instance, run *N* completely isolated countries.

the analysis of the interaction between migration, capital movements, and trade which is also addressed in our study. Overall, the CGE literature finds stronger implications of migration on wage and unemployment than those found in the empirical literature. The negative effects of immigration, in particular for low-skilled workers, are outweighed by positive effects coming from the integration of goods markets (e.g. Baldwin-Edwards, 1997). Therefore, most of the models predict that the EU Eastern enlargement results in higher wages and lower aggregate unemployment in both receiving and sending countries, which is in line with results that we provide in this paper. Besides, CGE models predict an increase of GDP in the receiving country and in the EU. This effect is even amplified if the creation of new trade between existing and new member states is taken into account (Boeri and Brücker, 2005). However, the gains in aggregate and per capita income can be reduced due to labor market rigidities. For instance, after the EU Eastern enlargement in 2004 the UK has opened the job market for new member states, while Germany has kept strong labor market regulations until 2011 (Pytliková, 2014). As a result, the UK has absorbed the majority of the immigration inflows in the post-enlargement period while Germany, who was the main destination in the pre-enlargement period, attracted only modest immigration flow. The net effects of the diversion of migration from Germany towards the UK are a higher GDP and employment growth in the UK as well as the decline of the joint GDP of Germany and the UK (Baas and Brücker, 2008). Our study contributes to this discussion, even if the model that we use has important differences with respect to the cited ones. It is worth noting that we consider both the performance of the union as a whole and the performance of the single countries of the union with respect to their identical counterparts as isolated countries (the control state). Our aim is not to study the impact of immigration (see Moreno-Galbis and Tritah, 2016 who examine both the EU and non-EU immigration to European countries) on the hosting country, but to study the distribution of the population in the union, according to some economic characteristics of the member countries, and to evaluate the overall effects by observing several economic indicators. Hence, in our model, the migration outflow from one country is at the same time immigration inflow for another country. We find that the absence of mobility frictions can harm the country with low productivity, as many workers, attracted by higher real wages, emigrate to the high tech country, provoking the disarray of the government budget and of the whole economy. On the other hand, we find that labor mobility is able to foster employment and income in the union, especially when the productivity gap between countries is not excessive.

3.3 Methodological Novelties

In order to be able address the kind of policy questions as outlined in Section 3.1, a modular and scalable simulation set-up is needed. In that sense, in this phase of the work our primary objective has been to create a simulation set-up in order to be able to study, for instance, the conditions under which two or more countries can benefit from becoming part of a union. Combining state-of-the art software engineering methodologies and agent-based computational economics, we have designed a complexity-wise scalable and flexible multi-country model, which is able to consider a wide variety of union configurations. In other words, the model enables us to create and control the economic characteristics of the countries joining a union, i.e., the level of integration of its markets, regulations, and institutional bodies. This section presents a set of core methodological novelties that have lead us to design, develop and employ presumably the most advanced and complex ABM simulation model to the date.

3.3.1 Scalable complexity

The simulation set-up that enables us to conduct controlled macroeconomic policy experiments has been possible via a rigorous modelling design approach. We have introduced two types scalability into modelling design:

1. Vertical scalability: Flexibility in modelling components
2. Horizontal scalability: Flexibility in population design and configuration

Vertical scalability

The first scalability refers to ability at being able to include or exclude agents, mechanisms, markets and policy instruments in an artificial economy with no or minimal necessity for code

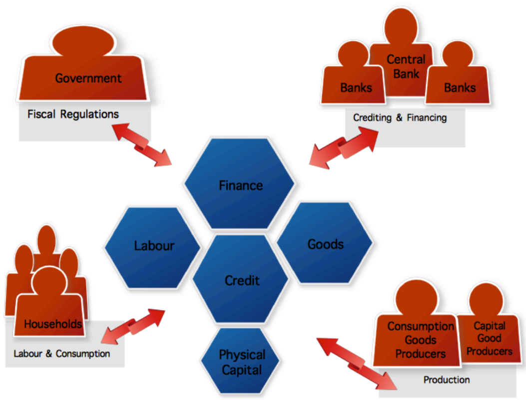


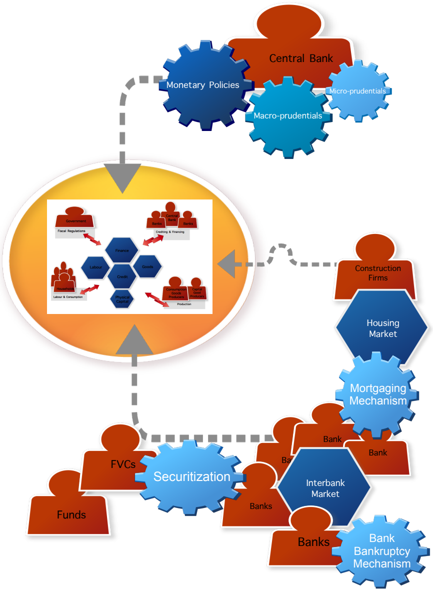
Figure 3.1: Base Eurace model (Teglio et al., 2010) before model refactoring and extensions.

implementation. The value offer in such a vertical scalability enables to focus on conceptual design and be able to examine and control impact of a sub-model such as housing market, a policy parameter such as mobility friction, or an agent behavior such as the speculative investment choices in financial markets.

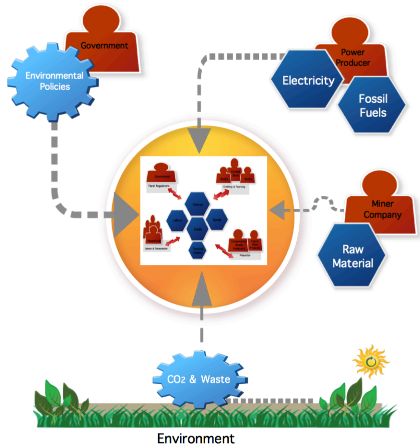
It should be noted that such vertical scalability has been possible due to the ability to design new agents, new agent behaviors or new agent-agent interactions incrementally.

A layered design strategy that reflects flexibility of underlining FLAME [4] framework (Kiran, 2017) has provided us the opportunity to follow a modular and incremental development process at adding new agents, markets and mechanisms to the base Eurace model. Figure 3.1 represents the state of the base model (Teglio et al., 2010) before the vertical extensions. Figure 3.2a demonstrates addition of new components that addresses financial securities and stability mechanisms (Teglio et al., 2018) while Figure 3.2b demonstrates the components that have enabled us to address policy stimulation towards green finance. In short, other than redesign and re-implementation of some of the previous components, a significant number of new features and components are added to the model. Namely, we have added a housing market, agents, mechanisms and markets for financial securities, and green sustainability related components and mechanisms. Figure 3.2 demonstrates available and configurable modelling futures after addition of new agents, mechanisms and markets.

[4] FLAME stands for Flexible Large scale Agent Modelling Environment. See `http://flame.ac.uk/`.



(a) New financial stability components (Teglio et al., 2018).



(b) New components on environmentally sustainable policies and regulations (Raberto et al., 2018).

Figure 3.2: Addition of new components to the base model.

The modularity of the design enables us to turn on and or turn off a market or a mechanism without any change at model description layer or at behavior implementation layer. In other words, by setting relevant configuration parameters of the model at initialization layer we are able to include or exclude certain components of the model. The enhanced modularity serves us in two ways. At one hand, we are able to conduct experiments in an incremental and controlled manner to analyze impacts of a new component, which is very crucial for validation of new modelling features. On the other hand, it gives flexibility to researcher at configuring an artificial economy that fits best to his or her research question without a necessity for redevelopment of an agent-based model from scratch.

Horizontal scalability

By horizontal scalability we refer to population design where an economic system is set up. The configuration options of the model enables us to set up a large family of artificial economies. Number of closed or open economies, unions or trading partnerships and the size

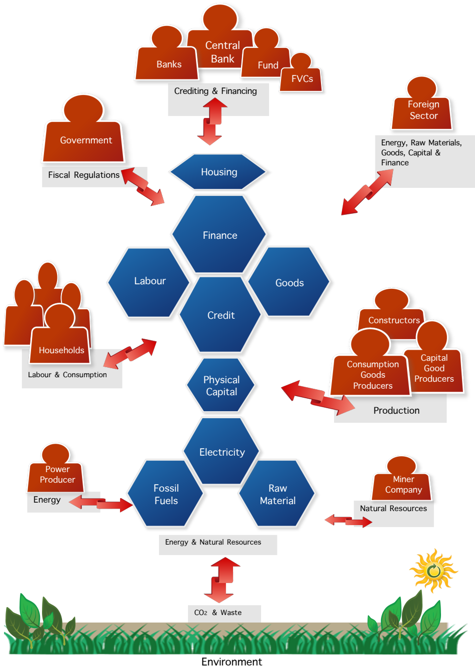


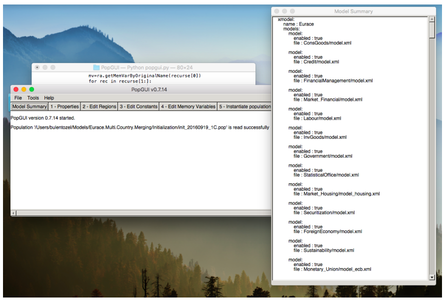
Figure 3.3: Available components of closed single country Eurace economy. Given the research and experiment design any combination of these components can be selected accordingly.

of each economy can be set. For instance, a step by step configuration of complex economic system can be obtained as follows:

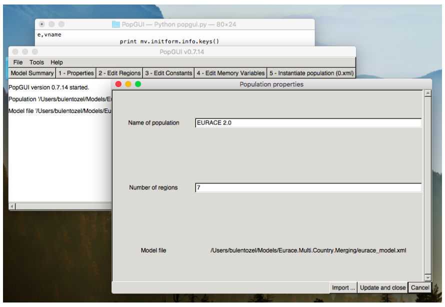
1. At the baseline a single country closed economy with desired markets and mechanisms is configured. Our population initialization tool, the PopGUI[5] graphical user interface application, is used to combine sub-models and to set the model parameters. Figure 3.4a depicts one of the dialog box of the PopGUI for this purpose. The PopGUI dialog box in the figure highlights list of enabled subcomponents.

2. A desired number of instances of the closed economy of previous stage is created. The replication can be created easily again via the PopGUI tool. The screenshot in Figure 3.4b exemplifies a creation of an economy with 7 identical and isolated economies.

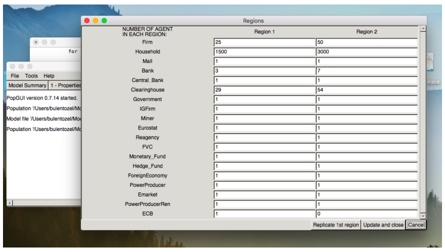
[5] `https://github.com/ICEACE/PopGUI`



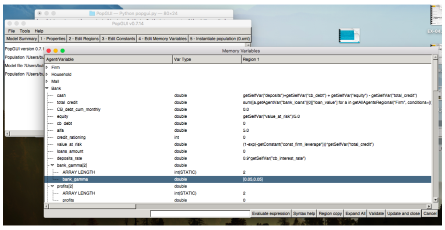
(a) A screen shot of the graphical user interface for population initialization with FLAME models, namely PopGUI, where the dialog box highlights the list of enabled subcomponents.



(b) Creation of an economy with 7 identical and isolated economies.



(c) Creation of a two country monetary union where member states has different populations in terms of households, firms, banks, etc.



(d) A screenshot of a dialogbox of PopGUI where memory variables of bank agents in the first country are being configured.

Figure 3.4: *Scaling horizontally.*

3. Number of agents in each country is configured. Figure 3.4c demonstrates creation of a two country monetary union where member states has different populations in terms of households, firms, banks, etc.

4. The countries in the same monetary union, the countries that can trade with each other, the countries that allow mobility of labor among them is configured. Figure 3.5 is depiction of an economy where 3 fully integrated countries form a monetary union. A fourth country out of the union is able to trade with the union and labor mobility between the union and that fourth country is allowed. A fifth country that has no trade and labor mobility at the initialization beyond its boundary also created in this scenario.

5. Finally, before instantiating the designed multi-country scenario, memory variables of each agent at each country is initialized. This final stage enables the researcher to be able to create countries with differing level of technology, human capital, etc. Besides, if

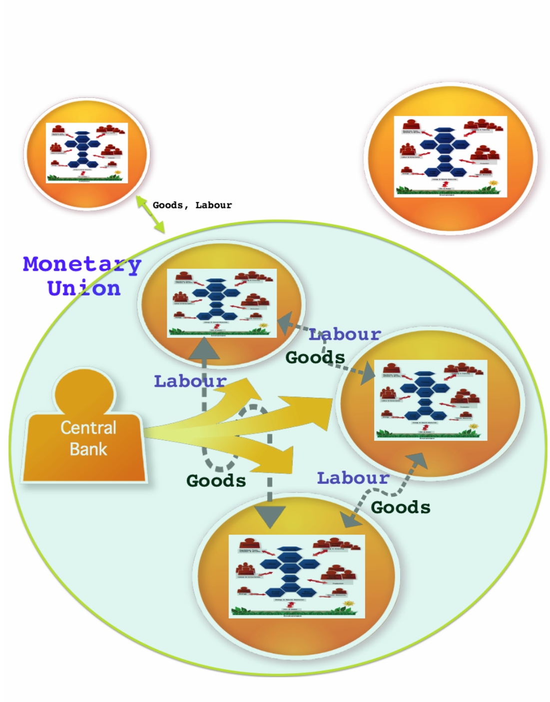


Figure 3.5: A multiple country configuration of the model. It is an economy where 3 fully integrated countries form a monetary union. A fourth country out of the union is able trade with the union and labor mobility between the union and that fourth country is allowed. There also exists an isolated fifth country.

necessary, for instance, a differing wealth distribution in each country can also be set at this step. Figure 3.4d is a screenshot of a dialogbox of PopGUI where memory variables of bank agents in the first country are being configured.

It should be noted that the model is designed in a generic way that it enables the researcher to configure it such that flow of goods and labor between countries in the model can emerge from individual and endogenous agent decisions. For instance, it can let the firms to decide individually and endogenously on the list of countries to export[6]. In a similar manner, households can individually and endogenously decide the list of foreign labor markets to observe and to move to.

[6]For the details of model specifications regarding export decisions at our first use case of the set up, see Section 2 in Petrovic et al. (2018). A summary of firms' decision mechanism for that case is provided in Section 3.4.

3.3.2 Accommodation of real agents within artificial economy

A major part of the work on multi-country simulation set up has taken place during the EU funded SYMPHONY[7] project. The multi-country version of the model was used as the game engine for the online game platform that was designed during the project. For the platform a global economy with multiple countries were configured and served as the simulation engine.

One of the key objectives then has been to enable human users of its platform to configure an artificial economy, initialize it and run it, and interact with it during the run time. In order to fulfill this major objective a number of new configuration parameters have been introduced to the model. In the current version of the symphony project platform, human users are able to take over the roles of government and central bank artificial agents. When the simulator is in the game mode and if the control of a designated agent is passed over to a human player, policy decision processes of the agent, such as setting the interest rate, are handed over from artificial agents to the game players during the run time. In other words, when in the game mode, the corresponding central bank agent skips its own policy making process and uses the interest rate that is decided by human player and announces it to the other human and non-human agents in the game.

This feature is accommodated in the model easily by exploiting the layered design approach. See Chapter 5 for overall design pattern for complex economic systems. The decisions of human players are incorporated into the model via the initialization layer. During the run time, we are able to take full snapshot of the economy at the end of each iteration when all the agents have reached to synchronization point, that is, to the end of an iteration. Such a frozen state of the economy can be used to initialize or resume a new simulation from that point onwards. This feature is used by the ABM engine of the Symphony platform that enables the game players steer the certain behaviors of artificial agents during the run time.

[7] https://cordis.europa.eu/project/rcn/110002_en.html/

3.3.3 Experiment set up with control groups

The modular and scalable modelling design approach has enabled us to create control groups that are isolated closed economies. Figure 3.6 demonstrates the simulation set-up that is configured for the work in Petrovic et al. (2018) and that is summarized and further discussed in this chapter.

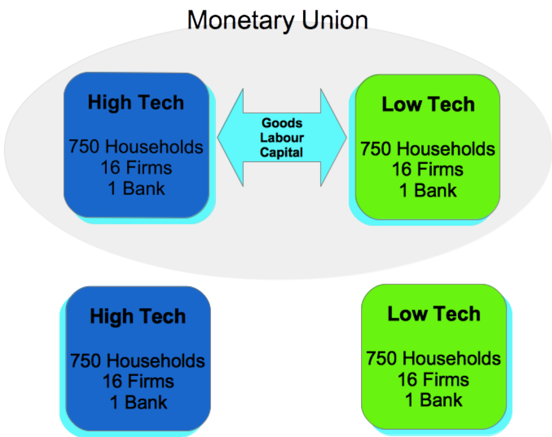


Figure 3.6: *Experiment set-up used to study policies joining a monetary union when there is technology difference between union members. High Tech and Low Tech within the union and out of the union are identical economies at the start of simulations. The economies out of the union are closed economies and used as control groups. See Section 3.3.3 for the details of the statistical measures devised for a comparative study where the isolated economies are used as control groups.*

A horizontally scalable economy design enables us to create controlled experiment groups that can be configured and run parallel test groups. For instance, in the study whose results are summarized and discussed in this chapter, a low tech closed economy serves as a control configuration against the low-tech test country who is part of a monetary union. At the start of a simulation the test country has exact population configuration as the control country in terms of the size of its markets, skill and capital distributions among households, and level of technology of its production firms. Being able to embody the test and control groups within the same simulation run enables us to expose both groups to the same random seed for each run; and when necessary examine stochastic variations between test and control group as of single runs; and then test statistical significances after having aggregated data from multiple runs for the same initial conditions.

In the case of the research motivations as explained above in this chapter, we have designed a 2×2 experimental setting with two countries that are part of a union and two isolated countries. The population design of a test group, namely the countries forming the union, and a control group, namely the isolated countries out of the union are depicted in Figure 3.6. The isolated countries are used as a benchmark to evaluate the net effects of belonging to the union. In particular, this setting allows us to compare the evolution of countries in the union with respect to their identical counterpart out of the union.

3.3.4 Statistical measures for Monte-Carlo simulations with controlled groups

Agent-based simulations, in general, provide very detailed data that should be aggregated and analyzed at the macro level. Our multi-country setup with the control groups of economies has lead us to employ novel aggregation and comparison procedures. In order to be able to compare and test relative dynamics of economies with or without a monetary union we have devised new statistical measures that take the control groups into consideration. The outcome of numerous simulations with different random seeds are used for these measures.

The 2×2 experimental setting explained in the previous section not only allows us to explore the differences between the union and the isolated countries but also within the countries belonging to the same union. In order to make full use of the generated data, we have devised a set of statistical measures which are useful for the interpretation of results, keeping in mind that we want to examine the evolution of specific features of a country (or union) always in relation with its country benchmark.

The variable Y represents a generic economic indicator under study, e.g.: GDP, number of yearly immigrants, total physical capital in the country, etc.

The average over seeds

$$\overline{Y}_t = \frac{1}{|\mathbb{S}|} \sum_{s \in \mathbb{S}} Y_t^s \tag{3.1}$$

This measure indicates the mean value of the economic indicator Y at month t overall considered seeds. $\mathbb{S}$ is the set of seeds used in the experiment, and $|\mathbb{S}|$ indicates the cardinality of the set, which here coincides with the number of elements, i.e., seeds. We use this type of measure in the time-varying graphs, while the next measures are used in the box-plots, and show the variation of a specific indicator across the different seeds $s \in \mathbb{S}$.

The mean of the sum

$$\begin{cases} \Sigma^s_{AB}(Y) = \frac{1}{|\mathbb{T}|}\sum_{t\in\mathbb{T}}(Y^s_{A,t} + Y^s_{B,t}) \\ \Delta\Sigma^s_{AB,CD}(Y) = \Sigma^s_{AB}(Y) - \Sigma^s_{CD}(Y) \end{cases} \tag{3.2}$$

Given a random seed s, the statistical measure $\Sigma^s_{AB}(Y)$ represents the average value in the time subset $\mathbb{T} \subset \mathscr{T}$ of the sum of the observed economic indicator Y in the two considered countries (A and B). We often use this measure to compare the value of an economic indicator in the union with the value of the same indicator in the isolated countries, therefore computing the difference $\Delta\Sigma^s_{AB,CD}(Y)$. In general (but not necessarily), countries A and B are in the union, while C and D are the isolated ones. If Y is real GDP, then $\Sigma^s_{AB}(Y)$ will be the average real GDP level in the union (if countries A and B belong to the union), and $\Delta\Sigma_{AB,CD}(Y)$ will be the difference between the average real GDP level of the union and the average real GDP level of the isolated countries.

For the sake of clarity, sometimes we use the relative difference instead of the difference, defined as $[\Sigma^s_{AB}(Y) - \Sigma^s_{CD}(Y)]/\Sigma^s_{CD}(Y)$. In this way, the gap between the union and the isolated countries is in relative terms (given in percentage) and can be grasped at first sight, e.g., the average GDP in the union is 10% higher than in the isolated countries.

The mean of the difference

$$\begin{cases} \Psi^s_{AB}(Y) = \frac{1}{|\mathbb{T}|}\sum_{t\in\mathbb{T}}(Y^s_{A,t} - Y^s_{B,t}) \\ \Delta\Psi^s_{AB,CD}(Y) = \Psi^s_{AB}(Y) - \Psi^s_{CD}(Y) \end{cases} \tag{3.3}$$

Given one random seed, the statistical measure $\Psi^s_{AB}(Y)$ represents the average value in the time subset $\mathbb{T}$ of the difference of the observed economic indicator Y between the two considered countries (A and B). This measure can be useful to explore the average difference between GDP of a country in the union with respect to its counterpart out of the union, or the average difference between GDP in the two countries of the union. If the setting is entirely symmetric, i.e., if all the countries are identical at the beginning, we expect that the mean value of this indicator across seeds should be zero.

Polarization, or local divergence

$$\begin{cases} \Upsilon^s_{AB}(Y) = \frac{1}{|\mathbb{T}|}\sum_{t\in\mathbb{T}}|Y^s_{A,t} - Y^s_{B,t}| \\ \Delta\Upsilon^s_{AB,CD}(Y) = \Upsilon^s_{AB}(Y) - \Upsilon^s_{CD}(Y) \end{cases} \tag{3.4}$$

Given one random seed, the statistical measure $\Upsilon^s_{AB}(Y)$ captures the divergence of countries A and B concerning the observed indicator Y. It is computed as the average value in the time subset $\mathbb{T}$ of the absolute difference of the observed economic indicator Y between the two considered countries (A and B). When the local divergence $\Upsilon^s_{AB}(Y)$ is high, it means that the values of Y in the two countries are on average very different and that the countries tend to "diverge". In general, we consider the difference $\Delta\Upsilon^s_{AB,CD}(Y)$ to compare the local divergence of countries in the union with the reference divergence of the isolated countries C and D. If we observe a high $\Delta\Upsilon^s_{AB,CD}(GDP)$, the distance between the GDP of the two countries of the union, is larger than the distance of their isolated counterparts, meaning that the union created inequality or polarization across countries.

3.4 Summary of results

This section summarizes the results of computational experiments that we have designed to study the macroeconomic implication of forming a union of countries. The details of model description including its validation, extensive analyses of results and discussions are presented in (Petrovic et al., 2018).

In this particular work, we have created a setup that enabled us to question when it is convenient for two countries to join a monetary union. The union is characterized by a fully integrated consumption goods market, labor mobility between member countries, and where stocks and bonds can be traded in an international financial market and the union central bank.

Firms employ physical capital and labor force to produce homogeneous durable consumption goods. Firms that are within a union deliver consumption goods to all malls within the union, while households shop only in the country of residence. Before the production takes place, firms plan the production quantities taking into account the expected demand and the current level of inventories at each specific market. Firms form beliefs about future demand based on past sales and calculate market specific planned production. Since the production is centralized in the country of origin, firms calculate the total planned production summing up all market specific planned outputs. The final output depends on the firms' production capacity and on available funds. If companies are not able to produce the entire planned quantity with the current capacity, they will look for additional workers and also invest in new physical capital. The number of new employees will be determined in the labor market, where the companies will compete among each other, while the amount of needed physical capital will be calculated maximizing the Net Present Value of the expected returns on investment. Investments are carried out if firms have sufficient available funds. In the case they are financially constrained, i.e. they do not have sufficient internal resources and they are rationed both in the credit and financial markets, investments will be adjusted accordingly. The details of model specifications are given in Section 2 of Petrovic et al. (2018).

3.4.1 Simulation setup

We design a 2×2 experimental setting with two countries that are part of a union, henceforth C_1^U and C_2^U, and two isolated countries, henceforth C_1^I and C_2^I. The isolated countries are always initialized as identical to the correspondent union members, i.e., at time zero $C_1^U = C_1^I$ and $C_2^U = C_2^I$, and they are used as a benchmark to evaluate the net effects of belonging to the union Countries in the union share a common currency and a union central bank, while isolated countries are non-trading closed economies. In particular, this setting allows us to compare the evolution of countries in the union with respect to their identical counterpart out of the union (that is C_1^U vs. C_1^I and C_2^U vs. C_2^I). In other cases, we will be interested to study some measures of convergence in the countries of the union, with respect to the benchmark (that is C_1^U and C_2^U vs. C_1^I and C_2^I). It should be noted that in this setup there is no trade between the countries in the union and the isolated countries out of the union. Each isolated country is a closed economy.

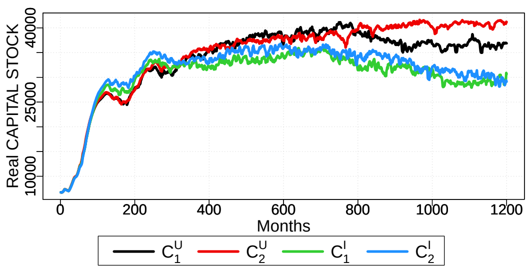
We have employed the statistical measures as described in Section 3.3.4 to make the crossed comparisons. We have designed three scenarios. Here summary of the findings from each scenario is reported. The extensive details and discussions on the results from computational experiments can be found in (Petrovic et al., 2018).

The general setup of the model includes four countries where each has 750 households, 16 firms, a single physical capital producer, a commercial bank, the central bank and the government. At the union level, there is also the Union Central Bank which controls the monetary policy of the union members. For each scenario presented above, we ran 30 independent Monte Carlo simulations, each one consisting of a time span $\mathscr{T}$ of $24,000$ iterations, which in our model stands for $1,200$ months or 100 years. A validation of the model dynamics is provided in the Appendix of Petrovic et al. (2018).

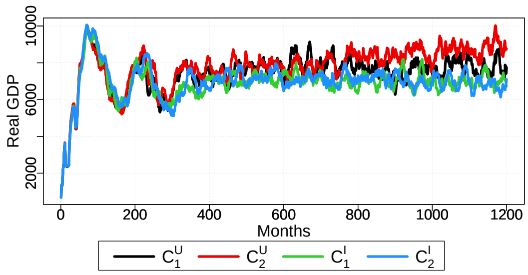
We initialize our model such that all economies are under-capitalized at time $t = 0$, which allow us to observe two different regimes. The first one is a capital accumulation regime, while the second is a stable path[8] capital stock regime. In this way, we can analyze two important conditions of the economy, and we can try to disentangle the effects of the proposed scenarios

[8]The model is characterized by endogenous business cycles, showing fluctuations, and even crises, also in the stable path regime, see e.g. Teglio et al. (2018) for details.

across the two economic regimes. As we will discuss in this results section, the first phase of capital accumulation exhibits far from the equilibrium dynamics and more fragile economies, where endogenous shocks can easily propagate across the markets. On the other hand, the second phase is more stable but always characterized by business cycles that can become turbulent in some cases. Figures 3.7a and 3.7b show the average time series of real capital stock and real GDP for a representative scenario (mobility friction $\rho = 0.8$). These figures reveal the two regimes of the economies. The results summarized here from the stable phase.



(a) Real capital stock



(b) Real GDP

Figure 3.7: Statistical measure "the average over seeds" $\overline{Y}_t$ given in equation 3.1. A scenario with mobility friction $\rho = 0.8$. C_1^U and C_2^U are countries in the union, whereas C_1^I and C_2^I are isolated countries. Time series on both panels exhibit two regimes. The regime in the period of first 400 months is characterized by the capital accumulation and huge fluctuation in real GDP, while in the period after 400 months the economy enters a stable path.

3.4.2 Scenario I: Union of identical countries

The first "basic scenario" aims at studying the impact of integration on the performance of the involved countries. We initialize all the countries as identical, i.e, $C_1^U = C_1^I = C_2^U = C_2^I$, and we study the implications of belonging to the union, that is, how C_1^U and C_2^U evolve with respect to C_1^I and C_2^I. In this scenario and in subsequent scenarios union is a monetary union, where the central bank sets a common monetary policy. It is characterized by a frictionless international goods market, i.e., households can buy products from both countries without any additional cost, and they are indifferent. The union also shares a common financial market where households can buy assets from each country, and a common labor market where households can move from one member state to the another.

Within this basic scenario, we examine how labor market frictions affect the performance of each union member and the union on aggregate under varying mobility friction constraint.

The mobility friction is represented by an overall exogenous proxy parameter ρ. It may entail migration costs, lack of support networks at a new host institute, difficulty in transfer of pension funds, or cultural differences. We have provided a theoretical discussion on how to represent these varying mobility friction factors endogenously under a multi-country or multi-region setting in (Ozel et al., 2015). Nevertheless, in this work we have opted to represent it as an exogenous experiment parameter. When $\rho = 0$ households are completely indifferent between working at home or abroad, while when $\rho = 1.2$ they have a strong preference for working at home. We did not add the results for higher ρ values to the presented plots both to improve readability and because they do not add any valuable behavior or information. It should be noted that the parameter is a multiplier on the wage offered abroad. The resulting amount serves as a proxy representing the cost of moving abroad. The extreme case is when $\rho = \infty$, where nobody moves[9].

We find that it is always convenient for two identical countries to join in a union. Not only the union as a whole outperforms the independent countries, but also each country of the union is better off with respect to its isolated version. This result is due to the integration of the goods and labor markets, which allow for a better allocation of resources in the union. However, if mobility frictions of workers are very low, the performance of the union is weakened, and inequality between countries in the union can even increase. In general, countries in the union also run better government budget, facing lower expenses, collecting more taxes and therefore providing more services (in the form of transfers in the model) and experiencing a higher welfare.

Figure 3.8, via a subset of key economic indicators, presents a direct comparison between the performance of the union and the aggregate performance of the isolated countries, for each mobility friction value. In particular, it plots the statistical measure $\Delta\Sigma^{s}_{AB,CD}(Y)$ of equation 3.2, representing, for each economic indicator Y, the difference between the value of Y in the union and in the isolated countries. If this difference is positive, it means that Y is higher in the union if it is negative, Y is higher in the isolated countries. If it is zero, there is no difference.

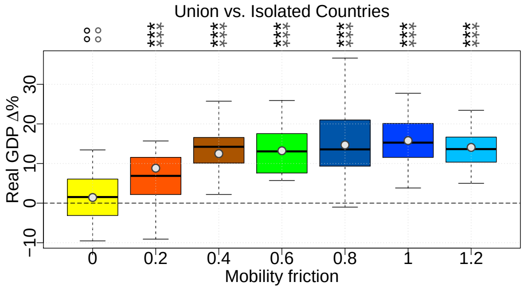
[9] See the relevant section in (Petrovic et al., 2018) for a further discussion on the range of the parameter.

In general, unless otherwise stated, the timespan $\mathbb{T}$ is the second half of the simulation, i.e., the last 50 years. This allows us to capture the economic dynamics in the stable path.

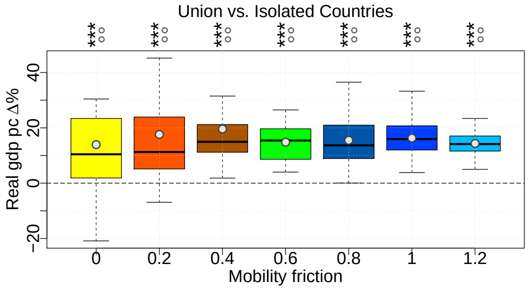
Some of the main economic indicators, such as real GDP per capita, real investments, real consumption, capital stock, and unemployment rate are presented in Figure 3.8. The economic activity is, in general, significantly higher in the union (around 10%-20% higher) with respect to the isolated countries, except for the case with the frictionless labor market ($\rho \leq 0.2$). Better economic performance is explained by the presence of international goods, and labor markets in the union. In particular, the international goods market allows for a better allocation of products across the two countries, where a potential decrease in the local demand is compensated by the demand of the foreign country. This flexibility leads to a lower, and more stable, unemployment rate, as shown in Figure 3.8f. To sum up, the union configuration allows for a more efficient economic adjustment in the cases of excess demand or supply in both the labor and goods market, finally outperforming the configuration with isolated countries. As a final remark, we should mention that the performance of the union depends on the considered scenario, as Figures 3.8a - 3.8e clearly show. In particular, the advantage of the union, with respect to the isolated countries, becomes weaker when mobility frictions ρ are too low. This point has been addressed and discussed in detail in Section 3.I. of Petrovic et al. (2018). In summary, we have seen that the relatively weaker performance of the union in the case of low mobility frictions mainly depends on the inefficient use of the capital stock between the two countries. As the union model does not allow for capital stock displacement, the smaller country, suffering from a drain of workers, does not fully use its available capital stock, while the larger country has an excess of households with respect to the available capital stock. Figures 3.8e shows that the total amount of capital stock in the union is much lower (even lower than in the isolated countries case) in absence of mobility frictions, confirming an inefficient use of capital.

3.4.3 Scenario II: Union of technologically differing countries

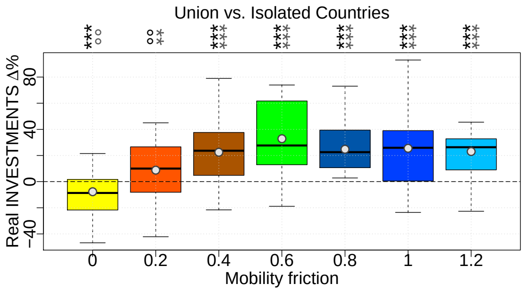
The second scenario is similar to the basic one, except for a difference in technology between the two countries. Another exogenous policy parameter γ_g is used as the technological indicator and can be high, γ_H, for high technology countries, or low γ_L, for low technology countries.



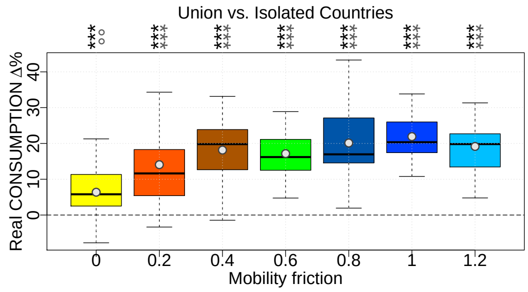
(a) Real GDP.



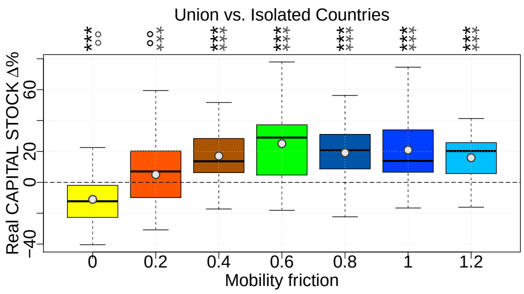
(b) Real GDP per capita.



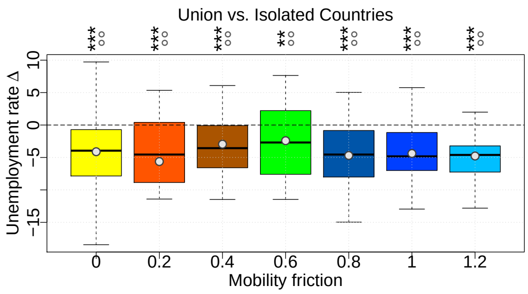
(c) Real investments.



(d) Real consumption.



(e) Real capital stocks.



(f) Unemployment rate.

*Figure 3.8: Statistical measure "the mean of the sum" $\Delta\Sigma^{s}_{AB,CD}(Y)$ given in equation 3.2. Panels a, b, c, d, and e show relative differences, while panel f shows differences between the countries in the union (C^U_1 and C^U_2) and the isolated countries (C^I_1 and C^I_2). The x-axis and colors indicate scenarios with respect to the value of mobility friction ρ. The solid lines in the bars represent median while dots denote mean. Note that, the box-plots include two statistical tests that are presented on the top of the figure for each box-plot. The left (darker) test measures whether mean is statistically different from zero, according to the null hypothesis H_0: mean is not statistically different from zero; while the right (lighter) test measures whether the given value of ρ is statistically different from the basic case of $\rho = 0$. Thus, the null hypothesis H_0 is: there is no statistical difference between the two cases. Stars (***, **, *) indicate the significance levels of 1%, 5%, 10% respectively, while "∘∘" indicates that the test is not significant. When the conditions are met we use a parametric paired t-test, and a non-parametric paired Wilcoxon rank-sum test otherwise.*

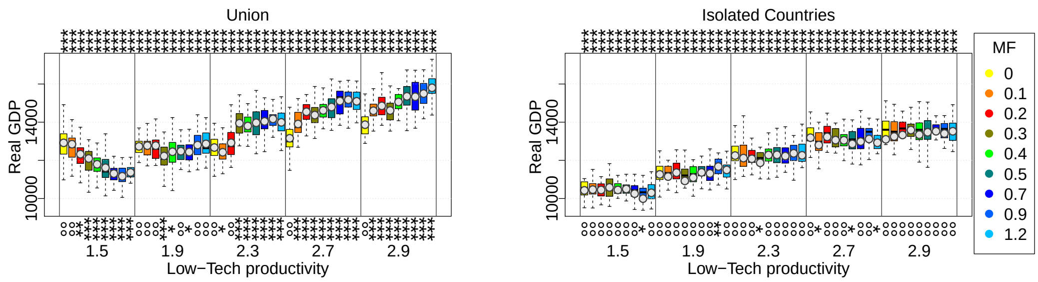
Adapting the notation to consider technology, we have two countries in the union, C^U_H and C^U_L with different level of technology, and two isolated countries, C^I_H and C^I_L, identical to the union members. We study the performance of the union, with respect to the isolated countries, for several degrees of the technological gap and mobility frictions.

Detailed results[10] show that when the two countries differ in productivity, it is again worth to form a union. However, the performance of the union is strongly affected by the size of the productivity gap among the countries. The most critical case is represented by a large productivity gap combined with very low mobility frictions of workers. The high technology country tends to attract workers and the union (intended as an abstract statistical entity) still benefits by a more productive employment of the labor force. However, the conditions of the low-tech country may collapse, leading also to a deterioration of the public sector, whose revenues decrease generally more rapidly than its spending. The public sector is therefore not able to revert the economic downturn.

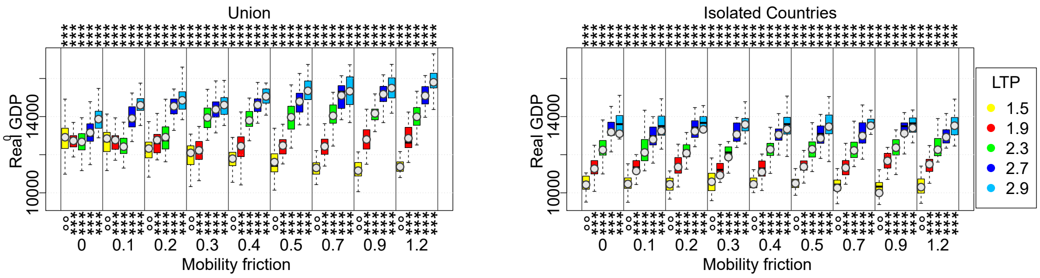
Figure 3.9 presents the performance of the union as a whole (displaying $\Sigma^{s}_{AB}(GDP)$, of Equation 3.2), instead of focusing on the single countries. The left part, concerning the union, and the right part, concerning the isolated countries, can be compared in order to analyze the impact of the union. It is worth noting that the total population is constant across the squares of the figure and therefore the real GDP also represents the real GDP per capita pattern in the union over the different scenarios.

Comparing the left and the right part of Figure 3.9, we observe that the real GDP of the union as a whole is always higher than the real GDP of the sum of the isolated countries. The explanation of this result recalls the one used for the case above, and it is mainly based on the presence of common markets. In the case of countries with different technologies, an additional reason for higher overall production in the union is that, whenever a household migrates from the low-tech country to the high-tech country, its productivity raises, along with the overall production in the union. We have seen that high-tech country is more populated than the low-tech one. Figure 3.10 clearly proves the result. It further shows that the population gap increases for lower mobility frictions and higher productivity gaps.

[10]For a detailed set of analyses on the dynamics of the union consisting of technologically differing members see Section 3.4 in Petrovic et al. (2018).



(a) Real GDP. Mobility frictions (MF legends) in the color code.



(b) Real GDP. Low-Tech productivity (LTP legends) in the color code.

*Figure 3.9: Statistical measure "the mean of the sum" $\Sigma^s_{AB}(Y)$ given in Equation 3.2. The left panels show the countries in the union (C^U_H and C^U_L), while the right panels show the isolated countries (C^I_H and C^I_L). On Figure 3.9a, the x-axis indicates different productivity levels γ_L of the low-tech country while colors indicate scenarios with different values of mobility frictions ρ. On Figure 3.9b, the x-axis indicates scenarios with different values of mobility frictions ρ while colors indicate different productivity levels γ_L of the low-tech country. The solid lines in the bars represent median while dots denote mean. Note that, the box-plots in this sample figure include two statistical tests that are presented on the top and on the bottom of the figure, for each box-plot. The test at the top measures whether the mean is statistically different from zero, according to the null hypothesis H_0: mean is not statistically different from zero; while the test at the bottom measures whether the mean of a given box is statistically different from the corresponding basic case, e.g. $\rho = 0$ for each case of low-tech country productivity γ_L. Thus, the null hypothesis H_0 is: there is no statistical difference between the two cases. Stars (***, **, *) indicate the significance levels of 1%, 5%, 10% respectively, while "∘∘" indicates that the test is not significant. When the conditions are met we use a parametric paired t-test, and a non-parametric paired Wilcoxon rank-sum test otherwise.*

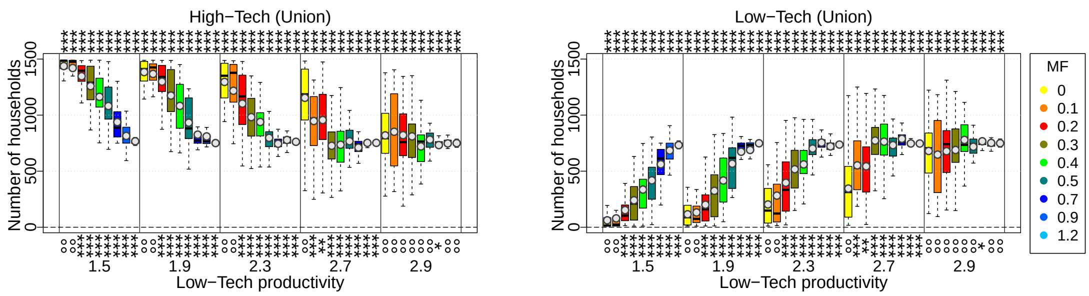


Figure 3.10: The number of households by countries. The x-axis indicates different productivity level γ_L of the low-tech country, while colors denote different values of mobility frictions ρ. The solid lines in the bars represent median while dots denote mean.

3.4.4 Scenario III: Union with a fiscal pool

The last scenario adds to the second one a fiscal policy measure (called "fiscal pool"), consisting in a common pool of liquidity, available at the union level, that comes from the budget surplus of each member country and can be redistributed in the case a country has to finance its budget deficit. The rationale behind this mechanism is to mitigate the unbalance, which is observed in the second scenario, between the two countries of the union. The performance of the countries in the union with or without the “fiscal pool” instrument is therefore examined.

Our results have shown that a fiscal integration mechanism is able to mitigate the inequality among countries, especially in the most critical cases. Sustaining the income in the low productivity country reduces emigration and raises the aggregate demand both for domestic and foreign products. Nevertheless, the average economic indicators in the union slightly decline, because a larger part of the production is reallocated in the low-tech country.

It is seen that the fiscal pool acts by preventing or restricting, the sources of inequality that have been described in the previous section. Figure 3.11 compares the real wage differential between the countries of the union with and without the fiscal pool mechanism. It shows that the wage differential is lower when the fiscal pool is active and the productivity gap is high (the right side of the picture, as usual, is the control group of isolated countries and does not present any difference). This lower wage differential moderates the emigration in the union, as reported in Figure 3.12a, showing that the low-tech country is more populated and the high-tech country is less populated when the fiscal pool is active. A key element is that the accumulation of capital stock is more balanced with the fiscal pool, as Figure 3.12b shows. Part of the capital stock of the high-tech country (which is lower) is now located in the low-tech country. Consequently, also the real GDP of the low-tech country increases because production is less dislocated to the high-tech country (see Figure 3.12c). Finally, the fiscal pool improves the well-being of the low-tech country in the most critical cases, i.e., when productivity gap is high and mobility frictions are low and slightly reduces the well-being in the high-tech country, measured as real GDP per capita in Figure 3.12d.

3.4.5 Conclusions

To sum up, our results suggest that a better fiscal integration would be useful if the policy target in the union is reducing inequalities among the countries, whereas it would not be benefi-

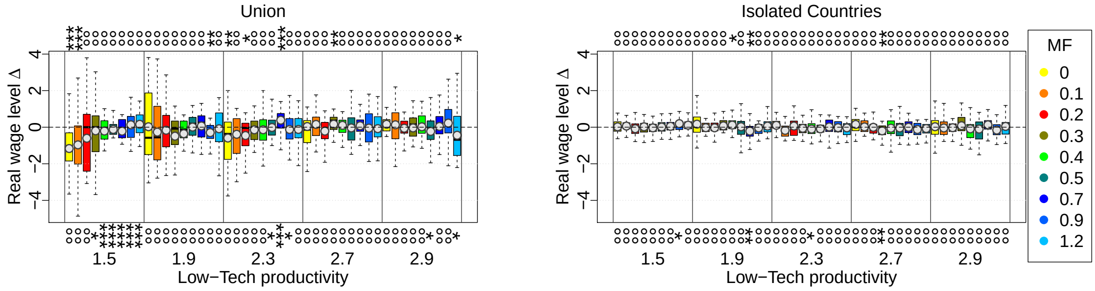
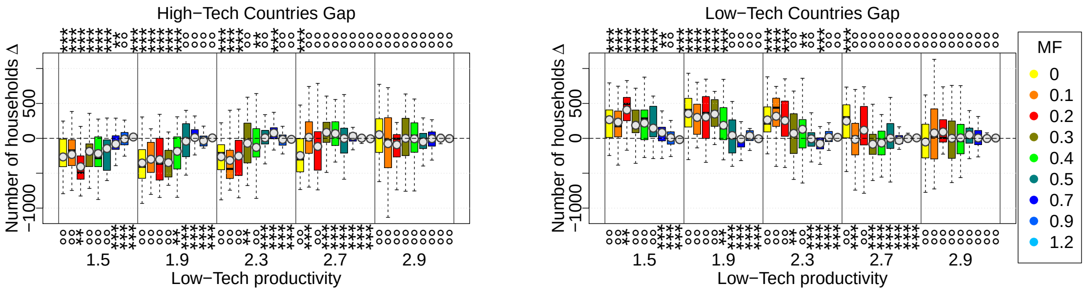


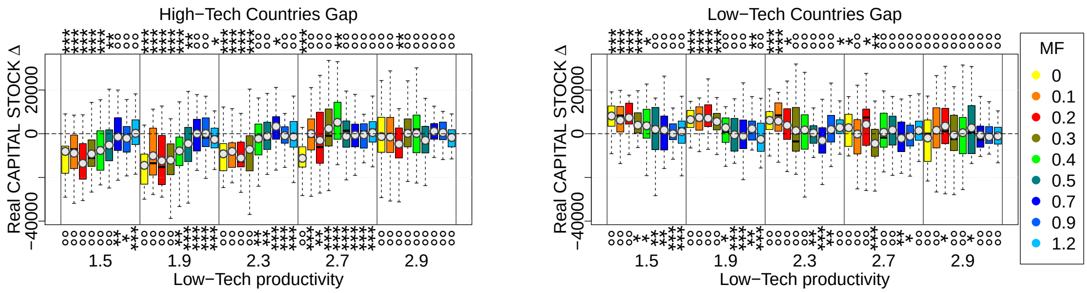
Figure 3.11: Statistical measure "the mean of the difference in difference" $\Delta\Psi^{s}_{AB,CD}(Y)$ given in Equation 3.3. The left panel shows the difference in difference between countries in the union (C^U_H and C^U_L) with and without the fiscal pool, while the right panel shows the difference in difference between isolated countries (C^I_H and C^I_L) with and without the fiscal pool. The x-axis indicates different productivity level γ_L of the low-tech country, while colors denote different values of mobility frictions ρ. The solid lines in the bars represent median while dots denote mean. See the note in Figure 3.9 for the interpretation on the reported statistical significances.

cial if the goal is to maximize the overall production of the union. This raises some interesting political issues about the kind of development strategy that a union (with particular reference to the European Union) want to pursue. Our study underlines that the objective of maximizing economic growth is not always in harmony with the objective of reducing inequality and acknowledging the structural and cultural difference that exist among countries.

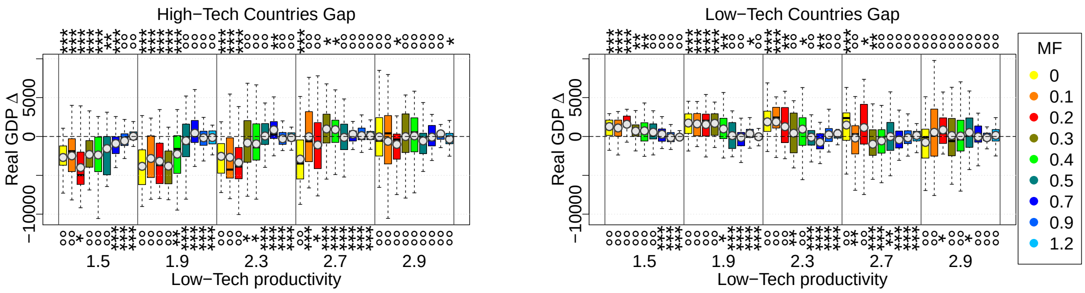
We remind that our work is based on the assumption of no productivity convergence among countries, which might be extreme but allows us to highlight the mentioned issues. In the case of productivity convergence, of course the economic inequality could be just healed by time, with lower need of political intervention. However, we also ignore in the paper the political/electoral implications which can bring to power parties seeking the destruction of the union. Therefore, if the union has to be conserved, policy makers not only should consider the objective to improve growth numbers at the union level, but also care about a redistribution of resources which could improve the stability of the union and its cultural and traditional heritage.



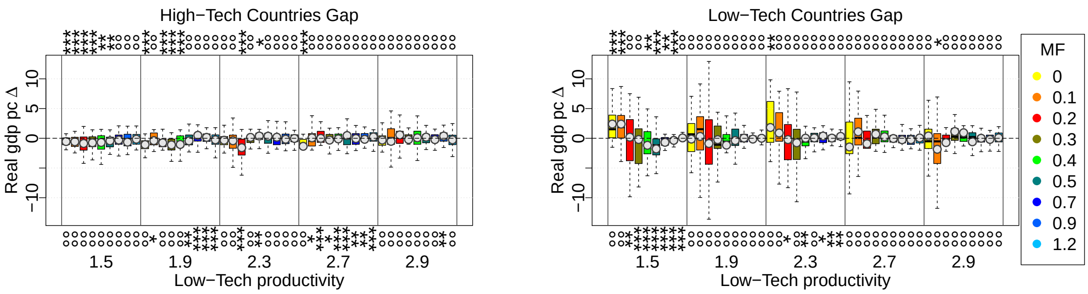
(a) Number of households.



(b) Real capital stock.



(c) Real GDP.



(d) Real GDP per capita.

Figure 3.12: Statistical measure “the mean of the difference in difference” $\Delta\Psi^{s}_{AB,CD}(Y)$ given in Equation 3.3. The left panels show the difference in difference between high-tech countries (C^U_H and C^I_H) with and without the fiscal pool, while the right panels show the difference in difference between low-tech countries (C^U_L and C^I_L) with and without the fiscal pool. The x-axis indicates different productivity level γ_L of the low-tech country, while colors denote different values of mobility frictions ρ. The solid lines in the bars represent median while dots denote mean. See the note in Figure 3.9 for the interpretation on the reported statistical significances.

Chapter 4

Stock-flow consistent network designs for agent-based models

This chapter presents two separate yet inter-related studies from a network theoretic perspective. Section 4.1 presents the details of a simulation set-up that serves to model and analyze risk and contagion at interbank networks. Section 4.2 presents modelling details of the work on forming liability links between two separate systems of interbank networks. Preliminary results and future directions are reported.

There is a longer term objective in these studies within the framework of complex ABM models. The aim is to generate stock-flow consistent network structures that can be plugged into the our large scale ABM simulation environment, the state-of-art of which is presented in Chapter 3. Being able to embed these network based components in a macroeconomic model provides a set of conceptual and methodological advantages. Empirically driven calibration, initialization of network relations, for instance in case of contagion model of Section 4.1, will enable us to address antecedents and consequences of endogenously generated shocks relevant to interbank-networks. The network fusion model of Section 4.2 will serve us to incorporate empirically observed credit or financial structures as part of our entry and exit mechanisms at multi-country economic integration scenarios.

4.1 Simulating dynamics of contagion in interbank markets

4.1.1 Motivation

During the last three decades, the banking sectors of advanced countries have undergone a remarkable process of concentration. This evident and known phenomenon has raised concerns about its effects on the competitiveness and stability of the banking industry (Beck et al., 2006; Battiston et al., 2012; Bikker and Haaf, 2002). In this respect, economic analysis has reached conflicting conclusions (Beck et al., 2007). On the one hand, some authors hold that the increase in concentration has reduced the competitiveness of the banking sector and that such market power generates higher profits, making the industry more resilient to shocks. On the other hand, the consolidation has generated systemically relevant banks, banks that are sufficiently large and sufficiently connected in the interbank network to pose serious threats of systemic contagion. In as much as these banks can count on implicit "too important to fail" policies, they have incentives to intensify risk-taking behavior and, in so doing, increase banking system fragility (Anginer and Demirguc-Kunt, 2014; S. Mishkin, 1999).

In this work, we have focused on one specific aspect of the relation between concentration and stability of the banking sector. We create a simulation set-up where using a parsimonious set of parameters we are able to characterize core-periphery interbank network structures. In a core-periphery interbank network, the core is composed of banks tightly connected among themselves and the periphery is composed of banks that are not connected to one another and are solely connected to one or few banks in the core. Then we study the effects that the core-periphery structure of the network of interbank obligations, induced by the concentration process, has on the exposure of the banking system to the risk of direct financial contagion. We primarily conjecture that core-periphery financial networks are 'robust-yet-fragile', in the sense that they are resilient to small shocks and fragile to the risk of widespread crises if hit by a sufficiently large shock.

The core-periphery network structure is a generalization of a star-shaped network, i.e. a network where all peripheral nodes are connected only with a single central node. More precisely, the core-periphery network is a multi-center star network where the central nodes tend to form a complete network among themselves, i.e. a network where each bank lends to every other bank. See Figure 4.2 for a simplified depiction of the structure that is generated by our set-up.

Recent analytic results show that both the complete, see Figure 4.1d, and the star-shaped, see Figure 4.1f, interbank networks have a 'robust-yet-fragile' nature, with respect to the risk of default contagion. Haldane and May (2011) first conjectured that highly connected networks might exhibit this feature: be resilient to small perturbations and, at the same time, be fragile in the sense of being exposed to widespread default cascades if hit by low probability-high impact shocks. Acemoglu et al. (2013) and Eboli (2013) demonstrate that in complete interbank networks there is no default contagion for external shocks smaller than a certain threshold, while the whole system defaults if hit by shocks larger that such a threshold. Castiglionesi and Eboli (2018) and Eboli (2013) show that star-shaped networks have the same 'robust-yet-fragile' feature of complete networks. The rationale for these results lies in the fact that both high connectivity and high centralization imply that the losses caused by the default of one or more banks tend to be evenly spread among all other network members. For the opposite reason, sparse and decentralized networks are more exposed to cases of default contagion (of limited scope) caused by small shocks and less exposed to the risk of a complete system meltdown. On these bases, we expect to find the same 'robust-yet-fragile' feature in a core-periphery network, since the latter is the joint of a complete and a star-shaped network.

We aim to test our conjecture running numerical simulations of default contagion on a range of randomly generated interbank networks designed to approach progressively a core-periphery structure. We expect that, as we move from random sparse networks towards sparse core-periphery networks, our simulations will show that such networks become progressively less exposed to episodes of local contagion caused by small shocks and more exposed to the risk of system-wide default crises caused by large shocks.

In this particular phase, we have an isolated and stylized interbank network model. There is only one type of agent: trading banks where interaction behavior between them is homogeneous and given. The banks in the network can be heterogeneous in as much as each bank is characterized by its own balance sheet. The values of the balance sheet headings of each bank are determined by setting the parameters of the model, where the assignments of debts, assets and equities to a bank are calibrated taking into account the position of the bank in the network. Accounting identity is assured both at each individual agent level as well as at the aggregate level for stock-flow-consistency. The shocks are exogenous and modeled ex-ante.

4.1.2 Model overview

In this particular work, we have designed and developed a set of modules to be able to address and test our conjectures. The overall model design is a layered process. It decouples the steps of a research on financial contagion where a cascaded procedure from network creation to data analysis is made possible:

1. a **network configuration module** that can generate stylized or random interbank network models with desired level of size, sparsity, connectivity and centralization;
2. a **balance-sheet configuration module** that generates stock-flow and network consistent balance sheet distributions according to modelling parameters;
3. a **shock-propagation model** that enables us to trace flow of the shocks from source nodes to sink nodes in the network;
4. and an **exogenous random shock model** which enable us create exogenous shock vectors where statistically sufficient number of permutations and differing shock amplitudes are created for systematic Monte Carlo simulations.

This simulation process as a whole is akin to the work in Nier et al. (2007). However, we have an extended and generalized approach which gives the flexibility at studying contagion regarding choices on different network structures, at creation and application of different shock sequences, and configuration of desired balance-sheet structures. For instance, as it can be seen in Section 4.1.7 where an exemplary case on probing a contagion process is demonstrated, unlike Nier et al. (2007) we are not limited to variations as of network connectivity. We are also able to introduce a variation at the level centralization within an interbank network. Our generic approach provides a modelling abstraction and hence flexibility for a research on contagion dynamics.

The underlining diffusion model in the current version of the simulator is based on Eboli (2013). The shocks whether internal or external are absorbed by the share-holders first. When total internal and external shock received by a bank exceeds its capital, it is transferred to its creditors. The credits are liquidity of the households deposited to the bank and loans taken from the other banks in the system. In the presented version of the contagion model for a given bank, i, each of its external depositor k, and its interbank loan owner, j, share the burden of excessive shocks proportionally to the size of their deposits h_{ik} or loans d_{ij}.

Modelling details and assumptions are presented subsequently.

4.1.3 Interbank network structures

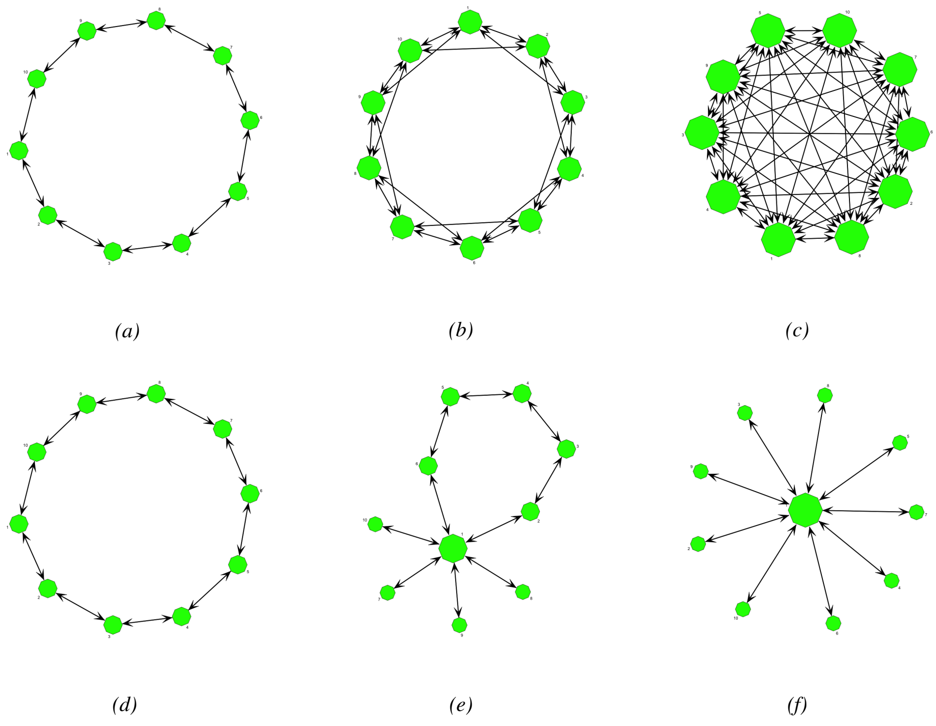
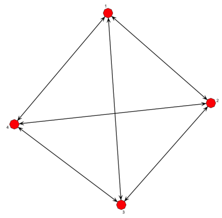
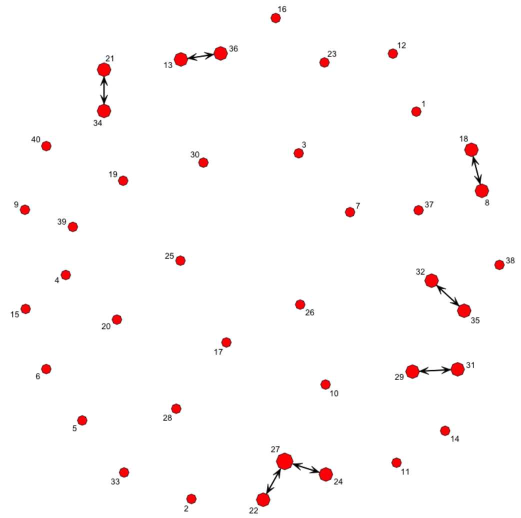


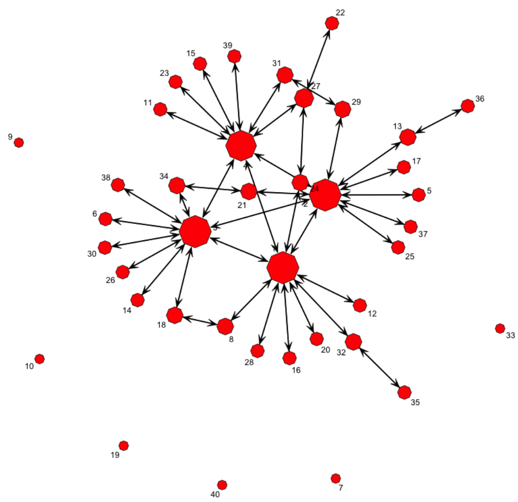
Figure 4.1: Generation of stylized regular graphs with constant connectivity and centralization levels. Figure 4.1a - 4.1c depicts where the circular graph is incrementally transformed into a fully connected graph while graph level centralization is kept constant. Figure 4.1d - 4.1f demonstrates the process where network connectivity is kept constant but centralization is increased to its maximal level ending in a perfect star.



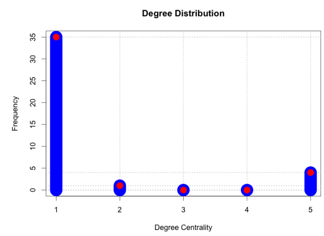
(a) Erdos-Renyi random graph, $G^{kk}(K, p_{kk})$, for the core component where $K = 4$ and $p_{kk} = 1$ that generates a fully connected core.



(b) Erdos-Renyi random graph, $G^{pp}(K, p_{pp})$, for the periphery component where $N = 40$ and $p_{pp} = 0.01$ that generates a very sparse connection among peripheral nodes.

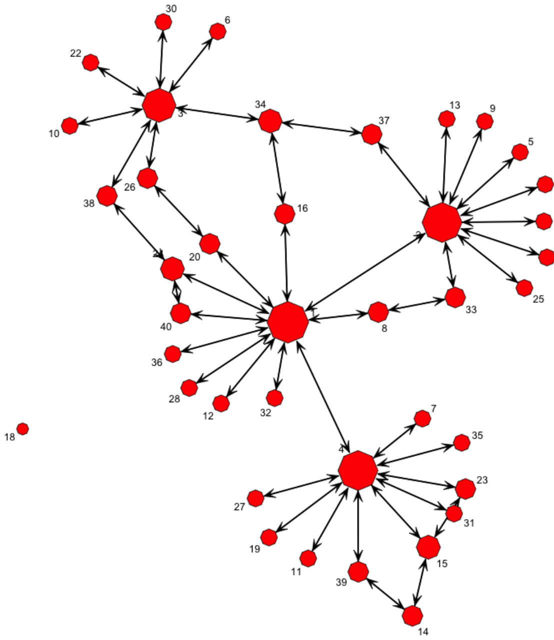


(c) A core periphery graph where new edges between nodes at the core component, fig. 4.2a, and the nodes at periphery, fig. 4.2b is added according a Bernoulli process with $p_{pk} = 0.7$.

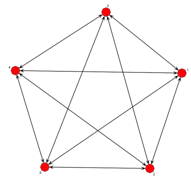


(d) The degree distribution of the resulting random core-periphery network in fig. 4.2c.

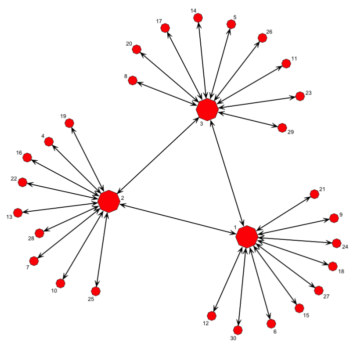
Figure 4.2: *Generation of a random core-periphery graph $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$, where $N = 40$, $K = 4$, $p_{kk} = 1.0$, $p_{pp} = 0.01$, and $p_{pk} = 0.7$. The resulting overall network **centralization**, $C_G = 0.22$ and **connectivity**, $= K_G = 0.05$.*



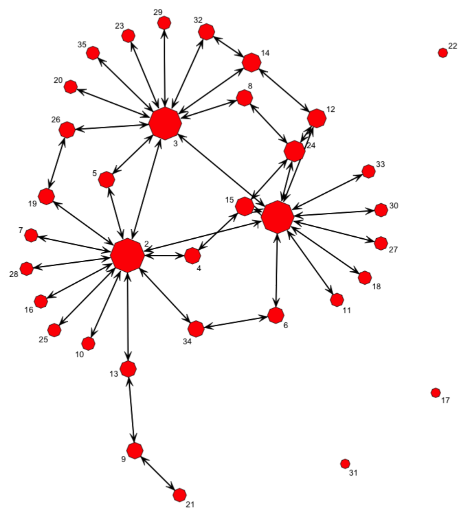
(a) A multi-core random graph. The multi-core random graph is generated by letting $p_{kk} = 0.2$.



(b) A complete graph which is a specific case of the random core-periphery network: $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$, where $N = K = 5$ and $p_{kk} = 1.0$.



(c) A perfectly balanced random core-periphery as a specific case of the random core-periphery network: $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$, where $N = 30$, $K = 3$ and $p_{kk} = p_{pk} = 1.0$ and $p_{pp} = 0$. Note that each periphery node is connected to only one of the core nodes.



(d) A random core-periphery with pendants.

Figure 4.3: Sample networks generated by core-periphery network model.

We have developed a network generation module that creates stylized networks such as *ring*, *star*, and *k-regular* networks, as well as, random networks with desired level of connectivity and centralization. Network connectivity and centralization are used to characterize interbank debt exposure. A link in the network is typically directed denoting a loan given from a bank i to another bank j. As such links represent interbank liabilities on the balance-sheets within the system. The total interbank liability d_i of a bank i is then summation of outgoing link weights d_{ij}:

$$d_i = \sum_{j=1}^{N} d_{ij}. \tag{4.1}$$

Then total exposure of an interbank network can be computed as $D = \sum_{i=1}^{N} d_i$.

Random core-periphery network

In this section, we present generation of random core-periphery networks. A k-core-periphery network can be characterized by a graph $G(K,N,E)$ where a few core nodes $K \subset N$ and $K \ll N$ are receiving majority of the edges, E, in the graph. Figure 4.2, for instance, is a core-periphery network with 4 designated core nodes. Barabasi–Albert preferential attachment model (Barabási and Albert, 1999) is typically employed in complex networks literature to be able to generate core-periphery-like network models. Barabási and Albert (1999) propose a network construction algorithm where a graph of N nodes is grown by attaching new nodes each with m edges that are preferentially attached to existing nodes with high degree. Resulting graph exhibit a scale-free node degree distribution that also defines core-periphery networks. The algorithm has two limitations. First, it does not allow to specify connectivity of the core nodes with each other. Second, it imposes an exact number of m links originated from a peripheral node.

Given aforementioned limitation of Barabasi–Albert model, we introduce a novel core-periphery network generation model where connectivity between core-to-core, periphery-to-core, and periphery-to-periphery nodes can be specified exclusively employing appropriate distribution functions. For this work, we have employed Erdos-Renyi graph model (Erdös and Rényi, 1959) where a distinct Bernoulli random variable indicating the presence of edge is used for each case. However, our framework is designed to accommodate a multi-level approach where separate probability distribution functions can be used connecting nodes across different levels or within a level. The probability distribution functions could be constructed using empirical data or analytical models. Section 4.2 presents our subsequent work Gencer and Ozel (2018) where a Barabasi–Albert preferential attachment model is generalized at fusing multiple core-periphery networks.

In a random Erdos-Renyi graph $G(N, p)$ with N vertices an edge between two nodes, e_{ij}, exists with a probability of $p \in (0,1)$ independently of every other edge. Let $e_{ij} \in \{0,1\}$ be a Bernoulli random variable indicating the presence of the edge. For the Erdos-Renyi model, random variables e_{ij} are independent and are set as follows:

$$e_{ij} = \begin{cases} 1, & \text{with } p \\ 0, & \text{with } 1-p \end{cases} \tag{4.2}$$

Each edge is included in the graph with a Bernoulli trial. The probability parameter p is considered as connectivity specification. The higher p the more connected a graph is. While $p = 0$ would generate a network with no links, $p = 1$ would generate a fully connected graph. Our random core-periphery graph $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$ is then characterized by 5 parameters, where each p is an independent Bernoulli random variable. Table 4.1 summarizes parameter descriptions.

Parameter	Description
N	Total number of nodes in the network
K	Total number of nodes in the core
p_{pp}	The Bernoulli probability of link formation between pairs of nodes in the periphery
p_{kk}	The Bernoulli probability of link formation between pairs of nodes in the core networks
p_{pk}	The Bernoulli probability of link formation between a periphery node and a core node

Table 4.1: Parameters of a random core-periphery network generation function $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$. Note that the specific case where $p_{kk} = p_{pp} = p_{pk} = p$ is equivalent to a typical Erdos-Renyi graph $G(N, p)$

The random core-periphery network generation module is simply the union of respective Erdos-Renyi random graphs. The panels in Figure 4.2 demonstrates the procedure. Figure 4.3 presents generation of various other network structures using the $G^{cp}(N, K, p_{kk}, p_{pp}, p_{pk})$ configuration function.

Definition 1 *Centralization, C_G, for a given graph $G(N,E)$ is a graph level index that is computed as follows:*

$$C_G = \frac{\sum_1^N \mid deg_G^{max} - deg_G(v) \mid}{(N-1)(N-2)}, \tag{4.3}$$

where $deg_G(v)$ is the degree centrality of node v, and deg_G^{max} is the maximum degree observed in $G(N,E)$. Given the fact that an interbank loan, d_{ij}, implies a network relation, a link at its graph theoretic representation, degree of a node in the graph is simply the number of distinct connections the node has:

$$deg_G(v) = \sum_{j=1}^{N} l_{vj}, \tag{4.4}$$

where

$$l_{vj} = \begin{cases} 1, & \textit{when } d_{vj} \geq 0 \textit{ or } d_{jv} \geq 0 \\ 0, & \textit{otherwise.} \end{cases} \tag{4.5}$$

The network *centralization* definition above is based on Freeman (1979), where degree centrality is used as the centrality score. The denominator in Equation 4.3 is a normalization factor. It denotes a theoretical maximum centralization score. According to this definition, i.e, while a fully connected interbank network configured by $G^{cp}(N, K = 0, p_{kk} = 1, p_{pp}, p_{pk})$, would exhibit a $C_G = 0$, a perfect core-periphery network configured by $G^{cp}(N, K = 1, p_{kk}, p_{pp} = 0, p_{pk} = 1)$, which is a single core star network, would exhibit a maximum possible centralization $C_G = 1$.

Definition 2 *Connectivity, K_G, for a given graph $G(N,E)$ is a graph level index that corresponds to the density of the graph and is computed as follows:*

$$K_G = \frac{\sum_1^N deg_G(v)}{2N(N-1)}, \tag{4.6}$$

where $deg_G(v)$ is computed the same as in Equation 4.4.

In different words, *connectivity* for a given network is computed as the total number of observed connections divided by the number of possible ties in the network (Wasserman and Faust, 1994). According to this definition, i.e, while a fully connected interbank network configured by $G^{cp}(N, K = 0, p_{kk} = 1, p_{pp}, p_{pk})$, would exhibit a $K_G = 1$, a perfect core-periphery network configured by $G^{cp}(N, K = 1, p_{kk}, p_{pp} = 0, p_{pk} = 1)$, which is a single core star network, would exhibit the smallest possible connectivity for a graph with $N > 1$ nodes. $K_G = \frac{1x(N-1)+(N-1)x1}{2N(N-1)} = \frac{1}{N}$. It should be noted that *star network*, is one of the minimally connected graph with $N > 1$ nodes. A *ring network* with $N > 2$ nodes would be another stylized network structure that exhibit a similar level of *connectivity* with $K_G = \frac{Nx2}{2N(N-1)} = \frac{1}{N-1}$. The minimum possible *connectivity* for a network is observed when each node is an *isolate* which would yield to $K_G = 0$.

Stylized network models

The random core-periphery generation module is able to produce a range of stylized network structures such as a complete graph or a perfect star. However, in order to test a number of theoretical conjectures a range of other regular and non-random graphs is needed. We have developed an additional network generation module that creates stylized graphs with desired network connectivity and centralization[1].

The inputs for the algorithm are the number of nodes in the network, N; the level of connectivity in the network K; and desired level of centralization, c, in the network. Keeping N and K constant, whereas varying c from 0 to N we are able to create a family of stylized

[1] See the *Centralize* module from our network library that we have developed for the simulator: `https://github.com/bulentozel/SimFinNet`.

networks from $C_G = 0$ network centrality to the maximum possible centrality while keeping the network connectivity constant. It should be noted that with $K = 1$ the algorithm generates a family of connected networks of the minimum connectivity. The maximum *centralization* $C_G = 1$ is achieved when $K = 1$ and $c = N$. For $K > 1$ and $c > N - K$ the algorithm produces a core-periphery like network with K fully connected core. The generated directed network is a symmetric one. That is each outgoing link is reciprocated. A link represents an interbank debt. Reciprocity is a modelling simplification that corresponds to liquidity swap between banks (Eboli, 2013; Nier et al., 2007).

Figure 4.1 demonstrates exemplary network outputs of the model. Figure 4.1a is a circular graph with minimal connectivity and $C_G = 0$ network centralization. Figure 4.1a is a *k-connected* regular graph, where using the circular graph of Figure 4.1a each node has established $K = 2$ new connections with other neighboring nodes. The network centralization is still 0. Figure 4.1c is a fully connected graph by adding more links to the initial circular graph incrementally. Note that the network centralization is still 0. Figure 4.1d is a circular graph with minimal connectivity and 0 network centralization. It is used as the starting point to create a maximally central graph with the same number of nodes and connections. Figure 4.1e is a *ring-star* graph, where the same number of nodes and connections of a ring graph is used and in 5 consequent steps the connections are directed to the designated star. The network *connectivity*, K_G, is maintained constant while *centralization*, C_G, is increased incrementally. A perfect star obtained by directing links of the initial ring incrementally to the designated star. Figure 4.1f is a fully central star graph where the network connectivity is the same as the originating circular graph.

4.1.4 Balance sheet configuration

Factors that are considered while configuring balance sheets of the banks in the system are (i) level of **capitalization**, ε, (ii) **exposure** to interbank debts, ϕ, (iii) amount of **external assets**, A, and (iv) **network position**, deg_G in the system. For a given bank, i, and its balance sheet entries e_i as of its equity, a_i as of its total external assets, h_i as of its total external debts such as deposits from households and firms, c_i as of interbank loans delivered, and d_i as of its total interbank debts, bank level capitalization and exposure is defined as follows:

$$\varepsilon = e_i/a_i + c_i, \tag{4.7}$$

$$\phi = d_i/h_i. \tag{4.8}$$

In our base model regarding balance sheet initialization, the aggregate network level identity of interbank debts D and loans C is also imposed at the node level for each bank:

$$c_i = d_i = \phi\, h_i. \tag{4.9}$$

Given the balance sheet identity:

$$a_i + c_i = h_i + d_i + e_i, \tag{4.10}$$

we yield following bank level configuration:

$$a_i = h_i + e_i. \tag{4.11}$$

Manipulating Equation 4.11 and using Equation 4.8, we can redefine h_i in terms of modal parameters $h_i(\phi, \varepsilon, h_i)$:

$$a_i = h_i + e_i = h_i + \varepsilon(a_i + \phi h_i) \tag{4.12}$$

$$a_i(1-\varepsilon) = h_i(1+\varepsilon\phi) \tag{4.13}$$

$$h_i = a_i \frac{1-\varepsilon}{1+\varepsilon\phi}. \tag{4.14}$$

In the base model, level of capitalization and interbank debt exposure rates are serving as model parameters and they hold at each individual level as well as at aggregate network level. That is, applying the node level exposure and capitalization rates assures the same ratios at the network level automatically by applying summation operation on the either side of the equations above: $A = \sum a_i$, $C = \sum c_i$, $H = \sum h_i$, $D = \sum d_i$, and $E = \sum e_i$ then $C = D$, $A = H + E$, $D = \phi H$, and $E = \varepsilon(A + C)$.

Parameter	Description
ε	Capitalization.
ϕ	Exposure
A	Total external assets

Table 4.2: Balance sheet configuration parameters for the base model.

It should be noted that the interconnection between **stock-flow and a network consistent balance sheet configuration** is implied by Equation 4.1, where $d_i = \sum_{j=1}^{N} d_{ij}$ and hence the total exposure is $D = \sum_i \sum_j d_{ij}$, where each $d_{ij} = w_{ij}$ is the **contagion bandwidth** for the corresponding link e_{ij}.

4.1.5 Shock propagation model

The shock propagation in the network is based on the balance sheet contagion model as described in Eboli (2013) and recently in Castiglionesi and Eboli (2018). In brief, shocks, whether internal or external, are absorbed by the share-holders first. Shocks exceeding the capital of a stressed bank transferred to its creditors. In our base model, each deposit owner h_{ik}, and each loan owner d_{ij} share the burden proportionally to the size of their deposits or loans at the defaulted bank.

The external asset a_i is the source of exogenous shocks. To define amplitude of an external shock with respect to the size of external asset a_i, we use a parameter $b \in [0, 1]$. That is, it captures the fraction of the value of the asset a_i which is lost. An exogenous shock is an assignment of value to the vector $[b]$ where at least one of its components assumes a strictly positive value. If $b > 0$ then the source node, i.e., the bank that is suffering a loss, sends to its direct descendants a financial loss equal to $b\,a_i$. The shock, i.e., the flow of losses out of the source nodes, is a vector of scalars $[ba]$. As a shock occurs, the involved source nodes release a flow of losses into the network. The propagation of these losses across the network is governed by the rules of limited liability, debt priority and pro-rata reimbursement of creditors. For simplicity, we assume that all debts have the same seniority. We distinguish about a common shock, that affects more than an agent in the network, from an idiosyncratic shocks, that is born by a single node (agent) only. When a node i suffers a loss, this loss is first absorbed by the net worth of the node. Only the residual loss, if any, is passed over to other nodes in the network. The losses that are offset by the equity of the agents in the network are born by households, in their capacity as shareholders, thus they exit from the flow of losses that circulate across the network to end up directly into the sink node. To represent this property, for each node i in the network, we introduce an *absorption function*:

$$\beta_i(\lambda_i) = min\left(1, \frac{\lambda_i}{e_i}\right), \tag{4.15}$$

where λ_i is the total amount of loss at the node i, either received externally via shocks on external assets or internally through loans given to other nodes within the network. The variable $\beta_i \in (0,1)$ measures the share of net worth lost by a node. If a node i receives a positive flow of losses, it first sends aims to cover it by its own equity equal to $\beta_i\, e_i$. In that respect, the equity of the bank as a financial intermediary measures its absorption capacity. If the losses suffered by i are larger than its net worth, then this node is insolvent and sends the residual loss $(\lambda_i\, e_i)$ to its creditors. Thus for each agent, we define a *shock propagation function*:

$$b_i(\lambda_i) = max\left(0, \frac{\lambda_i - e_i}{d_i + h_i}\right). \tag{4.16}$$

The variable $b_i \in [0,1]$ assumes a value of zero if the i-th bank is solvent, while it assumes a strictly positive value that indicate a default. In the latter case, the assets of the insolvent bank are liquidated and its creditors get a proportional refund. The variable b_i measures the fraction of the i-th agent's debt that is not recovered through liquidation, i.e., the loss-given-default ratio of the failing agent. When the i-th agent becomes insolvent, households receive a loss equal to $b_i h_{ij}$ (if $h_{ij} > 0$) while a node j which is a creditor of node i receives from the latter a loss equal to $b_i d_{ij}$. The loss born by a bank node is the sum of the losses, if any, received from its external and internal exposures:

$$\lambda_i = \lambda_i^{ext} + \lambda_i^{int} = \sum_k b^k a_i^k + \sum_j b_j d_{ji}, \tag{4.17}$$

where j is the debtor, i is the creditor and a_i^k define a set of external asset owned by node i with $k = 1..m$. Then a bank node i is in default state when total external and internal shock exceeds its equity:

$$\lambda_i = \sum_k b^k a_i^k + \sum_j b_j d_{ji} \geq e_i. \tag{4.18}$$

Note that, $\lambda_i^{ext} = \sum_k b^k a_i^k$ is the portion of the shock received from external shocks, and $\lambda_i^{int} = \sum_j b_j d_{ji}$ is the internal shock due to the contagion.

Definition 3 *A secondary default, $\Lambda_{secondary}$, occurs when a part or all of the initial net-worth $e_i(t=0)$, is caused due to accumulation of internal shock propagation up to time t: $\beta_i(t) = 1 \wedge \lambda_i^{int}(t) \geq 0$.*

Due to contagion an already insolvent bank may keep receiving internal shocks through the network. However, for clarity in our analyses a default is labeled as *secondary* only if the initial insolvency has been triggered due to a contagion according to the Definition 3.

4.1.6 Exogenous shock model

In this set-up the interbank network is shocked exogenously on their external asset portfolios. The shocks are applied in a sequential manner. That is, an external shock is applied one at a time. The shocks can be permuted according to assets or banks. When shocks are permuted according to assets, the bank holding the specific toxic asset is selected. Depending on the amount of asset in the portfolio of a bank, the same bank may be hit several different times. On the other hand, when the shocks are permuted according to banks, a bank is exposed to the shock all at once or iteratively until all of its toxic external assets are absorbed before moving on the next bank according to the permutation. When shocks are permuted according to banks then permutation vector holds the fraction of the total of external asset of the bank to be affected. In order to observe and record a detailed contagion dynamics, the simulator further divides that fraction of the external asset into smaller chunks and apply them iteratively until it is absorbed completely.

Depending on the shock application scheme the shocks are randomized according to banks or assets. In the case of a permutation on the banks, given N number of nodes there are $N!$ possible sequence of shocks. Nevertheless, given the structure of the network majority of the permutations can be equivalent to each other. In other words, the number of structurally distinct shock permutation may depend strictly on the network structure. For instance, in a complete network, where each bank is connected with all other banks and they all have the same balance sheet configuration, the symmetry of the network renders the sequence of the shocks irrelevant. In this class of networks, all of the $N!$ permutations have the same equivalent effect on the contagion process. In a perfect star, however, where all pendants are identical but the structure of the network is not symmetric, the number of total distinct shock permutation is N. Since an exogenous shock that hits the central node has a contagious effect that is different from the effect of a shock on a pendant node, the timing of the shock on the star node determines the distinctiveness of a shock. In that case, a shock can simply be characterized by the number of pendants hit before or after the designated central node.

4.1.7 Analyzing dynamics of a contagion process

In this section, the entire process from network initialization to the final state of a contagion process is demonstrated. Tables and figures presented in this section are the automatically produced by the simulation software that is developed during this work. A manual for the configuration of the simulator regarding the level of details and formats of output files can be accessed at the project repository[2].

Figure 4.4 demonstrates diffusion of contagion on a fully connected network. In this exemplary case, each bank receives shock one at a time. Entire external asset of the bank that receives the shock is affected. Red colored banks in the network indicate a default induced mainly due to a direct external shock. A black node indicates a secondary default, $\Lambda_{secondary}$, that is induced due to contagion. A gray node hints a stressed but not defaulted node due to transmission of shock from the other defaulting banks.

N	K	p_{pp}	p_{kk}	p_{pk}	K_G	C_G
15	2	0.00	1.00	1.00	0.13	0.51

Table 4.3: Network configuration report of the network generation module. The automatically generated output presents configuration parameters and features of a random core-periphery interbank network. The connectivity and centralization levels of the resulting network are, respectively, $K_G = 0.13$ and $C_G = 0.51$. The corresponding configuration function is $G^{cp}(N = 15, K = 2, p_{kk} = 1, p_{pp} = 0, p_{pk} = 1)$. Figure 4.5 visualizes the network.

Table 4.3 presents the configuration parameters that are used by the simulator to create the initial network structure. The connectivity and centralization levels of the resulting network are, respectively, $K_G = 0.13$ and $C_G = 0.51$. The corresponding configuration function is $G^{cp}(N = 15, K = 2, p_{kk} = 1, p_{pp} = 0, p_{pk} = 1)$. Figure 4.5 visualizes the snapshots of the output network.

Table 4.4 reports balance sheet and random shock configuration parameters. These inputs are applied to the network seen in Figure 4.5 which was configured by the parameters in Table 4.3. The resulting balance sheets are presented in Table 4.5. It should be noted that bank level level of capitalization and debt exposure is set by ε and ϕ respectively. A stands for the cumulative external assets in the system. According to the configuration in this table only a $2/3$ of the banks in the system will be sampled for a random shock order permutation; and at each round 70% of the external assets of the selected bank is wiped-off. Table 4.6 presents the growth of contagion due to application of the shock according to one of the random permutations. Table 4.7 is the report on the resulting final state of the contagion.

Table 4.6 presents the growth of a contagion according to network, balance sheet and shock configurations are given in Tables 4.3, 4.4 and 4.5. According to this automatically generated

[2]See `https://github.com/bulentozel/SimFinNet` for data, source code and documentation.

N	n_{shock}	r_{shock}	A	ε	ϕ
15	10	0.7	115.55	0.10	0.40

Table 4.4: Automatically reported balance sheet and random shock configuration parameters. These inputs are applied to the network seen in Figure 4.5 which was configured by the parameters in Table 4.3. The resulting balance sheets are presented in Table 4.5. It should be noted that bank level level of capitalization and debt exposure is set by ε and ϕ respectively. A stands for the cumulative external assets in the system. According to the configuration in this table only a $2/3$ of the banks in the system will be sampled for a random shock order permutation; and at each round 70% of the external assets of the selected bank is wiped-off. Table 4.6 presents the growth of contagion due to application of the shock according to one of the random permutations. Table 4.7 is the report on the resulting final state of the contagion.

report, one of the core receives a substantial external shock that causes a complete collapse of itself and its peripheral nodes. The other remaining core is weakened substantially. It should be noted that the probing parameter L_{contag} denotes the depth of propagation until a source shock is absorbed completely, that is either covered by a loss in the net-worths of inflicted banks or sinked at the deposits. L_{contag} can also be considered as the length of a shock wave until it looses its amplitude completely.

$Bank_i$	a	c	h	d	e
1	28.89	10.00	25.00	10.00	3.89
2	33.02	11.43	28.57	11.43	4.44
3	4.13	1.43	3.57	1.43	0.56
4	4.13	1.43	3.57	1.43	0.56
5	4.13	1.43	3.57	1.43	0.56
6	4.13	1.43	3.57	1.43	0.56
7	4.13	1.43	3.57	1.43	0.56
8	4.13	1.43	3.57	1.43	0.56
9	4.13	1.43	3.57	1.43	0.56
10	4.13	1.43	3.57	1.43	0.56
11	4.13	1.43	3.57	1.43	0.56
12	4.13	1.43	3.57	1.43	0.56
13	4.13	1.43	3.57	1.43	0.56
14	4.13	1.43	3.57	1.43	0.56
15	4.13	1.43	3.57	1.43	0.56

Table 4.5: The balance sheets of the banks according to the configuration parameters tabulated in Table 4.3 and Table 4.4. This report is generated automatically by the simulator software developed for the work.

Table 4.7 reports the final state of the contagion process that is presented in Table 4.6. It should be noted that if $r_{absorb} = 1$, the corresponding bank is insolvent. The $\Lambda_{secondary}$ reports whether it is a secondary default or not.

	N_{shock}^{source}	r_{shock}^{ext}	L_{contag}	$n_{defaults}$
1	1	0.70	6	7
2	4	0.70	6	7
3	6	0.70	6	7
4	8	0.70	6	7
5	9	0.70	2	8
6	10	0.70	6	8
7	11	0.70	2	9
8	12	0.70	6	9
9	13	0.70	2	10
10	15	0.70	2	11

Table 4.6: Growth of the contagion according to network, balance sheet and shock configurations given in Tables 4.3 , 4.4 and 4.5. Several snapshots of the contagion is visualized in Figure 4.5. According to this automatically generated report, one of the core receives a substantial external shock that causes a complete collapse of itself and its peripheral nodes. The other remaining core is weakened substantially. It should be noted that the probing parameter L_{contag} denotes the depth of propagation until a source shock is absorbed completely, that is either covered by a loss in the net-worths of inflicted banks or sinked at the deposits. L_{contag} can also be considered as the length of a shock wave until it looses its amplitude completely.

In this section, details on the analyses of a contagion process for a single shock vector is presented. The simulator has further features that help to conduct Monte Carlo simulations where the results from single runs are aggregated.

4.1.8 Results

We conjecture that core-periphery networks exhibit a 'robust-yet-fragile' feature. At this phase of the work, employing a simulation modules details of which are presented above, we have created a controlled set-up to test our conjectures via simulations.

We observe that a core-periphery network is the joint of a complete network and a star-shaped network. We characterize the core by the level of connectivity among the central nodes. We characterize the periphery by the ratio of the pendants node in the network. Based on these observations we have created a family of networks to decouple and measure the connectivity and centralization aspects of an interbank network. We have used the *Centralize* module from our network library that we have developed for the simulator. The network configuration parameters are the number of nodes in the network, N, the level of connectivity in the network K and desired level of centralization, c, in the network.

$Bank_i$	λ_i	r^{ext}_{shock}	λ^{int}_i	r_{absorb}	b_i	$\Lambda_{secondary}$
1	24.86	0.70	3.25	1.00	0.60	0
2	3.52	0.00	2.47	0.79	0.00	-
3	0.00	0.00	0.00	0.00	0.00	-
4	3.75	0.70	0.60	1.00	0.64	1
5	0.00	0.00	0.00	0.00	0.00	-
6	3.75	0.70	0.60	1.00	0.64	1
7	0.00	0.00	0.00	0.00	0.00	-
8	3.75	0.70	0.60	1.00	0.64	1
9	2.89	0.70	0.00	1.00	0.47	0
10	3.75	0.70	0.60	1.00	0.64	1
11	2.89	0.70	0.00	1.00	0.47	0
12	3.75	0.70	0.60	1.00	0.64	1
13	2.89	0.70	0.00	1.00	0.47	0
14	3.75	0.70	0.60	1.00	0.64	1
15	2.89	0.70	0.00	1.00	0.47	0

Table 4.7: The final state of the contagion process that is presented in Table 4.6. It should be noted that if $r_{absorb} = 1$, the corresponding bank is insolvent. The $\Lambda_{secondary}$ reports whether it is a secondary default or not. λ_i is the total amplitude of the shock received by the bank; λ^{int}_i displays the portion received due to contagion; r^{ext}_{shock} denotes the percentage of external assets of the bank is wiped off due to a direct exogenous shock; and b_i reports the final state of the shock propagation function for an inflicted bank node.

In all of the experiments size of the interbank network is fixed by setting $N = 64$. For our decoupling process we design two sets of experiments. In the first setup, we create a family of *k-regular* network structures, where network level centralization is fixed and minimal $C_G = 0$. Then we increase the network connectivity K_G incrementally from least possible to maximal connectivity. We create circular graphs as visualized in Figure 4.1a - 4.1c where moving from $K = 1$ regular graph, a ring, to $K = N-1$, a fully connected graph, we maintain $C_G = 0$. According to the network connectivity as described in Equation 4.6, then in this set-up the ring has the minimum connectivity of $K_G = \frac{1}{N-1} = \frac{1}{63} \approx 0.016$ and the fully connected network has the maximum possible connectivity, $K_G = 1$.

In the second set of the experiments, we use a family of network structures similar to the ones depicted in Figure 4.1d - 4.1f. Again fixing $N = 64$, this time we transform a ring into a perfect star, reshuffling the constant number of edges[3]. We call this family of networks as the *ring-star* transformation. It should be noted that $K_G = 0.016$ as above but the centralization is varied, according to Equation 4.3. It is incrementally grown from $C_G = 0$, in the case the ring

[3]In fact in the last transformation where we reach the perfect star, instead of 64 we have 63 edges loosing the last ring edge.

where each node has exactly the same number of connections, to $C_G = 1$ where the designated star node is incident to all edges, the interbank loan relations, in the system.

In both set-up each edges are bi-directional. An edge represents an interbank debt. Bi-directionality implies the reciprocity at the interbank debts. It is a modelling simplification that corresponds to liquidity swap between banks (Eboli, 2013; Nier et al., 2007).

N	C_G	K_G	A	ε	ϕ
64	0.0 to 1.0	0.016 to 1.0	100.0	0.06 to 0.12	0.2 to 0.8

Table 4.8: Simulation parameters. The size of the interbank network N, and aggregate external assets A, interbank loans C and debts D, the total amount of net-worth E and the household deposits H are kept constant as the invariants in each seed of Monte Carlo simulations.

Balance-sheets of the banks in each network configuration set-up are initialized according to the parameters defined previously in Table 4.2 and the network structure. In other words, the size and the structure of the interbank network so as the level of capitalization and the debt exposure of each node are used as the initialization parameters. Table 4.8 displays the simulation parameters. While the size of the interbank network N, and the network level volume of aggregate balance sheet entries, A, C, H, D, E are kept as the invariants, at one hand the impact of network structure is inspected by varying C_G and K_G, on the other hand impacts of total exposure and capitalization are inspected by varying ε and ϕ respectively. Individual bank level balance sheet entries are configured according to specifications that we have presented and discussed in Section 4.1.4.

In this work, each interbank link in the network has a certain bandwidth. Given $d_i = \sum_{j=1}^{N} d_{ij}$ and hence the total exposure is $D = \sum_i \sum_j d_{ij}$. leads to $d_{ij} = w_{ij} = \frac{D}{|\mathbb{E}|} = w_0$. $|\mathbb{E}|$ is the total number of edges in the network. At each simulation for a given initial configuration C_G, K_G, ε, ϕ then w_0 is the specific bandwidth for the configuration.

For the observations regarding network centralization C_G, we have used **c** simulator parameter incrementing it from 0 to 63, where each round an interbank loan from a peripheral node is moved to the designated central node. For the observations regarding network connectivity K_G, we have used the connectivity parameter **k** of the simulator. At each round it is incremented by 1 covering a ring up to a fully connected circular graphs in 64 steps. In order to examine impact of net-worth we have examined $\varepsilon \in (0.06, 0.08, 0.1, 0.12)$ according to empirically observed ratios. In a similar manner we have ϕ at 4 different ratios, $\phi \in (0.2, 0.4, 0.6, 0.8)$.

For each configuration, (C_G, K_G, ε, ϕ), 1000 unique random shock permutations are generated and applied. Each permutation denotes the order of banks that receive an external shock. The length of the permutation vector is equal to the number of banks in the system, $N = 64$. That is, at the end of each shock permutation all of the banks are exposed to the external shocks at a random fashion than the other permutations. The amplitude of the external shock that a bank receive is fixed $r_{shock} = 1.0$, wiping off all of its external assets. In the first set-up on the connectivity, the shock is applied at a single round; while in the second set-up on the centralization where banks exhibit heterogeneous balance sheet structures the total external asset of the bank is divided into multiple portions and hit in multiple rounds until it is depleted completely.

This yields to $64x(4+4) = 512$ distinct initial configuration for the first set-up, where the primary focus is on the role of connectivity. We have set $\varepsilon = 0.1$ while varying ϕ and $\phi = 0.4$ while we vary ε. In a similar manner, it yields to 512 distinct initializations for the case on the role of network centrality. In total, the results we present below are based on simulations with $2x512x1000 = 1,024,000$ distinct Monte Carlo seeds[4].

The results are presented in Figure 4.6 and Figure 4.7. The upper two panels in the figures present two contagion thresholds T_1 and T_{fin}. T_1 denotes the amount of accumulated shocks until the first secondary default in the system is observed. T_{fin} is the total of external shocks that is sufficient to cause a complete collapse of the financial system. Each data point is a box-plot summarizing the outputs from 1000 distinct shock permutation for the given configuration. Box-plots for T_1 and T_{fin} are drawn on the same figure for ease of comparisons.

Comparison of the contagion thresholds in Figures 4.6b to 4.6h reveals both stability and fragility of an interbank network with respect to the level of connectivity. It is seen that increased connectivity reduces the risk of any contagious default in the system providing a stability at the level of individual banks; however increased connectivity also increases the risk of

[4]This massive number of simulations are conducted on an on-premises super-computing facilities. A 64 nodes Supermicro server computer, run by Ubuntu Linux OS, with a 256GB of CPU RAM and 2TB of hard disk capacity is utilized.

a complete systemic collapse. This implies that along with increased connectivity individual risks are mitigated by the network absorbing the shocks from the individual banks until the point when a first secondary default occurs. Figures 4.6i to 4.6l suggest that the difference between the medians of the contagion thresholds decreases exponentially with the increase of connectivity. We observe that in fully connected networks they are exactly the same threshold. This numerically observed phenomenon coincides with the studies elsewhere where a shock that is sufficiently large to cause a single secondary default is also sufficiently large to cause the default of all banks in the network.

In the results from our second experiment set-up where we investigate impacts of centralization in the system we observe a similar phenomenon. Nevertheless, as Figures 4.7a to 4.7l suggest the dynamics of the contagion is different. Unlike in the case of low connectivity, at low levels of centralization in the system makes individual banks more vulnerable against external shocks. Increasing the centralization where peripheral nodes are trading more with the core banks their default avoidance chance is not as much improved. On the other side, the system as a whole is more stable for la very larger range of levels of centralization. The systemic failure is very sudden when the whole system is too central. This numerically observed phenomenon coincides with the 'too big to fail' debate, but our approach sheds more light on the dynamics.

Aforementioned contagion dynamics holds for the cases of increased ϕ and ε. In all cases increasing the *net-worth* improves the stability while increasing the *exposure* to interbank debts reduces the stability. It is worth mentioning that as the lower panels in Figure 4.6 and Figure 4.7 demonstrate, as of the configurations we have presented in this work, while the values of the first and final thresholds vary with ϕ and ε, the dynamics of their convergence does not change with these parameters.

Figure 4.8 further displays contagion dynamics as of distribution of secondary defaults derived from Monte Carlo simulations. In the case of connectivity, at the lower levels of network connectivity, it is seen that the secondary defaults are dispersed along a large range of external shocks pointing out a less likelihood of a systemic risk. However as the connectivity increases, we observe that secondary defaults are delayed but are cumulated at increasingly smaller ranges of external shocks pointing out higher risks of contagion. The case of centrality, the lower panel in the figure, present a different dynamics. Although probability of secondary defaults concentrates around a medium level external shock distribution is more dispersed.

4.1.9 Discussions

In this work we have focused on relations between concentration, connectivity and stability of the banking sector. We have introduced a novel framework where connectivity and concentration can be analyzed at the same time. We have designed and parametrized a simulation set-up for a two-tear financial system: a relatively dense connections in the core banks composing the first tier money center banks and a set of peripheral nodes composing the second tier financial institutions in the sense that most peripheral banks do not lend to each other directly but through the core banks acting as intermediaries.

As of empirical works, Craig and von Peter (2014) present a core-periphery model of interbank networks as a two-tier system. They use Bundesbank data on interbank exposures among 1800 banks German banks, and show that their model fits well the German banking system, which displays a two-tiered core-periphery structure, with a core composed of 45 banks only. Moreover, they find that size is a good predictor of the position of a bank in the network: they show that, on average, a bank in the core is 51 times larger than a bank in the periphery, and that large banks tend to be in the core and act as intermediaries between small banks, which tend to be in the periphery. The authors suggest that economies of scale and scope in the activity of large and well-diversified banks can explain this finding. Veld and van Lelyveld (2014) put forward the two-tier model and the fitting procedure by Craig and von Peter (2014) in Dutch banking system. They draw similar conclusions about the structure of their national interbank network. These empirical results strongly suggest that a high degree of concentration induces the emergence of core-periphery interbank networks.

As far as further empirical analyses are concerned, the prevailing view is that the consolidation process has rendered the systems more stable, i.e. less exposed to systemic crises. Mistrulli (2011) draws this conclusion with respect to the Italian interbank network, while Chang et al.

(2008) obtain similar results for the Brazilian banking sector. Evrensel (2008), using data on 79 countries, shows that concentration in the banking sector increases the period during which a country is not experiencing a crisis. Beck et al. (2006) analyze the banking sector of 69 countries and find that both concentration and competitiveness improve stability. Their results challenge the main theoretical argument in support of the view that concentration increases stability. As the authors put it: “The findings that (i) concentration lowers banking system fragility and (ii) low competition raises banking system fragility imply that future research needs to move beyond a simple “concentration–stability” versus “concentration–fragility” debate where concentration is viewed as a simple proxy for market power. [. . .] . . . these results (i) are inconsistent with the argument that concentration enhances stability by boosting the market power of banks and (ii) indicate that concentration is measuring “something else” besides market power “. They also remark “. . . the empirical work does not explain exactly why concentration increases banking system stability. Future work needs to more fully dissect the channels through which concentration influences bank stability.” (Beck et al., 2006, p1585 and p1599).

Our work is in the line of Beck et al. (2006) by creating a parsimonious simulation set-up that is also able to accommodate a two-tier modelling approach suggested by Craig and von Peter (2014) and validated by further empirical studies (Veld and van Lelyveld, 2014; Evrensel, 2008; Chang et al., 2008). The first round of the numerical analyses based on our simulation set-up may have policy implications.

We suggest that resilience of interbank networks can be increased by a complementarity between concentration and connectivity. We derive upon a combined interpretation from the two experiment set-ups. Our results imply that when stimulation towards more interbank trade between peripheral nodes of the second tier banks combined with a moderation towards connectivity between the money centers of the first-tier core banks together may provide a sustainable resilience to external shocks.

4.1.10 Summary and future work

Our preliminary results on stylized network structures confirm and enrich the conjectures elsewhere. We aim to extend the Monte-Carlo simulations to random core-periphery structures where a full range capital accumulation and exposure is scanned comparatively.

Longer term perspective in this line of study is to embed the interbank-network model within Eurace simulator as described in Chapter 3. Objective of such modular extension will enable us (i) address questions relevant interaction between real-economy and interbank-networks, (ii) be able to create an artificial economy set-up where shocks to financial markets are generated endogenously. The ability to have a simulation set-up where real and financial-markets are connected and where shocks are also endogenous may give a multitude of opportunities from an ABM stand point. Among others, regulations and their limitations, bailing-in vs bailing-out options, antecedents and consequences of contagions, etc can be studied adopting our controlled experiment set-up.

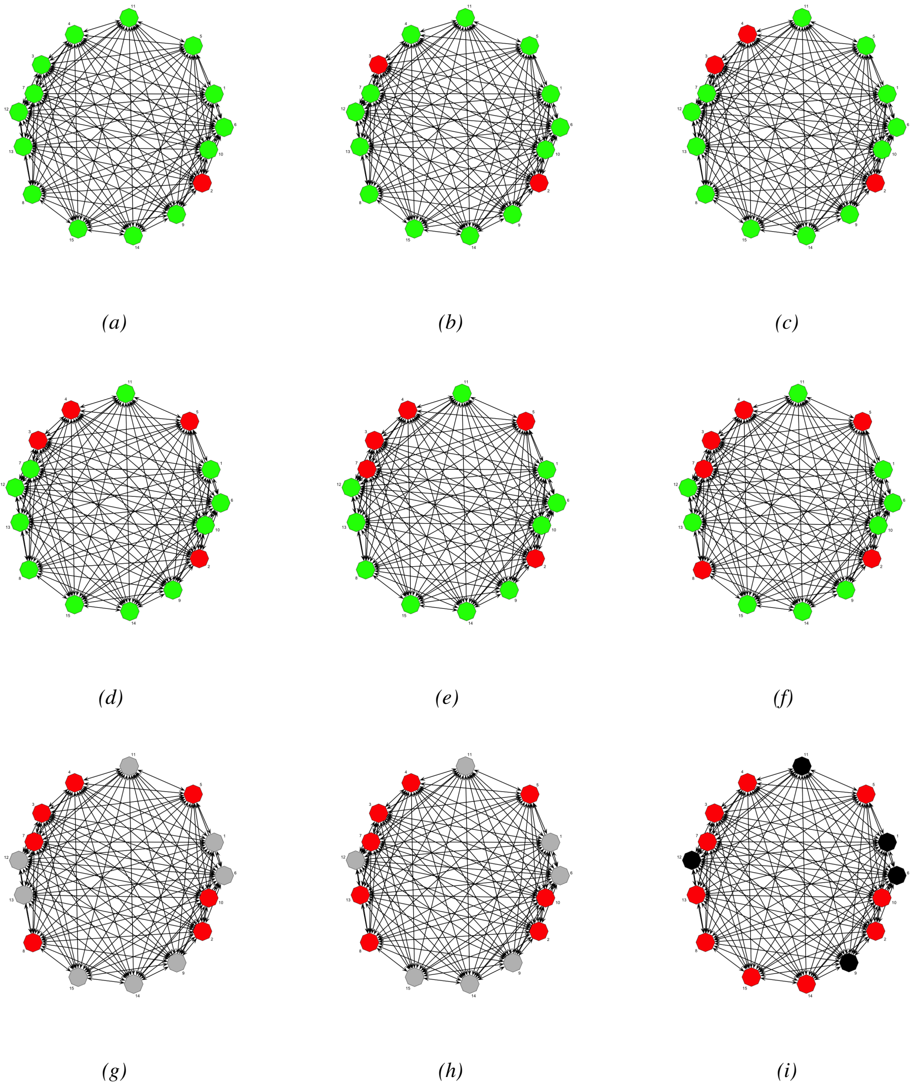
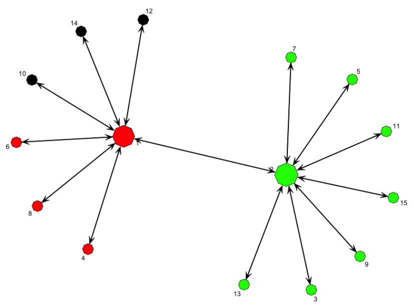
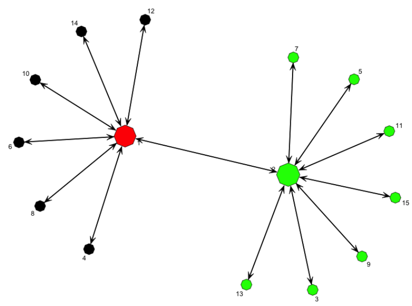
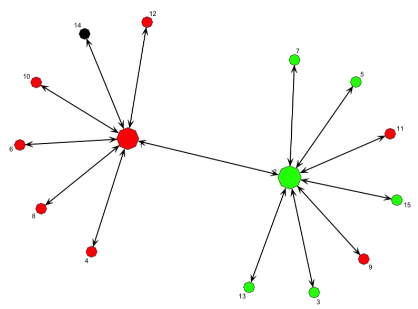


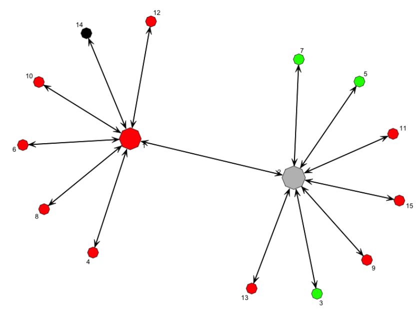
Figure 4.4: Shock propagation demonstration on a fully-connected network. Each node receives shock one at a time. Entire external asset of the shock receiving node is affected. Red colored nodes indicate a default induced mainly due to a direct external shock. A black node indicates a secondary default, $\Lambda_{secondary}$ that is induced due to contagion. A gray node hints a stressed but not defaulted node due to transmission of shock from the other defaulting banks.





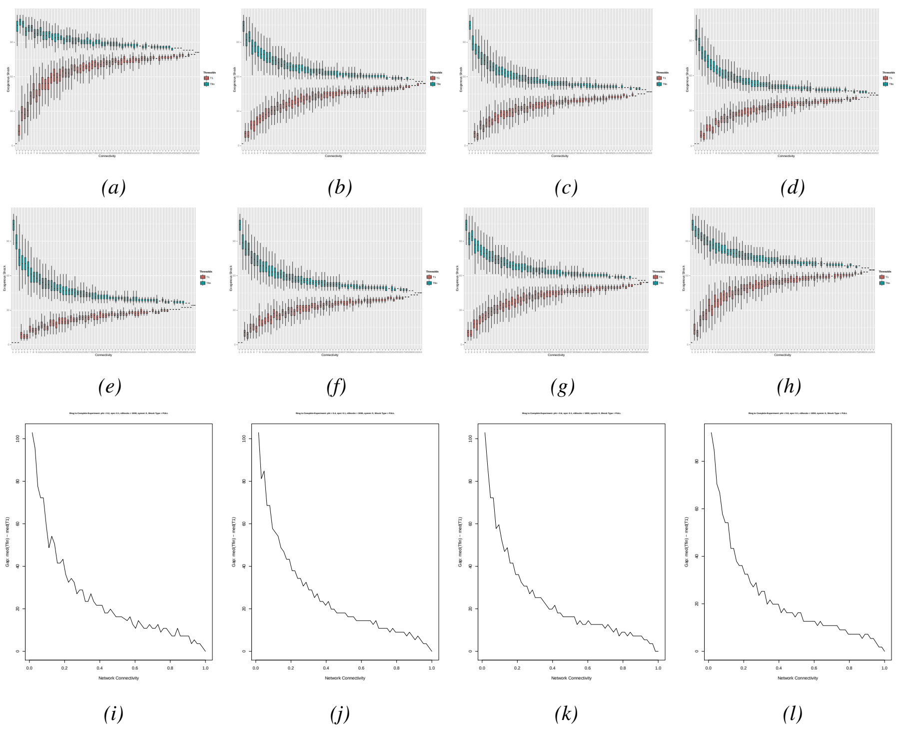
(a) *(b)*





(c) *(d)*

Figure 4.5: Shock propagation demonstration on a stylized multi-centered network. Each node receives shock one at a time. Entire external asset of the shock receiving node is affected. Red colored nodes indicate a default induced mainly due to a direct external shock. A black node indicates a secondary default, that is induced due to contagion. A gray node hints a stressed but not defaulted node due to transmission of shock from the other defaulting banks. In Figure 4.5a, we see that one of the central node has received external shock which wiped-off its remaining net-worth. Three of its pendant was hit earlier. Figure 4.5b is the case when the central node is collapsed first which caused defaults of all of its peripheric nodes.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Figure 4.6: Shock propagation with respect to differing connectivity levels. The vertical axis denote the amount external shocks observed for the threshold type. The horizontal axis represent the level of connectivity. Upper panel compares T_1 and T_{fin} with respect to increasing $\phi = 0.2, 0.4, 0.6, 0.8$ where $\varepsilon = 0.10$. The middle panel compares $T1$ and $T fin$ with respect to increasing $\varepsilon = 0.06, 0.08, 0.10, 0.12$ where $\phi = 0.40$. Lower panel displays the additional amount of external shock, $\Delta T = \overline{T}_{fin} - \overline{T}_1$, that would collapse the entire system. The differences between medians of the two thresholds are estimated for the measure. Comparisons are with respect to increasing $\phi = 0.2, 0.4, 0.6, 0.8$ where $\varepsilon = 0.10$ are displayed. The upper two panels in the figures present two contagion thresholds T_1 and T_{fin}. T_1 denotes the amount of accumulated shocks until the first secondary default in the system is observed. T_{fin} is the total of external shocks that is sufficient to cause a complete collapse of the financial system. Each data point is a box-plot summarizing the outputs from 1000 distinct shock permutation for the given configuration. Box-plots for T_1 and T_{fin} are drawn on the same figure.

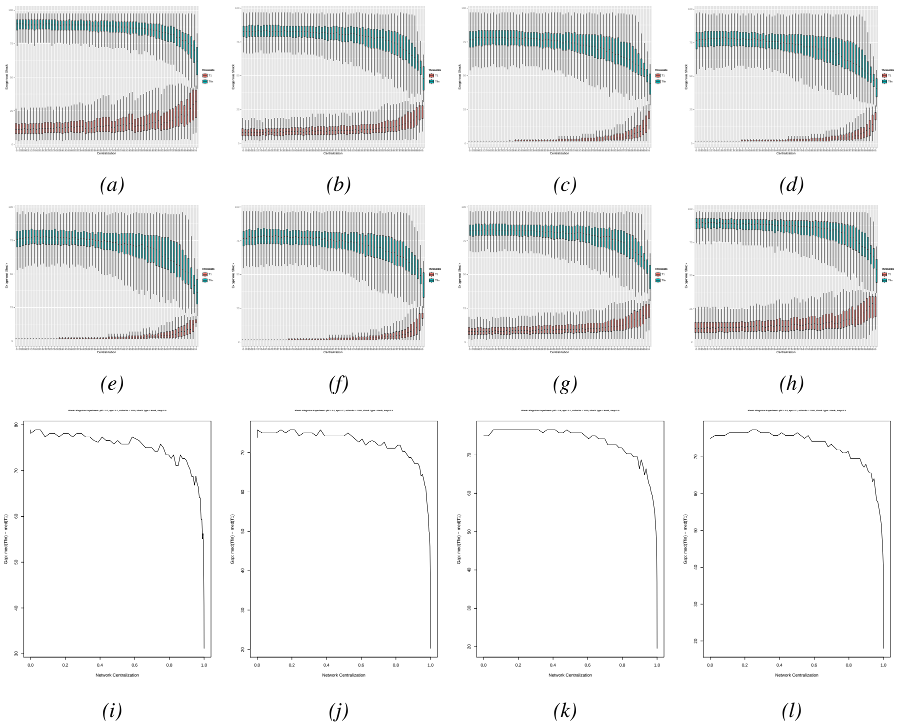
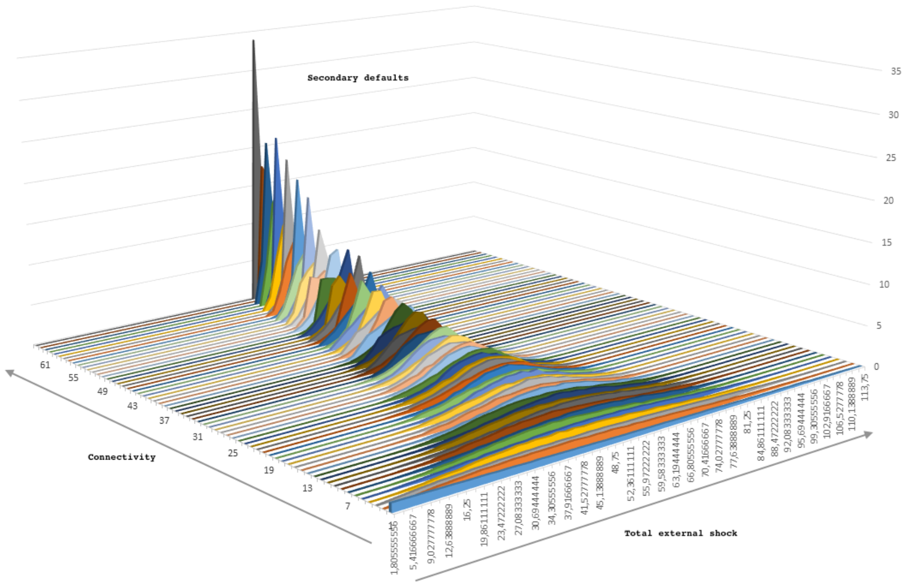
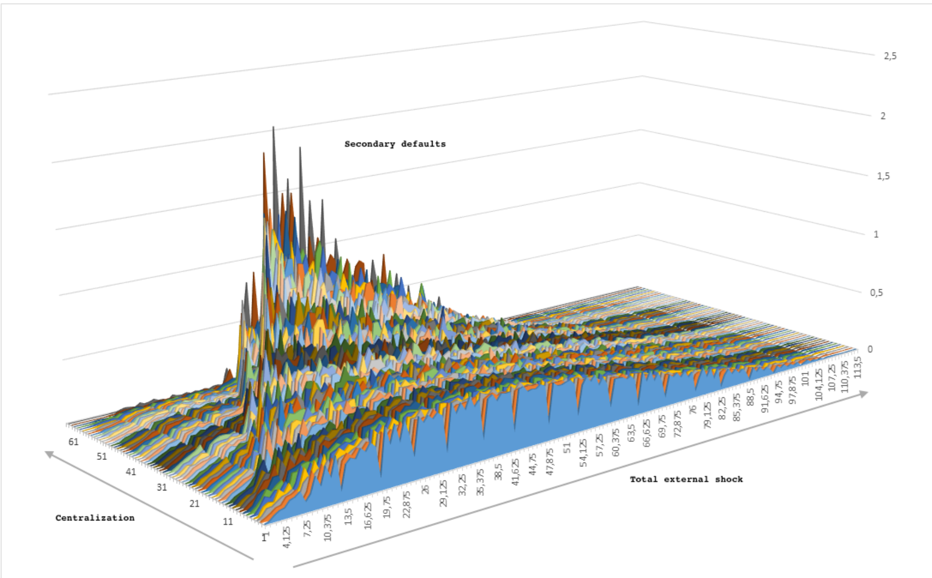


Figure 4.7: Shock propagation with respect to differing centralization levels. The vertical axis denote the amount external shocks observed for the threshold type. The horizontal axis represent the level of centralization. The upper panel compares T_1 and T_{fin} with respect to increasing $\phi = 0.2, 0.4, 0.6, 0.8$ where $\varepsilon = 0.10$. The middle panel compares $T1$ and $T fin$ with respect to increasing $\varepsilon = 0.06, 0.08, 0.10, 0.12$ where $\phi = 0.40$. The lower panel displays the additional amount of external shock, $\Delta T = \overline{T}_{fin} - \overline{T}_1$, that would collapse the entire system. The differences between medians of the two thresholds are estimated for the measure. Comparisons are with respect to increasing $\phi = 0.2, 0.4, 0.6, 0.8$ where $\varepsilon = 0.10$ are displayed. The upper two panels in the figures present two contagion thresholds T_1 and T_{fin}. T_1 denotes the amount of accumulated shocks until the first secondary default in the system is observed. T_{fin} is the total of external shocks that is sufficient to cause a complete collapse of the financial system. Each data point is a box-plot summarizing the outputs from 1000 distinct shock permutation for the given configuration. Box-plots for T_1 and T_{fin} are drawn on the same figure.



(a) Secondary defaults with varying network connectivity levels.



(b) Secondary defaults with varying network centralization levels.

Figure 4.8: Distribution of secondary defaults. For a selected connectivity and centralization the x-z plane can be read as a probability distribution like function on the number of secondary defaults with respect to the accumulated external shocks on the system. The total area for each color, representing a discrete level of connectivity (upper panel) or centralization (lower panel) is constant and equal to each other. This normalization enables the reader to compare and contrast accumulation of contagious risk for different network configurations.

4.2 Multi-level network formation model for economic interactions and integrations

Creating random network structures is one of the essential requirements for realistic simulations of complex networks. Real networks exhibit a multi-level structure which does not lend itself to existing generative models. This study considers the problem of fusing two random networks towards bridging the multi-level network creation problem. Using a computational, rather than an algebraic, approach we propose a generative model of fusion process. Based on a parsimonious set of parameters to describe the fusion process, we develop a model for simple graphs. In addition we develop a scheme for the case of weighted graphs, and discuss possibilities for directed graphs.

4.2.1 Motivation

In this work, we aim to design a network fusion model that enables us to create economic interaction structures akin to empirically observed credit or financial structures. In our short term research agenda, the model serves to generate multiple core-periphery structures of international financial systems where we are able to investigate integration of national core-periphery structures examining interactions and flows across national systems. As part of longer term research agenda, we aim to adopt stylized patterns as part of our entry and exit mechanisms at multi-country economic integration scenarios.

There is increasing interest in network research from various scientific disciplines (Borgatti et al., 2009). At the core of this interest is the complexity perspective which portrays a system “not as deterministic, predictable, and mechanistic, but as process dependent, organic, and always evolving" (Arthur, 1999, p107). This emerging interest blends naturally with simulation based approaches in fields ranging from biology to economics (Judd, 1997). Simulation of complex systems involves modeling of system constituents and the network structure of interaction between those constituents.

This work concerns the problem of creating random network structures as one of the essential requirements for realistic simulations of complex systems. While random networks is a long standing area of research (Barabási and Albert, 1999; Erdös and Rényi, 1959) available methods have significant shortcomings in terms of producing structures that correspond to real networks (Watts and Strogatz, 1998). Real networks tend to have a 'multi-level' structure which does not lend itself to modeling with a single algebraic scheme (Fricke and Lux, 2014). Computational, rather than algebraic, approaches has been explored to address this problem more recently (Pasta et al., 2013; Sallaberry et al., 2013; Zaidi, 2013).

Our study adds on to this emerging research thread by addressing the problem of abridging multiple levels in random network creation. We focus on the problem of interconnecting two micro level random networks to create a larger network at the macro level. In approaching this problem we develop a method which is driven by certain parameters which represents the characteristics of the final network that results from fusion of lower level networks.

In this respect, the procedure presented in this work is continuation of the network generation model described in Section 4.1.3. The flexibility and generalization we add in this work enables us identify empirically observed distribution functions regarding link allocations at interbank networks. Additionally, in this work we demonstrate how to allocate a given total interbank loans dispersed heterogeneously between banks.

The particular problem addressed in our study is fusion of two constituent graphs by adding edges that go between them. The generative model we develop uses a parsimonious set of parameters that describe the aggregate strength and dispersion of connection between the two constituents. We consider a scheme for choice of vertices that resonates well with established single-level random network creation models in the literature, while discussing consequences of this choice and possible alternatives.

4.2.2 A generative model for fusion of two simple graphs

Consider two simple graphs, $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$. The goal of the fusion process is to produce a new graph, $G = (V, E)$, such that $V_1 \cup V_2 = V$ and $(E_1 \cup E_2) \subset E$. The new graph, G, contains additional edges that go between the two constituent graphs. We denote this edge set as $E' = \{(v_1, v_2) | v_1 \in V_1, v_2 \in V_2\}$, and we denote its vertex cover as V'. Note that the fusion process adds no edges other than those, i.e. $E \setminus (E_1 \cup E_2) = E'$. The method described below concerns the creation of these additional edges, given certain parameters describing aggregate properties of E' as well as parameters that describe the stochastic processes for choice of vertices that are incident with it.

We characterize the fusion process with a minimal set of parameters describing the features of resulting graph. In the case of simple graphs the only parameter is the size of E', the *number of edges* to be created during fusion process, denoted as λ. Our generative algorithm, shown in Algorithm 1, consists of a loop which iterates λ times. At each step a pair of vertices is chosen, each from one of the constituent graphs, and a new edge is created which goes between the two graphs, abridging the next level in a multi-level structure.

Algorithm 1 The generative algorithm for fusion of simple graphs.

```
1: Set V ← V1 ∪ V2 and E ← E1 ∪ E2
2: Set i ← λ
3: while i > 0 do
4:     Choose a pair of vertices, v1 ∈ V1 and v2 ∈ V2, randomly from probability distribution
       P^v
5:     Add edge (v1, v2) to E
6:     Set i ← i − 1
7: end while
8: return G = (V, E) as the fused graph
```

One can think of various schemes for the choice of vertices to which a new edge will be incident with. In the case of a single-level random network two major schemes used in the literature are uniform choice model of Erdös and Renyi (1959) and preferential attachment model of Barabasi and Albert (1999). Here we limit ourselves to an adaptation of the preferential attachment model for the multi-level fusion process. In adapting the preferential attachment scheme into a generative process model, we consider a probability distribution, P^v, where the probability of a pair of vertices, $v_1 \in V_1$ and $v_2 \in V_2$, being chosen at each step as proportional to their degrees in their corresponding constituent graphs, denoted as $d_{G_1}(v_1)$ and $d_{G_2}(v_2)$:

$$P^v(v_1, v_2) = \frac{d_{G_1}(v_1) d_{G_2}(v_2)}{\Omega} \tag{4.19}$$

The normalization factor, Ω, appears so that the probabilities add up to one. The normalization factor can be found as:

$$\Omega = \sum_{x \in V_1, y \in V_2} d_{G_1}(x) d_{G_2}(y)$$

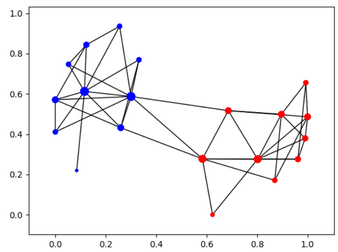
Some examples produced with the above generative model is displayed in Figure 4.9. The constituent graphs in these models are all created with Barabasi-Albert model, with $m = 3$. We have used NetworkX software for graph generation and visualization (Hagberg et al., 2008).

4.2.3 Adaptation of model for weighted graphs

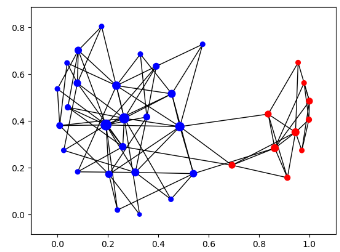
The introduction of edge weights into our generative model requires several modifications into the scheme outlined above in Algorithm 4.9. In describing the fusion process we need parameters other than the number of edges, λ. A second parameter, γ, describes the aggregate *strength* of those edges. The third parameter, δ, gives the *dispersion* of the weight over the new edges, by providing the standard deviation of normal distribution from which the new edge weights are drawn from, as a ratio of the mean of distribution. Together, these parameters are the only parameters of our generative model that describe the stochastic fusion of two weighted graphs, given in Algorithm 2.

In representing a weighted graph we denote an edge as (v_1, v_2, w) where w represents the edge weight, and degrees such as $d_{G_1}(v_1)$ and $d_{G_2}(v_2)$ are defined to be sum of link weights incident with a vertex, as usual with weighted graphs. Thus, the strength parameter, γ, can be expressed as expected sum of weights:

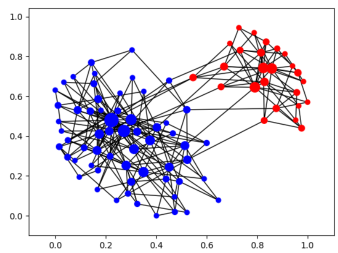
$$\gamma = \mathbb{E}\left[\sum_{(v_1, v_2, w) \in E'} w\right]$$



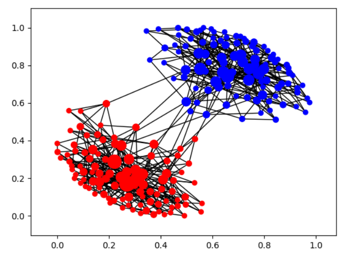
(a) $|V_1| = 10, |V_2| = 10, \lambda = 2$



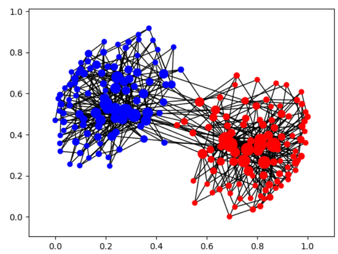
(b) $|V_1| = 10, |V_2| = 25, \lambda = 4$



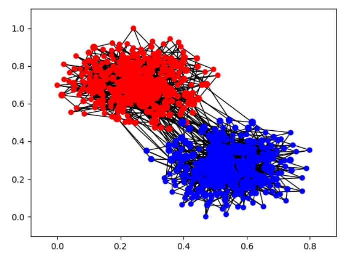
(c) $|V_1| = 25, |V_2| = 60, \lambda = 8$



(d) $|V_1| = 100, |V_2| = 100, \lambda = 10$



(e) $|V_1| = 100, |V_2| = 100, \lambda = 25$



(f) $|V_1| = 250, |V_2| = 250, \lambda = 60$

Figure 4.9: Fusion of simple graphs of various sizes

Algorithm 2 The generative algorithm for fusion of weighted graphs.

Set $V \leftarrow V_1 \cup V_2$ and $E \leftarrow E_1 \cup E_2$
Set $r \leftarrow \gamma$
Set $c \leftarrow True$
while c is True **do**
  Choose a pair of vertices, $v_1 \in V_1$ and $v_2 \in V_2$, randomly from probability distribution P^v
  Choose a weight, w, for edge $v_1 \leftrightarrow v_2$, randomly from probability distribution $P^e_{v_1,v_2}$
  if $\frac{w}{2} < r$ **then**
    Add edge (v_1, v_2) to E
    Set $r \leftarrow r - w$
  else
    Set $c \leftarrow False$
  end if
end while
return $G = (V, E)$ as the fused graph

Our design uses a weight dispersion scheme which resonates with the preferential attachment. In our scheme the weight of a new edge is the outcome of a random process whose probability distribution is dependent on the weighted degrees of the vertices it is incident with. Our scheme requires that the expected value of edge weight $\mathbb{E}[w]$, is proportional to $d_{G_1}(v_1)d_{G_2}(v_2)$.

In drawing weight of a new edge we only consider a normal distribution, $P^e_{v_1,v_2} = N(\mu_{v_1,v_2}, \sigma_{v_1,v_2})$, where the ratio of standard deviation and mean is fixed by our dispersion parameter:

$$\delta = \frac{\sigma_{v_1,v_2}}{\mu_{v_1,v_2}}$$

As a result of the preferential attachment scheme, the mean of weight distribution is constrained as follows:

$$\mu_{v_1,v_2} = \frac{d_{G_1}(v_1)d_{G_2}(v_2)}{\Theta} \tag{4.20}$$

where Θ is a normalization constant.

With these parameters defined, we can consider the strength parameter as a description of the expected value of sum of weights to find the normalization parameter Θ:

$$\gamma = \mathbb{E}\left[\sum_{(v_1,v_2,w)\in E'} w\right]$$

$$\gamma = \lambda\,\mathbb{E}[w]$$

$$\gamma = \lambda \sum_{v_1\in V_1, v_2\in V_2} P^v(v_1,v_2)\,\mathbb{E}\left[P^e_{v_1,v_2}\right]$$

$$\gamma = \lambda \sum_{v_1\in V_1, v_2\in V_2} P^v(v_1,v_2)\mu_{v_1,v_2}$$

Replacing the choice distribution from Eq. 4.19 and constraint from Eq. 4.20 in the above, we find:

$$\gamma = \lambda \sum_{v_1\in V_1, v_2\in V_2} \frac{d_{G_1}(v_1)d_{G_2}(v_2)}{\Omega}\frac{d_{G_1}(v_1)d_{G_2}(v_2)}{\Theta}$$

$$\gamma = \frac{\lambda}{\Omega\Theta} \sum_{v_1\in V_1, v_2\in V_2} d_{G_1}(v_1)^2 d_{G_2}(v_2)^2$$

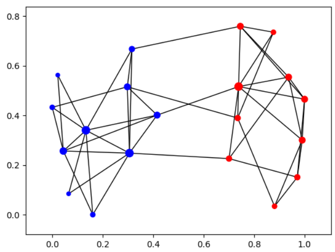
Thus we find Θ as

$$\Theta = \frac{\lambda}{\Omega\gamma} \sum_{v_1\in V_1, v_2\in V_2} d_{G_1}(v_1)^2 d_{G_2}(v_2)^2$$

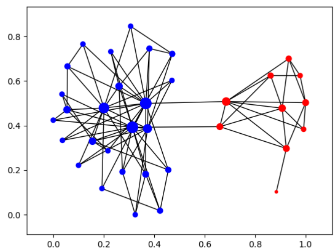
Some examples produced with the weighted version of generative model are shown in Figure 4.10.

Please note that with the above scheme, the resulting fused graph preserves the degree order of vertices during the fusion process. Consider two vertices, $u_1 \in V_1$ and $v_1 \in V_1$, with degrees $d_{G_1}(u_1)$ and $d_{G_1}(v_1)$ prior to fusion process. The expected value of their degrees after fusion can be computed as follows:

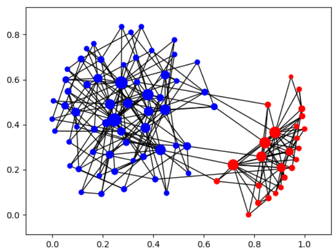
$$\begin{aligned}
\mathbb{E}\left[\, \tilde{d}_G(u_1)\right] &= d_{G_1}(u_1) + \textstyle\sum_{u_2\in V_2} P^v(u_1,u_2)\mathbb{E}\left[\, P^e_{u_1,u_2}\right] \\
&= d_{G_1}(u_1) + \textstyle\sum_{u_2\in V_2} P^v(u_1,u_2)\mu_{u_1,u_2} \\
&= d_{G_1}(u_1) + \textstyle\sum_{u_2\in V_2} \frac{d_{G_1}(u_1)d_{G_2}(u_2)}{\Omega}\frac{d_{G_1}(u_1)d_{G_2}(u_2)}{\Theta} \\
&= d_{G_1}(u_1) + d_{G_1}(u_1)^2 \underbrace{\sum_{u_2\in V_2} \frac{d_{G_2}(u_2)^2}{\Omega\Theta}}_{X} \\
&= d_{G_1}(u_1) + d_{G_1}(u_1)^2 X
\end{aligned}$$



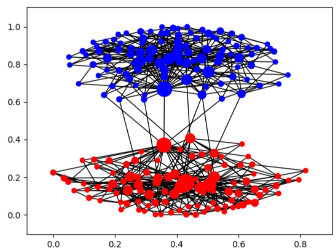
(a) $|V_1| = 10, |V_2| = 10, \lambda = 3, \gamma = 5$



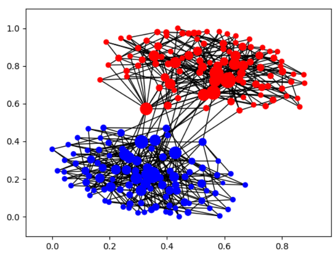
(b) $|V_1| = 10, |V_2| = 25, \lambda = 4, \gamma = 7$



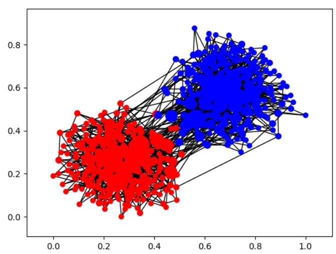
(c) $|V_1| = 25, |V_2| = 60, \lambda = 8, \gamma = 14$



(d) $|V_1| = 100, |V_2| = 100, \lambda = 10, \gamma = 15$



(e) $|V_1| = 100, |V_2| = 100, \lambda = 25, \gamma = 40$



(f) $|V_1| = 250, |V_2| = 250, \lambda = 60, \gamma = 100$

Figure 4.10: Fusion of weighted graphs of various sizes

Similarly for v_1:

$$\mathbb{E}\left[\,\tilde{d}_G(v_1)\right] \quad = \quad d_{G_1}(v_1) + d_{G_1}(v_1)^2 X$$

Now if we consider an inequality as follows in the pre-fusion graph:

$$0 \leq d_{G_1}(u_1) \leq d_{G_1}(v_1)$$

it is straightforward to see that the same ordering is expected to be preserved in the fused graph, by replacing the ordering in computed expected degrees after fusion:

$$0 \leq d_{G_1}(u_1) + d_{G_1}(u_1)^2 X \leq d_{G_1}(v_1) + d_{G_1}(v_1)^2 X$$

Note that $\forall\, v \in G : d_G(v) \geq 1 \; or \; d_G(v) = 0$ holds.

4.2.4 Considerations for directed case

Directed graphs does not present any particular obstacle to adopting our generative model. A particular consideration is about the parameter set to define directed (weighted or unweighted) fusion process. If one wishes a fusion where the aggregate strength of arcs between the two constituent graphs must be the same, then one set of strength and number of edges parameters would be sufficient. Otherwise, in the asymmetric case one needs two set of those parameters for each direction. The weighted or unweighted fusion process can simply be applied in both directions separately with the corresponding parameters.

4.2.5 Summary and further work

We have limited our generative model to only two constituent graphs. It seems straight forward to extend the generation into multiple graphs, and even to multiple levels of fusion.

An important limitation of our study is validation of the fusion process against real multi-level graphs. Such a validation will require and assessment of similarity between real graphs and the artificial ones created with out generative model. However, graph similarity is largely discussed in the literature as vertex similarity (Blondel et al., 2004), and seems to be lacking flexibility for such a validation. Further work is required for an assessment and possible adaptation of graph similarity measures.

Chapter 5

A design pattern for complex and large scale stock-flow consistent agent-based models

5.1 Motivation

Agent-based models have been proven to be able to incorporate the two aspects of a micro-founded macroeconomic models for policy analyses. On the one hand, it enables to design interacting heterogeneous agents with bounded rationality. It adopts the behavioral rules of the agents borrowed from the managerial and decision economics. On the other hand, ABMs have proven to be able to accommodate top-down policy experimentations such as fiscal and monetary interventions. However, ABM practices are criticized at lacking a methodological maturity at developing large scale, re-usable and accessible models. Deriving upon hands-on experience through a sequence of research and development on ABMs in economics, majority of which have been presented in earlier chapters, in this chapter I like to elaborate on a methodological framework that can be employed at large scale agent-based models for policy analysis in economics.

The consolidation of this methodological approach is not only based on personal or team experiences at the design, implementation and simulation of ABMs but also derives upon the know-how that is implicit within the computational ABM frameworks and the reported experiences of other research groups within the domain. This chapter, in that sense, highlights an over-arching methodological approach based on a series of researches that I have involved in as a co-author of the papers. Design and development of ABM in economics has been covered in numerous monographs elsewhere. A systematic and comprehensive review of the models to this day is reviewed by Dawid and Delli Gatti (2018). The objective in this chapter is however limited to the set of methodological novelties that have arisen within the PhD study that has lead to fulfillment of this dissertation work.

The framework combines a set of novelties for design, implementation and simulation of stock-flow-consistent ABM models: (i) a decoupled initialization phase where stock-flow-consistent network of balance-sheet structures, as well as, other complex agent-agent interactions can be set-up ex-ante, (ii) a steady-state transition phase, where a stable and stock-flow consistent state of the model is determined prior to policy experiment via Monte-Carlo simulations, (iii) a well defined unit of design at the implementation of agent actions, where the focus is on an atomic sate of an agent, (iv) an agent behavior library, where previously implemented atomic agent behaviors can be re-used as the building blocks of a large scale model, (v) a messaging protocol, where direct or indirect agent-agent communications are standardized, (vi) a state transition diagram, where event occurrence periodicities, sequences, synchronizations, communications and other conditions can be sketched graphically or via a high level domain specific markup language, (vii) a model configuration tree, where previously implemented components such as markets can be turned on or off via model configuration parameters prior to initialization and simulation phases.

In essence, the methodological framework develops upon modular and layered design approaches inherited from state-of-the art software development technologies. This modular design pattern has given us the flexibility at creating vertical and horizontal scalable complex economic systems as described in Chapter 3.

5.2 Behaviors vs interactions

Modularity is achieved by decoupling atomic components of a socio-economic system at the design stage. In a multi-agent system, each agent is endowed with a finite set of attributes. Values of these attributes can stay constant during the simulation life time of an agent or can be altered through agent's interactions with the other agents in the system or with its environment. Combination of values that these memory variables attain together with the combination of signals or messages they receive from the other agents or from the environment determine the state of an agent. Hence theoretically, an agent may exhibit an infinite number of states. Nevertheless a simulation life time of an agent can be observed as a finite and specific sequence of state transitions. In that respect, at an atomic level, a simulation model design can be transferred to a design of state-transitions for each agent type in a model.

In that respect a state transition can be considered as the unit of design. Design components of an ABM can be listed as follows:

- Policy parameter: The set of exogenous variables, such as the household mobility friction variable we have used in Chapter 3.
- Agent type: Firm, Bank, Household, etc. Both varying number of agent types as well as multiple instance of each agent with possibly different state variables enables the construction of a **multi-agent system**.
- Memory variable: The set of attributes for each agent type in the model. For instance, balance sheet entries of a firm is a subset of the agent's memory variables. They are namely the *state variables*. It should be noted that the endogenously or exogenously set values for these variables lead **heterogeneity** in the model.
- Message: Communication received from other agents in the system. For instance, a mortgage payment sent by a household to a bank is represented by a message, likewise a job offer from a firm to a household. Thus not only coordination and *communication between agents* but also asset or debt flow between agents are realized via messages.

- Behavior: Any autonomous action of an agent that either alter the state of the agent or that leads the agent to alter the state of its environment or another agent's in the system or both.

- Environment: It is an abstract component. The assigned values of policy parameters along with aggregate state of all agents in a simulation step determine the environment where an agent acts and interacts. In that respect, from an implementation point of view, design and assignment of policy parameters and a design of state transitions for each agent one by one corresponds to design of an ever changing dynamic simulation environment.

Given the components above, design of agent types, agent memory variables, set of messages between agents (interactions), set of agent functions (behaviors), model parameters (policy parameters), and markets or mechanisms via a selection and combination of a subset of previously designed messages and functions can be decoupled from each other. That is, design and implementation of each component can be done separately and incrementally.

5.2.1 Unit of design

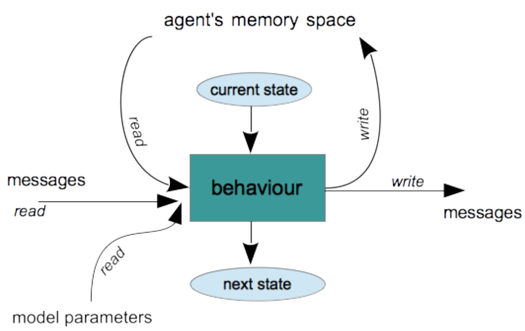


Figure 5.1: Unit of design.

The unit of design is roughly given in Figure 5.1. The block in the middle represents the implementation of a behavior. A behavior, in terms of design terminology, corresponds to any function that possibly alters the memory space of the agent itself. A function may also result in sending out a message to other agents with or without changing its own memory state. As the figure suggests a function and hence a behavior depends on the current memory of the agent itself and the state of the environment. The interaction with the environment is either via a direct access to the model parameters and/or via a set of messages received from the other agents within the system.

The novelty of this approach stems from the fact that a model designer can focus on a self-consistent and sound behavior design and implementation independent from the design of an overall complex system.

5.2.2 Behavior library

An atomic design unit approach enables the model designer to build a library of reusable functions. A function can be as simple as an agent behavior such as in which the agent checks/reads in policy rate posted by the central bank and updates its own corresponding memory variable or as complex as an advanced learning and adaptation mechanism such as an internal neural network model which may update trading strategy of the agent at financial markets. Or a set of different functions can be designed to be used interchangeably. For example, both a Leontief and a Cobb-Douglas production function can be made available in the library. Depending on the conceptual model then one or the other can be selected accordingly. As a rule of thumb, simplicity and a minimal computation in behavior design is considered in order to increase a re-use chance of existing implementations. A minimal behavior can be described as a function that causes a minimum number of changes in the agent's memory space or at its interactions with other agents. An example function implementation from the Eurace model library is depicted in Figure 5.4 where a Firm's loan request action is presented.

5.2.3 State transitions

A state transition unit as presented in Figure 5.1 is the building block for scalable and complex ABM models that we have developed. Figure 5.2 depicts a generic toy model with two different agent types. A model implementation in principle comprises sequencing of agent state transitions. An entire state diagram is then the design a generic simulation loop adopting

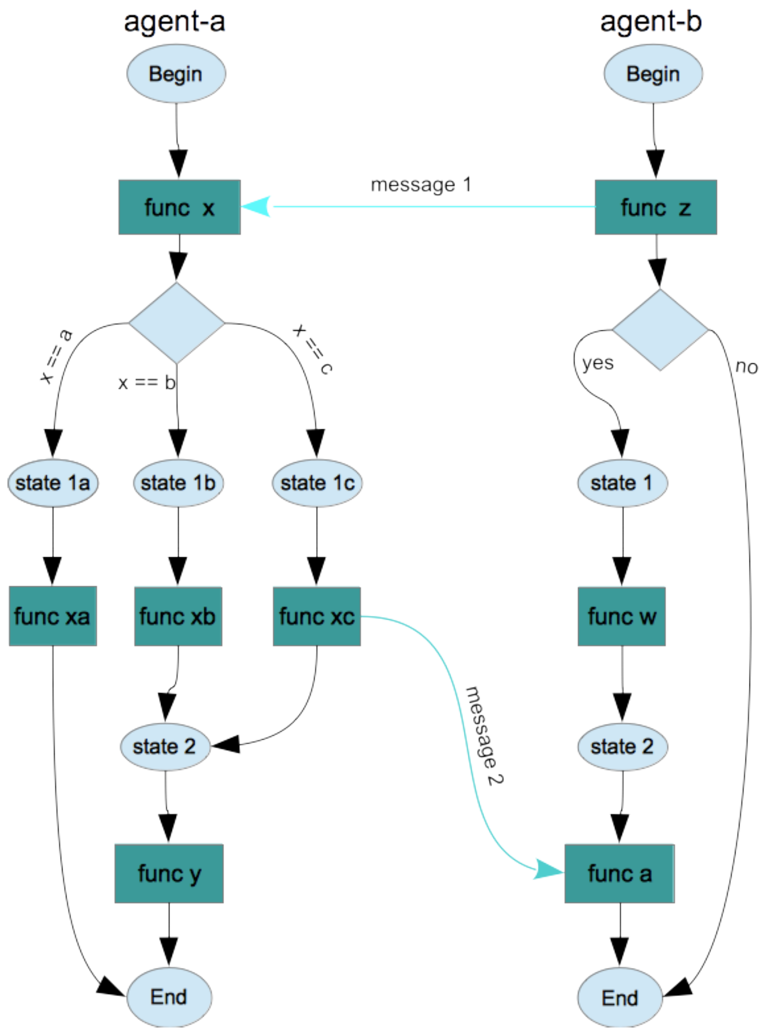
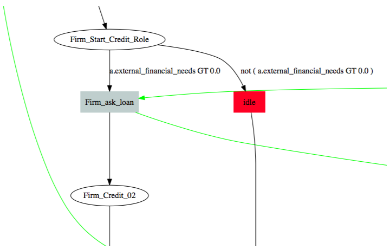


Figure 5.2: Iteration loops for two hypothetical agents at an imaginary model. Agent-a can be for instance a household while agent-b is a firm.

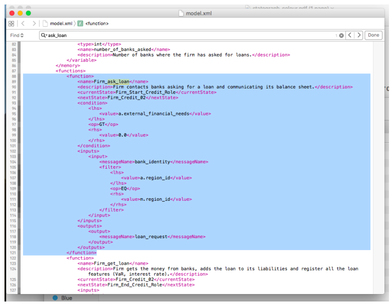
atomic design units. Activation of each state can be conditioned by the state of the simulation environment, the point in the time, or the communications from the other agents.

5.2.4 Behavior activation

Figure 5.3 and Figure 5.4 together display a state transition block within Eurace model where Firm agents credit mechanism is implemented. As pointed out above state transitions can be conditioned by a number of external or internal factors: (i) activation time as of daily, weekly, monthly, quarterly or yearly calendar, (ii) due to value of an exogenous policy parameters,



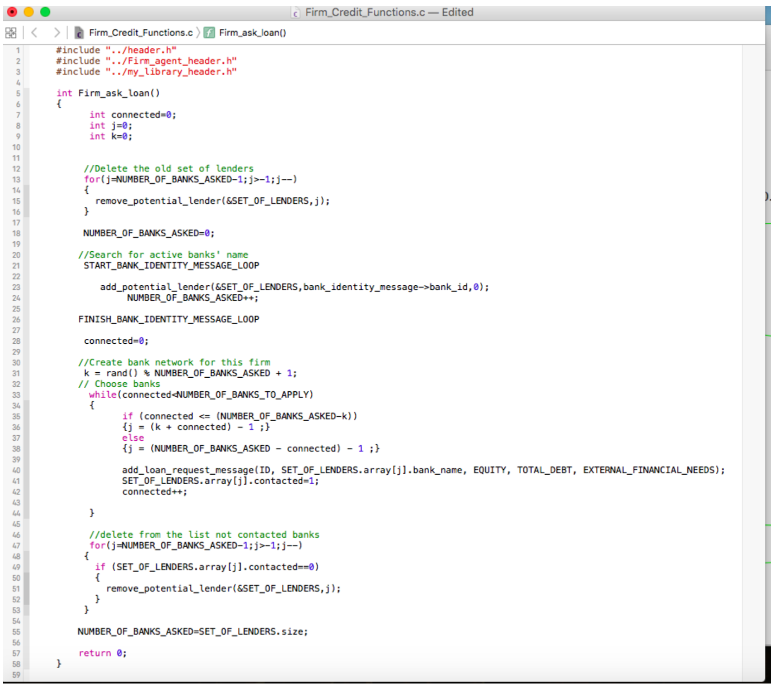
(a) State transition graph.



(b) Conditions on state transitions.

Figure 5.3: *Conditional state transitions. A snippet from Eurace model. The panel on the left is a graphical visualization of a particular state of a consumption good producer. The display on the right is its implementation via a high level modeling description language that is used in Eurace and Iceace models. The xmml (eXtended Machine Mark-up Language) is an XML based tool that helps to construct an entire state diagram of a model (Kiran, 2017).*

(iii) due to a communication interaction from another agent, (iv) or simply due to a specific combination of agent's internal memory state, such as activation of insolvency procedure due to balance-sheet structure.



```
#include "../header.h"
#include "../Firm_agent_header.h"
#include "../my_library_header.h"

int Firm_ask_loan()
{
     int connected=0;
     int j=0;
     int k=0;


    //Delete the old set of lenders
    for(j=NUMBER_OF_BANKS_ASKED-1;j>=-1;j--)
    {
      remove_potential_lender(&SET_OF_LENDERS,j);
    }

    NUMBER_OF_BANKS_ASKED=0;

   //Search for active banks' name
    START_BANK_IDENTITY_MESSAGE_LOOP

       add_potential_lender(&SET_OF_LENDERS,bank_identity_message->bank_id,0);
            NUMBER_OF_BANKS_ASKED++;

   FINISH_BANK_IDENTITY_MESSAGE_LOOP

    connected=0;

   //Create bank network for this firm
    k = rand() % NUMBER_OF_BANKS_ASKED + 1;
   // Choose banks
     while(connected<NUMBER_OF_BANKS_TO_APPLY)
     {
           if (connected <= (NUMBER_OF_BANKS_ASKED-k))
           {j = (k + connected) - 1 ;}
           else
           {j = (NUMBER_OF_BANKS_ASKED - connected) - 1 ;}

           add_loan_request_message(ID, SET_OF_LENDERS.array[j].bank_name, EQUITY, TOTAL_DEBT, EXTERNAL_FINANCIAL_NEEDS);
           SET_OF_LENDERS.array[j].contacted=1;
           connected++;

     }

     //delete from the list not contacted banks
     for(j=NUMBER_OF_BANKS_ASKED-1;j>=-1;j--)
    {
      if (SET_OF_LENDERS.array[j].contacted==0)
      {
        remove_potential_lender(&SET_OF_LENDERS,j);
      }
    }

   NUMBER_OF_BANKS_ASKED=SET_OF_LENDERS.size;

   return 0;
}
```

Figure 5.4: An implementation example from Eurace model's behavior library. The panel displays a code snippet from a consumption good producer firm. In this unit of design, a loan request behavior relies on the agent's memory space, and some external communications. The function checks/reads in available banks in the system, keeps a track of the ones that has been contacted. The contact is made my the messaging mechanism where a request is placed. The firm reports the current state of its own equity and outstanding debt along with the amount of debt request.

5.2.5 Synchronization of interactions

As it is suggested by Figure 5.2 - 5.3, at each iteration, agents in the models run their respective state-transition diagram concurrently. An iteration for an agent corresponds to a traversal of the agent through its state transition diagram. The very common synchronization point for all agents is the end of each iteration which typically points to the end of a calendar day. Once all agents have reached to their respective 'End' state, the internal logical simulation clock is incremented and agents rerun their state-transition diagram.

Communications are handled via a message board system which enables asynchronous communication patterns within an iteration. It should be noted that state transitions are also dependent on expected interactions with other agents. Thus the atomic design unit together with conditional state transitions not only enable us have vertically scalable complex models but also enable us to assure easily verifiable stock-flow consistency within the economy. Any interaction that includes flow of assets, debts or equity from one agent to agent due to payments, creation, write-off or delivery of credit money, or change in any ownership is immediately accompanied with a balance-sheet update on both ends of the flow. In most of our models, at the end of a calendar day, accounting identity is checked autonomously by each agent.

5.3 Initialization and calibration of stock-flow consistent models

Sensitive dependence on initial conditions is a known problem to ABMs small or large. Initialization and calibration of stock-flow consistent models are inherently a constrained based problem. It requires design and simultaneous solution of a large number of equations which are not necessarily always linear. Solutions are used to initialize variables within memory space of agents in the model.

5.3.1 Layered initializations for stock-flow consistency

In all of the models research results of which have been presented in this dissertation, we have applied a layered initialization. There are two stages of a layered initialization:

1. Initialization of agent balance sheets that secures initial **stock consistency**
2. Initialization of agent-agent interactions that secures initial **flow consistency**

Initial average wage offer in the economy is used as the initialization unit of measure which is generally equal to one unit of the currency in the economy. Then as part of the first layer of initialization distribution function on household wealth, firms' and banks' assets and debts are identified. Depending on the research question sound and consistent empirically validated stylized ratios between balance sheet entries and distribution functions on balance-sheet ratios as well as values across agents are employed. After having set the size of the economy as of initial wage, average wage offer asset, debt, and equity are allocated accordingly. Accounting identity at each individual agent level as well as at the aggregate levels are checked to secure stock consistency.

For the second layer of initialization agent-agent interaction patterns need to be used. The flow of credit, assets or equity from one economic agent to another is handled by implicit or explicit network relations in a model that match accumulation of stocks distributed in the first phase.

5.3.2 Modelling and initializing of complex network structures

Some examples for agent-agent interactions are:

- Firm-Household employment relations, which should be consistent with initial firm size distribution, individual firm's production capacity, level of technology at each firm and households' skill distribution.
- Firm-bank credit relations, which needs to meet credit distribution in the system.

- Household-Bank and Firm-Bank deposit networks, which needs to be consistent with the distribution and total of liquidity in the system.
- Household-Firm ownership structure, which needs to be consistent with share distributions among households as well as distribution of other traded financial assets.
- Bank-Bank credit networks, which should be consistent with interbank financial network model and bank balance sheet distributions.

In most of our research cases random graph models are employed and integrated into the population design and initialization stage of modelling. In the research papers where we have employed Eurace model (Ozel et al., 2016; Raberto et al., 2017; Petrovic et al., 2018; Raberto et al., 2018) we have used homogeneous distributions for initial distribution of wealth among households and firm sizes. This in return enabled us to use uniform random graph models at the initialization of, e.g., employment relation, deposit allocation and credit networks. However, in case of the research where we have employed Iceace model (Bjarnason et al., 2015; Erlingsson et al., 2016), for instance, employment relations have been formed endogenously at the very first simulation step using the decentralized nature of our labor market mechanism.

On the other hand, in our work on resilience of inter-bank credit markets (Ozel et al., 2018) stages of layered initialization is reversed: an interbank network configuration is designed algorithmically with desired connectivity and centralization features. The node level link structure from the configured network is used as input to create stock-flow-consistent balance-sheet distributions. The research has focused on resilience of network structures against external asset shocks which has lead us primacy to connection types and then configuration of balance-sheets consistently prior to Monte-Carlo experiments.

5.3.3 Assuring steady state initializations

Assuring a steady state[1] initialization for a complex agent based models, where there are multiple type of agents, mechanisms and markets, prior to a simulation run time is a challenging task. Additionally, heterogeneity, for instance, in speculative behaviors at housing markets or at financial markets, or at firm production planning generally result in a mis-match at initialization of agent memory variables, productive capital allocations, etc. Such mismatches are generally exhibited by large oscillations in macro-economic variables such as GDP per capita or unemployment levels. Our two-layered initialization as outlined in Section 5.3.1 reduce such oscillations to some extend but are yet not able to eliminate them completely. An elimination of such steep and deep oscillations that stem from initialization mismatches would shorten the transition phases of the artificial economies.

Failing to acknowledge such transitional phase in the models may misguide the interpretation of simulation results. As we have presented via Figure 3.7b in Chapter 3, transitional and steady state phases of simulations need to be delimited. In the respective model, since there is neither population nor technology growth a steady state is regime is safely identified when capital accumulation reaches to its full capacity as it is observed in the upper panel of Figure 3.7.

In a model where there is an endogenous growth in production technology or population, it is suggested to run the simulations without any growth until the model reaches to its full production capacity. The rationale for the suggestion is a heuristic one. The overall objective is to assure a stable state of the artificial economy as the starting point prior to running multitudes of Monte-Carlo simulations to examine growth related factors. Decoupling growth dynamics would also mean decoupling growth related path dependency from initial conditions. The technological convergence study by Dawid et al. (2017) applies the method. They use one of such steady state snapshot of the economy as the initial state of their experiments.

In summary, a combination of two techniques can be suggested for the assurance of a steady-state regime of a simulation stage:

[1]It should be noted as it can be seen in Figure 3.7 by steady-state we refer to a regime in the artificial economy where business cycles exist and endogenous and where effect of large oscillations due to improper initialization of resources in the economy is phased out automatically by model's internal dynamics.

- Applying a multi-layered initialization and calibration not only for (i) stock-flow-consistent balance sheet initialization, and (ii) consistent agent-agent interactions, but also behaviorally consistent agent memory variables.
- Running the stock-flow consistent model where exogenous variables and growth dynamics are turned off and then using a selected snapshot of the economy from the end of the transitional phase as the initial state for subsequent experiments.

5.3.4 Incremental calibration

Section 3.3.1, has introduced a methodological novelty that scales up/down an ABM model by either extending/shrinking the modeling details or components (vertical scalability) or by changing population size and variations (horizontal scalability). Section 2.1.4 demonstrates a case where a housing market is added to the base Eurace model. Introduction of new components needs to cover recalibration of the base model to be able to accommodate new agents, agents' additional memory spaces, behaviors and new agent-agent interactions seamlessly and in a conceptually sound manner. In that respect, housing market calibration can be considered as a case-based demonstration on how stylized facts from actual empirical studies and initial average wage in the model are combined for a consistent recalibration. It should be noted that as discussed in Section 5.3.1 the initial wage offer functions as the unit of measure for numerical calibrations for the variables which are represented in terms of mean of exchange in an economy. This calibration premise has lead us to identify typically observed housing wealths with respect to average wages in contemporary economies as the reference value during re-initialization of the extended model. Such recalibration processes are specifically vital at being able to compare and contrast simulation findings from the extended model with respect previous outcomes from the base model.

5.4 Tools for validation and analysis

An up to date validation practices on ABMs elsewhere within macroeconomics studies have been surveyed by Fagiolo et al. (2018). The authors further suggest a theoretical framework that discusses validation approaches via three different dimensions: "(i) comparison between artificial and real-world data; (ii) calibration and estimation of model parameters; and (iii) parameter space exploration" (p. 2). As the survey authors acknowledge, validation approaches within the field are still at an exploration and discovery phase. In this section, I limit the discussion by pointing out to our hands-on experiences through developing and employing relatively very advanced models within the field.

5.4.1 Business cycles and stylized facts

Stylized facts, in short, are empirically observed regularities. They serve us to check whether our model outputs are able to exhibit sufficiently similar patterns to the real world data. We have employed dynamic correlation techniques and comparison of distributions. For instance, in our work where we have specifically examined impact of mortgage credits on real economy (Raberto et al., 2017), we have examined dynamics of business cycles in terms of GDP, loans, mortgages, investments and consumptions conducting pair-wise cross-correlations between respective time series. Figure 2.13 which is also presented in Ozel et al. (2016) demonstrates that mortgages in our model is leading the business cycle as it has been reported elsewhere in real world (European Central Bank, 2013). The appendix of our recent work Petrovic et al. (2018) provides an extended presentation of statistical analyses of model dynamics with respect to stylized facts.

5.4.2 Sensitivity analysis

We perform sensitivity analysis exercises in order to check the responses of the model to variations against exogenous model parameters as well as to population sizes.

Parameter sensitivity Experiment ranges and intervals of our policy parameters such as mobility friction in Petrovic et al. (2018) as presented in Chapter 3 or equity-to-asset ratio in Ozel et al. (2016) which has served as a stock-control regulatory instrument, see Chapter 2.1, are determined after conducting Monte-Carlo simulations (Metropolis and Ulam, 1949) with numerous random seeds. On the other hand, in our work on resilience of different financial network shocks (Ozel et al., 2018) we have conducted a parameter sensitivity analysis in order to determine sufficiently small amplitudes of incremental asset shocks on the system where we could observe bank defaults. Simulation data, on which actual analyses are conducted, are generated after such test runs.

Population sensitivity Analysis of a model response against differing population size, i.e., number of households, firms, banks, etc in the model, contributes to measurement regarding the stability of the model. In order to demonstrate the stability of the extended version of Eurace model, for instance, in Ozel et al. (2016), keeping all other parameters constant, we have run Monte-Carlo simulations with double and half population sizes, with respect to the population size to be used in dissemination of results. The statistical comparisons and tests on distributions confirm the stability of the model and have been presented in the appendix of the respective article.

5.4.3 Analytical validation

Analytical validation is only possible for few small scale models where boundary conditions and basins of attraction can be studied Fagiolo et al. (2018). Analytical examination of more complex models can be conducted to some extend when model specification of a baseline model with uniform distribution of relevant agent variables.

In one of our work, we have compared macroeconomic implications of different mortgage types (Bjarnason et al., 2015). We have combined model specification regarding households' mortgage debt repayment schemes and a set of sample simulated data to compare expected volume of principal payments in the economy under differing mortgage type enforcement regimes[2]. Then consistency of simulation data from Monte-Carlo experiments is compared against analytical findings[3]. However, it should be noted that although both analytical and simulation results foresee the additional mortgages in the economy, it has been the micro-level data from the simulations that enabled us to examine the impact of additional mortgage repayments on housing wealth distributions and hence its relevance to policy making.

5.4.4 Statistical measures for controlled groups

Chapter 3.3 have introduced the methodological novelty from our scalable and flexible multi-country simulation set-up. The set-up enables a modeller to design control and test economies which are exposed to the same population initialization procedure and that can be run exposed to the same random seeds. In order to be able to compare and test relative dynamics of test and control group economies we have devised new statistical measures. Section 3.3.4 provides detailed specifications of the three new statistics that are introduced by Petrovic et al. (2018): (i) comparison of averages over seeds, (ii) comparison of means of aggregate variables (iii) comparison of the mean of the differences.

[2]See Figure 2 in Bjarnason et al. (2015).
[3]See the results section in Bjarnason et al. (2015).

Summary

The major contributions presented in this work are four-fold: (i) design, analyses and discussion on housing market regulation, (ii) design and development of a scalable multi-country experiment set-up, (iii) design and development of a novel interbank simulation model, (iv) and a methodological guideline that has been consolidated through design, development and validation of large-scale ABMs.

The design and integration of variants of housing markets within closed artificial economies has served us (i) examine stylized relation between mortgage credits and business cycles, (ii) experiment with alternative and prudent mortgage regulating instruments, (iii) examine macroeconomic impacts of different mortgage types, and (iv) investigate impact of policies towards green finance when speculative lending channel via housing market is prevalent in the system. Firstly, our models confirm that the dynamics of mortgages is supporting the theory of endogenous nature of credit money giving a contribution to a debate that has grown stronger over the last two decades. In general, regulations allowing for a high leverage of the banking tend to inflate asset bubbles and boost the economy in the short run, while result in bubble bursts and economic depression in the medium and long run. Secondly, our findings, however, also suggest that stimulating impact of mortgage credits can sustain growth and stability when regulated via complementary instruments. Following some recent discussion, a stock control regulation that targets households net wealth (a stock), instead of income (a flow), is designed and analyzed. Results show that stock control regulation can be effectively combined with debt-service-to-income ratio (DSTI) in order to increase the stability of the housing market and of the whole economy. Moreover, stock control regulation exhibits the interesting property to

directly affect mortgage distribution among households. Thirdly, we have further examined regulatory options through enforcement of different mortgage types. Our results suggest that inflation-indexed mortgages, where interest rate is fixed throughout the term and principal debt is indexed to consumer price index, can mislead households' expectations of risk encouraging them to buy more housing due to their low initial amortizations which, in turn, stimulates housing prices. The results further hint that in long-run inflation-indexed mortgages create relatively more uneven housing wealth distribution among households. We also find that the effectiveness of standard monetary policy tools is diminished when inflation-indexed mortgages are used. Besides, our simulation results point out that banks partake in the interest rate risk with fixed rate mortgages but bear little or no risk with adjustable rate, where interest rate follows the rate of the Central Bank plus a constant spread, or inflation-indexed mortgages. Lastly, we have examined macro-prudential policies that may help to stimulate banking sector to shift from speculative lending, the cause of asset bubbles and economic crises, to an energy efficient production technology. As of the regulatory instrument, we have introduced a differentiation of capital requirements according to the destination of lending, demanding higher bank capital in the case of speculative lending via mortgages. Results suggest that the proposed regulation is able to foster investments and capital accumulation in the short term, improving the energy efficiency of firms. However, reducing mortgages with a restrictive banking regulation has a negative impact on total private credit, and thus on endogenous money supply, weakening consumption and aggregate demand. In the long term, the contraction of total credit becomes stronger, and the negative outcomes on aggregate demand also affect investment making the energy efficiency become negligible.

The work on a scalable multi-country experiment set-up has enabled us address the conditions under which two or more countries can benefit from becoming part of a union. Our results suggest that for similar countries, it is always beneficial to join in a union, although a lack of mobility frictions can weaken its performance. Even if countries have different productivities, the performance of the union is in general better than the performance of the isolated countries. The exception is when the productivity gap between member countries and labor mobility across borders are both too high. In this case, the union can even exacerbate the gap between the member states. We have devised and tested a fiscal pool body to measure to what extend it could alleviate causes of a structural difference, such as high tech and productive member versus a low tech and underdeveloped member. Our findings suggests that stronger fiscal integration via transfers from surplus countries to deficit countries helps reducing inequality between such members, supporting a sustainability of the monetary union.

As part of the methodological consolidation effort while studying complex and interactive mechanisms within ABMs a particular attention is dedicated to network models. A set of algorithms have been developed that creates random or stylized network structures with desired properties for the initialization of agent-agent connections. In the study where we have created stock-flow-consistent interbank networks with desired level of network connectivity and centralization, we have seen that a medium density of connections in regular networks is already sufficient to induce a 'robust-yet-fragile' response to insolvency shocks, while the same occurs in star networks only when the centralization is very high.

Following guidelines are suggested for design and development of large scale agent-based-models: (i) employment of decoupled initialization phase where stock-flow-consistent network of balance-sheet structures, as well as, other complex agent-agent interactions can be set-up ex-ante, (ii) assurance of a steady-state phase, where a stable and stock-flow consistent state of the model is determined prior to policy experiment via Monte-Carlo simulations, (ii) a well defined unit of design at the implementation of agent actions, where the focus is on an atomic sate of an agent, (iv) establishment of an agent behavior library, where previously implemented atomic agent behaviors can be re-used as the building blocks of a large scale model, (v) a communication protocol, where direct or indirect agent-agent communications are standardized, (vi) a state transition diagram, where event occurrence periodicities, sequences, synchronizations, communications and other conditions can be sketched graphically or via a high level domain specific markup language, (vii) a model configuration tree, where previously implemented components such as markets can be turned on or off via model configuration parameters prior to initialization and simulation phases.

Future research directions

Theoretical research directions:

1. design and analyses variants of monetary policies within a monetary union that is subject to technological differences and mobility frictions,
2. policy analysis an economic union with or without a common currency,
3. comparison of an economic union with or without a common fiscal policy.

Methodological research directions:

1. completing the re-engineering and the re-factoring work on the Eurace multi-country set-up,
2. adding multiple currencies to be able to enable trade between economies with differing currencies,
3. embedding the interbank-network model within Iceace and Eurace models,
4. implementing the layered initialization phases exclusively within Eurace and Iceace models,
5. adding a differentiated consumption good production and relevant mechanisms to the Eurace multi-country set-up.

Bibliography

Acemoglu, D., A. Ozdaglar, and A. Tahbaz-Salehi (2013, January). Systemic risk and stability in financial networks. Working Paper 18727, National Bureau of Economic Research.

Aglietta, M., E. Espagne, and B. Perrissin-Fabert (2015). *A proposal to finance low carbon investment in Europe.* France Strategie, Paris.

Aiello, F. and V. Pupo (2012). Structural funds and the economic divide in italy. *Journal of Policy Modeling 34*(3), 403 – 418.

Alesina, A., R. J. Barro, and S. Tenreyro (2002). Optimal currency areas. *NBER macroeconomics annual 17*, 301–345.

Anderson, G., P. Bunn, A. Pugh, and A. Uluc (2014). The potential impact of higher interest rates on the household sector: evidence from the 2014 NMG Consulting survey. *Bank of England Quarterly Bulletin 54*(4), 419–433.

Anginer, D. and A. Demirguc-Kunt (2014). Has the global banking system become more fragile over time? *Journal of Financial Stability 13*, 202 – 213.

Arestis, P. and P. Howells (1999). The supply of credit money and the demand for deposits: a reply. *Cambridge Journal of Economics*, 115–119.

Arthur, W. B. (1999). Complexity and the economy. *science 284*(5411), 107–109.

Ashraf, Q., B. Gershman, and P. Howitt (2017). Banks, market organization, and macroeconomic performance: An agent-based computational analysis. *Journal of Economic Behavior & Organization 135*, 143 – 180.

Axtell, R., D. Farmer, J. Geanakoplos, E. Carella, B. Conlee, J. Goldstein, M. Hendrey, P. Kalikman, D. Masad, N. Palmer, and C.-y. Yang (2014). An Agent-Based Model of the Housing Market Bubble in Metropolitan Washington, D.C. Technical report, Deutsche Bundesbank Spring Conferences on Housing Markets and the Macroeconomy.

Baas, T. and H. Brücker (2008). Macroeconomic consequences of migration diversion: a cge simulation for germany and the uk. Technical report, IAB-Discussion Paper.

Baffoe-Bonnie, J. (1998). The dynamic impact of macroeconomic aggregates on housing prices and stock of houses: a national and regional analysis. *The Journal of Real Estate Finance and Economics 17*(2), 179–197.

Baldwin-Edwards, M. (1997). The emerging european immigration regime: some reflections on implications for southern europe. *JCMS: Journal of Common Market Studies 35*(4), 497–519.

Baptista, R., J. D. Farmer, M. Hinterschweiger, K. Low, D. Tang, and A. Uluc (2016). Macroprudential policy in an agent-based model of the uk housing market. *Bank of England Quarterly Bulletin*.

Barabási, A.-L. and R. Albert (1999). Emergence of scaling in random networks. *science 286*(5439), 509–512.

Battiston, S., J. D. Farmer, A. Flache, D. Garlaschelli, A. G. Haldane, H. Heesterbeek, C. Hommes, C. Jaeger, R. May, and M. Scheffer (2016, February). Complexity theory and financial regulation. *Science 351*(6275), 818–819.

Battiston, S., D. D. Gatti, M. Gallegati, B. Greenwald, and J. E. Stiglitz (2012). Liaisons dangereuses: Increasing connectivity, risk sharing, and systemic risk. *Journal of Economic Dynamics and Control 36*(8), 1121–1141.

Beck, T., A. Demirguc-Kunt, and R. Levine (2006). Bank concentration, competition, and crises: First results. *Journal of Banking and Finance 30*(5), 1581 – 1603.

Beck, T., A. Demirguc-Kunt, and R. Levine (2007, Mar). Finance, inequality and the poor. *Journal of Economic Growth 12*(1), 27–49.

Benartzi, S. and R. H. Thaler (1995). Myopic loss aversion and the equity premium puzzle. *The Quarterly Journal of Economics 110*(1), 73–92.

Bikker, J. and K. Haaf (2002). Competition, concentration and their relationship: An empirical analysis of the banking industry. *Journal of Banking & Finance 26*(11), 2191–2214.

Bjarnason, T., E. J. Erlingsson, B. Ozel, H. Stefansson, J. T. Sturluson, and M. Raberto (2015). Macroeconomic effects of varied mortgage instruments studied using agent-based model simulations. Technical report.

Blondel, V. D., A. Gajardo, M. Heymans, P. Senellart, and P. Van Dooren (2004). A measure of similarity between graph vertices: Applications to synonym extraction and web searching. *SIAM review 46*(4), 647–666.

Blum, J. and M. Hellwig (1995). The macroeconomic implications of capital adequacy requirements for banks. *European Economic Review 39*(3), 739–749.

Boeri, T. and H. Brücker (2005). Why are europeans so tough on migrants? *Economic Policy 20*(44), 630–703.

Boldrin, M. and F. Canova (2001). Inequality and convergence in europe's regions: reconsidering european regional policies. *Economic Policy 16*(32), 206–253.

Borgatti, S. P., A. Mehra, D. J. Brass, and G. Labianca (2009). Network analysis in the social sciences. *Science 323*(5916), 892–895.

Borsch-Supan, A. (1994). Housing Market Regulations and Housing Market Performance in the United States, Germany, and Japan. In *Social Protection versus Economic Flexibility: Is There a Trade-Off?* University of Chicago Press.

Branch, W. A. and B. McGough (2018). Heterogeneous expectations and micro-foundations in macroeconomics. In C. Hommes and B. LeBaron (Eds.), *Handbook of Computational Economics*, Volume 4 of *Handbook of Computational Economics*, pp. 3 – 62. Elsevier.

Broz, T. (2005). The theory of optimum currency areas: a literature review. *Privredna kretanja i ekonomska politika 104*(2005), 53–78.

Bubb, R. and P. Krishnamurthy (2015). Regulating Against Bubbles: How Mortgage Regulation Can Keep Main Street and Wall Street Safe - from Themselves. SSRN Scholarly Paper ID 2558110, Social Science Research Network, Rochester, NY.

Caiani, A., E. Catullo, and M. Gallegati (2018). The effects of fiscal targets in a monetary union: a multi-country agent-based stock flow consistent model. *Industrial and Corporate Change*, 1–32.

Caiani, A., A. Godin, E. Caverzasi, M. Gallegati, S. Kinsella, and J. E. Stiglitz (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control 69*, 375–408.

Campiglio, E. (2016). Beyond carbon pricing: the role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecol Econ 121*, 220–230.

Carroll, C. D. (2001, Summer). A theory of the consumption function, with and without liquidity constraints. *Journal of Economic Perspectives 15*(3), 23–45.

Case, K. E., E. L. Glaeser, and J. M. Quigley (Eds.) (2009). *Housing markets and the economy: risk, regulation, and policy: essays in honor of Karl E. Case*. Cambridge, Mass: Lincoln Institute of Land Policy.

Castiglionesi, F. and M. Eboli (2018). Liquidity flows in interbank networks. *Review of Finance 22*(4), 1291–1334.

Catte, P., N. Girouard, R. Price, and C. André (2005). The contribution of housing markets to cyclical resilience. *OECD Economic Studies 2004*(1), 125–156.

Caverzas, E. and A. Godin (2015). Post-keynesian stock-flow-consistent modelling: a survey. *Cambridge Journal of Economics 39*(1), 157–187.

Chang, E. J., E. J. A. Lima, S. M. Guerra, and B. M. Tabak (2008). Measures of interbank market structure: An application to brazil. *Brazilian Review of Econometrics 28*(2).

Chen, T.-T., B. Zheng, Y. Li, and X.-F. Jiang (2017). New approaches in agent-based modeling of complex financial systems. *Frontiers of Physics 12*(6).

Cincotti, S., M. Raberto, and A. Teglio (2010a). Credit money and macroeconomic instability in the agent-based model and simulator eurace. *Economics: The Open-Access, Open-Assessment E-Journal 4*(2010-26).

Cincotti, S., M. Raberto, and A. Teglio (2010b). Credit money and macroeconomic instability in the agent-based model and simulator eurace.

Cincotti, S., M. Raberto, and A. Teglio (2012). Macroprudential policies in an agent-based artificial economy. *Revue de l'OFCE* (5), 205–234.

Craig, B. and G. von Peter (2014). Interbank tiering and money center banks. *Journal of Financial Intermediation 23*(3), 322–347.

Dagher, J. and N. Fu (2011). What Fuels the Boom Drives the Bust; Regulation and the Mortgage Crisis. IMF Working Paper 11/215, International Monetary Fund.

Dawid, H. and D. Delli Gatti (2018). Agent-based macroeconomics. In C. Hommes and B. LeBaron (Eds.), *Handbook of Computational Economics*, Volume 4 of *Handbook of Computational Economics*, pp. 63 – 156. Elsevier.

Dawid, H., S. Gemkow, P. Harting, K. Kabus, M. Neugart, and K. Wersching (2008). Skills, innovation, and growth: An agent-based policy analysis. *Journal of Economics and Statistics 228*(2+3), 251–275.

Dawid, H., P. Harting, and M. Neugart (2014). Economic convergence: Policy implications from a heterogeneous agent model. *Journal of Economic Dynamics and Control 44*, 54–80.

Dawid, H., P. Harting, and M. Neugart (2017). Fiscal transfers and regional economic growth. *Review of International Economics*, 1–21.

Deaton, A. (1992). Household saving in ldcs: credit markets, insurance and welfare. *The Scandinavian Journal of Economics 94*(2), 253–273.

Delli Gatti, D., M. Gallegati, B. Greenwald, A. Russo, and J. E. Stiglitz (2010). The financial accelerator in an evolving credit network. *Journal of Economic Dynamics and Control 34*(9), 1627–1650.

Deloitte Real Estate (2014). Property index Overview of European Residential Markets European housing 2013. Technical report.

Dimakopoulos, N., A. Triantafillou, P. Kokkinakis, K. Giannakakis, R. M. Brown, M. Papler, L. Rei, B. Ozel, E. Bothos, L. Robinson, and L. Ponta (2014). Definition of system architecture. Technical report, EU Comission. CORDIS. SYMPHONY Delieverble D52: Orchestrating Information Technologies and Global Systems Science for Policy Design and Regulation of a Resilient and Sustainable Global Economy. Contract no.: 611875.

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

Dosi, G., G. Fagiolo, and A. Roventini (2010, September). Schumpeter meeting keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control 34*(9), 1748–1767.

Dubecq, S. and I. Ghattassi (2009). Consumption-wealth ratio and housing returns. Technical Report 264, Banque de France.

Eboli, M. (2013). A flow network analysis of direct balance-sheet contagion in financial networks. Technical report, Kiel Institute for the World Economy.

Erdös, P. and A. Rényi (1959). On random networks. *Pub. Math 6*, 290–297.

Erlingsson, E. J., B. Ozel, A. Teglio, H. Stefansson, J. T. Sturluson, and M. Raberto (2016). Wealth and Income Inequality Dynamics andCredit Rationing: An Agent-Based Approach. Technical report.

Erlingsson, E. J., A. Teglio, S. Cincotti, H. Stefansson, J. T. Sturluson, and M. Raberto (2014). Housing market bubbles and business cycles in an agent-based credit economy. *Economics:*

The Open-Access, Open-Assessment E-Journal 8(2014-8).

European Central Bank (2013). Monthly Bulletin October, 2013. Technical report.

Evrensel, A. Y. (2008, October). Banking crisis and financial structure: A survival-time analysis. *International Review of Economics & Finance 17*(4), 589–602.

Fagiolo, G., M. Guerini, F. Lamperti, A. Moneta, and A. Roventini (2018). *Computer Simulation Validation. Fundamental Concepts, Methodological Frameworks, Philosophical Perspectives*, Chapter Validation of Agent-Based Models in Economics and Finance. Springer.

Farmer, J. and D. Foley (2009). The economy needs agent-based modelling. *Nature 460*(7256), 685–686.

Ferron, C. and R. Morel (2014). Smart unconventional monetary (sumo) policies: giving impetus to green investment. *Climate Report 46*.

FinansInspektionen Mortgage Survey (2014). The swedish mortgage market 2014. Technical report.

Frankel, J. A. and A. K. Rose (1997). Is emu more justifiable ex post than ex ante? *European Economic Review 41*(3), 753–760.

Frankel, J. A. and A. K. Rose (2001). The endogenity of the optimum currency area criteria. *The Economic Journal 108*(449), 1009–1025.

Freeman, L. (1979). Centrality in social networks i: Conceptual clarification. *Social Networks 1*, 215–239.

Fricke, D. and T. Lux (2014). Core–periphery structure in the overnight money market: evidence from the e-mid trading platform. *Computational Economics*, 1–37.

Gallegati, M., B. Greenwald, M. G. Richiardi, and E. J. Stiglitz (2008). The asymmetric effect of diffusion processes: Risk sharing and contagion. *Global Economy Journal 8*(3).

Gareth, A., B. Philip, A. Pugh, and A. Uluc (2014). The Potential Impact of Higher Interest Rates on the Household Sector: Evidence from the 2014 NMG Consulting Survey. *Bank of England Quarterly Bulletin Q4*.

Ge, J. (2014). Who Creates Housing Bubbles? An Agent-Based Study. In S. J. Alam and H. V. D. Parunak (Eds.), *Multi-Agent-Based Simulation XIV*, Volume 8235, pp. 143–150. Berlin, Heidelberg: Springer Berlin Heidelberg.

Gencer, M. and B. Ozel (2011). *Agent-Based Modeling of Economic Systems: The EURACE Project Experience*. Number ISBN: 978-605-60504-5-9. Ecomod Press.

Gencer, M. and B. Ozel (2018). Multi-level fusion of random networks. Technical report, UJI Working Papers 2018/??

Gharaie, E., N. Blismas, and R. Wakefield (2012). Little's law for the Us house building industry. In *Proceedings for the 20th Annual Conference of the International Group for Lean Construction*.

Gilbert, N., J. C. Howksworth, and P. A. Swinney (2009). An Agent-Based Model of the English Housing Market. *Association for the Advancement of Artificial Intelligence*.

Hagberg, A. A., D. A. Schult, and P. J. Swart (2008, August). Exploring network structure, dynamics, and function using NetworkX. In *Proceedings of the 7th Python in Science Conference (SciPy2008)*, Pasadena, CA USA, pp. 11–15.

Haldane, A. G. and R. M. May (2011, 01). Systemic risk in banking ecosystems. *Nature 469*.

Howells, P. G. (1995). The demand for endogenous money. *Journal of Post Keynesian Economics*, 89–106.

Judd, K. L. (1997). Computational economics and economic theory: Substitutes or complements? *Journal of Economic Dynamics and Control 21*(6), 907–942.

Kenen, P. (1969). The theory of optimum currency areas.

Kiran, M. (2017). *X-Machines for Agent-Based Modeling: FLAME Perspectives*. Chapman and Hall.

Kydland, F. E., P. Rupert, and R. Sustek (2012). Housing Dynamics over the Business Cycle. NBER Working Paper 18432, National Bureau of Economic Research, Inc.

Lavoie, M. and W. Godley (2012). *Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth* (2nd edition ed.). Palgrave Macmillan.

Levin, E. J. and R. E. Wright (1997). The impact of speculation on house prices in the united kingdom. *Economic Modelling 14*(4), 567–585.

Meh, C. A., Y. Terajima, D. X. Chen, and T. Carter (2009). Household Debt, Assets, and Income in Canada: A Microdata Study. Technical Report 2009-7.

Meh, C. A., Y. Terajime, D. X. Chen, and T. Carter (2009). Household debt, assets, and income in canada: A microdata study. Technical Report ISSN 1914-0558, Bank of Canada.

Meijers, H., J. Muysken, and O. Sleijpen (2015). The deposit financing gap: another dutch disease. *European Journal of Economics and Economic Policies 12*(1), 32–50.

Mélitz, J. (1995). The current impasse in research on optimum currency areas. *European Economic Review 39*(3), 492 – 500. Papers and Proceedings of the Ninth Annual Congress European Economic Association.

Metropolis, N. and S. Ulam (1949). The monte carlo method. *ournal of American Statistical Association, 44*, 335–341.

Mistrulli, P. E. (2011, May). Assessing financial contagion in the interbank market: Maximum entropy versus observed interbank lending patterns. *Journal of Banking & Finance 35*(5), 1114–1127.

Monfort, M., J. C. Cuestas, and J. Ordóñez (2013). Real convergence in europe: A cluster analysis. *Economic Modelling 33*, 689 – 694.

Moreno-Galbis, E. and A. Tritah (2016). The effects of immigration in frictional labor markets: Theory and empirical evidence from eu countries. *European Economic Review 84*, 76 – 98. European Labor Market Issues.

Muellbauer, J. (2012). When is a Housing Market Overheated Enough to Threaten Stability? Technical Report 623, University of Oxford, Department of Economics, Discussion Paper Series.

Muellbauer, J. and A. Murphy (2008). Housing markets and the economy: the assessment. *Oxford review of economic policy 24*(1), 1–33.

Neuberger, D. and R. Rissi (2012). Macroprudential banking regulation: Does one size fit all? Thuenen-Series of Applied Economic Theory 124, University of Rostock, Institute of Economics.

Nier, E., J. Yang, T. Yorulmazer, and A. Alentorn (2007). Network models and financial stability. *Journal of Economic Dynamics and Control 31*(6), 2033 – 2060. Tenth Workshop on Economic Heterogeneous Interacting Agents.

Nikiforos, M. (2016). A nonbehavioral theory of saving. *Journal of Post Keynesian Economics 39*(4), 562–592.

Nikiforos, M. and G. Zezza (2017). Stock-flow consistent macroeconomic models: a survey. *Journal of Economic Surveys 31*(5), 1204–1239.

Nikolaidi, M. (2014). Securitisation, wage stagnation and financial fragility: A stock-flow consistent perspective. In *116th Annual Conference of the Association for Heterodox Economics.*

Nordhaus, W. D. (2013). *The climate casino: risk, uncertainty, and economics for a warming world.* Yale University Press, New Haven.

Ozel, B., M. Eboli, A. Teglio, and A. Toto (2018). Robust-yet- fragile: A simulation model on exposure and concentration at interbank network. Technical report, UJI Working Papers 2018/??

Ozel, B., R. C. Nathanael, M. Raberto, A. Teglio, and S. Cincotti (2016). Macroeconomic implications of mortgage loans requirements: an agent based approach. Technical report, UJI Working Papers 2016/05.

Ozel, B., M. Petrovic, A. Teglio, L. Ponta, M. Raberto, A. Mazzoccheti, S. Cincotti, M. Gallegati, R. Grilli, A. Colasante, and A. Palestrini (2015). Final version of large-scale multi-country agent-based model of the macroeconomy. Technical report, SYMPHONY Deliverable D3.3: Orchestrating Information Technologies and Global Systems Science for Policy Design and Regulation of a Resilient and Sustainable Global Economy. Contract no.: 611875.

Pasta, M. Q., Z. Jan, A. Sallaberry, and F. Zaidi (2013). Tunable and growing network generation model with community structures. In *Cloud and Green Computing (CGC), 2013 Third International Conference on*, pp. 233–240. IEEE.

Petrovic, M., B. Ozel, A. Teglio, M. Raberto, and S. Cincotti (2018). Should i stay or should i go: an agent-based setup for a monetary union. *Submitted to European Economic Review*.

Pytliková, M. (2014). The effect of eu enlargements and labour market openings on migration.

Raberto, M., R. Nathanael, B. Ozel, A. Teglio, and S. Cincotti (2017). *Theory and method of evolutionary political economy*, Chapter Credit-driven business cycles in an agent-based macro model, pp. 182 – 192. Routledge.

Raberto, M., B. Ozel, L. Ponta, A. Teglio, and S. Cincotti (2018). From financial instability to green finance: the role of banking and monetary policies in the eurace model. *Journal of Evolutionary Economics*, 1–37.

Raberto, M., A. Teglio, and S. Cincotti (2008). *Prospect Theory Behavioral Assumptions in an Artificial Financial Economy*, Volume 614 of *Lecture Notes in Economics and Mathematical Systems*, pp. 55–66. Springer.

Raberto, M., A. Teglio, and S. Cincotti (2012a). Debt, deleveraging and business cycles: an agent-based perspective. *Economics: The Open-Access, Open-Assessment E-Journal 6*(2012-27), 1–49.

Raberto, M., A. Teglio, and S. Cincotti (2012b). Debt deleveraging and business cycles. an agent-based persperctive. *The Open-Access, Open-Assessment E-Journal 6*, 2012–27.

Riccetti, L., A. Russo, and M. Gallegati (2013). Leveraged network-based financial accelerator. *Journal of Economic Dynamics and Control 37*(8), 1626–1640.

Richiardi, M. (2015). The future of agent-based modelling. *Economics Papers, Economics Group, Nuffield College, University of Oxford. No 2015-W06*.

Rozenberg, J., S. Hallegatte, B. Perrissin-Fabert, and J.-C. Hourcade (2013). Funding low-carbon investments in the absence of a carbon tax. *Climate Policy 13*(1), 134–141.

Russo, A., M. Catalano, E. Gaffeo, M. Gallegati, and M. Napoletano (2007). Industrial dynamics, fiscal policy and R&D: Evidence from a computational experiment. *Journal of Economic Behavior & Organization 64*(3-4), 426–447.

S. Mishkin, F. (1999, February). Financial consolidation: Dangers and opportunities. *Journal of Banking & Finance 23*(2-4), 675–691.

Sallaberry, A., F. Zaidi, and G. Melançon (2013). Model for generating artificial social networks having community structures with small-world and scale-free properties. *Social Network Analysis and Mining 3*(3), 597–609.

Santos, J. A. (2001). Bank capital regulation in contemporary banking theory: A review of the literature. *Financial Markets, Institutions & Instruments 10*(2), 41–84.

Saunders, A. and L. Allen (2010). *Credit Risk. Measurement In and Out of the Financial Crisis*. Wiley.

Schelling, T. C. (1978). *Micromotives and macrobehavior*. New York: W.W. Norton and Co.

Secchi, D. (2017). Agent-based models of bounded rationality. *Team Performance Management: An International Journal 23*(1/2), 2–12.

Skingsley, C. (2007, May). Households' debt under microscope. SVERIGES RIKSBANK - Speech.

Sondermann, D. (2014). Productivity in the euro area: any evidence of convergence? *Empirical Economics 47*(3), 999–1027.

Stiglitz, J. E. (1997). The role of government in the economies of developing countries. *E. Malinvaud*.

Svensson, L. E. (2014a, 5). The household debt ratio is an unsuitable risk measure – there are much better ones. Eknomistas - Speech.

Svensson, L. E. (2014b). Resilience, Debt, and Net Worth: Has Resilience Increased with Higher Debt-to-Income Ratios? Technical report.

Taylor, J. B. (1993). Discretion versus policy rule in practice. In *Carnegie-Rochester Conference Series on Public Policy*, Volume 39, pp. 195–214.

Teglio, A., A. Mazzocchetti, L. Ponta, M. Raberto, and S. Cincotti (2018). Budgetary rigour with stimulus in lean times: Policy advices from an agent-based model. *Journal of Economic Behavior & Organization, forthcoming*.

Teglio, A., M. Raberto, and S. Cincotti (2010). Balance sheet approach to agent-based computational economics: The Eurace project. In *Combining Soft Computing and Statistical Methods in Data Analysis*, Volume 77 of *Advances in Intelligent and Soft Computing*, pp. 603–610. Springer Berlin / Heidelberg.

Teglio, A., M. Raberto, and S. Cincotti (2012a). The impact of banks' capital adequacy regulation on the economic system: An agent-based approach. *Advances in Complex Systems 15*(supp02), 1250040.

Teglio, A., M. Raberto, and S. Cincotti (2012b). The impact of banks' capital adequacy regulation on the economic system: An agent-based approach. *Advances in Complex Systems 15*(supp02).

Tesfatsion, L. (2003). Agent-based computational economics: modeling economies as complex adaptive systems. *Information Sciences 149*(4), 262 – 268.

Tesfatsion, L. and K. Judd (2006). *Agent-Based Computational Economics*, Volume 2 of *Handbook of Computational Economics*. North Holland.

The Financial Services Authority (2011). Mortgage Market Review: Proposed package of reforms. Technical report.

Tibaijuka, A. (2013). *Building prosperity: Housing and economic development*. Routledge.

Todd, A., P. Beling, W. Scherer, and S. Y. Yang (2016, Dec). Agent-based financial markets: A review of the methodology and domain. In *2016 IEEE Symposium Series on Computational Intelligence (SSCI)*, pp. 1–5.

Tsionas, E. G. (2000). Productivity convergence in europe. *Eastern Economic Journal 26*(3), 297–320.

Veld, D. and I. van Lelyveld (2014). Finding the core: Network structure in interbank markets. *Journal of Banking & Finance 49*(C), 27–40.

Wasserman, S. and K. Faust (1994). *Social Network Analysis*. Structural Analysis in the Social Sciences. Cambridge University Press.

Watts, D. J. and S. H. Strogatz (1998, June). Collective dynamics of 'small-world' networks. *Nature 393*(6684), 440–442.

WB (2015). *State and trends of carbon pricing*. World Bank Publications.

Wolf, S., S. Fürst, A. Mandel, W. Lass, D. Lincke, F. Pablo-Martí, and C. Jaeger (2013). A multi-agent model of several economic regions. *Environmental Modelling & Software 44*, 25 – 43.

Yeh, A., J. Twaddle, and M. Frith (2005). Basel II: A new capital framework. Technical report, Reserve Bank of New Zealand: Bulletin, vol. 68, no. 3.

Zaidi, F. (2013). Small world networks and clustered small world networks with random connectivity. *Social Network Analysis and Mining 3*(1), 51–63.

Zezza, G. (2007). Growth, the housing market and the distribution of income. In *Developments in Economic Theory and Policy Conference*.

Zezza, G. (2008). Us growth, the housing market and the distribution of income. *Journal of Post Keynesian Economics 30*(3), 379–405.