Bank of England

Agent-based modeling at central banks: recent developments and new challenges

Staff Working Paper No. 1,122
February 2025

András Borsos, Adrian Carro, Aldo Glielmo, Marc Hinterschweiger, Jagoda Kaszowska-Mojsa and Arzu Uluc

Bank of England

Staff Working Paper No. 1,122

Agent-based modeling at central banks: recent developments and new challenges

András Borsos,[1] Adrian Carro,[2] Aldo Glielmo,[3] Marc Hinterschweiger,[4] Jagoda Kaszowska-Mojsa[5] and Arzu Uluc[6]

Abstract

Over the past decade, agent-based models (ABMs) have been increasingly employed as analytical tools within economic policy institutions. This paper documents this trend by surveying the ABM-relevant research and policy outputs of central banks and other related economic policy institutions. We classify these studies and reports into three main categories: (i) applied research connected to the mandates of central banks, (ii) technical and methodological research supporting the advancement of ABMs; and (iii) examples of the integration of ABMs into policy work. Our findings indicate that ABMs have emerged as effective complementary tools for central banks in carrying out their responsibilities, especially after the extension of their mandates following the global financial crisis of 2007–09. While acknowledging that room for improvement remains, we argue that integrating ABMs into the analytical frameworks of central banks can support more effective policy responses to both existing and emerging economic challenges, including financial innovation and climate change.

Key words: Agent-based models, household analysis, financial institutions, central bank policies, monetary policy, prudential policies.

JEL classification: C63, E37, E58.

---

(1) Magyar Nemzeti Bank, Complexity Science Hub Vienna and Institute for New Economic Thinking at the Oxford Martin School. Email: borsosa@mnb.hu
(2) Banco de España and Institute for New Economic Thinking at the Oxford Martin School. Email: adrian.carro@bde.es
(3) Banca d'Italia. Email: aldo.glielmo@bancaditalia.it
(4) Bank of England. Email: marc.hinterschweiger@bankofengland.co.uk
(5) Narodowy Bank Polski, Institute for New Economic Thinking at the Oxford Martin School and Institute of Economics, Polish Academy of Sciences. Email: jagoda.kaszowska@inepan.waw.pl
(6) Bank of England. Email: arzu.uluc@bankofengland.co.uk

 This paper will be a contributed chapter to the Santa Fe Institute edited volume: The Economy as a Complex Evolving System, Part IV.

The Bank's working paper series can be found at www.bankofengland.co.uk/working-paper/staff-working-papers

Bank of England, Threadneedle Street, London, EC2R 8AH
Email: enquiries@bankofengland.co.uk

ISSN 1749-9135 (on-line)

1 Introduction

Over the last decade, there has been increasing interest in developing and using agent-based models (ABMs) at central banks. This paper sheds light on the drivers of this trend and reviews these models.

Historically, the main functions of central banks have consisted of ensuring price stability; providing liquidity during crises, i.e., being the lender of last resort; supervising financial institutions; and providing payment systems. In the last 15 years, these functions have expanded considerably for two main reasons. First, the global financial crisis (GFC) of 2007-2009 revealed the need for a holistic understanding of the financial system in order to ensure financial stability. Hence, many jurisdictions expanded the remits and responsibilities of their central banks in order to address systemic risks by introducing, for instance, macroprudential regulations, macro stress testing, central clearing, restrictions on remuneration, and resolution powers over failing or failed institutions.

Second, a large number of potential new challenges—not directly linked to the GFC—have emerged or increased in relevance. A nonexhaustive list of these risks includes cybersecurity, such as the disruption of a large financial institution, a financial market, or a critical third-party provider; climate change, including both physical impacts and those derived from the transition to a net-zero economy; cryptocurrencies, including their potential for competing with or destabilizing traditional sectors of the financial system as well as the role of central bank digital currencies (CBDCs); and an increase in economic inequality. In many of these areas, central banks have already gained new powers to address these challenges. All of these developments have led to an increased demand for analytical tools to help policymakers understand how best use these newly acquired powers. Given the novelty, variety, and potential complexity of the policies under consideration, policymakers increasingly rely on a broad range of models and methodologies, including ABMs.

Over this period, steadily increasing computational power and major advancements in data availability have enabled the development of large-scale, data-driven, and policy-oriented ABMs. At the same time, the potential for applying this methodology in economics has increased due to the growing trend of interdisciplinary research within this field, in particular in conjunction with computer and data science. There are several advantages for central banks to use ABMs to address policy-relevant questions. First, ABMs offer a high level of heterogeneity across multiple dimensions and allow for complex interactions between heterogeneous agents. Second, they can generate nonlinear dynamics similar to those observed in the real world, such as boom and bust cycles. Third, ABMs provide a flexible framework not only for assessing the impact of various policy scenarios on multiple aggregate measures, such as Gross Domestic Product (GDP) and unemployment, but also for evaluating the distributional effects of these policies on, for instance, different segments of the economy. Finally, this flexibility also allows for capturing both the particularities of a given country and the details of real-world policies, as well as for promptly adapting the model to changing economic circumstances.

Several policymakers have explicitly addressed the key features and advantages of ABMs in their speeches and publications, calling for more research and attention to be devoted to this approach or even advocating for its inclusion as part of a broader suite of modeling techniques available to central banks. Two prominent examples are Jean-Claude Trichet while he was president of the European Central Bank (Trichet, 2010, 2011, 2013, ECB) and Andrew Haldane while he was chief economist of the Bank of England (Haldane, 2016, 2019; Haldane and Turrell, 2018, BoE). Stress testing is one of the areas where the potential contributions of ABMs were acknowledged early on, including in several working papers by various international policy institutions related to central banking (Henry et al., 2013, ECB; Bookstaber et al., 2014, OFR; Demekas, 2015, IMF; BCBS, 2015).

In the last decade, the development of policy-oriented ABMs has significantly accelerated, due to their increased recognition and the involvement of more researchers and material resources. In this paper, we review research that has been undertaken at central banks and, to some degree, at other government bodies and international organizations with a similar policy focus.[1] We assign a research publication to a central bank or related institution if at least one author was affiliated with it at the time of publication.[2] The institutions covered in this paper are listed in alphabetical order

[1]For a more in-depth historical account of the emergence and growth of ABM research in the specific case of the Bank of England, see Plassard (2020). For a broader review of ABM research in economics, mostly conducted in academia, see Axtell and Farmer (Forthcoming).

[2]Since the aim of this review is to highlight the increasing interest in ABMs in central banks and related policy institutions, we focus on research conducted, at least partially, in this type of organizations. It should be noted, however, that this research does not necessarily represent the official views of the respective central banks or other organizations. For the sake of simplicity, we may still refer to it as research *by* or *at* central banks.

Acronym	Central bank	Jurisdiction
BCB	Banco Central de Bolivia	Bolivia
BCBr	Banco Central do Brasil	Brazil
BCL	Banque Centrale du Luxembourg	Luxembourg
BCRP	Banco Central de Reserva del Perú	Peru
BCU	Banco Central del Uruguay	Uruguay
BdE	Banco de España	Spain
BdF	Banque de France	France
BdI	Banca d'Italia	Italy
BdM	Banco de México	Mexico
BoC	Bank of Canada	Canada
BoE	Bank of England	United Kingdom
BoG	Τράπεζα της Ελλάδος	Greece
BoR	Банк России	Russian Federation
BRC	Banco de la República	Colombia
CBI	Central Bank of Ireland	Ireland
DBB	Deutsche Bundesbank	Germany
DN	Danmarks Nationalbank	Denmark
DNB	De Nederlandsche Bank	Netherlands
ECB	European Central Bank	Euro Area
MNB	Magyar Nemzeti Bank	Hungary
NBP	Narodowy Bank Polski	Poland
OeNB	Oesterreichische Nationalbank	Austria
RBNZ	Reserve Bank of New Zealand	New Zealand
SP	Suomen Pankki	Finland
Acronym	Other relevant institutions	Jurisdiction
BCBS	Basel Committee on Banking Supervision	Member countries
CEMLA	Centro de Estudios Monetarios Latinoamericanos	Member countries
DGT	Direction Générale du Trésor	France
ESRB	European Systemic Risk Board	European Union
IMF	International Monetary Fund	Member countries
OFR	Office of Financial Research	United States of America
WB	World Bank	Member countries

Table 1: List of central banks and other relevant institutions cited in this paper.

by the acronym used to refer to them in Table 1. Furthermore, we adopt a broad interpretation of what an ABM entails, and we focus on the fundamental similarities between modeling approaches rather than the small variations in the terminology used to describe them. Following Farmer and Foley (2009), an ABM can be broadly defined as "a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules". As such, we consider most network models and system-wide stress tests, among others, to be within the scope of this paper.

The rest of this paper is organized as follows. Section 2 outlines ABM research developed by central banks in relation to their various mandates. Section 3 focuses instead on the technical research central banks have conducted on the methodology itself. Section 4 presents a few examples of the application of ABMs for central bank policy work. In Section 5 we draw the main conclusions of this review and point at future research avenues for ABMs at central banks.

2 Research Related to Central Bank Mandates

The recent changes in the economy, financial system, and society described in the Introduction have been leading to shifts in the role and mandate of central banks. At the same time, there is a need to search for new methods that could help researchers comprehend the complexity of the ongoing processes and inform policymakers on how to effectively design, calibrate, and implement policies. Figure 1 provides an overview of how central bank research using ABMs has evolved over time. Research on payment systems was one of the first use cases; however, following the GFC, financial stability ABMs have become predominant. Several studies on price stability and climate change have emerged since 2016, while work on CBDCs only began in 2021.

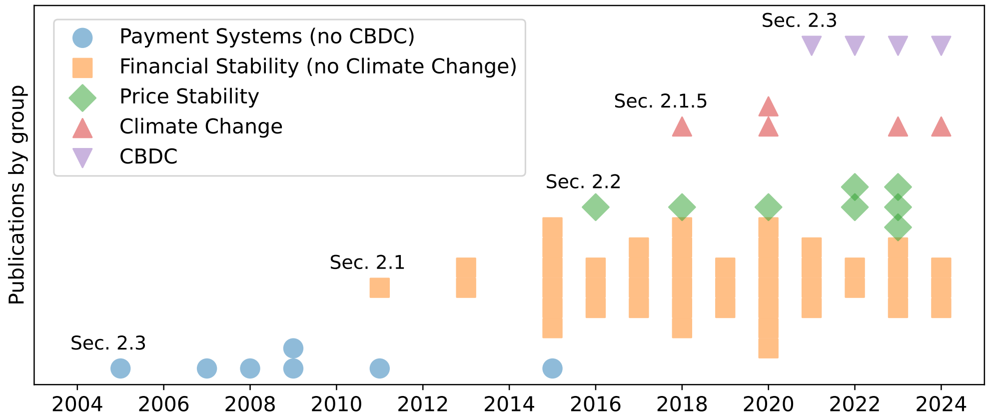

Figure 1: A timeline of publications from central banks and related institutions using agent-based models. Different application domains are highlighted by different colors (available online only) and symbols and are discussed in detail in the respective sections. For example, publications related to climate change are indicated via a red upward-pointing triangle and are discussed in Section 2.1.5.

2.1 Financial Stability

This section explores the application of ABMs for analyzing and mitigating systemic risk, which poses a threat to financial stability. Systemic risk "can be defined as a risk of disruption to financial services that is caused by an impairment of all or parts of the financial system and has the potential to have serious negative consequences for the real economy" (Caruana, 2010, BIS). As the GFC has shown, risks can emerge in corners of the financial system that are considered to be relatively insignificant before they materialize. However, risks can spread rapidly and engulf institutions at the core of the system, which can then further propagate and amplify these risks. In the following this subsections, we categorize these models into five areas: *(i)* interbank market, *(ii)* financial markets, *(iii)* interaction between financial and real sectors, *(iv)* housing market, and *(v)* climate change.

2.1.1 Interbank Market

Numerous central bank research projects have contributed greatly to the development and application of network models that feature contagion processes within the banking system. This rich branch of the literature provides advancements along several strands, most importantly regarding *(i)* the formation and reconstruction of bank networks and *(ii)* the spreading of shocks via different contagion channels in the banking system. Although most of the works listed in this section have contributed to both of these topics, we have categorized them into these two groups based on their primary focus.

Modeling the incentives behind the formation of bank networks can help central banks better understand the emergence of systemic risk in the interbank market. This can be used as a basis for designing policies aimed at lowering such risks. Hałaj and Kok (2013, ECB) propose a network reconstruction method that provides a way to assess the resilience of the banking system without observing its actual topology. Aymanns and Georg (2015, DBB), Hałaj and Kok (2015, ECB), Wolski and van de Leur (2016, ECB), and Chan-Lau (2017, IMF) focus instead on modeling the endogenous development of networks in the interbank market.

Regarding contagion channels, many central bank studies on bank networks consider only a single channel. Barucca et al. (2020, BoE) build a model in which the value of the non-interbank assets of banks is uncertain, while Bardoscia et al. (2019, BoE) extend this work with the possibility for banks to default at any point in time rather than at fixed maturity. Parallel to these developments, Liu et al. (2020, OFR) build an ABM consisting of thousands of banks together with their empirically observed decision rules, while Hałaj (2020, BoC) use the ABM of Hałaj (2018, BoC) calibrated to empirical data from Canada to model contagion on the interbank market. Lastly, Carro and Stupariu (2024, BdE) also consider the incomplete information and the heterogeneous expectations of agents in interbank contagion.

Several central bank studies also attempt to combine multiple contagion channels in order to capture the overall extent of systemic risks more comprehensively. Poledna et al. (2015, BdM), Cuba et al. (2021, BCRP) and Yanquen et al. (2022, BRC) use the multilayer version of the DebtRank model (a pivotal work by Battiston et al., 2012) to combine different types of exposures, such as credit, derivatives, foreign exchange, and securities, for the Mexican, Peruvian, and Colombian banking systems, respectively. Georg (2013, DBB), Montagna and Kok (2016, ECB), Roncoroni et al. (2021a, BoC, ECB, ESRB), and Poledna et al. (2021, BdM, CEMLA) consider another critical contagion channel, the overlapping portfolios of banks, while Montagna et al. (2021, BoE) define three separate contagion layers based on whether banks are affected through solvency, liquidity, or fire sales. Regarding some of the applications of these models, Hüser et al. (2018, ECB, DBB) and Siebenbrunner et al. (2024, OeNB) use multilayer contagion models to analyze the consequences of bail-in policies, while Farmer et al. (2020, BoE) propose a stress testing framework for the European financial system with multiple network layers and interactions among the different channels.

2.1.2 Financial Markets

Given their relevance for the stability of the financial system, as well as for the effective transmission of monetary policy, financial markets are closely monitored by central banks. In this context, ABMs have been used to study different risks emerging in financial markets as well as to explore the impact of various policies to address such risks.

First, limit order book models have been developed at various institutions to study the emergence of flash crashes in financial markets.[3] These models have been able to reproduce important stylized facts of financial asset returns, such as fat tails (leptokurtic distribution), volatility clustering, and a decaying autocorrelation over moderate time lags. For instance, Bookstaber et al. (2015, OFR) show that heterogeneity in trading decision cycles can have a strong impact on the provision of liquidity and market stability, thereby increasing the likelihood of extreme price movements. This provides support for regulator-imposed pauses in trading (circuit breakers), as they reduce the heterogeneity of the decision cycles. In line with this conclusion, Kårvik et al. (2018, BoE) also show that an increase in the trading speed of high-frequency market participants leads to more prevalent flash episodes, while implementing circuit breakers, which are triggered by large price movements, reduces the magnitude and frequency of such episodes. Paddrik et al. (2017, OFR) demonstrate that financial stability metrics using more detailed market microstructure data, which is usually available only to regulators and exchanges, have the greatest predictive power as early-warning indicators of impending market destabilization in the form of flash crashes. Bookstaber and Paddrik (2015, OFR) extend this model by introducing sequential auctions, which produce more realistic market dynamics.

Second, in order to understand the dynamics observed in real financial markets, central bank researchers have also explored the use of heterogeneous agent models with adaptive expectations. In particular, Hommes and Vroegop (2019, BoC) provide an explanation for the co-movement in asset markets by extending the seminal asset pricing model of Brock and Hommes (1998) to the case of two different (though ex ante identical) asset markets with spillover effects between them. In a single market setting, Di Francesco and Hommes (2023, BoC) propose the inclusion of agents with perfect foresight, which can be approximated by using a machine learning algorithm. Furthermore, they develop a measure of investor bias based on natural language processing of Twitter data. Using a similar methodology to model the dollarization of household deposits, Khabibullin and Ponomarenko (2022, BoR) are able to capture the varying sensitivity of dollarization to exchange rate developments in a context of heightened volatility.

A third focal point of central bank research about financial markets has been on the specific risks posed by various forms of leverage. For instance, building on a model of leveraged asset purchases with margin calls, Kerbl (2011, OeNB) studies the implications of several regulatory measures on market liquidity and stability. In particular, he finds that a short selling ban reduces volatility but increases tail risk; a transaction tax reduces the occurrence of crashes but increases volatility; only a mandatory risk limit is beneficial for both liquidity and volatility; and there are non-negligible

[3]A flash crash is a swift, steep, and highly volatile drop in the price of a security that happens in a very short time and is quickly followed by a rapid recovery.

interactions between these regulations. Breuer et al. (2015, OeNB) focus instead on the exchange of leveraged assets and bonds in a model with a continuous double auction mechanism. They validate recent general equilibrium theory results regarding endogenous leverage and its impact on asset pricing, and they highlight the critical role played by the institutional details of the exchange. Building on previous models of leverage targeting among banks, Levelt et al. (2021, BoC, DNB) allow banks to repeatedly choose between leverage targeting and an expected utility optimization strategy. They find that, while cycles are still observed, their amplitude decreases as compared to a system of fully leverage targeting banks.

Fourth, central bank research has also explored the consequences of the rise in passive investment strategies among funds investing in the corporate bond market. In particular, Braun-Munzinger et al. (2018, BoE) show that a larger fraction of passive investment funds can increase the tail risk of larger yield dislocations. Furthermore, they also show that spreading redemptions over longer time periods can mitigate the impact of shocks during stressed periods, when investor outflows are unusually large.

Finally, several strands of the literature have built network models of financial contagion similar to those described above for the interbank market, although crucially including other types of financial institutions, such as asset managers, investment funds, insurance companies, or central counterparties (CCPs). Importantly, these institutions are allowed to interact with each other in various markets. Caccioli et al. (2024, BoE) model fire sales contagion through common asset holdings between banks, open-ended investment funds, and insurance companies in the United Kingdom. Sydow et al. (2024, ECB, BdI, BoE, BoG, BCL, BdF, CBI, DNB, DBB), Hałaj (2018, ECB), and Calimani et al. (2022, ECB, BoC) explicitly include other types of financial institutions, such as asset managers or investment funds. A common finding of these studies is that banks that are active in both the interbank and the securities market have a central role in propagating shocks. Bookstaber et al. (2018, OFR) include prime brokers, hedge funds, and cash providers, among others, in their ABM and assess the risk of fire sales on both the asset and funding sides. Kotlicki et al. (2022, BoE) focus on the counterparty credit risk stemming from reinsurance contracts for both life and non-life insurers, which can act as a source of financial contagion in the UK reinsurance sector. BoE (2021) and Tompaidis (2017, OFR) propose supervisory stress tests for CCPs.

2.1.3 Interaction between the Financial and Real Sectors

An increasing number of studies focus on financial stability concerns originating from network connections outside of the financial system. Silva et al. (2017, BCBr) and Silva et al. (2018, BCBr) use a network framework to analyze the feedback effects between the Brazilian financial sector and the real economy by observing not only the bank network but also the loan contracts between the banks and their clients. Both Silva et al. (2020, BCBr) and Alexandre et al. (2023, BCBr) investigate the impact of monetary policy shocks on the Brazilian economy by using similar network model setups. Landaberry et al. (2021, BCU, BdM, CEMLA) take into account not only bank–firm links but also the intrafirm network in Uruguay using a survey about these connections. In a similar manner, Borsos and Mérő (2020, MNB) build a simulation model of shock propagation based on the observation of the entire Hungarian multilayer bank network, the bank–firm loan connections, and the firm-level supplier network of the country. Kaszowska-Mojsa and Pipień (2020, NBP) also represent bank–firm interactions in a general macroeconomic ABM environment designed to simulate the economic consequences of macroprudential policies. Lastly, Ponomarenko and Sinyakov (2018, BoR) examine the impacts of different regulatory regimes in a model that also includes interactions between the financial and real sectors. However, these interactions are defined in a more general manner, without explicitly addressing the topology of the loan and deposit markets.

2.1.4 Housing Market

The GFC has shown how a downturn in the housing market can destabilize the financial system and the real economy. Since then, several countries have implemented prudential tools such as loan-to-value (LTV), loan-to-income (LTI), and debt-service-to-income limits to help contain risks originating in the housing market. ABMs provide a natural setting to investigate the potential impacts of these housing tools on the housing market. First of all, ABMs are able to capture the high degree of heterogeneity in the housing market, such as households with varying ages, incomes, and wealth profiles, as well as housing stock with different qualities. Second, ABMs can generate nonlinear dynamics similar to those observed in real housing markets, such as housing booms and busts. Importantly, these dynamics emerge endogenously from the complex interactions between different types of households based, for instance, on their housing tenure, i.e., on whether they are renters, first-time buyers, home movers, or buy-to-let investors. Finally, ABMs enable researchers to incorporate potentially complex policy interventions, such as policies targeting a certain segment of the market (e.g., residential mortgages) and/or involving thresholds (e.g., a soft LTI limit).

The model by Baptista et al. (2016, BoE) was the first housing ABM developed by central bank researchers to study the impact of housing tools on the housing and mortgage markets. This model builds on the seminal work of Axtell et al. (2014) by incorporating realistic life-cycle dynamics, both a buy-to-let sector and an autonomous rental market, as well as a more realistic double-auction market mechanism. With these new features, the authors are able to analyze the impact of housing policies on different types of households in the United Kingdom, such as renters, first-time buyers, home movers, and buy-to-let investors. This model has been extended and improved in various directions, as well as adapted and calibrated to different national housing markets: in Denmark by Cokayne (2019, DN) and Cokayne et al. (2024, DN, RBNZ, BoE); in Italy by Catapano et al. (2021, BdI) and Catapano (2023, BdI); in Spain by Carro (2023, BdE); and in the UK by Carro et al. (2023, BdE, BoE). These models are used to conduct counterfactual analyses in order to understand the impact of different LTV and LTI limits on credit and house price cycles. These studies find a dampening effect of these housing tools on mortgage lending and house price cycles. Some other key findings from these studies can be summarized as follows: housing tools lead to a reduction in household indebtedness, loan riskiness, mortgage default, and negative equity, and an increased demand for lower quality houses; first-time buyers are affected more by these policy interventions; policies targeting the owner-occupier mortgage market can have spillover effects to buy-to-let mortgages/house purchases, and therefore affect the rental market as well; when calibrating an individual housing tool, the calibration of other policies and the joint distribution of risk characteristics should be taken into account.

Building on Baptista et al. (2016, BoE), though significantly departing from it, Mérő et al. (2023, MNB) develop a 1:1 scale model of the Hungarian residential housing market, incorporating detailed characteristics of four million households and the entire housing stock. This type of very granular and detailed ABM is useful for studying the impact of a range of policies, from macroprudential tools to family support programs. Furthermore, this high level of granularity allows for close monitoring of the effects of these policies across, for instance, different regions of the country. Laliotis et al. (2020, ECB) and Bauer and Krakovitch (2021, DGT) build on the original model of Axtell et al. (2014) to develop housing ABMs for European economies and the French housing market, respectively. These models are then used to evaluate the impact of various housing tools. Based on a simpler approach, Bolt et al. (2019, DNB) and Emenogu et al. (2021, BoC) introduce a small ABM component into a standard user cost of capital (housing) model in order to represent endogenous switching between heterogeneous expectations. While Bolt et al. (2019, DNB) use this model to identify housing bubbles and crashes across different countries, Emenogu et al. (2021, BoC) use it to build indicators of housing exuberance for a broad set of Canadian cities.

It is important to note that all the models described above are partial, in the sense that they all focus exclusively on the housing and mortgage markets, thereby neglecting the multiple feedback effects between these sectors and the rest of the economy. A major breakthrough in this regard is the model recently proposed by Bardoscia et al. (2025, BoE, BdE), which incorporates Carro et al. (2023, BdE, BoE)'s housing ABM into Popoyan et al. (2017)'s macroeconomic ABM. By properly accounting for these feedback effects in a stock-flow consistent manner, this model enables researchers to understand the impact of housing tools on the broader economy as well as to conduct comprehensive cost and benefit analyses.

2.1.5 Climate Change

In recent years, an increasing number of central banks and financial supervisors have come to identify climate change as a potential source of risk to financial stability (Carney, 2015; Gros et al., 2016; NGFS, 2019; Dunz and Power, 2021; BCBS, 2021; Brunetti et al., 2021). On the one hand, regulatory changes aimed at fostering the transition to a low-carbon economy may entail important shifts in the use of energy, with potential macroeconomic consequences, as well as a sudden revaluation of carbon-intensive assets (transition risk). On the other hand, the increased exposure to natural hazards driven by climate change can lead to significant financial costs for companies and households, such as repair and replacement expenses for damaged infrastructure, as well as to losses due to the disruption that these hazards cause to businesses (physical risk).

Most of the ABMs developed by central banks to study the impact of climate change have focused on transition risks. In this context, Roncoroni et al. (2021b, BdM, CEMLA) expand on the interbank network contagion model of Barucca et al. (2020, BoE) by also considering the indirect contagion between banks and investment funds via common asset exposures, and they use this expanded model to focus on transition-related shocks derived from various climate policy scenarios. They find that, during a disorderly low-carbon transition, stronger market conditions enable the adoption of more ambitious climate policies without increasing systemic risk. Expanding on Hałaj (2018, BoC) and Hałaj (2020, BoC), the network contagion model developed by Bruneau et al. (2023, BoC) includes banks, investment funds, insurance companies, and pension funds, and it also considers various contagion channels, such as interbank lending, common asset exposures, and fire sales. They find that certain types of entities, such as investment funds, are more likely to amplify transition shocks within the financial system, while others, such as pension funds, tend to dampen them. Focusing on the real economy, Stangl et al. (2024, MNB) build a model of shock propagation through supply chains, which they calibrate using the entire firm-level production network of the Hungarian economy. With this model, they are able to identify optimal emission reduction strategies with a minimum of additional unemployment and economic losses. In particular, they find that, for a given emission reduction (20%), the most effective strategy minimizes job and output losses (both 2%), while a naive approach targeting the largest emitters results in significantly higher losses (28% in jobs, 33% in output).

Considering both transition and physical risks, Gourdel and Sydow (2023, ECB) develop a model of short-term stress propagation in the investment fund sector which takes into account both cross-holdings of fund shares and overlapping exposures. In terms of transition risk, they find that the diverse sustainability investment strategies of funds act as a limiting factor for contagion and network amplification. Physical risk, on the contrary, is found to be more equally distributed across funds, also leading to more substantial contagion losses. Also taking into account both transition and physical risks, Gourdel et al. (2024, WB, ECB) build a stock-flow consistent behavioral model (based on Monasterolo and Raberto, 2018) in order to examine the reciprocal influence between climate, the real economy, and the financial system. They find that an orderly transition yields early benefits by lowering emissions and promoting economic growth, while a disorderly transition worsens economic output and financial stability. Furthermore, if coupled with a higher degree of physical risk, a disorderly transition can also lead to a strong economic contraction (12% fall in GDP). Finally, they find that climate policy credibility plays an important role in accelerating the transition to a low-carbon economy and in decreasing the risk of carbon-stranded assets for investors.

2.2 Price Stability

This section explores ABMs that have been used to investigate the implications of monetary policy. Since the 1990s, central banks have primarily relied on dynamic stochastic general equilibrium (DSGE) models and econometric analyses for this task. Recently, however, central banks have made increasing efforts to incorporate alternative modeling approaches such as ABMs into their toolkits.

One of the most important contributions in this regard is the paper by Poledna et al. (2023, BoC), who develop a macroeconomic ABM of the small open economy of Austria that can compete with benchmark vector autoregression and DSGE models in out-of-sample forecasting of macro variables. Crucially, the model not only serves as a competitive forecasting framework for aggregate variables but also enables detailed sector-level forecasts due to its agent-based nature. As an application, the authors present projections for the medium-term macroeconomic impacts resulting from the lockdown measures implemented in Austria in response to the COVID-19 pandemic. Hommes et al. (2024, BoC) build on this model by adapting and recalibrating it to the Canadian economy, as well as by extending it in three main directions: *(i)* increased household heterogeneity (e.g., heterogeneous incomes); *(ii)* a dynamic monetary policy; and *(iii)* a more sophisticated price-setting rule for firms allowing for a decomposition of inflation into demand-pull, expectations, and cost-push factors. With this extended model, the authors are able to explore the main drivers behind the post-pandemic inflation surge in Canada and analyze the uneven impact of the lockdown across households and industries. Using this same model, Grazzini et al. (2023, BoC) delve deeper into the dynamics of post-pandemic inflation in Canada, tracing its origins back to the lifting of economic restrictions in mid-2020, which triggered demand-pull inflation. Finally, Hommes and Poledna (2023, BoC) extend the original model by Poledna et al. (2023, BoC) with a financial accelerator mechanism, which paves the way for its application in analyzing and potentially forecasting financial crises in the absence of any exogenous shock. In particular, they calibrate this extended model to the euro area and focus on three recent economic crises: the financial crisis of 2007-2008 and the subsequent Great Recession; the European sovereign debt crisis; and the COVID-19 recession. Importantly, the out-of-sample forecasts produced by this model are, in general, significantly better than those of the benchmark vector autoregression and DSGE models.

Several other ABMs investigate issues that are relevant for monetary policy. De Grauwe and Gerba (2016, BdE) develop a behavioral macroeconomic framework with bounded rationality and provide a comparison of impulse responses to monetary policy shocks against a DSGE model with rational expectations. Their findings indicate that the impulse responses of the bounded rationality model are more closely aligned with the empirical evidence on the effects of monetary policy shocks. Alexandre et al. (2023, BCBr) also study the impact of monetary policy shocks, in particular to enhance our understanding of the financial network channel of monetary policy transmission. Although the model does not consider a fully endogenous monetary policy, it helps to assess how exogenous shocks to the policy interest rate affect some key topological measures of the bank-firm credit network through simulations. Khabibullin et al. (2018, BoR) develop an ABM that includes a realistic mechanism of money creation and assumes different scenarios of foreign reserve accumulation in Russia.

The evolution of central bank mandates has led to increased research on the interplay between monetary policy frameworks and financial stability regulations (see Section 2.1). In this context, Alexandre and Lima (2020, BCBr) study the impact of various combinations of monetary policy and prudential regulation frameworks on macroeconomic and financial stability. In particular, they focus on several rules for setting interest rates as well as various capital requirement regulations (specifically, different types of cyclical buffers). They find that *(i)* the effectiveness of a given policy (e.g., interest rate rule) depends on the specification of the other policy it is combined with (e.g., capital requirement rule); *(ii)* interest rate smoothing is more effective than the traditional Taylor rule and a leaning against the wind rule; and *(iii)* there is no trade-off between achieving monetary and financial stability. At the intersection of monetary policy and financial stability analysis, Deryugina et al. (2022, BoR) use ABMs and New Keynesian models to generate artificial credit cycle episodes. They show that the decrease in the measures of the natural rate of interest so widely discussed in the literature does not always reflect changes in macroeconomic fundamentals but rather reflects the effect of the measurement technique around peaks in the credit cycle.

To summarize, while the use of ABMs in monetary policy is not yet widespread, the papers discussed above demonstrate the value of this approach. In particular, these studies have highlighted ABMs' ability to provide useful insights even during periods of high uncertainty, such as the COVID-19 pandemic. Moreover, ABMs have also proven useful in enhancing our understanding of the interaction between monetary policy and other policies, such as fiscal, macroprudential, and even social policies, provided we consider the potential redistributive effects of monetary policy (Gleiser et al., 2024, NBP). Further research on this topic is crucially needed.

2.3 Payment Systems and Central Bank Digital Currencies

With the rapid rise of digital technologies in the early 2000s, central banks have been compelled to evaluate the opportunities and risks associated with new forms of digital payments. Computer simulations have proven particularly suited for this task, given their natural ability to reproduce specific payment flows under controlled conditions. In this context, the decentralized modeling approach of ABMs offers the additional advantage of permitting the analysis of emergent macroscopic patterns from detailed microscopic behavioral changes.

The first wave of research in payment systems simulations revolved around the study of real-time gross settlement (RTGS) systems. RTGS simulations were pioneered by the Bank of Finland through the development and use of the general software *Bank of Finland Payment and Settlement Simulator* (*BoF-PSS*), which also encompasses simulators based on ABMs (Leinonen and Soramäki, 2003; Leinonen, 2009, SP). Notably, the simulation software created by the Bank of Finland (2024) has been licensed to more than 90 central banks and continues to be enhanced to this day. Following this, other central banks have proposed ABMs for similar purposes. Alentorn et al. (2011, BoE, BIS) develop an ABM for assessing the risks and costs associated with different payment systems design choices. Galbiati and Soramäki (2011, BoE) use ABMs to study the properties of the game-theoretic equilibria that are achieved when banks try to optimize liquidity costs within an RTGS system. Arciero et al. (2008, BdI) set up an ABM to simulate and analyze the macroscopic impact of a disruptive event that happens at the level of a single bank. Caceres-Santos et al. (2020, BCB, BdM, CEMLA) assess the systemic risk of the Bolivian high-value payment system and interbank market by characterizing the properties of both networks and performing stress-testing experiments. The advent of electronic payments for retail use also led to an interest in ABM simulations for these payment technologies. Alexandrova-Kabadjova and Negrín (2009, BdM) and Alexandrova-Kabadjova et al. (2015, BdM) use ABMs to assess how network effects and payment fees impact the growth of card payment networks.

Recently, with the rise of native digital asset technologies, central banks have begun to explore the potential for issuing direct liabilities in the form of central bank digital currencies (CBDCs). Researchers at central banks and other policy institutions have analyzed the potential effects of this novel means of payment using ABM simulations. Gross and Siebenbrunner (2022, IMF) study how bank loans could be granted in a CBDC-dominated financial system where all money is digital and directly issued by the central bank. Martens (2021, DNB) study the crowding-out effects of CBDCs on traditional cash and deposits across various scenarios, including simulations of deposit-like and cash-like CBDCs to examine the impact of CBDC competitiveness and the critical role of network effects. Gross and Letizia (2023, IMF) quantitatively explore the potential implications of a CBDC on banking profitability through an ABM that encompasses banks modeled as learning agents setting the remuneration rates in a competitive game. Benedetti et al. (2024, BdI) simulate a scaled-down hypothetical European CBDC based on blockchain technologies for studying its trade-offs between liquidity, payment success rate, throughput, and latency.

3 Technical and Methodological Research

Agent-based models are highly computational tools and, for this reason, can greatly improve over time through the ever-growing availability of data and computational power. However, this also means that technical and methodological research efforts are particularly important for the success of the approach and the progressive mitigation of its limitations. In this section, we review some directions of methodological progress that are currently being investigated and point at relevant contributions from central banks and related institutions.

A first direction of methodological progress lies in the development of very large-scale models. Following the categorization of Axtell and Farmer (Forthcoming), we can divide ABMs in three broad classes: *(1)* 'small-scale' models that qualitatively reproduce some stylized facts; *(2)* 'medium-scale' models that quantitatively reproduce aggregate economic data, and which serve to link micro and social levels; *(3)* 'large-scale' models in which micro-data are used to quantitatively identify the behavior of individuals through calibration or estimation procedures in order to recreate or predict important economic phenomena. Significant improvements in data availability and computational capabilities, coupled with the increased prevalence of interdisciplinary research in economics (especially in conjunction with computer and data science), are leading to a rapid progression of the field toward the latter category, and even toward models that aim for a 1:1 representation. These models have the advantage of often being directly calibrated using microdata and could lead to authentic digital twins of the real economy, as was also advocated in Haldane (2019, BoE). Key contributions in this area include the work of Mérő et al. (2023, MNB), which establishes the first central banking model at a 1:1 scale with the real-world. Furthermore, Hosszú et al. (2024, MNB) present an in-depth analysis of the implications of downscaling economic ABMs, concluding that optimal model size is often larger than previously imagined. Lastly, in Glielmo et al. (2024, BdI) researchers introduce an open-source software package designed to support the development of large-scale macroeconomic models.

A second direction of methodological progress involves the exploitation of machine learning algorithms and software tools for model calibration on large volumes of data. This could enable more accurate and more efficient calibrations and, at the same time, eliminate the need for the lengthy, human-driven trial-and-error process that would otherwise be required. A prominent contribution in this area is the work of Benedetti et al. (2022, BdI), which introduces a software package specifically designed for ABM calibration encompassing, e.g., search methods based on machine learning surrogates, genetic algorithms, or low discrepancy sequences. The software had been originally designed for calibrating the ABM of the Italian housing market (Catapano et al., 2021, BdI) and was later expanded, re-engineered, and made available in open source. Additionally, Glielmo et al. (2023, BdI) explore how reinforcement learning algorithms can accelerate the calibration process of ABMs.

A third direction of methodological progress is motivated by the rapid rise of artificial intelligence (AI). In the future, AI software agents with complex decision-making behavior could be integrated within ABMs, thereby ensuring realism and lifting the modeler's need to specify precise behavioral rules in advance. Important contributions in this area include the work of Atashbar and Shi (2022, IMF) which investigates the application of reinforcement learning to enhance traditional macroeconomic models with learning agents. The work suggests that, combined with this technique, ABMs can be used to simulate complex economies featuring numerous learning and interacting economic agents. Complementarily, Brusatin et al. (2024, BdI) expand a traditional macro ABM by incorporating reinforcement learning agents which derive behavioral rules from the rational maximization of a reward function. Additionally, Hill et al. (2021, BoE) leverage reinforcement learning to solve a hybrid model that combines features of both macro ABMs and general equilibrium models. Looking ahead, we can imagine large language models (LLMs) to be used as models for human decision-making in ABMs, as also suggested by Coletta et al. (2024, BdI) in their assessment of the capability of existing LLMs to effectively capture subrational human behavior.

A final promising future development lies in the exploitation of recent advancements in automatic differentiation coming from the deep learning community to build ABMs that can be differentiated algorithmically. Having access to the derivative of the simulation results with respect to any model parameter would facilitate conducting a sensitivity analysis, ultimately improving the interpretability and trustworthiness of the resulting ABMs even for researchers and policymakers who are not experts in the field. This area of research is only now beginning to attract researchers from the ABM community and has not yet been pursued at central banks.

4 Applications in Policy Work

Agent-based approaches have already been used by several central banks to inform actual policy processes. While the specific analytical tools and methodologies used by central banks in their policy work are sometimes not explicitly mentioned, we collect in this section examples where such use of ABMs has been publicly disclosed.

The European Central Bank was among the first to recognize the value of this methodology and to use it to inform some of its policy work and assessments, particularly in relation to the contagion of distress in financial networks and systemic risk monitoring. For instance, it has highlighted the importance of understanding the financial system as a complex and dynamic network, and it has advocated for the development of contagion models with behavioral features to gain a deeper understanding of systemic risk and improve the identification of systemically important institutions (ECB, 2010; Adam et al., 2019, ECB). Furthermore, a number of its policy reports in the last decade have included contributions based on the use of such models. For example, ECB (2012) and Hałaj et al. (2013, ECB) address the emergence of the network of interbank exposures, as well as the potential effect of macroprudential policies on the structure of the resulting network. Cappiello et al. (2015, ECB), Covi et al. (2018, ECB), and Covi et al. (2019, ECB) focus on measuring systemic risk and identifying systemically important institutions based on network models that account for different subsets of contagion channels (from direct exposures to overlapping portfolios and fire sales). Finally, Dubiel-Teleszynski et al. (2022, ECB) uses a system-wide stress testing framework with multiple contagion channels and various types of institutions (banks, investment funds, and insurance companies) to analyze the impact of a severe climate change stress scenario (disorderly transition) on the financial system.

The Bank of England was also among the early adopters of agent-based modeling, incorporating this methodology into some of its policy analyses and evaluations (Plassard, 2020; Turrell, 2016, BoE). It has used system-wide stress tests in which banks and non-bank financial institutions, such as insurers, central counterparties, pension funds, hedge funds, and other types of managed funds have participated (BoE, 2023). It has also used its housing ABM, among other evidence, to inform its analysis of financial stability risks stemming from the UK buy-to-let market (Zemaityte et al., 2023, BoE).

The Magyar Nemzeti Bank, the central bank of Hungary, has also extensively used this methodology. Specifically, it has used its housing market ABM to assist in answering several questions of financial stability, such as the impact of loan-to-value ratio limits, financial support, or increased utility costs on households (see, for instance, MNB, 2021a,c, 2022b). It has also used the same model for questions related to the housing market more specifically, such as the impact of increases in home construction costs and in the base interest rate on housing and credit markets (see, for instance, MNB, 2021b, 2022a). Additionally, the Magyar Nemzeti Bank has also embedded a version of the Borsos and Mérő (2020, MNB) network model into its liquidity stress testing framework to represent various contagion channels in the banking system. The results of this stress test exercise have been regularly published in the Financial Stability Reports of the Magyar Nemzeti Bank since 2016 (MNB, 2016).

Another example is the Bank of Canada, which has been a pioneer in incorporating ABMs into its general toolkit for macroeconomic projections and policy analysis. In fact, it has recently become the first central bank to formally acknowledge a role for this methodological approach within its official modeling strategy. In particular, Coletti (2023, BoC) outlines a strategic plan for developing a suite of models to better support a risk management approach to monetary policy that recognizes the significant uncertainties in how the economy functions. In this context, ABMs are explicitly included within the category of *specialty models*, which are defined as models whose goal is to consider "alternative plausible economic structures that are too complex to include in the core model or its variants." The role played by ABMs within the modeling strategy of the Bank of Canada has been further discussed by Gosselin and Kozicki (2023, BoC), who address the challenges involved in adapting research-oriented models for policy use. Specifically, they highlight that the macroeconomic ABM by Hommes et al. (2024, BoC), described above in Section 2.2, has been particularly informative during the COVID-19 lockdowns and subsequent supply chain issues.

Finally, it is worth emphasizing that, over time, a growing number of central banks are incorporating this methodology into their policy analysis toolkit, as a complement to their existing tools. For instance, the most recent Financial Stability Report of the Banco de España employs a network contagion model for the first time to evaluate the potential contagion losses resulting from a severe shock to the Spanish banking system (BdE, 2024).

5 Conclusion

We have reviewed the literature on the use of ABMs by central banks and related policy institutions over the last decade, focusing particularly on how these models have helped address traditional central banking mandates — such as price stability and financial stability — as well as the new challenges that emerged following the global financial crisis and the COVID-19 pandemic.

The strengthening and consolidation of this relatively novel tool of economic investigation seems particularly timely in relation to the new challenges that central banks will have to face in the coming years, and for which a range of modern instruments will certainly be needed. We have already described some of these challenges and how ABMs could be used to address them. For example, we referred to the proliferation of digital assets and the potential introduction of a CBDC, and described how ABMs can serve as valuable analytical tools in this context due to their ability to simulate individual monetary transactions within structured and realistic payment networks. Another relevant challenge concerns the analysis and regulation of nonbank financial intermediaries. This growing sector already accounts for more than 50% of total financial assets in the euro area, and while it is difficult to include within traditional modeling frameworks, it can be easily modeled in an ABM along with its interaction with the banking sector. In recent decades, economic inequality has increased considerably in almost all advanced economies. This phenomenon also poses a challenge for central banks, both because of its macroeconomic impact on inflation and growth and for the analysis of any potential unintended redistributive consequences of monetary and financial stability policies. The ability of ABMs to naturally model heterogeneity in both wealth and income makes them particularly suitable for these studies. Finally, it is also worth mentioning that some global processes that are not strictly economic or financial in nature still appear to be of interest to central banks for their potential disruption of certain markets. For example, climate change and the green energy transition can have significant effects on the energy or housing markets, digital innovation and the rise of AI are likely to cause significant changes to the labor market, and geopolitical tensions can cause disruptions of global supply chains.

Given their key strengths, ABMs could be valuable tools for analyzing each of the described trends. First, intrinsically nonequilibrium shocks, e.g., an abrupt suspension of certain supply chains, can be difficult to model accurately within traditional equilibrium frameworks, while ABMs are well suited for this purpose. Second, the granular and heterogeneous nature of ABMs is a highly valuable feature for providing practical policy advice, e.g., for differentiating the specific job categories that are most vulnerable to being replaced by AI. Third, ABMs have the potential to be coupled with simulation models from disciplines other than economics in order to provide a richer and timelier picture of the phenomenon being studied. For example, the effects of climate change on house prices could be examined by coupling a housing market model with geographical or environmental models. Similarly, the economic effects of another possible pandemic could be studied by coupling an economic ABM with a detailed model of the transmission of infectious diseases.

The advantages of ABMs come with some challenges. The granular and heterogeneous nature of ABMs, while enabling rich and diverse agent behaviors, also presents difficulties. Defining the behavioral rules that govern agent interactions can be complex, particularly when deviating from standard economic assumptions, and often requires novel approaches at the frontier of economic theory. Precise calibration of parameters is challenging, especially when empirical data is scarce.

Simulating large numbers of heterogeneous agents in a dynamic environment makes the model computationally intensive and complex. Due to the nonlinear nature of agent interactions, tracing the pathways from specific behaviors or rules to emergent outcomes demands significant time and effort. Moreover, large-scale ABMs require specialized skills, such as programming, data processing, and simulation modeling, which often necessitate interdisciplinary research teams. While these challenges limit the widespread use of ABMs in some institutions, continuous technological and methodological advancements are gradually reducing these barriers. Alleviating computational constraints, in particular, could help address modeling challenges, especially in the crucial calibration phase of ABMs.

To summarize, agent-based modeling has proven to be an effective analytical tool for central banks in carrying out their responsibilities, especially after the expansion of their mandates following the global financial crisis. While there is still significant room for improvement, ongoing advancements in the methodology provide a solid foundation for the future. Considering the many challenges that modern economies will face in the coming years, from digital currencies to climate risks, ABMs represent a unique opportunity for central banks to enrich their analytical frameworks to promptly provide informed policy responses.

References

Adam, Michał, Paul Bochmann, Maciej Grodzicki, Luca Mingarelli, Mattia Montagna, Costanza Rodriguez d'Acri and Martina Spaggiari. (2019). "Assessing the systemic footprint of euro area banks". Financial Stability Review, November 2019, Special Feature B, European Central Bank. Available at https://www.ecb.europa.eu/press/financial-stability-publications/fsr/special/html/ecb.fsrart201911_02~5fd45e4b5a.en.html [Accessed: 2025/01/22].

Alentorn, Amadeo, Sheri Markose, Stephen Millard and Jing Yang. (2011). "Designing large value payment systems: An agent-based approach". Discussion Paper, No. 700 November 2011, Department of Economics, University of Essex. Available at https://repository.essex.ac.uk/3714/1/dp700.pdf [Accessed: 2025/01/22].

Alexandre, Michel, and Gilberto Tadeu Lima. (2020). "Combining monetary policy and prudential regulation: An agent-based modeling approach". *Journal of Economic Interaction and Coordination*, 15, pp. 385–411.
https://doi.org/10.1007/s11403-017-0209-0

Alexandre, Michel, Gilberto Tadeu Lima, Luca Riccetti and Alberto Russo. (2023). "The financial network channel of monetary policy transmission: An agent-based model". *Journal of Economic Interaction and Coordination*, 18, pp. 533–571.
https://doi.org/10.1007/s11403-023-00377-w

Alexandrova-Kabadjova, Biliana, Sara G. Castellanos-Pascacio and Alma L. García-Almanza. (2015). "The adoption process of payment cards: An agent-based approach". In *Banking, Finance, and Accounting: Concepts, Methodologies, Tools, and Applications*. IGI Global, pp. 1228–1252.
https://doi.org/10.4018/978-1-4666-6268-1.ch066

Alexandrova-Kabadjova, Biliana, and José Luis Negrín. (2009). "What drives the network's growth? An agent-based study of the payment card market". Working Paper, 1143, European Central Bank.
https://doi.org/10.2139/ssrn.1522034

Arciero, Luca, Claudia Biancotti, Leandro d'Aurizio and Claudio Impenna. (2008). "Exploring agent-based methods for the analysis of payment systems: A crisis model for StarLogo TNG". *Temi di Discussione (Working Paper)*, 686.
https://doi.org/10.2139/ssrn.1290520

Atashbar, Tohid, and Rui Aruhan Shi. (2022). "Deep reinforcement learning: Emerging trends in macroeconomics and future prospects". IMF Working Paper, WP/22/259, International Monetary Fund.
https://doi.org/10.5089/9798400224713.001

Axtell, Robert L., and J. Doyne Farmer. (Forthcoming). "Agent-based modeling in economics and finance: Past, present, and future". *Journal of Economic Literature*. Available at https://www.aeaweb.org/articles?id=10.1257/jel.20221319 [Accessed: 2025/01/22].

Axtell, Robert L., J. Doyne Farmer, John Geanakoplos, Peter Howitt, Ernesto Carrella, Ben Conlee, Jon Goldstein, Matthew Hendrey, Philip Kalikman, David Masad, Nathan Palmer and Chun-Yi Yang. (2014). "An agent-based model of the housing market bubble in metropolitan Washington, DC". In *Deutsche Bundesbank's Spring Conference on "Housing markets and the macroeconomy: Challenges for monetary policy and financial stability"*. pp. 5–6. https://doi.org/10.2139/ssrn.4710928

Aymanns, Christoph, and Co-Pierre Georg. (2015). "Contagious synchronization and endogenous network formation in financial networks". *Journal of Banking & Finance*, 50, pp. 273-285. https://doi.org/10.1016/j.jbankfin.2014.06.030

Bank of Finland. (2024). *Payment and Settlement System Simulator (BoF-PSS3)*. Available at: https://www.suomenpankki.fi/en/money-and-payments/payment-and-settlement-system-simulator/. [Accessed: 2024/03/21].

Baptista, Rafa, J. Doyne Farmer, Marc Hinterschweiger, Katie Low, Daniel Tang and Arzu Uluc. (2016). "Macroprudential policy in an agent-based model of the UK housing market". Staff Working Paper, 619, Bank of England. https://doi.org/10.2139/ssrn.2850414

Bardoscia, Marco, Paolo Barucca, Adam Brinley Codd and John Hill. (2019). "Forward-looking solvency contagion". *Journal of Economic Dynamics and Control*, 108, p. 103755. https://doi.org/10.1016/j.jedc.2019.103755

Bardoscia, Marco, Adrian Carro, Marc Hinterschweiger, Mauro Napoletano, Lilit Popoyan, Andrea Roventini and Arzu Uluc. (2025). "The impact of prudential regulations on the UK housing market and economy: Insights from an agent-based model". *Journal of Economic Behavior & Organization*, 229. https://doi.org/10.1016/j.jebo.2024.106839

Barucca, Paolo, Marco Bardoscia, Fabio Caccioli, Marco D'Errico, Gabriele Visentin, Guido Caldarelli and Stefano Battiston. (2020). "Network valuation in financial systems". *Mathematical Finance*, 30(4), pp. 1181-1204. https://doi.org/10.1111/mafi.12272

Battiston, Stefano, Michelangelo Puliga, Rahul Kaushik, Paolo Tasca and Guido Caldarelli. (2012). "Debtrank: Too central to fail? Financial networks, the FED and systemic risk". *Scientific Reports*, 2(1), pp. 1–6. https://doi.org/10.1038/srep00541

Bauer, Arthur, and Nicolas Krakovitch. (2021). "Macroprudential mortgage lending measures". Tresor-Economics, No. 277, Direction générale du Trésor, Ministère de l'Économie, des Finances, et de la Relance. Available at https://www.tresor.economie.gouv.fr/Articles/dacc9963-8021-48f9-8b34-3b125e5bf291/files/a11a4da9-9784-4ea0-8838-b8bd1ac37188 [Accessed: 2025/01/22].

BCBS. (2015). "Making supervisory stress tests more macroprudential: Considering liquidity and solvency interactions and systemic risk". Working Paper, 29, Basel Committee on Banking Supervision (BCBS). Available at https://www.bis.org/bcbs/publ/wp29.htm [Accessed: 2025/01/22].

BCBS. (2021). "Climate-related risk drivers and their transmission channels". Report, April 2021, Basel Committee on Banking Supervision (BCBS). Available at https://www.bis.org/bcbs/publ/d517.htm [Accessed: 2025/01/22].

BdE. (2024). "Financial sector risks and resilience". Financial Stability Report, Autumn 2024, Banco de España. Available at https://www.bde.es/f/webbe/Secciones/Publicaciones/InformesBoletinesRevistas/InformesEstabilidadFinancera/24/FSR_2024_2_Ch2.pdf [Accessed: 2025/01/22].

Benedetti, Marco, Gennaro Catapano, Francesco De Sclavis, Marco Favorito, Aldo Glielmo, Davide Magnanimi and Antonio Muci. (2022). "Black-it: A ready-to-use and easy-to-extend calibration kit for agent-based models". *Journal of Open Source Software*, 7(79), p. 4622. https://doi.org/10.21105/joss.04622

Benedetti, Marco, Francesco De Sclavis, Marco Favorito, Giuseppe Galano, Sara Giammusso, Antonio Muci and Matteo Nardelli. (2024). "Self-balancing semi-hierarchical payment channel networks for central bank digital currencies". In *2024 IEEE International Conference on Pervasive Computing and Communications Workshops and other Affiliated Events (PerCom Workshops)*. IEEE, pp. 530–536.
https://doi.org/10.1109/PerComWorkshops59983.2024.10503409

BoE. (2021). "Supervisory stress testing of central counterparties". Discussion Paper, 1000, Bank of England (BoE). Available at https://www.bankofengland.co.uk/paper/2021/supervisory-stress-testing-of-central-counterparties [Accessed: 2025/01/22].

BoE. (2023). *The Bank of England's system-wide exploratory scenario exercise*. Available at https://www.bankofengland.co.uk/financial-stability/boe-system-wide-exploratory-scenario-exercise/boe-swes [Accessed: 2025/01/22].

Bolt, Wilko, Maria Demertzis, Cees Diks, Cars H. Hommes and Marco Van Der Leij. (2019). "Identifying booms and busts in house prices under heterogeneous expectations". *Journal of Economic Dynamics and Control*, 103, pp. 234–259.
https://doi.org/10.1016/j.jedc.2019.04.003

Bookstaber, Richard, Michael Foley and Brian Tivnan. (2015). "Market liquidity and heterogeneity in the investor decision cycle". Working Paper, 15-03, Office of Financial Research.
https://doi.org/10.2139/ssrn.2648459

Bookstaber, Richard, and Mark E. Paddrik. (2015). "An agent-based model for crisis liquidity dynamics". Working Paper, 15-18, Office of Financial Research.
https://doi.org/10.2139/ssrn.2664230

Bookstaber, Richard, Mark E. Paddrik and Brian Tivnan. (2018). "An agent-based model for financial vulnerability". *Journal of Economic Interaction and Coordination*, 13, pp. 433–466.
https://doi.org/10.1007/s11403-017-0188-1

Bookstaber, Rick, Jill Cetina, Greg Feldberg, Mark Flood and Paul Glasserman. (2014). "Stress tests to promote financial stability: Assessing progress and looking to the future". *Journal of Risk Management in Financial Institutions*, 7(1), pp. 16–25.
https://doi.org/10.69554/SVZG1421

Borsos, András, and Bence Mérő. (2020). "Shock propagation in the banking system with real economy feedback". MNB Working Papers, 2020/6, Magyar Nemzeti Bank. Available at https://www.mnb.hu/letoltes/mnb-wp-2020-6-final.pdf [Accessed: 2025/01/22].

Braun-Munzinger, Karen, Zijun Liu and Arthur E. Turrell. (2018). "An agent-based model of corporate bond trading". *Quantitative Finance*, 18(4), pp. 591-608.
https://doi.org/10.1080/14697688.2017.1380310

Breuer, Thomas, Martin Jandačka, Martin Summer and Hans-Joachim Vollbrecht. (2015). "Endogenous leverage and asset pricing in double auctions". *Journal of Economic Dynamics and Control*, 53, pp. 144–160.
https://doi.org/10.1016/j.jedc.2015.02.004

Brock, William A., and Cars H. Hommes. (1998). "Heterogeneous beliefs and routes to chaos in a simple asset pricing model". *Journal of Economic Dynamics and Control*, 22(8), pp. 1235-1274.
https://doi.org/10.1016/S0165-1889(98)00011-6

Bruneau, Gabriel, Javier Ojea-Ferreiro, Andrew Plummer, Marie-Christine Tremblay and Aidan Witts. (2023). "Understanding the systemic implications of climate transition risk: Applying a framework using canadian financial system data". Staff Discussion Paper, 2023-32, Bank of Canada.
https://doi.org/10.34989/sdp-2023-32

Brunetti, Celso, Benjamin Dennis, Dylan Gates, Diana Hancock, David Ignell, Elizabeth K. Kiser, Gurubala Kotta, Anna Kovner, Richard Rosen and Nicholas K. Tabor. (2021). "Climate change and financial stability". FEDS Notes, 2021-03-19, Board of Governors of the Federal Reserve System.
https://doi.org/10.17016/2380-7172.2893

Brusatin, Simone, Tommaso Padoan, Andrea Coletta, Domenico Delli Gatti and Aldo Glielmo. (2024). "Simulating the economic impact of rationality through reinforcement learning and agent-based modelling". In *Proceedings of the 5th ACM International Conference on AI in Finance*. pp. 159–167.
https://doi.org/10.1145/3677052.3698621

Caccioli, Fabio, Gerardo Ferrara and Amanah Ramadiah. (2024). "Modelling fire sale contagion across banks and non-banks". *Journal of Financial Stability*, 71, p. 101231.
https://doi.org/10.1016/j.jfs.2024.101231

Caceres-Santos, Jonnathan, Anahi Rodriguez-Martinez, Fabio Caccioli and Serafin Martinez-Jaramillo. (2020). "Systemic risk and other interdependencies among banks in bolivia". *Latin American Journal of Central Banking*, 1(1), p. 100015.
https://doi.org/10.1016/j.latcb.2020.100015

Calimani, Susanna, Grzegorz Hałaj and Dawid Żochowski. (2022). "Simulating fire sales in a system of banks and asset managers". *Journal of Banking & Finance*, 138, p. 105707.
https://doi.org/10.1016/j.jbankfin.2019.105707

Cappiello, Lorenzo, Mattia Montagna and Linda Rousová. (2015). "Systemic risk, contagion and financial networks". Financial Stability Review, November 2015, Special Feature C, European Central Bank. Available at https://www.ecb.europa.eu/pub/pdf/fsr/art/ecb.fsrart201511_03.en.pdf [Accessed: 2025/01/22].

Carney, M. (2015). *Breaking the tragedy of the horizon - climate change and financial stability*. Speech given at Lloyd's of London, 29 September. Available at https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability [Accessed: 2025/01/22].

Carro, Adrian. (2023). "Taming the housing roller coaster: The impact of macroprudential policy on the house price cycle". *Journal of Economic Dynamics and Control*, 156, p. 104753.
https://doi.org/10.1016/j.jedc.2023.104753

Carro, Adrian, Marc Hinterschweiger, Arzu Uluc and J. Doyne Farmer. (2023). "Heterogeneous effects and spillovers of macroprudential policy in an agent-based model of the UK housing market". *Industrial and Corporate Change*, 32(2), pp. 386-432.
https://doi.org/10.1093/icc/dtac030

Carro, Adrian, and Patricia Stupariu. (2024). "Uncertainty, non-linear contagion and the credit quality channel: An application to the Spanish interbank market". *Journal of Financial Stability*, 71, p. 101226.
https://doi.org/10.1016/j.jfs.2024.101226

Caruana, Jaime. (2010). "Systemic risk: How to deal with it?" Other publications, Bank for International Settlements (BIS). Available at https://www.bis.org/publ/othp08.htm [Accessed: 2025/01/22].

Catapano, Gennaro. (2023). "Borrower based measures analysis via a new agent based model of the italian real estate sector". Questioni di Economia e Finanza (Occasional Papers), 822, Bank of Italy.
https://doi.org/10.2139/ssrn.4849455

Catapano, Gennaro, Francesco Franceschi, Michele Loberto and Valentina Michelangeli. (2021). "Macroprudential policy analysis via an agent based model of the real estate sector". Temi di Discussione (Working Paper), 1338, Bank of Italy.
https://doi.org/10.2139/ssrn.3891583

Chan-Lau, Jorge A. (2017). "ABBA: An agent-based model of the banking system". IMF Working Papers, 2017/136, International Monetary Fund.
https://doi.org/10.5089/9781484300688.001

Cokayne, Graeme. (2019). "The effects of macro-prudential policies on house price cycles in an agent-based model of the Danish housing market". Working Paper, 138, Danmarks Nationalbank. Available at https://www.nationalbanken.dk/media/dafdshbq/working-paper-nr-138.pdf [Accessed: 2025/01/22].

Cokayne, Graeme, Eddie Gerba, Andreas Kuchler and Rasmus Pank Roulund. (2024). "“Thank me later”: Why is (macro)prudence desirable?" *Journal of Financial Stability*, 71, p. 101227.
https://doi.org/10.1016/j.jfs.2024.101227

Coletta, Andrea, Kshama Dwarakanath, Penghang Liu, Svitlana Vyetrenko and Tucker Balch. (2024). "LLM-driven imitation of subrational behavior: Illusion or reality?" *arXiv preprint arXiv:2402.08755*. Available at https://arxiv.org/pdf/2402.08755 [Accessed: 2025/01/22].

Coletti, Donald. (2023). "A blueprint for the fourth generation of Bank of Canada projection and policy analysis models". Staff Discussion Paper, 2023-23, Bank of Canada.
https://doi.org/10.34989/sdp-2023-23

Covi, Giovanni, Christoffer Kok and Barbara Meller. (2018). "Using large exposure data to gauge the systemic importance of SSM significant institutions". Macroprudential Bulletin, No. 5, April 2018, European Central Bank. Available at https://www.ecb.europa.eu/press/financial-stability-publications/macroprudential-bulletin/html/ecb.mpbu201804_01.en.html [Accessed: 2025/01/22].

Covi, Giovanni, Mattia Montagna and Gabriele Torri. (2019). "Economic shocks and contagion in the euro area banking sector: A new micro-structural approach". Financial Stability Review, May 2019, Special Feature B, European Central Bank. Available at https://www.ecb.europa.eu/press/financial-stability-publications/fsr/special/html/ecb.fsrart201905_2~073bba7192.en.html [Accessed: 2025/01/22].

Cuba, Walter, Anahi Rodriguez-Martinez, Diego A. Chavez, Fabio Caccioli and Serafin Martinez-Jaramillo. (2021). "A network characterization of the interbank exposures in Peru". *Latin American Journal of Central Banking*, 2(3), p. 100035.
https://doi.org/10.1016/j.latcb.2021.100035

De Grauwe, Paul, and Eddie Gerba. (2016). "Stock market cycles and supply side dynamics: Two worlds, one vision?" Documento de Trabajo, 1626, Banco de España.
https://doi.org/10.2139/ssrn.2859977

Demekas, Dimitri. (2015). "Designing effective macroprudential stress tests: Progress so far and the way forward". IMF Working Papers, 2015/146, International Monetary Fund.
https://doi.org/10.5089/9781513513621.001

Deryugina, Elena, Maria Guseva and Alexey Ponomarenko. (2022). "The credit cycle and measurement of the natural rate of interest". *Journal of Central Banking Theory and Practice*, 11(1), pp. 87–104.
https://doi.org/10.2478/jcbtp-2022-0004

Di Francesco, Tommaso, and Cars H. Hommes. (2023). "Sentiment-driven speculation in financial markets with heterogeneous beliefs: A machine learning approach". *Available at SSRN 4429858*.
https://doi.org/10.2139/ssrn.4429858

Dubiel-Teleszynski, Tomasz, Fabio Franch, Gábor Fukker, Debora Miccio, Michela Pellegrino and Matthias Sydow. (2022). "System-wide amplification of climate risk". Macroprudential Bulletin, No. 17, June 2022, European Central Bank. Available at https://www.ecb.europa.eu/press/financial-stability-publications/macroprudential-bulletin/html/ecb.mpbu202206_2~1bec56088f.en.html [Accessed: 2025/01/22].

Dunz, Nepomuk, and Samantha Power. (2021). "Climate-related risks for ministries of finance: An overview". Note, May 2021, Coalition of Finance Ministers for Climate Action. Available at https://www.financeministersforclimate.org/sites/cape/files/inline-files/Climate-Related%20Risks%20for%20Ministries%20of%20Finance%20-%20An%20Overview%20(CFMCA)_1.pdf [Accessed: 2025/01/22].

ECB. (2010). "Financial networks and financial stability". Financial Stability Review, June 2010, Special Feature D, European Central Bank. Available at https://www.ecb.europa.eu/pub/pdf/fsr/art/ecb.fsrart201006_04.en.pdf [Accessed: 2025/01/22].

ECB. (2012). "Evaluating interconnectedness in the financial system on the basis of actual and simulated networks". Financial Stability Review, June 2012, Special Feature C, European Central Bank. Available at https://www.ecb.europa.eu/pub/pdf/fsr/art/ecb.fsrart201206_03.en.pdf [Accessed: 2025/01/22].

Emenogu, Ugochi, Cars H. Hommes and Mikael Khan. (2021). "Detecting exuberance in house prices across canadian cities". Staff Analytical Note, 2021-9, Bank of Canada.
https://doi.org/10.34989/san-2021-9

Farmer, J. Doyne, and Duncan Foley. (2009). "The economy needs agent-based modelling". *Nature*, 460(7256), pp. 685–686.
https://doi.org/10.1038/460685a

Farmer, J. Doyne, Alissa M. Kleinnijenhuis, Paul Nahai-Williamson and Thom Wetzer. (2020). "Foundations of system-wide financial stress testing with heterogeneous institutions". Staff Working Paper, 861, Bank of England.
https://doi.org/10.2139/ssrn.3601846

Galbiati, Marco, and Kimmo Soramäki. (2011). "An agent-based model of payment systems". *Journal of Economic Dynamics and Control*, 35(6), pp. 859–875.
https://doi.org/10.1016/j.jedc.2010.11.001

Georg, Co-Pierre. (2013). "The effect of the interbank network structure on contagion and common shocks". *Journal of Banking & Finance*, 37(7), pp. 2216-2228.
https://doi.org/10.1016/j.jbankfin.2013.02.032

Gleiser, Ilan, J. Doyne Farmer, Jagoda Kaszowska-Mojsa and Sam Bydlon. (2024). *How agent-based models powered by HPC are enabling large scale economic simulations*. Available at: https://aws.amazon.com/blogs/hpc/how-agent-based-models-powered-by-hpc-are-enabling-large-scale-economic-simulations/ [Accessed: 2025/01/22].

Glielmo, Aldo, Marco Favorito, Debmallya Chanda and Domenico Delli Gatti. (2023). "Reinforcement learning for combining search methods in the calibration of economic ABMs". In *Proceedings of the Fourth ACM International Conference on AI in Finance*, ICAIF '23. Association for Computing Machinery, p. 305–313.
https://doi.org/10.1145/3604237.3626889

Glielmo et al. (2024). *BeforeIT.jl: Behavioural agent-based economic forecasting*. Available at: https://github.com/bancaditalia/BeforeIT.jl [Accessed: 2025/01/22].

Gosselin, Marc-André, and Sharon Kozicki. (2023). "Making it real: Bringing research models into central bank projections". Staff Discussion Paper, 2023-29, Bank of Canada.
https://doi.org/10.34989/sdp-2023-29

Gourdel, Régis, Irene Monasterolo, Nepomuk Dunz, Andrea Mazzocchetti and Laura Parisi. (2024). "The double materiality of climate physical and transition risks in the euro area". *Journal of Financial Stability*, 71, p. 101233.
https://doi.org/10.1016/j.jfs.2024.101233

Gourdel, Régis, and Matthias Sydow. (2023). "Non-banks contagion and the uneven mitigation of climate risk". *International Review of Financial Analysis*, 89, p. 102739.
https://doi.org/10.1016/j.irfa.2023.102739

Grazzini, Jakob, Cars H. Hommes, Sebastian Poledna and Yang Zhang. (2023). "Understanding post-pandemic inflation dynamics with a behavioral macroeconomic model of the Canadian economy". *Available at SSRN 4381235*.
https://doi.org/10.2139/ssrn.4381235

Gros, Daniel, Philip R. Lane, Sam Langfield, Sini Matikainen, Marco Pagano, Dirk Schoenmaker and Javier Suarez. (2016). "Too late, too sudden: Transition to a low-carbon economy and systemic risk". Report of the Advisory Scientific Committee, No 6 / February 2016, European Systemic Risk Board. Available at https://www.esrb.europa.eu//pub/pdf/asc/Reports_ASC_6_1602.pdf [Accessed: 2025/01/22].

Gross, Marco, and Elisa Letizia. (2023). "To demand or not to demand: On quantifying the future appetite for CBDC". IMF Working Paper, WP/23/009, International Monetary Fund.
https://doi.org/10.5089/9798400228780.001

Gross, Marco, and Christoph Siebenbrunner. (2022). "Money creation and liquid funding needs are compatible". In *Central Banking, Monetary Policy and the Future of Money*, chap. 6. Edward Elgar Publishing, pp. 154-186.
https://doi.org/10.4337/9781800376403.00013

Hałaj, Grzegorz. (2018). "System-wide implications of funding risk". *Physica A: Statistical Mechanics and its Applications*, 503, pp. 1151–1181.
https://doi.org/10.1016/j.physa.2018.08.060

Hałaj, Grzegorz. (2020). "Resilience of Canadian banks to funding liquidity shocks". *Latin American Journal of Central Banking*, 1(1), p. 100002.
https://doi.org/10.1016/j.latcb.2020.100002

Hałaj, Grzegorz, and Christoffer Kok. (2013). "Assessing interbank contagion using simulated networks". *Computational Management Science*, 10, pp. 157–186.
https://doi.org/10.1007/s10287-013-0168-4

Hałaj, Grzegorz, and Christoffer Kok. (2015). "Modelling the emergence of the interbank networks". *Quantitative Finance*, 15(4), pp. 653–671.
https://doi.org/10.1080/14697688.2014.968357

Hałaj, Grzegorz, Christoffer Kok and Mattia Montagna. (2013). "Gauging the effectiveness of cross-sectional macro-prudential tools through the lens of interbank networks". Financial Stability Review, November 2013, Special Feature C, European Central Bank. Available at https://www.ecb.europa.eu/pub/pdf/fsr/art/ecb.fsrart201311_03.en.pdf [Accessed: 2025/01/22].

Haldane, Andrew G. (2016). *The dappled world.* Speech given at the GLS Shackle Biennial Memorial Lecture, 10 November. Available at https://www.bankofengland.co.uk/speech/2016/the-dappled-world [Accessed: 2025/01/22].

Haldane, Andrew G. (2019). *Is all economics local?* Speech given at the Sheffield Political Economy Research Institute (SPERI) Annual Lecture, University of Sheffield, 7 May. Available at https://www.bankofengland.co.uk/speech/2019/andy-haldane-sheffield-political-economy-research-institute-annual-lecture-2019 [Accessed: 2025/01/22].

Haldane, Andrew G., and Arthur E. Turrell. (2018). "An interdisciplinary model for macroeconomics". *Oxford Review of Economic Policy*, 34(1-2), pp. 219-251.
https://doi.org/10.1093/oxrep/grx051

Henry, Jérôme, Christoffer Kok, Adrien Amzallag, Patrizia Baudino, Inês Cabral, Maciej Grodzicki, Marco Gross, Grzegorz Hałaj, Markus Kolb, Miha Leber, Cosimo Pancaro, Matthias Sydow, Angelos Vouldis, Maik Zimmermann and Dawid Żochowski. (2013). "A macro stress testing framework for assessing systemic risks in the banking sector". Occasional Paper, 152, European Central Bank.
https://doi.org/10.2139/ssrn.2337894

Hill, Edward, Marco Bardoscia and Arthur E. Turrell. (2021). "Solving heterogeneous general equilibrium economic models with deep reinforcement learning". *arXiv preprint arXiv:2103.16977.*
https://doi.org/10.48550/arXiv.2103.16977

Hommes, Cars H., Mario He, Sebastian Poledna, Melissa Siqueira and Yang Zhang. (2024). "CANVAS: A Canadian behavioral agent-based model for monetary policy". *Journal of Economic Dynamics and Control*, p. 104986.
https://doi.org/10.1016/j.jedc.2024.104986

Hommes, Cars H., and Sebastian Poledna. (2023). "Analyzing and forecasting economic crises with an agent-based model of the euro area". *Available at SSRN 4381261.*
https://doi.org/10.2139/ssrn.4381261

Hommes, Cars H., and Joris Vroegop. (2019). "Contagion between asset markets: A two market heterogeneous agents model with destabilising spillover effects". *Journal of Economic Dynamics and Control*, 100, pp. 314-333.
https://doi.org/10.1016/j.jedc.2018.10.005

Hosszú, Zsuzsanna, András Borsos, Bence Mérő and Nikolett Vágó. (2024). "The more the merrier? – The optimal choice of scaling in economic agent-based models". *Available at SSRN 4751602.*
https://doi.org/10.2139/ssrn.4751602

Hüser, Anne-Caroline, Grzegorz Hałaj, Christoffer Kok, Cristian Perales and Anton van der Kraaij. (2018). "The systemic implications of bail-in: A multi-layered network approach". *Journal of Financial Stability*, 38, pp. 81–97.
https://doi.org/10.1016/j.jfs.2017.12.001

Kårvik, Geir-Are, Joseph Noss, Jack Worlidge and Daniel Beale. (2018). "The deeds of speed: An agent-based model of market liquidity and flash episodes". Staff Working Paper, 743, Bank of England.
https://doi.org/10.2139/ssrn.3222692

Kaszowska-Mojsa, Jagoda, and Mateusz Pipień. (2020). "Macroprudential policy in a heterogeneous environment—An application of agent-based approach in systemic risk modelling". *Entropy*, 22(2), p. 129.
https://doi.org/10.3390/e22020129

Kerbl, Stefan. (2011). "Regulatory medicine against financial market instability: What helps and what hurts?" Working Paper, 174, Oesterreichische Nationalbank. Available at https://www.oenb.at/dam/jcr:aefbbe58-021b-4514-b96c-6ffb4aaefc0a/wp174_tcm16-240232.pdf [Accessed: 2025/01/22].

Khabibullin, Ramis, and Alexey Ponomarenko. (2022). "An empirical behavioral model of household's deposit dollarization". *Journal of Economic Interaction and Coordination*, 17, pp. 827–847.
https://doi.org/10.1007/s11403-022-00345-w

Khabibullin, Ramis, Alexey Ponomarenko and Sergei Seleznev. (2018). "Forecasting the implications of foreign exchange reserve accumulation with an agent-based model". Working Paper Series, 37, Bank of Russia.
https://doi.org/10.2139/ssrn.3282108

Kotlicki, Artur, Andrea Austin, David Humphry, Hannah Burnett, Philip Ridgill and Sam Smith. (2022). "Network analysis of the UK reinsurance market". Staff Working Paper, 1000, Bank of England. Available at https://www.bankofengland.co.uk/-/media/boe/files/working-paper/2022/network-analysis-of-the-uk-reinsurance-market.pdf [Accessed: 2025/01/22].

Laliotis, Dimitrios, Alejandro Buesa, Miha Leber and Javier Población. (2020). "An agent-based model for the assessment of LTV caps". *Quantitative Finance*, 20(10), pp. 1721–1748.
https://doi.org/10.1080/14697688.2020.1733058

Landaberry, Victoria, Fabio Caccioli, Anahi Rodriguez-Martinez, Andrea Baron, Serafin Martinez-Jaramillo and Rodrigo Lluberas. (2021). "The contribution of the intra-firm exposures network to systemic risk". *Latin American Journal of Central Banking*, 2(2), p. 100032.
https://doi.org/10.1016/j.latcb.2021.100032

Leinonen, Harry (ed.) (2009). *Simulation analyses and stress testing of payment networks.* (Scientific monographs, E:42). Bank of Finland. Available at https://publications.bof.fi/handle/10024/45688 [Accessed: 2025/01/22].

Leinonen, Harry, and Kimmo Soramäki. (2003). "Simulating interbank payments and securities settlement mechanism with the BoF-PSS2 simulator". Research Discussion Paper, 23, Bank of Finland.
https://doi.org/10.2139/ssrn.3016759

Levelt, Eva, Kostas Mavromatis and Cars H. Hommes. (2021). "Leverage cycles when banks have a choice". *Available at SSRN 3882467.*
https://doi.org/10.2139/ssrn.3882467

Liu, Anqi, Mark E. Paddrik, Steve Y. Yang and Xingjia Zhang. (2020). "Interbank contagion: An agent-based model approach to endogenously formed networks". *Journal of Banking & Finance*, 112, p. 105191.
https://doi.org/10.1016/j.jbankfin.2017.08.008

Martens, Menno. (2021). *Adoption and implications of CBDC: An agent-based modelling approach.* Master's thesis, University of Twente. Available at https://essay.utwente.nl/89014/ [Accessed: 2025/01/22].

Mérő, Bence, András Borsos, Zsuzsanna Hosszú, Zsolt Oláh and Nikolett Vágó. (2023). "A high-resolution, data-driven agent-based model of the housing market". *Journal of Economic Dynamics and Control*, p. 104738.
https://doi.org/10.1016/j.jedc.2023.104738

MNB. (2016). "Box 10: Modelling channels of contagion in the banking sector". Financial Stability Report, May 2016, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/financial-stability-report-2016-may.PDF [Accessed: 2025/01/22].

MNB. (2021a). "Box 2: Agent-based housing market model: Impacts of the regulation regarding the loan-to-value ratio and of the COVID crisis". Financial Stability Report, June 2021, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/financial-stability-report-2021-june.pdf [Accessed: 2025/01/22].

MNB. (2021b). "Box 2: Impact of a rise in home construction costs on the housing market based on an agent-based housing market model". Housing Market Report, November 2021, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/laka-spiaci-jelente-s-2021-november-eng.pdf [Accessed: 2025/01/22].

MNB. (2021c). "Box 6: Effects of family support measures on the housing loan market on the basis of an agent-based model". Financial Stability Report, December 2021, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/financial-stability-report-december-2021.pdf [Accessed: 2025/01/22].

MNB. (2022a). "Box 3: Impacts of the rise in the base rate on housing and credit markets". Housing Market Report, May 2022, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/laka-spiaci-jelente-s-2022-ma-jus-eng.pdf [Accessed: 2025/01/22].

MNB. (2022b). "Special topic: Manageable risks in the vulnerable loan portfolios". Financial Stability Report, November 2022, Magyar Nemzeti Bank (MNB). Available at https://www.mnb.hu/letoltes/financial-stability-report-november-2022.pdf [Accessed: 2025/01/22].

Monasterolo, Irene, and Marco Raberto. (2018). "The EIRIN flow-of-funds behavioural model of green fiscal policies and green sovereign bonds". *Ecological Economics*, 144, pp. 228–243. https://doi.org/10.1016/j.ecolecon.2017.07.029

Montagna, Mattia, and Christoffer Kok. (2016). "Multi-layered interbank model for assessing systemic risk". Working Paper, 1944, European Central Bank. https://doi.org/10.2139/ssrn.2830546

Montagna, Mattia, Gabriele Torri and Giovanni Covi. (2021). "On the origin of systemic risk". Staff Working Paper, 906, Bank of England. https://doi.org/https://doi.org/10.2139/ssrn.3778199

NGFS. (2019). "A sustainable and responsible investment guide for central banks' portfolio management". Technical document, October 2019, Network for Greening the Financial System (NGFS). Available at https://www.ngfs.net/sites/default/files/medias/documents/ngfs-a-sustainable-and-responsible-investment-guide.pdf [Accessed: 2025/01/22].

Paddrik, Mark E., Roy Hayes, William Scherer and Peter Beling. (2017). "Effects of limit order book information level on market stability metrics". *Journal of Economic Interaction and Coordination*, 12, pp. 221–247. https://doi.org/10.1007/s11403-015-0164-6

Plassard, Romain. (2020). "Making a breach: The incorporation of agent-based models into the Bank of England's toolkit". GREDEG Working Paper, No. 2020-30, Groupe de REcherche en Droit, Economie, Gestion (GREDEG CNRS), Université Côte d'Azur, France. Available at https://ideas.repec.org/p/gre/wpaper/2020-30.html [Accessed: 2025/01/22].

Poledna, Sebastian, Serafin Martinez-Jaramillo, Fabio Caccioli and Stefan Thurner. (2021). "Quantification of systemic risk from overlapping portfolios in the financial system". *Journal of Financial Stability*, 52, p. 100808. https://doi.org/10.1016/j.jfs.2020.100808

Poledna, Sebastian, Michael Gregor Miess, Cars H. Hommes and Katrin Rabitsch. (2023). "Economic forecasting with an agent-based model". *European Economic Review*, 151, p. 104306. https://doi.org/10.1016/j.euroecorev.2022.104306

Poledna, Sebastian, José Luis Molina-Borboa, Serafin Martinez-Jaramillo, Marco van der Leij and Stefan Thurner. (2015). "The multi-layer network nature of systemic risk and its implications for the costs of financial crises". *Journal of Financial Stability*, 20, pp. 70-81. https://doi.org/10.1016/j.jfs.2015.08.001

Ponomarenko, Alexey, and Andrey Sinyakov. (2018). "Impact of banking supervision on banking system structure: Conclusion from agent-based modelling". *Russian Journal of Money and Finance*, 77(1), pp. 26–50.
https://doi.org/10.31477/rjmf.201801.26

Popoyan, Lilit, Mauro Napoletano and Andrea Roventini. (2017). "Taming macroeconomic instability: Monetary and macro-prudential policy interactions in an agent-based model". *Journal of Economic Behavior & Organization*, 134, pp. 117–140.
https://doi.org/10.1016/j.jebo.2016.12.017

Roncoroni, Alan, Stefano Battiston, Marco D'Errico, Grzegorz Hałaj and Christoffer Kok. (2021a). "Interconnected banks and systemically important exposures". *Journal of Economic Dynamics and Control*, p. 104266.
https://doi.org/10.1016/j.jedc.2021.104266

Roncoroni, Alan, Stefano Battiston, Luis O. L. Escobar-Farfán and Serafin Martinez-Jaramillo. (2021b). "Climate risk and financial stability in the network of banks and investment funds". *Journal of Financial Stability*, 54, p. 100870.
https://doi.org/10.1016/j.jfs.2021.100870

Siebenbrunner, Christoph, Martin Hafner-Guth, Ralph Spitzer and Stefan Trappl. (2024). "Assessing the systemic risk impact of bank bail-ins". *Journal of Financial Stability*, 71, p. 101229.
https://doi.org/10.1016/j.jfs.2024.101229

Silva, Thiago Christiano, Michel Alexandre and Benjamin Miranda Tabak. (2017). "Systemic risk in financial systems: A feedback approach". *Journal of Economic Behavior & Organization*, 144, pp. 97-120.
https://doi.org/10.1016/j.jebo.2017.09.013

Silva, Thiago Christiano, Michel Alexandre and Benjamin Miranda Tabak. (2018). "Bank lending and systemic risk: A financial-real sector network approach with feedback". *Journal of Financial Stability*, 38, pp. 98-118.
https://doi.org/10.1016/j.jfs.2017.08.006

Silva, Thiago Christiano, Solange Maria Guerra, Michel Alexandre and Benjamin Miranda Tabak. (2020). "Micro-level transmission of monetary policy shocks: The trading book channel". *Journal of Economic Behavior & Organization*, 179, pp. 279-298.
https://doi.org/10.1016/j.jebo.2020.09.013

Stangl, Johannes, András Borsos, Christian Diem, Tobias Reisch and Stefan Thurner. (2024). "Firm-level supply chains to minimize unemployment and economic losses in rapid decarbonization scenarios". *Nature Sustainability*, pp. 1–9.
https://doi.org/10.1038/s41893-024-01321-x

Sydow, Matthias, Aurore Schilte, Giovanni Covi, Marija Deipenbrock, Leonardo Del Vecchio, Pawel Fiedor, Gábor Fukker, Max Gehrend, Régis Gourdel, Alberto Grassi, Björn Hilberg, Michiel Kaijser, Georgios Kaoudis, Luca Mingarelli, Mattia Montagna, Thibaut Piquard, Dilyara Salakhova and Natalia Tente. (2024). "Shock amplification in an interconnected financial system of banks and investment funds". *Journal of Financial Stability*, 71, p. 101234.
https://doi.org/10.1016/j.jfs.2024.101234

Tompaidis, Stathis. (2017). "Measuring systemwide resilience of central counterparties". *Journal of Financial Market Infrastructures*, 6(4), pp. 41-54.
https://doi.org/10.21314/JFMI.2018.098

Trichet, Jean-Claude. (2010). *Reflections on the nature of monetary policy non-standard measures and finance theory*. Speech given as an opening address at the ECB Central Banking Conference, Frankfurt, 18 November. Available at https://www.ecb.europa.eu/press/key/date/2010/html/sp101118.en.html [Accessed: 2025/01/22].

Trichet, Jean-Claude. (2011). "Intellectual challenges to financial stability analysis in the era of macroprudential oversight". *Banque de France Financial Stability Review*, No. 15, pp. 139–149. Available at https://publications.banque-france.fr/sites/default/files/medias/documents/financial-stability-review-15_2011-02.pdf [Accessed: 2025/01/22].

Trichet, Jean-Claude. (2013). "Unconventional monetary policy measures: Principles-Conditions-Raison d'etre". *International Journal of Central Banking*, 9(1), pp. 229-250. Available at https://www.ijcb.org/journal/ijcb13q0a11.htm [Accessed: 2025/01/22].

Turrell, Arthur E. (2016). "Agent-based models: Understanding the economy from the bottom up". Quarterly Bulletin, Q4, Bank of England. Available at https://www.bankofengland.co.uk/quarterly-bulletin/2016/q4/agent-based-models-understanding-the-economy-from-the-bottom-up [Accessed: 2025/01/22].

Wolski, Marcin, and Michiel van de Leur. (2016). "Interbank loans, collateral and modern monetary policy". Working Paper, 1959, European Central Bank. https://doi.org/10.2139/ssrn.2839816

Yanquen, Eduardo, Giacomo Livan, Ricardo Montañez-Enriquez and Serafin Martinez-Jaramillo. (2022). "Measuring systemic risk for bank credit networks: A multilayer approach". *Latin American Journal of Central Banking*, 3(2), p. 100049. https://doi.org/10.1016/j.latcb.2022.100049

Zemaityte, Gabija, Elspeth Hughes and Katherine Blood. (2023). "The buy-to-let sector and financial stability". *Bank of England Quarterly Bulletin*. Available at https://www.bankofengland.co.uk/quarterly-bulletin/2023/2023/the-buy-to-let-sector-and-financial-stability [Accessed: 2025/01/22].