Making a breach: the incorporation of agent-based models into the Bank of England's toolkit

By Romain Plassard[1]

Abstract

After the financial crisis of 2008, several central banks incorporated agent-based models (ABMs) into their toolkit. The Bank of England (BoE) is a case in point. Since 2008, it has developed four ABMs. Under which conditions could ABMs breach the walls of the BoE? Then, there is the issue of the size of the breach. In which divisions economists used ABMs? Was agent-based modeling used to inform a wide range of policies? Last but not least, there is the issue of the fate of ABMs at the BoE. Is the breach going to narrow or, on the contrary, to widen? What are the forces underlying the deployment of ABMs at the BoE? My article aims to address these issues. I show that institutional reforms were central to the use of ABMs at the BoE. I also show that so far, ABMs have been a marginal tool at the BoE. They were not used to inform monetary policy. Neither were they used to coordinate the BoE's microprudential, macroprudential, and monetary policies. ABMs were only used to inform the BoE's macroprudential policy. I conclude the article by examining the conditions for a broader use of ABMs at the BoE.

JEL Codes: Bank of England, agent-based models, macroprudential policy, monetary policy, DSGE models.

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1. A new tool for central banks

After the financial crisis of 2008, leading policy makers advocated for the use of agent-based modeling. Jean-Claude Trichet was a case in point. While he was President of the European Central Bank (ECB), Trichet explained:

> The key lesson I would draw from [the crisis] is the danger of relying on a single tool, methodology or paradigm. Policy makers need to have input from various theoretical perspectives and from a range of empirical approaches. Open debate and a diversity of views must be cultivated. We do not need to throw out our DSGE [Dynamic Stochastic General Equilibrium] and asset-pricing models: rather we need to develop complementary tools to improve the robustness of our overall framework […] Agent-based modelling dispenses with the optimization assumption and allows for more complex interactions between agents. [It is therefore] worthy of our attention (2010: p. 5).[2]

Three years after Trichet's advocacy, a first agent-based model (ABM) emerged at the ECB. Grzegorz Halaj and Christoffer Kok used it to assess the resilience of the European banking sector (2013). Since then, other ABMs have been developed within the ECB (Montagna and Kok, 2016; Halaj and Henry, 2017; Halaj, 2018). The modeling technique thus ended up taking roots at the ECB. It turns out that the ECB is not an isolated case. Other central banks have incorporated ABMs into their toolkit. It was notably the case of the Bank of England, of the Federal Reserve Board, and of the Norges Bank.

This change in central banks' toolkits raises issues. While the 2008 crisis was a global phenomenon, not all central banks adopted ABMs in its aftermath. For instance, neither the Bank of France nor the Swiss National Bank did. It follows a first issue: Under which conditions ABMs breached the walls of central banks? Then, there is the issue of the size of the breach. In which divisions economists used ABMs? Was agent-based modeling used to inform a wide range of policies? Last but not least, there is the issue of the fate of ABMs in central banks. Is the breach going to narrow or, on the contrary, to widen? What are the forces underlying the deployment of ABMs in central banks? My article aims to address these issues. My case study is the Bank of England (BoE).

[2] Excerpt from Trichet's opening address at the ECB Central Banking Conference, "Reflections on the nature of monetary policy, non-standard measures, and finance theory" (18 November 2010).

ABMs did not incorporate the BoE's toolkit at once. The technique was used a first time in 2008, by Marco Galbiati and Kimmo Soramäki. But there was no follow-up. Nothing related to agent-based modeling was proposed at the BoE until 2016. However, since 2016, BoE's staff has developed three ABMs (Baptista et al., 2016; Braun Munzinger et al., 2016; Kårvik et al., 2018). Moreover, there has been several discussions about the benefits to use ABMs in central banks (Haldane, 2016; Turrell, 2016; Haldane and Turrell, 2017; 2019). All this suggests that changes occurred at the BoE between 2008 and 2016. Identifying these changes will help to understand why ABMs breached the walls of the BoE. Then, the BoE is where the development of ABMs was the most sustained. The number of articles devoted to agent-based modeling is much higher at the BoE than in other central banks. Focusing on the BoE will therefore allow to provide the richest account on the use of ABMs in central banks.

In the process, I will contribute to three distinct research areas. First, I will contribute to the history of complexity economics. The emergence of fields like econophysics or agent-based computational economics has been studied. But historians focused on the academia (Mirowski, 1989; Fontana, 2010; Colander, 2006). By contrast, my article studies the emergence of agent-based modeling in a policy-making institution. Then, I will contribute to the history of modeling in central banks. So far, historians have focused on the use of large-scale macroeconometric models (e.g., Backhouse and Cherrier, 2017; Acosta and Rubin, 2019). No historian has ever addressed the use of ABMs in central banks. Last but not least, I will contribute to clarify how current changes in regulations occurred. Political scientists have been concerned with the use of macroprudential policies in central banks (Baker, 2013; Braun, 2015; Goodhart, 2015; Thiemann et al, 2017; Thiemann, 2019). However, they have placed little or no emphasis on the tools used in the policy making process.

By contrast, I analyze the properties of agent-based modeling. I discuss how ABMs are built, explain why they can be appropriate for describing the operation of market economies, and indicate their limitations. At the same time, I realized that such an analysis was not enough to address the use of ABMs. ABMs breached the wall of the BoE after the worst financial crisis since 1929. In these challenging times, the UK regulatory system underwent large reforms. In particular, the Parliament expanded the mandate of the BoE. After 2012, the Bank had the responsibility to ensure financial stability in the UK. Then, mainstream economics was under fire after the crisis. It was particularly true for DSGE models (Krugman, 2009; Buiter, 2010; Romer, 2016). Finally, the development of ABMs depends on hardware and software (Turrell, 2017). Therefore, I had to replace the use of ABMs in its political, institutional, intellectual,

and material context. This led me to use a large variety of sources including legal documents, political speeches, BoE's reports, and blog posts. This also led me to contact BoE's economists. Most of them replied to my questions. Some, like Arthur Turrell or Karen Braun-Munzinger, even accepted an interview.

On that basis, I could address the incorporation of ABMs into the BoE's toolkit. I show that institutional reforms were central to the use of ABMs at the BoE. I also show that so far, ABMs have been a marginal tool at the BoE. I conclude the article by examining the conditions for a broader use of ABMs at the BoE.

2. Post crisis regulation

In the aftermath of the 2008 crisis, the UK regulatory system was reformed. In 2012, the Parliament abolished the institution responsible for supervising and regulating the financial sector – i.e., the Financial Services Authority. This led the BoE to have the operational responsibility for the financial stability policy. Then, starting from 2014, the BoE launched a large transformative plan. It involved a change in its research and data strategies. As a result, not only the BoE's missions changed but also the way they were performed. I show that this was central to the incorporation of ABMs into the BoE's toolkit.

2.1 Restructuration of the UK regulatory system

All around the world, policy makers blamed the financial crisis on the failure of regulatory systems. In the UK, Lord Adair Turner was a case in point. While he was the head of the Financial Services Authority (FSA), Turner acknowledged the failure to remove the system-wide risks that were building up before Northern Rock's collapse. His diagnosis appeared in a report, "The Turner Review: A Regulatory Response to the Global Banking Crisis" (2009). Turner explained:

> The Bank of England tended to focus on monetary policy analysis as required by the inflation target, and while it did some excellent analytical work in preparation of the *Financial Stability Review*, that analysis did not result in policy responses designed to offset the risks identified. The FSA focused too much on the supervision of individual institutions, and insufficiently on wider sectoral and system-wide risks. Accordingly, the vital activity of macro-

> prudential analysis, and the definition and use of macro-prudential tools, fell between two stools (2009: p. 84).

Since 1998, the BoE had control over monetary policy.[3] Its mission was to reach the inflation target set by the Government. At the same time, the BoE shared the responsibility for the financial stability policy with the FSA.[4] Its mission involved monitoring financial market infrastructures (e.g., inter-bank payment systems) and reporting on potential risks for the stability of the whole economy. However, the BoE did not have to translate its *Financial Stability Review* into policy recommendations. Neither did it have the mandate to implement macro-prudential policies. The BoE could intervene only in exceptional circumstances, and to provide financial support to an institution already in difficulties.[5] Prudential regulation was, however, part of the FSA's responsibilities.[6] Unfortunately, when supervising and regulating financial institutions, the FSA neglected system-wide risks. It controlled risk exposure at the individual level, assuming that the behavior of one financial institution was independent of other's (2009: p.45; p. 87). Therefore, the UK regulatory system could hardly prevent the financial turmoil.

To avoid it from happening again, Turner proposed to redefine the institutional arrangements between the BoE and the FSA (2009: p. 84). But his proposition was not retained. In 2010, a new government was elected with an agenda to abolish the FSA. In their "program for government," David Cameron and Nicholas Clegg committed to "bring forward proposals to give the Bank of England control of macro-prudential [and] micro-prudential regulation" (2010: p. 9). Their Chancellor of the Exchequer, George Osborne, explained why during his 2010 Mansion House speech. According to Osborne, "only independent Central Banks [had] the broad macroeconomic understanding, the authority, and the knowledge required to [remove

[3] Independence of the BoE was promoted by Tony Blair's first government and codified under the Bank of England Act 1998.

[4] A memorandum of understanding between the BoE, the FSA, and the Treasury defined how the three institutions co-operated in the area of financial stability. For a detailed description of the co-operation framework, see the Annex of the Bank of England Quarterly Bulletin (May 1998).

[5] "In exceptional circumstances [and with the agreement of the Treasury], it will undertake official financial support operations, to limit the risks of problems affecting individual institutions spreading to other parts of the financial system" (1998: p. 95).

[6] The FSA was responsible for "i) the authorization and prudential supervisions of banks, building societies, investment firms, insurance companies and friendly societies; ii) the supervision of financial markets and of clearing and settlement systems; iii) the conduct of operations in response to problem cases affecting firms, markets and clearing and settlement systems […]; iv) regulatory policy in these areas" (1998: p. 97). The FSA was also responsible for protecting consumers in financial services (e.g., fair consumer credit), and for ensuring the respect of ethical and legal rules (e.g., prohibition of insider trading). This aspect of the financial regulation is left aside in my article.

systemic risks].” Central Banks therefore had to be responsible for the macro-prudential policy. Then, the experience of bailouts “[showed] that Central Banks [needed] to be familiar with every aspects of the institutions that they [had] to support. So, they must be responsible for day-to-day micro-regulation as well” (2010). Osborne concluded that the FSA was to be dissolved and that the BoE had to be fully responsible for the financial stability policy (2010).

The Financial Services Act 2012 set the new institutional design. It created two independent bodies inside the BoE: the Prudential Regulation Authority (PRA) and the Financial Policy Committee (FPC). On one side, the PRA was responsible for the micro-prudential regulation. Its goal was to supervise and regulate financial institutions including banks, building societies, insurance companies or credit unions. This involved undertaking stress-tests, establishing liquidity requirements, and ensuring their application. The FPC, on the other side, was responsible for the financial stability of the whole system. This involved identifying, monitoring, and taking actions to control systemic risks. For instance, the FPC decided on the countercyclical capital buffer applied to UK financial firms.[7] The Financial Services Act therefore enlarged the BoE’s missions. Since it came into force, the BoE has had the responsibility to ensure financial and monetary stability in the UK.

2.2 Reform of the BoE

A few months after the Financial Services Act came into force, Mark Carney became the BoE’s governor.[8] His nomination took place at a critical moment. Not only because the BoE had to operationalize the Parliament mandate. But also because the Bank’s working culture was under attack. Several reports indicated problems in the policy-making process. This was the case in William Winters’s “Review of the Bank of England’s framework for providing liquidity to the banking system” (2012).[9] According to Winters, the BoE tended to rule out policy options because it was too hierarchical an institution (2012: p. 108). Operational changes were therefore needed. In 2014, after an extensive staff consultation, Carney launched a large reform of the

[7] Countercyclical capital buffer was part of the macroprudential tools introduced by the Basel Committee III. For more information, see “Basel III: a global regulatory framework for more resilient banks and banking systems” (2010).

[8] The Financial Services Act came into force on 1 April 2013. Carney became the BoE’s governor in July 2013, for a term of 8 years.

[9] See also “Review of the Bank of England’s provision of emergency liquidity assistance” (Ian Plenderleith, 2012) and “Review of the monetary policy committee’s forecasting capabilities” (David Stockton, 2012).

BoE.[10] 15 "initiatives" were identified to build "an institution that [worked] as One Bank, to exploit the complementarities and synergies across [its] policy functions" (2014: p. 1). We will focus on the "One Bank Research Agenda" and on the implementation of a "New Approach to Data and Analysis."

One Bank Research Agenda

Carney's reform provided changes in how the BoE conducted research. Carney elaborated on their content during the "Launch Conference" of the "One Bank Research Agenda" (2015a). Three strategic reorientations can be highlighted.

First, Carney (2015a) changed the BoE's research agenda. Before the crisis, the effectiveness of monetary policy was the main area of research. The question was how to maintain price stability in the UK (2015a: pp. 1-2). However, since 2012, the BoE was not only responsible for maintaining monetary stability but also for ensuring financial stability in the UK. This forced to consider new questions (2015a: p. 2). For instance, Carney required to address the coordination between microprudential, macroprudential, and monetary policies. According to Carney, the Central Banks's pursuit of price stability contributed to the build-up of systematic risks. This was because a low and predictable interest rates environment encouraged risk-taking in the economy. Carney concluded that researchers had to help the BoE to find the good mix between monetary, macroprudential, and microprudential policies. This resulted in a first research axis, "Policy frameworks and interactions" (2015a: p. 3). Four other themes composed the One Bank Research Agenda.[11] They addressed "all aspects of central banking," in order to assist the BoE in fulfilling its mandate (2015a: p. 3).

Second, Carney institutionalized joint working at the BoE. The organizational health check identified a "silo culture" at the BoE.[12] The majority of the staff complained about the lack of projects with colleagues from other divisions and/or from other directorates. It considered that this silo culture weakened the capacity to address cross-cutting issues and, in

[10] In 2013, Carney commissioned an organizational health check to McKinsey and Company. The resulting information was used to devise his reform, "One Mission, One Bank: promoting the good of the people of the United Kingdom" (2014).

[11] The "One Bank Research Agenda" was composed of five themes, "Policy frameworks and interactions" (2015a: p. 3), "Evaluating regulation, resolution and market structures" (2015a: p. 3), "Policy operationalization and implementation" (2015a: p. 3), "New data, methodologies, and approaches" (2015a: p. 4), and "Response to fundamental change" (2015a: p. 4). For a short presentation of the five themes, see the BoE's "One Bank Research Summary" (2015b).

[12] I could not access McKinsey's organizational health check. But its main results can be found in "Progress delivering the 'One Mission, One Bank' strategy" (2017).

turn, could prevent the BoE from fulfilling its mandate. Action was therefore needed. Carney proposed to create "a new Research Hub" (2015a: p. 3). Inside the Research Hub, a small team of permanent staff was supposed to work on cross-bank research projects. At the same time, the Research Hub's permanent staff was also supposed to help colleagues from other divisions to carry out their own research. Therefore, the Research Hub offered a space where skills from across the BoE were used to address cross-cutting issues.

Third and finally, Carney (2015a) promoted multidisciplinary research. According to Carney, "policymaking [could] benefit tremendously from advances in all fields of economics and finance; from psychology to epidemiology; from computer science to law" (2015a: p. 3). One reason for promoting multidisciplinary research was to better exploit the large volume of available data on corporate and household behavior (2015a: p. 4; 2015b p. 5). According to Carney, its treatment was strategic, particularly because it could "enhance [the BoE's] forecasting and stress-testing capabilities" (2015a: p. 4). The problem was that much of the data collected was "unstructured" (2015a: p. 4; 2015b: p. 5). Therefore, standard econometric techniques could not be used for extracting information. But machine learning or natural language processing could. Carney concluded that the BoE had to open its door to disciplines other than economics and finance.

A New Approach to Data and Analysis

When preparing his reform, Carney identified problems in how the BoE collected and used data.[13] One problem had emerged because of the expansion of its mandate. After the crisis, several regulatory bodies required financial firms to disclose more data about their activities. The European Parliament was a case in point. To regulate the insurance industry, it voted a directive (n° 2009/138/CE) requiring every insurance company to report its assets on a security-by-security basis. Together with other regulatory initiatives, this resulted in an increasing volume of granular data reported to national regulators.[14] In the UK, the FSA had the responsibility to collect and analyze these data for a few years. But after the Financial Services

[13] Some problems were reported during the staff consultation. In particular, the staff criticized the lack of means to share data across the institution. For more details, see "Progress Delivering the 'One Mission, One Bank' strategy" (2017).

[14] Two other regulatory initiatives can be mentioned. In 2009, the Financial Stability Board designed a new template for systemic banks. It involved the reporting of their exposures on a counterparty-by-counterparty basis. Besides, in 2012, the European Market Infrastructure Regulation required the reporting of transactional derivatives data. For more details on these two regulatory initiatives, see "Understanding financial linkages: a common data template for global systemically important banks" (2011) and https://ec.europa.eu/info/business-economy-euro/banking-and-finance/financial-markets/post-trade-services/derivatives-emir_en.

Act came into force, it became the BoE's, through the PRA. At the same time, the FPC called for using new sources of information including market intelligence or social media.[15] There was a conviction that such information could assist in better anticipating the build-up of systemic risk and in taking more efficient macro-prudential measures. Accordingly, the BoE not only had to process granular data. To fulfill its new mandate, it also considered enlarging the scope of data to be used. Therein lay the problem.

The BoE lacked in-house skills to tap into granular, frequently updated, and multimedia data. In other words, it had almost no experience with "big data" processing.[16] This was acknowledged by several BoE's staff including David Bholat. In a report summarizing a conference on "Big data and Central Banks," Bholat explained:[17]

> The Bank of England traditionally has not dealt much with big data. Data volume historically [had] been low because [the BoE's] primary sources [had] been summary financial statements and aggregate statistics […] Data velocity also has been slow because these statistics and financial statements [were] reported in the main at most on a quarterly frequency and revised with lags. And although the Bank [had] a history of gathering qualitative data through survey and interviews with external contacts, overall the variety of data [had] been minimal because most formal analysis undertaken in the Bank [used] structured data sets, that is, numeric data stored in row and column formats (2015: p. 86).

Since the BoE did not have in-house skills to address big data, it had to be reformed. Carney proposed to create the Advanced Analytics (AA) Division. At that time, Bholat took part in the creation process. He remembered that senior managers "didn't go straight to a productionized solution. [They] began with pilots. They started out with a small team hired specifically to think about what the data strategy should be [in the division]. They concluded that it would be best [collecting and analyzing] data at a more granular level." Then, Bholat remembered that senior managers "[had not] just hired economists who [had] completed data

[15] See for instance "The Financial Policy Committee's powers to supplement capital requirements" (2013: p. 37).
[16] High volume, high frequency, and/or high variety characterize big data. This was how International Business Machine defines big data. See, for example, "2,5 quintillion bytes of data created every day. How does CGG & Retail manage it?" (2013). This is also how the BoE defines by data. For further details on the issues posed by the transition to big data, see "The Future of Central Bank Data" (Bholat, 2013: p. 186) or "Big data and Central Banks" (Bholat, 2015: p. 86).
[17] The conference, organized by the BoE, took place on 2 and 3 July 2014. Its goal was to "discuss the IT estate, analytical techniques, governing arrangements, and strategic objectives central banks are developing around big data" (Bholat, 2015: p. 86).

science courses." There was a conviction that "multidisciplinary team [approached] problems differently and [brought] different perspectives, thereby problem-solving in a more creative way than homogenous team." Accordingly, "the majority of people who [worked] within the division [were not] economists. They [were] physicists, mathematicians, computer scientists, and there was even an experimental psychologist and a linguist."[18] Last but not least, the AA Division was designed to collaborate with other parts of the institution. This was stressed by the head of the Division, Paul Robinson, during a conference on "Big Data: Building Strategies for Central Banks in light of the Data Revolution" (2015). Robinson showed that his division was already part of several research projects at the BoE. For instance, the AA division contributed to a large study of the UK housing market. By analyzing surveys and transactional data, its staff intended to explain why house prices were increasing, and how to fight against it. At the same time, AA division's staff sought to tap into the Consumer Price Index to predict the UK inflation rate. It followed that since its creation, the AA Division worked with the BoE's monetary and financial stability directorates.

2.3 Supply and demand for ABMs

Since the creation of the AA division, the use of ABMs has largely increased at the BoE. Before 2014, only one ABM had been developed in the institution (Galbiati and Soramäki, 2008). In contrast, three ABMs have been elaborated since 2014 (Baptista et al., 2016; Braun Munzinger et al., 2016; Kårvik et al., 2018). More generally, agent-based modeling has become a topic of discussions at the BoE. In 2016, Turrell discussed the pros and cons of ABMs in a literature review. Then, Turrell joined the BoE's chief economist, Andrew Haldane, to advocate for the use of ABMs models in central banks (2017; 2019). All this suggests that the creation of the AA division played a role in the establishment of ABMs at the BoE. The question is why. Turrell's hiring, a physicist specialized in Monte-Carlo simulations, offers an answer. Turrell joined the AA division in October 2015. Since then, the physicist has contributed to most of the works around ABMs at the BoE.[19] Not only did he write the literature review and the articles

[18] Quotations are from an interview conducted by Daniel Hinge, the report editor of *Central Banking*. The interview took place during a forum organized by BearingPoint, on 7 August 2018. During this forum, *Central Banking* had "convened a panel of experts to discuss the innovative ways Central Banks [were] making use of big data." The panel was composed of Bholat and of Jyry Hokkanen, head of Statistics at the Sveriges Riksbank. The full length of the discussion can be found on the website of *Central Banking*, under the title "Putting big data into action" (2018).

[19] In his lit review, Turrell indicated that "agent-based models are called by different names in different disciplines, including Monte Carlo Simulations in the physical sciences" (2016: p. 174). For more information on his work in physics and on the reasons why he decided to work at the BoE, see "Why I left physics for economics" (2017, The Guardian). You can also listen to a podcast from Central Banking. It is available on the Journal's

with Haldane. But Turrell also built the ABM used by Karen Braun-Munzinger and Zijun Liu (2016).[20] Therefore, the AA division offered a platform for the development of ABMs at the BoE.

Within the BoE, Turrell provided access to a supply of ABMs.[21] It was a condition for their establishment in the institution. But it was not enough. A demand for ABMs was also necessary.[22] The demand emerged due to the expansion of the BoE's mandate. At least two reasons explained why. First, the modeling technique displayed a number of relevant features to inform the financial stability policy. Carney acknowledged it. When launching the One Bank Research Agenda, he argued that "it [was] important to exploit developments in advanced analytics of large data sets to formulate better policy. They will improve our understanding of household and corporate behavior, the macroeconomy and risks to the financial system" (2015a: p. 4). No modeling technique was mentioned in particular. But Carney had in mind agent-based computational economics. Indeed, the use of ABMs was advocated in the summary presentation of the One Bank Research Agenda:

> The application of microeconometric or agent-based techniques to data from surveys of individual households, administrative data, and information from credit bureaux could play an important role in quantifying and understanding [household and corporate] behavior – for example, the impact of an interest rate change or a portfolio loan to value or debt to income cap on households, or the underlying drivers of indebtedness and its links to business cycles, arrears and defaults (2015b: p. 5).

When building an ABM, it is possible to specify in detail how economic agents behave, how they interact with each other, and how they interact with their environment. Once it is done, most of the information contained in a survey and/or in an administrative document can be used to calibrate the model. ABMs therefore provide a useful tool for taping into granular data.

website: https://www.centralbanking.com/central-banks/economics/economic-modelling/3812816/podcast-arthur-turrell-on-agent-based-modelling.

[20] Geir-Are Kårvik, Joseph Noss, Jack Worlidge, and Daniel Beale later extended the model built by Turrell to address flash crashes (2018: p. 3).

[21] Arzu Uluc is another BoE's economist capable of elaborating ABMs. I obtained this information thanks to Francesca Monti, a member from the Monetary Policy Outlook Division. Monti "[suggested me] to get in touch with Arzu Uluc (in cc), who is one of our most prolific ABM modelers" (email of 11 July 2019).

[22] Carolin Brendel also tried to identify the determinants of this demand for ABMs. Her strategy consisted of listing arguments raised in the academia and in the main central banks where ABMs are used. For more details, see Brendel (2018).

According to Carney, this could be of benefit to the BoE. By clarifying how financial crisis emerge and propagate to the real economy, ABMs could assist the BoE in securing financial stability in the UK.

Along with Carney, other BoE's economists also claimed that ABMs offered a useful tool to inform the financial stability policy. The point was made in every working paper where BoE's economists developed an ABM. Baptista et al.'s (2016) was a case in point. In the introduction, it is explained that:

> The ABM approach enables the modelling of different actors in the housing market in detail. It allows for non-linear dynamics, such as booms and busts, which come naturally from the interaction of buyers and sellers in the market. Furthermore, it permits an evaluation of the impact of policies which target a certain segment of the market, such as the Bank of England's loan-to-income (LTI) flow limit that came into force in October 2014 (2016: p. 3).

The capacity to model heterogeneity is useful to inform the financial stability policy. Not only because heterogeneity is central to the dynamic of financial markets. But also because policy makers can be concerned with subgroups of economic agents or subsets of products. This happened to the FPC in 2014. To reduce risks from the housing market, the FPC recommended to limit the proportion of new mortgages granted to agents with an LTI ratio at or above 4,5. To what extent the increase in the number of mortgages with high LTI ratios explained the ongoing house price growth? What was the cap allowing to reduce house price growth without overly reducing the housing activity? These were the type of questions an ABM could address. But this was not all. Another advantage of agent-based modeling was to explain cyclical dynamics endogenously. This advantage was mentioned by Baptista et al. (2016), but without explaining why it mattered when formulating the financial stability policy. Haldane and Turrell were more explicit. By showing that the actual operation of markets could generate crises, ABMs would allow to understand the causes of fluctuations and, in turn, could help to reduce their frequency and their severity (2017: p. 9; 2019: p. 45).

Second, ABMs offered a tool for addressing the coordination between microprudential, macroprudential, and monetary policies. The Head of the Research Hub, Misa Tanaka, made this observation during a discussion. In an e-mail, she claimed that:

> One can easily have a (possibly triple-mandate) monetary policy, micro-prudential policies, macro-prudential policies lender-side (such as Countercyclical Capital Buffer) and borrower-side (such as affordability tests) in a single [agent-based] model. Therefore, central banks with broad responsibilities can naturally look at ABMs to study the interaction between all those policies.[23]

ABMs can be adapted to a wide range of institutional contexts. For instance, a macroeconomic ABM can describe an economy where a central bank is responsible for monetary and financial stability policy.[24] To be more specific, the model can include a monetary policy rule, the capital requirements set up by the Basel Committee III, and rules to adjust countercyclical capital buffer. Under these circumstances, provided that the model is correctly calibrated, policy makers would have a framework for coordinating monetary, microprudential, and macroprudential policies. Hence why Tanaka suggested that it was worth exploring ABMs at the BoE.

But Tanaka's observation not only shows that the expansion of the BoE's mandate created a demand for ABMs. It also shows how Carney's reform contributed to stimulate this demand. Tanaka is the team leader of a new unit of the BoE. The Research Hub was established under Carney's reform, in 2015. As a reminder, it was part of the institutional arrangements designed to break with the BoE's silo culture. What would have happened if the Research Hub and/or the One Bank Research Agenda had not been created? It is hard to know for sure. But the BoE's research is likely to have remained fragmented and have neglected cross-cutting issues. Typically, the complementarities between monetary, microprudential, and macroprudential policies would not have been at the top of the agenda. It follows that without Carney's reform, the BoE's staff would have had less incentives to look for tools like ABMs.

3. A tool to inform the BoE's macroprudential policy

Since the implementation of Carney's reform, the BoE has developed an ABM of the housing market (Baptista et al, 2016), an ABM of the corporate bond market (Braun-Munzinger et al, 2016), and an ABM of the foreign exchange market (Kårvik et al., 2018). This involved ten in-

[23] I received the e-mail on 16 July 2019. Originally, I had contacted Haldane. But Haldane asked Tanaka to reply to me, on behalf of the BoE (email of 6 July 2019).

[24] For instance, see "Taming Macroeconomic Instability: Monetary and Macroprudential Policy Interactions in an Agent-Based Model" (Popoyan et al, 2017).

house economists.[25] I identified where they worked at the time –i.e., their division and the associated directorate. Information is summarized below:

ABMs	Economists	Divisions	Directorates
Housing market	Marc Hinterschweiger	Financial Policy	Prudential Policy
	Katie Low	Macro-Financial Risks	Financial Stability Strategy and Risk
	Arzu Uluc	Macro-Financial Risks	Financial Stability Strategy and Risk
Corporate bond market	Karen Braun-Munzinger	Capital Markets	Financial Stability Strategy and Risk
	Zijun Liu	Capital Markets	Financial Stability Strategy and Risk
	Arthur Turrell	Advanced Analytics	Monetary Analysis
Foreign exchange market	Geir-Are Kårvik	Sterling Markets	Markets
	Joseph Noss	Capital Markets	Financial Stability Strategy and Risk
	Jack Worlidge	Capital Markets	Financial Stability Strategy and Risk
	Daniel Beale	Stress-Testing	Financial Stability Strategy and Risk

Table 1. ABMs at the BoE

Table 1 shows that the development of ABMs involved several BoE's divisions. The list includes the Capital Markets Division, the Macro-Financial Risks Division, the Sterling Markets Division, and the Stress-Testing Division. Table 1 also reveals the involvement of several directorates. There were the Monetary Analysis, the Markets, the Prudential Policy, and the Financial Stability Strategy and Risk Directorates. That diversity raises the issue of the use of ABMs at the BoE. Some divisions, like the Sterling Markets, are responsible for informing the BoE's monetary policy. Others, like the Stress-Testing Division, are responsible for informing the BoE's financial stability policy. Besides, some directorates are responsible for the BoE's monetary and financial stability policies. This is the case of the Markets Directorate. Does it follow that ABMs were used to coordinate the BoE's macroprudential and monetary policies? More generally, which policy ABMs intended to inform?

[25] There were also three external economists: Rafa Baptista, Doyne Farmer, and Daniel Tang (Institute for New Economic Thinking). They contributed to the development of the ABM of the housing market.

3.1 Clusters within the BoE

According to Table 1, the three ABMs were developed by economists belonging to the Financial Stability Strategy and Risk Directorate. Then, table 1 shows that two of the three ABMs were developed by economists working in the Capital Markets Division. Finally, table 1 shows that the ABM of the housing market involved mainly economists from the Macro-Financial Risks Division. To understand the use of ABMs at the BoE, it might therefore be useful to know the responsibilities of the Financial Stability Strategy and Risk Directorate, of the Capital Markets Division, and of the Macro-Financial Risks Division.

I found information on each BoE's body while reading job descriptions. In 2019, the BoE opened a Senior Manager position in the Capital Markets Division. Here is how the division and its associated directorate were presented:

> The Financial Stability Strategy and Risk (FSSR) Directorate is responsible for identifying cross-cutting risks to UK financial stability, assessing the resilience of the UK financial sector and developing policy solutions to ensure financial stability. Within FSSR, Capital Markets Division (CMD) is responsible for assessing risks to financial stability arising from financial markets and non-bank financial institutions. They help the Financial Policy Committee (FPC) to develop policies to mitigate those risks and hence to improve the resilience of the UK financial system.

In 2019, the BoE also opened a Research Assistant position in the Macro-Financial Risk Division. The description included details on the Team who worked on the ABM of the housing market:

> Macro-Financial Risks Division is responsible for addressing risks to financial stability stemming from the UK real economy. [Its] Household Team undertakes extensive analysis of residential property market, owner-occupier and buy-to-let mortgage markets, consumer credit, and the distribution of household income relative to debt.

In the light of these two job descriptions, one can imagine the role of ABMs at the BoE. They were a tool to inform the BoE's macroprudential policy. It is confirmed by analyzing how BoE's economists used agent-based modeling.

3.2 Pattern in the use of ABMs

There is a pattern in the use of ABMs. First, BoE's economists focused on markets and economic agents monitored by the FPC. Second, they sought to model amplification mechanisms. Third and finally, each ABM served to test the effects of macroprudential policies.

An ABM of the housing market

When Baptista et al started to work together, the FPC was concerned about developments in the housing market. In particular, the FPC was concerned about the growth of the buy-to-let sector. This is clear from the Financial Stability Reports of July and December 2015. Data showed that "in the year to 2015 Q1, the stock of buy-to-let lending expanded by 8%. Buy-to-let lending [accounted] for 15% of the stock of outstanding mortgages, and 18% of the total flow of new mortgage lending" (Financial Stability Report, 2015a: p. 25). According to the FPC, such dynamism posed risks to financial stability (Financial Stability Report, 2015a: p. 25; 2015b: p. 31). On the one hand, the FPC argued that buy-to-let investors put upward pressure on house prices and, in turn, contributed to increase household indebtedness. It followed the build-up of vulnerabilities in the UK banking system. On the other hand, the FPC argued that buy-to-let investors could amplify house price falls in the downturn. "Buy-to-let borrowers [were] potentially more vulnerable to rising interest rates because loans [were] more likely to be interest only and extended on floating-rate terms" (Financial Stability Report of June 2015a: p. 25). Moreover, a survey commissioned by the BoE showed that around 60% of buy-to-let investors would sell their properties if prices were to fall by more than 10% (Financial Stability Report, 2015b: p. 31). The FPC concluded that the behavior of buy-to-let investors could test the resilience of the UK banking system. Under these circumstances, the FPC chose to monitor developments of the buy-to-let sector and, more generally, of the housing and mortgage markets (Financial Stability Report, 2015a: p. 25; 2015b: p. 31).

In 2016, Baptista et al modeled the housing and mortgage markets. Within their ABM, the mortgage market involved households and a representative bank. Households demanded mortgage loans to the bank. Their demand was supposed to be met as long as households conformed to rules set by a Central Bank (e.g., caps on loan-to-income or on loan-to-value ratios). The housing market, on the other side, was where households competed for properties. By assumption, there were 10000 households. The pool included renters, owner-occupiers, and buy-to-let investors. Each category of households had different behavior. For instance, renters decided whether to buy or keep renting a house. In contrast, buy-to-let investors decided

whether to sell or buy rental properties. The interactions between households, the bank, and the central bank formed the ABM of the housing market.

Once calibrated, the model was used to account for boom-bust cycles in the UK housing market. It was part of a strategy to validate the ABM. Baptista et al performed several comparisons between model simulations and real data (2016: pp. 28-32). One comparison consisted in checking whether the model could generate housing cycles with different magnitudes and different durations. It was the case, just like in reality (2016: p. 29). Moreover, Baptista et al were interested in determining how central the behavior of buy-to-let investors was in housing cycles. They performed several experiments. One consisted in turning off the expectation channel. Under these circumstances, buy-to-let investors no longer bought in rising prices and sold in falling prices. It resulted in an almost complete removal of housing cycles (2016: p. 29). Another experiment consisted in increasing the proportion of buy-to-let investors. The opposite result was obtained. The larger the buy-to-let market was, the higher the magnitude and the frequency of housing cycles were (2016: p. 34). Baptista et al concluded that the speculative behavior of buy-to-let investor was central to housing cycles.

Last but not least, Baptista et al used their ABM to test the effects of macroprudential policies. To be more specific, they studied the dynamics of the housing market when no more than 15% of new mortgages could be granted to households with an LTI ratio at or above 3,5. They showed that the implementation of this LTI flow limit could dampen housing cycles. In particular, model simulations showed that house price growth had a lower standard deviation in the policy scenario (2016: p. 38).

An ABM of the corporate bond market

When Braun-Munzinger et al started to work together, the FPC was concerned about developments in fixed-income markets. In particular, it was concerned about developments in the sterling corporate bond market. This is clear from the Financial Stability Reports of July and December 2015. The FPC wondered whether the sterling corporate bond market had become less liquid. Some indicators, like the corporate bond liquidity risk premia, showed that it had not (Financial Stability Report, 2015a: p. 18). However, other information suggested a deterioration of its liquidity. The sharp decrease of corporate bonds in dealer inventories was a case in point (Financial Stability Report, 2015a: p. 17; 2015b: p. 53). According to the FPC, "there [was] evidence that dealers had become less willing to expand their inventories"

(Financial Stability Report, 2015a: p. 17) during periods of stress. The sterling corporate bond market could therefore be disrupted by large sales orders.

The problem was that large orders might happen more often than in the past. This had to do with the development of funds offering investors short-term redemptions. Assets under the management of "open-ended investment funds" had largely increased since the financial crisis (Financial Stability Report, 2015b: p. 33). According to the FPC, such dynamism posed risks to financial stability. "The recent rapid growth in open-ended funds, and their continued investment in less liquid assets, [had] reinforced the risk that large-scale investor redemptions could result in sales of assets by funds that might test markets' ability to absorb them. The risk [was] that this could impair market liquidity, which [was] already fragile, particularly in markets that [were] important for extending funding to the real economy" (Financial Stability Report, 2015b: p. 23). Typically, "an overshoot in bond spreads may unnecessarily reduce the ability of some companies to service refinanced debt, threatening their solvency […] In addition, some firms may be deterred from raising new financing, resulting from a cancellation of investments that would otherwise have been expected to be profitable" (Financial Stability Report, 2015b: p. 23). The resulting losses could test the resilience of financial institutions. Under these circumstances, the FPC chose to monitor the development of open-ended funds and of the corporate bond market.

In 2016, Braun-Munzinger et al modeled the corporate bond market. It was represented by a pool of investors, open-ended funds, and a market maker. The pool of investors generated cash inflow and outflow. This depended on the rate of return of the corporate bond index and on the rate of return of the fund in which they had invested money (2016: p. 4). By assumption, open-ended funds could report different performances because they had different investment strategies. Some funds believed in the existence of a fundamental value (2016: p. 2). They sold (bought) whenever the price of the corporate bond was above (below) it. Other funds were supposed to ride the market (2016: p. 2). They sold (bought) corporate bonds when their price decreased (increased). The rest of the funds were passive (2016: p. 3). They invested a fixed fraction of the wealth they managed in corporate bonds. In the end, the price of corporate bonds was set by the market maker according to the law of supply and demand (2016: p. 3).

Once calibrated, the ABM served to account for overshoot in corporate bond prices. The ambition, the method, and the result were presented on Bank's Underground, the blog of the

BoE.[26] "In a novel application of agent-based modelling, [Braun-Munzinger et al examined] how investors redeeming the corporate bonds held for them by open-ended mutual funds [could] cause feedback loops in which bond prices [felt] further, posing risks to financial stability." Their method consisted of introducing shocks on funds' expected loss rate, and to run simulations. Whenever funds expected more companies to fail, they demanded higher yields. Feedback loops followed. "Initially, yields [increased] as value traders [rebalanced] their portfolios, with momentum traders following the increase in yield. Eventually, the yield overshoots what value traders [believed] it to be worth, so they [began] to buy again, reversing the yield increase. Momentum traders now [intervened] in the opposite direction, pushing yields down further. These events [contributed] to the swings which eventually [settled] to the new stable yield."

In addition to replicating feedback loops, the ABM also served to test the effects of macroprudential policies. To be more specific, Braun-Munzinger et al were interested in determining the effects of introducing longer redemption periods. "They ran simulations in which redemptions were split over 20 trading days rather than taking place on a single trading day. [They] then compared the maximum dislocation in yield for redemptions over simple day versus redemptions over 20 trading days". They found out that when redemption took place over longer periods, fluctuations of the corporate bond price were dampened. Moreover, the stronger the shock on funds' expectations, the stronger the dampening effect. Spreading redemptions over longer periods of time was therefore more efficient during stress.

An ABM of flash crashes

When Kårvik et al started to work together, the FPC was concerned about the electronification of markets. In particular, it was concerned about what appeared to result from automated and high frequency trading: flash crashes –i.e., episodes during which large and rapid adjustments in the price of an asset occurred, without any change in economic fundamentals. This is clear from the Financial Stability Report of November 2017. The FPC argued that "the growth of electronic and automated trading [had] given rise to a series of flash episodes" (Financial Stability Report, 2017: p. 50). Examples included US equities (6 May 2010), US Treasuries (15 October 2014), and the sterling-US dollar exchange rate (7 October 2016). According to the FPC, flash episodes had not posed risks to financial stability yet. This was "because they had

[26]The post can be found on Bank Underground, https://bankunderground.co.uk/2016/08/16/forming-strong-bonds-dynamics-in-corporate-bond-markets/.

been short-lived, and prices [had stabilized] relatively quick" (Financial Stability Report, 2017: p. 50). However, the situation could change. In particular, flash crashes could last longer in the future. In this case, losses could test the resilience of financial institutions. The FPC concluded that it was wise to monitor the development of "fast markets," particularly in the light of the flash episode in the sterling exchange rate (Financial Stability Report, 2017: p. 51).

In 2018, Kårvik et al modeled a fast market. On the one hand, asset trading was somehow automated in their ABM. Each agent was supposed to follow "predetermined trading rules in a manner analogous to how algorithmic trading [behaved] in reality" (2018: p. 2). Kårvik et al assumed that a "fundamental trader bought (sold) if market prices [were] lower (higher) than its estimate of fundamental value"; that a "momentum trader bought (sold) if prices [had] been rising (falling)"; that a "noise trader traded with a random size in a random direction"; and that two "market makers earn "profits from buying at the bid price and selling at the ask" (2018: p. 7). On the other hand, Kårvik et al sought to model high frequency trading. Within their ABM, market makers had different frequencies of exchange. "One market maker [traded] at a high frequency […] while the other [traded] at a low frequency" (2018: p. 6). This meant that, on average, the "fast" market maker traded more than the "slow" market maker. In the same spirit, Kårvik et al considered that the momentum trader could either trade at a high frequency or a low frequency (2018: p. 6).

Once calibrated, the model served to determine how and to what extent high frequency trading contributed to flash crashes (2018: p. 17). Kårvik et al showed that flash crashes emerged endogenously in their ABM. "An initial movement in market price [led] to a reduction in risk taking by high-frequency market makers, who [withdrew] their provision of liquidity in order to reduce the risk of being adversely selected by market participants with information about the true price of the asset. At the same time, other high-frequency traders [consumed] liquidity by selling securities into already falling markets. This [led] to a rapid and self-fulfilling reduction in price, which [took] place at a horizon shorter than that over which lower-frequency traders [could] step to return prices to a level commensurate with fundamentals" (2018: p. 4). Then, Kårvik et al showed that the greater the frequency of exchange, the higher the prevalence of flash crashes. This was because a high frequency of exchange tended to give more weight to the procyclical behavior of the market maker and of the momentum trader (2018: p. 19).

Last but not least, Kårvik et al used their model to test the effects of macroprudential policies. They were interested in evaluating "the degree to which the introduction of circuit

breakers – that is, mandated trading halts that [came] into effect after a price move of a given magnitude – might curb the frequency and/or the severity of flash episodes" (2018: p. 20). They found out that circuit breakers not only reduced the severity but also the prevalence of flash crashes.

In a nutshell, the ABM of flash crashes was used in the same way as the other two ABMs. It met concerns raised by the FPC, explained positive feedback loops in asset prices, and tested the effects of macroprudential tools. This has two implications. The first implication relates to how ABMs informed the BoE's macroprudential policy. No ABM could account for the propagation of financial stress in the banking system. Banks were not incorporated either in the ABM of the corporate bond market nor in the ABM of flash crashes. At the same time, there was only one bank in the ABM of the housing market, and it could not go bankrupt.[27] Therefore, ABMs could not be used to perform stress tests. It follows a limited capacity of use in the area of macroprudential policy. The second implication is more straightforward. No ABM could inform the BoE's monetary policy or its interaction with the macroprudential policy. The real sector was neither represented by the ABM of the corporate bond market nor by the ABM of flash crashes. Besides, the interaction between the real and financial sectors was limited in the ABM of the housing market. Baptista et al (2016) showed how household indebtedness contributed to house price inflation. However, they did not analyze the evolution of the general price level. The model did not allow it. By assumption, households chose how much to consume. But "the only effect of consumption [was] to determine household wealth, which in turn [affected] the downpayments and available mortgages" (2016: p. 14). There was no aggregate demand. At the same time, neither firms' behavior nor the market for goods were formalized by Baptista et al (2016). Under these circumstances, the model could not track how credit restrictions reduced aggregate demand and lead inflation to undershoot the target. Hence why it could not serve to address monetary policy or its interactions with the macroprudential policy.

4. Expanding the use of ABMs

Baptista et al acknowledged the limits of their ABM (2016: p. 40). But they did not leave the matter there. The ABM of the housing market was under review after 2016. The goal was to

[27] Baptista et al explained that "because their model [did] not seek to capture bankruptcy dynamics (such as default and foreclosure), [they] ensured that payments [were] always made by artificially injecting as much as necessary to the bankrupt households" (2016: p. 10).

test the effects of more macroprudential policies. Likewise, other BoE's economists including Haldane sought to expand the use of ABMs. In total, three projects can be distinguished.

4.1 Three projects

On 27 June 2018, Hinterschweiger and Uluc presented their ABM in a seminar organized at the Organization of Economic Cooperation and Development (OECD).[28] At the end of the presentation, the Economic Counselor of the German Delegation asked why they did not consider banking competition. Hinterschweiger explained that it was due to the original scope of the project. At first, the team was interested in determining the role of households in housing cycles. However, the project had evolved. At that time, Hinterschweiger indicated that the introduction of banking competition was on the agenda. This would allow to have a better framework for analyzing financial crises, and to address the coordination between different macroprudential policies. Hinterschweiger explained:

> As you may know, the Financial Policy Committee has the power to set sectoral capital requirements on mortgages in the UK. [The model could be used to explain] what happens if you have a loan-to-value policy and a sectoral capital requirement on banks, [and] how do they interact.

Then, there was a project to use agent-based modeling to conduct stress tests. The project was part of a strategy outlined in "The Bank of England's approach to stress testing the UK banking system" (2015). To better assess the resilience of the UK financial system, the BoE sought "to develop its capability to model system-wide dynamics, including amplification mechanisms and spill-overs" (2015: p. 6). It was a challenging task. "Models of interactions between some parts of the financial system [existed, but they were] in their infancy and [were] not readily adaptable for use in a forward-looking stress-testing context" (2015: p. 31). At the same time "models [needed] good data and there [were] gaps in the data on interlinkages between different parts of the financial system (2015: p. 31). Therefore, the BoE supported empirical and theoretical research in the area of system-wide stress testing (2015: p. 31).

In this context, BoE's economists considered the use of ABMs. Two groups can be distinguished. On one side, there were Yuliya Baranova, Jamie Coen, Pippa Lowe, Joseph Noss,

[28] The seminar was organized by the OECD's New Approach to Economic Challenges Initiative. To access its record, see http://www.oecd.org/naec/events/new-analytical-tools-and-techniques/policies-for-housing-market-newinsights-from-an-agent-based-model.htm.

and Laura Silvestri. In their view, agent-based modeling could be used to incorporate investment funds into the current BoE's stress-test model. In particular, it could be used to feature heterogeneity among investment decisions (Baranova et al, 2017: p. 10). In parallel, a different research strategy was pursued at the BoE. The Bank joined forces with the Institute for New Economic Thinking (INET) to develop a brand-new framework. Baptista, Farmer, Alissa Kleinnijenhuis, Thom Wetzer, and Paul-Nahai Williamson led the project. Their goal was to conduct stress-tests in a framework combining network analysis with agent-based simulations (Baptista et al, 2017: p. 3).[29]

Last but not least, there was a project to use ABMs in the monetary policy process. The project has never been expressed in an explicit manner. But it transpires in the articles Haldane and Turrell devoted to agent-based modeling. In every article, Haldane and Turrell made the case for a broader use of ABMs in policy making. The area of monetary policy was no exception. On one side, Haldane and Turrell claimed that ABMs could be used to inform monetary policy. Academic works proved it. Haldane indicated that Dosi et al (2015) used an ABM "to study the effects of fiscal and monetary policies" (2016: p. 19). In the same spirit, Haldane and Turrell stressed that Popoyan et al (2017) used an ABM to "explore the interdependence between macroprudential regulation and monetary policy" (2017: p. 16; 2019: p. 52). On the other side, Haldane and Turrell explained that monetary policy was a relevant area of application for agent-based modeling. In 2016, Haldane drew a parallel between the practice of monetary policy and the features of ABMs. "Rather than solving a complex inter-temporal trade-off, monetary policy in practice [seemed] to mimic simple rules of thumb […] In ABMs, the behavior of agents [was] characterized not by Euler conditions, but by behavioral rules of thumb" (p. 23). Besides, Haldane and Turrell argued that ABMs could be used to address the effects of heterogeneity on monetary policy transmission (2017: 16; 2019: p. 54). It followed good reasons to incorporate ABMs into the toolkit of the Monetary Analysis Directorate.

4.2 Three challenges

The three projects face common challenges. The first concerned coding. Expertise in computer programming is central to the development of ABMs. Hinterschweiger acknowledged it during the seminar at the OECD:

[29] See: https://www.banxico.org.mx/publicaciones-y-prensa/seminarios/network-models-and-stress-testing-for-financial-st/%7B53ED5883-862C-573C-0C03-EC88568F509E%7D.pdf.

> What we discovered quite soon was that we needed programing expertise: how do you code the model, how do you implement the code, how to make sure that it is running in a reasonable amount of time (because you can create [a model] that takes days to run).

Of course, the bigger the model, the more difficult it is to code. This was the problem posed by the introduction of banking competition into the ABM of the housing market. Adrian Carro, a new collaborator from INET, explained:

> In order to have competition [between banks], you need a diversity of mortgages [which] adds a certain degree of complexity to the code.

Therefore, the challenge was to contain the complexity of the code without sacrificing the realism of the model. The same applied in the other two projects.

The second challenge concerned calibration. Calibrating ABMs is a difficult task. On one side, it requires to have a lot of micro-level data. This is because ABMs usually involve a large number of parameters. For instance, more than fifty parameters composed the ABM of the housing market (Baptista et al, 2016: p. 50). On the other side, calibration poses computational complexity. Kårvik et al explained:

> [Calibration] is achieved by maximizing the 'joint coverage ratio' – a technique proposed in Franke and Westerhoff (2012) […] This criterion finds parameters values that maximize the proportion of simulated price series for which the above moments of the simulated series of prices fall within 98% confidence intervals of their empirical counterparts. This is achieved by means of a numerical grid search over a feasible bounded set of parameters (2018: p. 13).

They added in a footnote:

> Whilst this may not ensure a globally optimal solution, it is necessary to keep the computational burden manageable (2018: p. 13).

Limiting the number of parameters is therefore necessary to implement the calibration method.[30] The more parameters that need to be calibrated, the more difficult it is to determine

[30] There are other calibration methods. Haldane and Turrell referred to "techniques based on vector autoregressions and machine learning" (2017: p.19; 2019: p. 55). However, the most common approach is Franke and Westerhoff's (2012).

which values maximize the joint coverage ratio. Calibration may even become impossible. Therein lay the second challenge. Each project implied to build large ABMs. The problem was that the larger the model, the higher number of parameters.

Finally, each project had to face resistances *vis-à-vis* agent-based modeling. It is particularly true with the project to use ABMs in the monetary policy process. Here is how Monti reacted when I asked her about the potential use of ABMs by the Monetary Policy Committee (MPC):

> The narrative is one of the key elements of the forecast, and one that the MPC considers absolutely crucial. ABMs are not able to provide a coherent well understood story, where the drivers and the mechanisms of the dynamics are clear. It is also not clear how to do policy analysis with ABMs. While I wouldn't argue that DSGE models are immune to the Lucas critique, they have a clear definition of deep, policy invariant, parameters. It's hard to argue (in my view) that the decision rules in ABMs are plausibly policy invariant.[31]

One cannot claim that Monti's reaction is representative of what economists and policymakers think about ABMs in the MPC. But Monti contributed to inform the BoE's monetary policy. More importantly, she contributed to elaborate the "suite of models" used in the monetary policy process (Burgess et al, 2013). Therefore, Monti's reaction is worth considering. It shows the difficulties Haldane and Turrell could have to convince their colleagues to use ABMs in the monetary policy area.

Monti raised the issue of the structure of ABMs. But their use in policy making posed other problems. Tanaka gave me a list:

> There are issues in using ABMs for policy analysis: 1. ABMs are not nearly as far along as neoclassical models in terms of a consolidated body of accepted theory and supporting empirical evidence. To be a tool for policy recommendation, the model needs to be plausible and convincing, and there needs to be empirical evidence to back it up. Many ABMs are not sufficiently tested on empirical data. 2. They have many parameters (typically dozens) that are often difficult to calibrate. 3. Results will depend on the choice of initial condition, which is not easy to pick. 4. ABMs are based on behavioral rules that

[31] E-mail of 23 July 2019.

> are often arbitrary. 5. Black box: ABMs quickly get very complex, and it can be very hard to understand which model ingredient drives the main results. As a result it is often difficult to identify clear transmission mechanisms within ABMs. 6. On forecasting they do not perform as well as other classes of models (DSGEs and VARs).[32]

For all these reasons, it could be difficult to expand the use of ABMs at the BoE. The third and last challenge was therefore to convince BoE's economists of the benefits of adding ABMs into their toolkit.

5. The fate of ABMs at the BoE

The context is favorable to the deployment of ABMs. The 2008 crisis revealed the weaknesses of mainstream tools like DSGE or VAR models. In 2015, Carney claimed that "during its depths, the lessons of history and insights from psychology were more valuable than precisions of dynamic programming. Our workhorse models didn't have financial sectors; meaning questions of financial stability were not even asked, let alone answered" (p. 2). Likewise, in 2016, Haldane argued that DSGE models "offered a spectacularly poor guide to the economy's dynamics around the time of the global financial crisis" (p. 7). Strong criticisms therefore emerged from the top of the BoE's hierarchy. At the same time, experts in DSGE modeling started questioning their tool. It happened to Jesper Lindé, Frank Smets, and Rafael Wouters in "Challenges for Central Banks' Macro Models" (2016). While discussing the progress made by the post-crisis generation of DSGE models, they claimed that: "extensions [went] some way in accounting for features of the Great Recession and its aftermath, but they [did] not suffice to address some of the major challenges associated with the use of non-standard monetary policy and macroprudential measures" (2016: p. 1). Under these circumstances, it has become harder to refuse insights from other methodologies or disciplines. At the BoE, the use of machine learning is a case in point. This "econometrics from computer scientists" was used to predict the UK inflation rate and to model financial distress propagation.[33] Just like DSGE or VAR models, machine learning therefore served to inform the BoE's monetary and financial stability policy. Why this could not happen to ABMs?

[32] E-mail of 6 July 2019.

[33] For more information, see "Machine learning at central banks" (Chakraborty and Joseph, 2017). See also: https://bankunderground.co.uk/2017/11/10/new-machines-for-the-old-lady/

The development of big data could help. More and more data are created every day. Most of it comes from social media and from internet research. For instance, it is estimated that 40000 searches are performed every second on Google. This amounts to 1,2 trillion search per year.[34] Of course, not all the data is of interest to policymakers. But part of it could be, notably in the monetary policy process. This was stressed by Haldane, in "Will Big Data Keep Its Promise?" (2018). Haldane indicated that "the UK Office for National Statistics [was] exploring the use of 'web scraping' to complement existing price collection methods. The ONS [had] so far collected 7000 quotes per *day* for a group of grocery items, which [was] larger than the current *monthly* collection for those items in the CPI [Consumer Price Index]" (2018: p. 6). Since the creation of the AA Division, the BoE has had in-house skills to tap into such data. Moreover, the BoE is improving its storage capacity. This was indicated by Bholat during an interview with *Central Banking* (2018). When the Report Editor asked: "Do you use service clouds?", Bholat replied: "Not yet, but we are about to – we are on the process of undertaking a project on the cloud" (2018). Under these circumstances, BoE's economists will have the capacity to access more and more micro-level data. The calibration of ABMs might therefore become easier in the future.

Last but not least, hardware and software are also improving. Turrell made this point during a conference, "Heterogenous agents and agent-based modeling: the intersection of policy and research" (2017).[35] "We heard yesterday about a simulation which involved 120 million agents to reproduce the whole of the US economy. [It implies that] supercomputers are available in some universities. [Besides] I think software has seen the most amazing revolution in the last few years. I mean, it's amazing how many of the projects we talked about yesterday used Python. I love Python. If I think in the coding time that switching to [Python] has saved me compared to when I used to write agent-based models in C++, it is truly astonishing!" Constraints in the elaboration of large ABMs are therefore decreasing.[36] For all these reasons, a broader use of agent-based modeling can be expected at the BoE.

However, it will require additional investments in research. On one side, the construction of granular datasets is a time-consuming process. Bholat explained: "I would say

[34] See https://hostingtribunal.com/blog/big-data-stats/ (consulted on 16 June 2020).
[35] See http://people.brandeis.edu/~blebaron/agentConference/Turrell/Turrell.html.
[36] According to Turrell, developments of artificial intelligence could also allow ABMs to be immune to Lucas's (1976) critique: "Advanced artificial intelligence could make agent-based models more Lucas-critique proof by having agents respond realistically to new circumstances. A glimpse into what is possible in this respect was given recently when an artificial intelligence repeatedly beat a trained fighter pilot in an air-to-air combat simulation – an extremely demanding scenario for a computer" (2016: p. 184).

probably 50% of a data scientist's job is trying to clean up the datasets, whether naturally numerical or text-based. Obviously, if it's text there's a whole process by which you need to convert those words into numbers prior to doing the analysis, but even with regulatory return data you have to perform validity checks and possibly infer missing values" (2018). Therefore, more data will be available if the BoE hires data scientists or invests in a technology to automate the data cleaning process (2018). On the other side, expertise in computer programming is needed. Turrell explained: "No matter how good the software is, you need to have some programing skills to use it […] Actually, I have people who e-mail me all the time at the Bank and say 'Oh, I think that an agent-based model might be quite good for this'. But they just have no programing experience, and that is a real big barrier" (2017). Therefore, the bank will either need to hire staff with programming skills or to outsource the activity.

So far, the BoE has sponsored the use of ABMs in the financial stability area. The most recent outcome is a system-wide stress testing model (Farmer et al, 2020). However, there was nothing comparable in the monetary policy area. Nothing concrete happened since Haldane and Turrell called for a broader use of agent-based modeling. Therefore, the ABMs' capacity to breach the walls of the MPC remains uncertain.

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