USING AGENT-BASED MODELING TO ASSESS THE IMPLICATIONS OF CHANGING LIQUIDITY CONDITIONS

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ABSTRACT

The Great Recession (2007-2009) and reverberating effects during the global financial crisis had profound impacts on the US Federal Reserve system, especially the Federal funds market. In response to the financial crisis, the Federal Reserve took unprecedented action, along with other major central banks. In particular, the Fed responded by lowering the target Federal funds rate, providing credit to financial institutions, and eventually engaging in a series of large-scale asset purchase programs comprising quantitative easing (QE). As the Federal Reserve seeks to unwind its positions, the impacts of monetary policy normalization are a matter of wide-ranging debate. Clearly, the US Federal Reserve will continue to use traditional economic models to better understand unfolding challenges and evaluate proposed policy alternatives. This paper looks at adding agent-based modeling and simulation to the toolkit. In particular, a combination of coarse-grained and fine-grained models are used to simulate monetary policy normalization.

Keywords: agent-based modeling (ABM), financial crisis, monetary policy, quantitative easing (QE).

1 INTRODUCTION

The Global Financial Crisis of 2008 and reverberating effects during the Great Recession had profound impacts on financial markets and the monetary system. In response to the crisis, central banks around the world took unprecedented action in order to ease financial conditions. In the US, the Federal Reserve (Fed) responded by providing credit to financial institutions, lowering interest rates (through the target federal funds rate), providing additional forward guidance, and eventually engaging in a series of large-scale asset purchase programs known as *quantitative easing* (QE). As a result, the Fed's balance sheet has undergone a more than five-fold increase since the start of the crisis, with total assets growing from roughly $850 billion to more than $4.5 trillion and banking reserves expanding from $20 billion to more than $2 trillion. At this point, the Federal Reserve has embarked on a program of *monetary policy normalization* which implies an unwinding of these extraordinary positions.

The impact of this new phase of monetary policy normalization is a matter of wide-ranging debate. While the Fed has acted cautiously and been quite transparent about its gradual approach toward reducing the balance sheet, significant uncertainty around the effects of the unwind remains. The exact impact on financial markets and institutions depends on the actions (and reactions) of all financial system participants. Policy normalization will unfold from a unique starting point, at a time when the US Treasury is embarking on a significant fiscal stimulus program and within a new untested regulatory environment. There is little or no historical precedent to inform policy makers about the range (and likelihood) of possible scenarios. So, debate is understandable, but what tools are available to help us evaluate policy alternatives?

Clearly, the US Federal Reserve and counterparts around the world will continue to use existing models to better understand unfolding challenges and evaluate proposed policy alternatives. This paper looks at adding agent-based modeling and simulation to the toolkit. We present a hierarchy of agent-based models to assess the implications of the reserve drain resulting from the unwind of the Fed's balance sheet.

- A sectoral (aggregate) flow-of-funds model (FED) explores the speed with which banking reserves are expected to decline, based on the Fed's communicated System Open Market Account (SOMA) portfolio unwind plan and using basic portfolio assumptions across all sectoral agents (including the US Treasury, GSEs and foreign central banks).
- The sectoral flow-of-funds model is combined with more granular agent-based models, such as the US banking sector (BNK) in order to analyze the impact of the decline in reserves on banks. The granular bank model implements basic actions (and constraints) for banks and non-bank private sector agents and focuses on the emergence of stress triggered by liquidity constraints and signaled through interbank lending activity (Fed funds market). We use regulatory balance sheet data to model the many types of banks and associated business models that influence decision making. A similar granular approach is focused on foreign central banks.

The overall goal is to develop agent-based models that support simulation as a complement to traditional economic models for policy evaluation. In our view, agent-based approaches are particularly well-suited for modeling financial markets, which are typically complex ecosystems of heterogeneous agents. Agent-based modeling uses simulation, based on the interactions of many individually instantiated autonomous agents, to generate the emergent behaviors associated with complex systems (and hopefully inform theory). For a persuasive and much more expansive case for agent-based modeling, see Richard Bookstaber's book *End of Theory* (Bookstaber 2017).

2 MONETARY POLICY NORMALIZATION, THE FED'S BALANCE SHEET AND LIQUIDITY CONDITIONS

The past decade of accommodative monetary policy has contributed to lower interest rates, a reduction in financial risk premia and a significant increase in macro liquidity (as measured by the monetary base). While it is generally assumed that the shift to a restrictive stance will have an opposing effect on all three variables, discussions among market participants initially focused on the implications for interest rates and risk premia.

As the Fed unwinds the assets on its balance sheet through maturing US Treasury debt and agency mortgage-backed securities, other investors will have to step in and finance the debt roll over. When private sector agents (banks and non-bank entities) finance assets rolling off the Fed's balance sheet, bank reserves are reduced.

While the Fed's balance sheet unwind will (ceteris paribus) lead to a significant reduction in the level of reserves, it is important to note that the level of banking reserves is affected by additional dynamics, unrelated to the Fed's balance sheet unwind. Over any given period, a reserve drain occurs when there is a net flow of funds from the private sector (banks and non-bank entities) to non-private sector agents, which include the US Treasury, foreign central banks and other entities that maintain deposit accounts at the Federal Reserve (participating in the FEDWIRE payment system). We intend to analyze the effect of the Fed's balance sheet unwind within the broader context of these dynamics, including the effects of the following forces.

- *Fiscal policy*: The US Treasury's fiscal stimulus program is expected to have a significant impact on liquidity, affecting the overall level of liquidity as well as its distribution across financial system participants.
- *Monetary policy*: In addition to the SOMA portfolio unwind, banking reserves are impacted by changes in private sector "Reverse Repo Program" balances (RRP). Furthermore, increases in the amount of currency in circulation (keeping pace with GDP growth and other sources of increased currency demand) are offset by decreases in bank reserves.
- *Foreign central bank* reserve portfolio management is also a factor, as impacted by the dynamics of global trade and the relative performance of foreign economies.
- Finally, the impact of declining reserves on wider financial conditions is a function of the many portfolio balancing decisions made by *private sector agents* (including banks and non-bank entities). This sector is made up of a large number of individual entities with very different business models, a natural fit for agent-based modeling and simulation (at a more granular level).

In combination with the Fed SOMA portfolio unwind, the first three items affect the speed with which reserves leave the system. Associated dynamics are incorporated in the coarse-grained sectoral flow of funds (FED) model. The implications of private sector agent decisions are modeled through the granular banking (BNK) model, which aims to analyze the emergence of stress triggered by liquidity constraints and signaled through interbank lending activity (in the Fed funds market). Given the uncertainty around the banking sector's need for reserves in the new regulatory environment, it is anticipated that regulators will be closely monitoring developments in interbank lending markets in order to detect clues about banks' underlying demand for reserves. One of the critical indicators of stress can be found in the Fed funds market, where banks interact to borrow and lend excess reserves. As noted by analysts at Goldman Sachs in a recent report, monitoring buildup of stress may turn out to be somewhat complicated in practice as "The Fed will want to end the normalization before reserves become scarce to maintain a precautionary buffer that ensures the floor system remains effective as both banks' need for reserves and the volume of non-reserve liabilities fluctuate." We posit that agent-based simulation methods can provide valuable perspective here, as they allow us to project the timing and circumstances of systemic stress buildup due to reserve draining.

3 PRIOR WORK

Financial networks have been the subject of multiple research studies in the recent past. The global crisis of 2008 put banking networks under some scrutiny and many research studies have been conducted to study them in the past decade (Haldane and May 2011, Cont, Moussa, and Santos 2010). Though, theoretical researchers have studied inter-dependencies between financial institutions, not a lot of empirical studies have been conducted in this area. The absence of empirical evidence poses a significant issue for regulatory agencies developing new policies, highlighting the need for further studies (Furfine 2003). This has led many researchers to employ simulation as a method to study issues in this domain (Elsinger, Lehar, and Summer 2005).

Contagion in financial networks is one area which has been studied using simulation as a methodology. Simulation studies have been conducted to stress test different aspects of the networks, some of them have focused on the stability of the network in the face of an external shock (Huang, Zhuang, Yao, and Uryasev 2016, Nier, Yang, Yorulmazer, and Alentorn 2008, Ashcraft and Duffie 2007, Chakraborty, Gaeta, Dutta, and Berndt 2017); whereas other studies have focused on the role of network structure on stability (Cont, Moussa, and Santos 2010, Haldane and May 2011, Boss, Elsinger, Summer, and Thurner 4 2004, Markose, Giansante, and Shaghaghi 2012). Haldane et al. (Haldane and May 2011) discuss the systemic risk in the banking ecosystem, focusing on the various financial instruments that were used during the financial crisis to optimize returns while minimizing risks. Drawing analogies between the dynamics of banking networks and that of contagions (as infectious diseases spread throughout a population); the complexity and stability of these networks have been tested in further studies. Rama Cont et al. (Cont, Moussa, and Santos 2010), for example, emphasizes how network structure plays a role in protecting against the spread of crisis behaviors. Michael Boss (Boss, Elsinger, Summer, and Thurner 4 2004), using a similar approach, tested out network structure and alternative interbank network topologies.

Our research focuses on applying agent-based modeling and simulation to the Federal funds market. The study begins to showcase how we can use these simulations as a tool to evaluate future policies that the Federal reserve can implement during balance sheet normalization.

4 THE FEDERAL RESERVE, MONETARY POLICY AND THE FED FUNDS MARKET

The US Federal Reserve System (Fed) was established through the Federal Reserve Act of 1913 to provide the nation with a safer and more flexible financial system. As such, the Fed is responsible for the conduct of monetary policy (focused on the dual goals of stable prices and maximum employment) and ensuring the stability of the financial system (as well as the safety and soundness of individual institutions). In its conduct of monetary policy, the Fed targets the level of interest rates in money markets, which are an essential part of the "plumbing" of the financial system (Chalermchatvichien, Jumreornvong, Jiraporn, and Singh 2014). Money markets are wholesale markets for low-risk, short-term IOUs. They operate as networks of banks and non-bank financial intermediaries who borrow and lend amongst themselves for relatively short maturities. Under normal market conditions, money markets exhibit high liquidity and transaction volumes.

Within money markets, the Fed's main operational target is the Federal funds rate, the overnight interest rate at which banks (and other eligible institutions) lend reserve balances (deposits kept at Federal Reserve banks) to each other in the Fed funds market. In guiding the Fed funds rate to its target level, the Fed historically has used *open market operations* which change the amount of reserves in the system (altering the supply). Open market operations rely on two key features: reserve requirements and reserve scarcity (Carpenter, Demiralp, Ihrig, and Klee 2015).

Reserve requirements create demand for Federal Reserve balances as banks are required to hold a fraction of their deposits in reserves at the Fed. The Fed controls the supply of reserves and generally has kept overall reserve balances scarce, fostering an active interbank lending market and allowing the Fed to affect the market-determined level of the Fed funds rate by making small changes in the supply of aggregate reserves. Figure 1 highlights the scarcity of reserves prior to 2007, with excess reserves (the amount by which the total available reserves exceed required reserves) hovering below $2 billion USD.

In 2007/2008, the US financial system faced an imminent crisis which required an aggressive response from the Federal Reserve. The Fed responded by lowering the target Federal funds rate and providing credit to

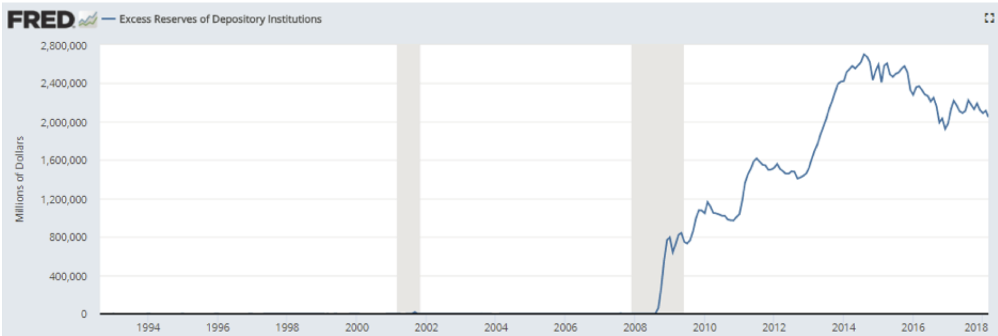

Figure 1: Excess reserves of depository institutions (source: Federal Reserve).

financial institutions. When the Fed funds rate reached its zero lower bound, the Fed expanded its operational framework to include "non-conventional" measures, including forward guidance and the implementation of large-scale asset purchase programs (or QE). The unconventional policy measures aimed at providing additional monetary accommodations by putting downward pressure on longer-term interest rates. While the Federal Reserve maintained an accommodative monetary policy, significant new regulations were enacted to strengthen the liquidity and solvency of financial institutions.

The Fed's QE programs led to an abundant supply of new reserves. Figure 1 clearly shows that post 2008, excess reserves increased from $2 billion USD to more than $2.6 trillion USD. With reserves no longer scarce, the fundamental structure of the Fed funds market changed and the Fed was required to implement new tools for its conduct of monetary policy. In December 2015, the Fed started the process of monetary policy normalization by raising its short-term interest rate target. In a world without reserve scarcity, traditional open market operations are no longer effective and the Fed resorted to paying depository institutions *interest on excess reserves* (IOER).

In October 2017, the Fed embarked on the second leg of its monetary policy normalization efforts, aimed at reducing the overall size of its balance sheet. The Fed laid out a gradual approach to reducing its balance sheet, using phased out re-investment of maturing positions in its Treasury and agency debt portfolio. As the Fed pares down its balance sheet, portfolio maturities that are refinanced by the private sector trigger an equivalent decrease in the amount of reserves in the system. The expected draining of excess reserves will proceed in a regulatory environment that is significantly different from the pre-crisis era.

4.1 Pre-Crisis Monetary Policy

In the years leading up to the crisis, the Fed operated a balance sheet under $900 billion. Table 1 includes a high-level view of the Fed's balance sheet as of January 25, 2007. At that time, the Fed's securities portfolio stood at $797.5 billion ("Securities"), with total banking reserves at $6.25 billion ("Reserves").

Table 1: Federal Reserve balance sheet as of January 25, 2007, numbers in million USD (source: Federal Reserve, https://www.federalreserve.gov/releases/h41/20070125/, with analysis by authors).

Assets		Liabilities	
Gold, SDR	$13,241	Currency	$803,339
Securities	**$797,487**	**Reserves**	**$6,248**
Loans	$319	Other Deposits	$12,366
Other	$77,561	Reverse Repo	$29,410
		Capital	$37,245
Total	$888,608	Total	$888,608

In this environment of scarce reserves, the Fed conducted monetary policy through open market operations, increasing reserves when targeting a lower Fed funds rate (decreasing reserves when targeting a higher rate). In its open market operations, the Fed adds to (sells from) its securities holdings, leading to an increase (decrease) in banking reserves. Table 2 includes a schematic overview of the impact of open market operations on the balance sheets of the main entities (including the Fed, the banking sector and the public or non-bank private sector). We highlight major balance sheet changes that occur when the Fed targets a decrease in the Fed funds rate and sells Treasury Notes ("UST") to reduce the amount of reserves.

Table 2: Illustrative balance sheet changes following Fed open market operations aimed at raising Fed funds rate through lowering supply of reserves (the public is assumed the ultimate buyer of Treasury notes).

Federal Reserve		Banking Sector		Non-Banking Private Sector	
Assets	Liabities	Assets	Liabities	Assets	Liabities
UST -$100	Reserves -$100	Reserves -$100	Deposits -$100	Deposits -$100 UST +$100	

4.2 Crisis Response: Quantitative Easing (QE)

Three successive rounds of QE led to a dramatic expansion of the Fed's balance sheet. Table 3 highlights the size and composition of the Fed's balance sheet as of September 28, 2017. Note the increase of the balance sheet to $4.5 trillion, with securities holdings at $4.4 trillion and reserves at $2.2 trillion.

Table 3: Federal Reserve balance sheet as of September 28, 2017, numbers in million USD (source: Federal Reserve, https://www.federalreserve.gov/releases/h41/20170928/, with analysis by authors).

Assets		Liabilities	
Gold, SDR	$16,241	Currency	$1,578,950
Securities	**$4,395,596**	**Reserves**	**$2,212,709**
Loans	$233	Other Deposits	$263,039
Other	$98,412	Reverse Repo	$407,683
		Capital	$48,101
Total	$4,510,482	Total	$4,510,482

The impact of quantitative easeing (QE) on balance sheets of the various entities is outlined in Tables 4 (assumes the banking sector is the ultimate seller of securities) and 5 (assumes the public or non-banking private sector as the ultimate seller). Note: Table 5 essentially reverses the flows found above in Table 2.

Table 4: Illustrative balance sheet changes resulting from QE (banking sector is assumed the ultimate seller of Treasury notes to the Fed).

Federal Reserve		Banking Sector		Non-Banking Private Sector	
Assets	Liabities	Assets	Liabities	Assets	Liabities
UST +$100	Reserves +$100	Reserves +$100 UST -$100			

5 THE FEDERAL RESERVE SYSTEM MODEL (FED)

The coarse-grained FED model includes the major participants in the Federal Reserve system. All entities that maintain USD accounts at the Fed (i.e. entities holding Fed issued deposits), as well as the non-banking private sector are modeled using five representative agents. In addition to the Federal Reserve itself, the model includes agent classes for the US Treasury, banking sector, non-banking private sector (including the general public), GSEs and foreign central banks. One objective of our model is to accurately implement the mechanisms that result in changes to the balance sheets of these market participants. To that end, the

Table 5: Illustrative balance sheet changes resulting from QE (non-banking private sector, or the public, is assumed the ultimate seller of Treasury notes to the Fed).

Federal Reserve		Banking Sector		Non-Banking Private Sector	
Assets	Liabities	Assets	Liabities	Assets	Liabities
UST +$100	Reserves +$100	Reserves +$100	Deposits +$100	Deposits +$100 UST -$100	

model includes simplified balance sheets and behaviors for each of these agents and captures the resulting aggregate flow of funds. This coarse-grained model (FED) is combined with a fine-grained banking model (BNK) to create a high-fidelity hierarchical model of the Fed funds market. The outline below lists all the agent classes used in the FED model.

- **Federal Reserve:** Currently a single agent represents the Federal Reserve, or more accurately the aggregate balance sheet, even though there are a dozen individual Federal Reserve district banks spread across the country.
- **US Treasury:** The Treasury is also represented as a single agent, which maintains a deposit account at the Federal Reserve and issues Treasury bonds. All the Treasury's publicly issued bonds are held by the agents in the coarse-grained model: Fed, banking sector, non-banking private sector, GSEs and foreign central banks.
- **Banking Sector:** This serves as a high-level aggregate representative bank covering domestic banks as well as subsidiaries and affiliates of foreign banks. Basically, a single agent is used to present a unified balance sheet in the coarse grained model. When coupled with the fine-grained bank model, this aggregate banking sector captures otherwise unspecified banks (the remainder in the sector).
- **Non-Banking Private Sector:** This is a single agent that represents the general balance sheet of all non-bank private sector entities (here "the public"). As outlined above, net new purchases of US Treasury notes by the public have a significant impact on the banking sector as they result in a loss of reserves but also an overall contraction of the banking sector (loss of valuable client deposits). Net new purchases of US Treasuries by the banking sector do not lead to a contraction of banking sector balance sheets, but changes the composition of bank assets (reserves for US Treasury notes).
- **Government-Sponsored Enterprises (GSEs):** This serves as a high-level aggregate agent covering the various government sponsored enterprises that hold accounts at the Fed. GSEs include mortgage agencies (Fannie Mae, Freddie Mac and Ginnie Mae) and Federal Home Loan Banks (FHLBs).
- **Foreign Central Banks:** This serves as a high-level aggregate agent covering all various foreign central banks holding accounts at the Fed. Similar to the banking sector and GSE coarse-grained agents, the central bank agent captures the aggregate behavior of any central bank not individually specified in the fine-grained model.

The simplest version of this model implements these six agent classes: the Federal Reserve, the US Treasury, regulated banks, the public (or non-banks), GSEs and foreign central banks. This minimal agent landscape can capture essential behaviors such as changes to the balance sheets while the Federal Reserve pursues quantitative easing (QE) or tightening (QT) policies. The interactions between agents arise from shared balance sheet accounts (reflected in the implementation), which transmit changes across agents. This is very different from the market mechanism used in the fine-grained interbank lending model.

5.1 Preliminary Simulation Results

The coarse-grained, six agent model of the Federal Reserve system was initially tested by simulating the basic responses to major policy actions (as outlined in Sections 4.1 and 4.2). In first case shown here, the

Federal Reserve stopped re-investing maturing Treasury notes and the banking sector steps in to buy newly issued notes. Figure 2 shows the balance sheet changes over time. Note that the banking sector agent (Bks) swaps reserve balances for Treasury securities, while the Federal Reserve agent (Fed) echoes the decline in reserves. The Fed decline in Treasury securities reflects the maturing notes rolling off the balance sheet.

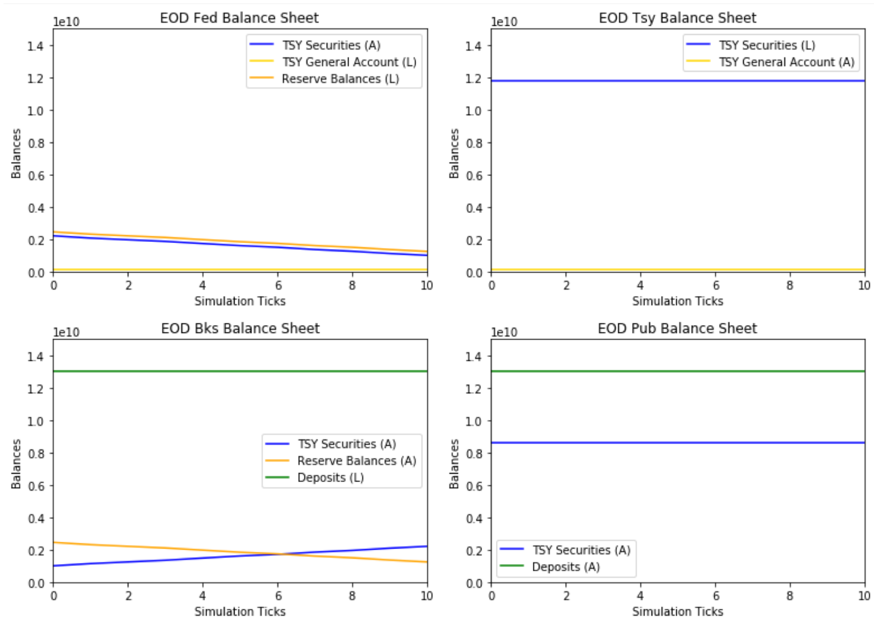

Figure 2: Agent balance sheet changes over time as new securities are purchased by the banking sector (balance sheet amounts are shown in thousands, on a y-axis scale of $15 trillion).

A similar analysis considers the balance sheet changes as the public (non-banking sector) steps in as the ultimate buyer of newly issued notes. The public agent (Pub) uses deposits to purchase new securities. The banking sector has a corresponding decline in deposits (as the public withdraws funds) and a drop in reserve balances. The Fed also shows an associated decline in reserve balances. Again, the Fed decline in Treasury securities reflects maturing notes. These expected balance sheet changes are an important check on the ABM implementation.

6 SIMULATING POLICY EFFECTS

One of the overall goals of this work is to add agent-based modeling and simulation to our toolkit for evaluating financial regulatory policy. As a first application, simulations were run based on the high-level forces outlined in Section 2, including fiscal policy, monetary policy, foreign central bank reserve management and the actions of the non-banking private sector. The policies reflect a combination of publicly declared plans from the US Treasury and Federal Reserve (as these entities strive to be somewhat transparent), along with various industry analyses and some questions open for debate. The core accounts and starting balances for the simulation are shown in Table 6. Many of these accounts appear on more than one agent balance sheet (held as assets or liabilities). Again, these commonly held accounts allow the agents to interact.

A set of policy parameters define the policy being evaluated, specifying some of the key behaviors that many other agents must respond to as the simulation unfolds. The US Treasury (TSY) agent drives fiscal policy by implementing debt financing (as first determined by government spending). The monthly deficit is assumed to be $7,500,000,000 throughout the simulation. In addition, the target for the Treasury General Account (TGA) is set to $500,000,000,000 (from a starting value of $93,893,000,000).

Table 6: The FED model core agent accounts with initial balances as of December 26, 2013.

Account Description	Account Name	Initial Balance
Banking sector reserves (held at the Fed)	BKS Reserves	$2,450,730,000,000
Banking sector US Treasuries holdings	BKS Tsies	$1,000,000,000,000
Foreign central bank cash holdings	FCB Cash	$5,254,000,000
Foreign central bank US Treasuries	FCB Tsies	$3,000,000,000,000
Fed currency in circulation (CCY)	FED CCY	$1,238,524,000,000
Fed SOMA mortgage-backed securities (MBS)	FED SOMA MBS	$1,496,943,000,000
Fed SOMA US Treasuries	FED SOMA Tsies	$2,208,829,000,000
Non-banking sector (NBS) deposits	NBS Deposits	$13,000,000,000,000
NBS Reverse "Repo" Program (RRP)	NBS RRP	$200,000,000,000
NBS US Treasuries holdings	NBS RRP	$8,600,000,000,000
Treasury general account (TGA) held at Fed	TSY GA	$93,893,000,000

Of course, the Fed is a key agent in this model, driving monetary policy. As part of the balance sheet unwind, the Fed has set a runoff schedule for its System Open Market Account (SOMA) US Treasuries holdings (see https://www.newyorkfed.org/markets/opolicy/operating_policy_170920) with monthly runoffs between $6 and $30 billion for 2017-2018. The schedule is read into the FED agent and converted into daily (tick-by-tick) runoff amounts. The same schedule also specifies the Fed SOMA mortgage-backed securities (MBS) holdings, giving rise to an additional runoff stream. The Reverse "Repo" Program (RRP) has a target of $10,000,000,000 (from a starting value of $200,000,000,000) and a horizon of 40 ticks. Finally, the currency in circulation (CCY) is assumed to grow at 7%.

The participation of foreign central banks (FCB) is held relatively constant during this simulation with a growth rate of 5% for US Treasuries holdings and cash. Of course, the behavior of foreign central banks, especially the largest, is one of the areas of speculation. This is fodder for further simulations and perhaps another fine-grained expansion of the model with individual agents for the biggest foreign central banks.

The remaining flows relate to the actions taken by the banking sector (BKS) and non-banking private sector (NBS) in the model. The question here is which sector will pick up the slack in purchasing newly issued US Treasuries. For now, the sectors shares are 10% for the banking sector and 90% for the non-banking sector. All of these parameters reflect the policies adopted by agencies such as the US Treasury and Federal Reserve, as well as key behavioral assumptions that can be modified in subsequent simulations.

Figure 3 summarizes the results of simulations using the parameters discussed above by showing selected balance sheet items for key agents over time (or ticks). Considering the panels in turn, the end-of-day account balances for agent BKS0 (upper left) shows the overall decline in deposits (held by non-banking private sector entities) This follows from the fact that non-banking firms are buying up US Treasuries and therefore withdrawing the funds to make those purchases. Also notice that the banking sector (BKS) reserves briefly rise and then begin a long decline. Given the Fed unwind, this decline in banking sector reserves is expected, but it is the pace of this decline that is of interest as a simulation result. Finally, notice the decline in the Reverse "Repo" Program (RRP), causing the temporary upward move in the banking reserves.

The non-banking sector (lower left) highlights the decline in NBS deposits and upward move in US Treasury holdings as new issues are purchased. The RRP account also appears on this balance sheet. The foreign central bank combined balance sheet (upper right) shows the relatively stable (albeit slowly rising) US Treasury and cash holdings. Again, this is an interesting area for future work. Finally, the US Treasury balance sheet (lower right) shows all of the agent holdings, with a rise in the non-banking sector holdings (due to new issue purchases) and a decline in the Fed holdings from planned portfolio runoffs. There is also a consistent rise in the US Treasury General Account (TGA) as certain banking reserves leave the system. Overall, the simulation seems to capture the major flow of funds in this complex market ecosystem.

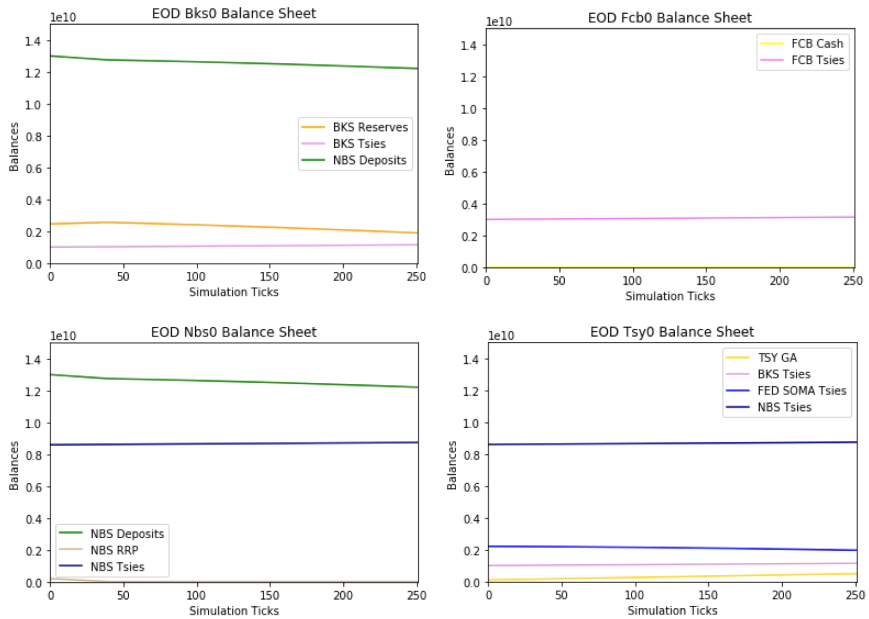

Figure 3: Agent balance sheet changes over time as runoff policies are pursued and new investments purchased by the banking and non-banking sectors (balance sheet amounts are shown in thousands, on a y-axis scale of $15 trillion).

Figure 4 shows a more detailed view of the Fed agent balance sheet (using a reduced y-axis scale of $5 trillion). This highlights the important balance sheet changes, including the reduction in the Fed's US Treasuries holdings as per the planned runoff. One of the most important simulation results is the decrease in banking sector (BKS) reserves. It is this critical account that is likely to cause stress to appear in the banking sector as reserves become scarce. The drop here is not too severe with banking reserves rising at the outset, but then dipping below $2 trillion. However, it is important to note that this is basically a one year simulation (252 ticks) and the runoff schedule starts somewhat gently becoming much larger toward the end of the year. The brief rise in the banking reserves is due to the initial runoff in the Reverse "Repo" Program (over the first two months), see the initial drop in Figure 4 for NBS RRP.

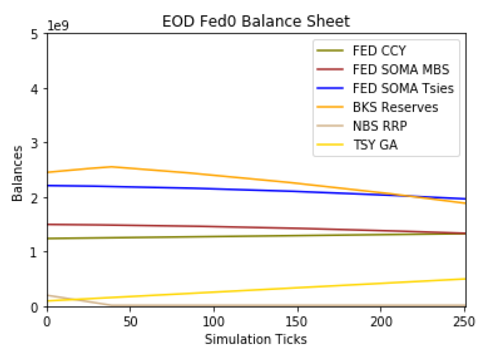

Figure 4: The Fed0 agent balance sheet changes over time as runoff policies are pursued (balance sheet amounts are shown in thousands, on a y-axis scale of $5 trillion).

This is a first simulation experiment that looks at the effects of major policy directions from the US Treasury and Federal Reserve over a one year period. The initial results of this agent-based approach are promising, but subsequent steps should improve the simulations. These next steps include defining more detailed banking sector and foreign central bank agents, as well as simulating a variety of scenarios.

7 CONCLUSION

The use of agent-based simulation holds great potential for regulators and monetary authorities looking to assess potential instabilities in financial markets and analyze the effectiveness of crisis responses. Existing methods of analysis either directly or indirectly rely on observations drawn from the past and their track record is somewhat lackluster when dealing with phenomena that do not have historical data. The past decade of unparalleled global monetary stimulus contributed to a financial environment that is without precedent and—in the eyes of many participants—severely distorted (Jacobs and King 2016).

It is in this “new financial normal” that the gradual exit from accommodative monetary policy (which—in the US—started at the end of 2017) will proceed. While regulators signal their intent to have the process run quietly in the background, some practitioners and academics fear that the exit may prove turbulent. A 2015 research note from Credit Suisse (Pozsar 2014) highlights the unprecedented nature of the unwind as stated below.

“First, the Fed will raise interest rates using new tools. Second, the money flows that liftoff will generate, both on and offshore, will dwarf those involved in past hiking cycles. Third, liftoff will occur in a financial environment completely redesigned through Basel III: bank balance sheets are now subject to liquidity and funding rules that have never been stress-tested in a hiking cycle before. No matter how transparent the Fed has been about the start and pace of liftoff, the combination of new tools and a redesigned financial system may cause turbulence in money, FX and Treasury markets on purely ‘mechanical’ grounds.”

It is important to note that the trajectory and outcome of the monetary policy unwind depend on the actions of market participants. As the Fed raises rates and unwinds its balance sheet, investors will likely re-balance portfolios while banks strategically respond to the liquidity risk implications of reserve draining.

We believe that agent-based simulations can provide valuable insight into the mechanics and outcome of the unwind. Simulations allow the analysis of likely outcomes for a wide range of scenarios, using simple behavioral assumptions across the ecology of market participants.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the National Science Foundation (NSF Award 1445403) and the Office of Financial Research (OFR) in providing funding for this research.

REFERENCES

Ashcraft, A. B., and D. Duffie. 2007. “Systemic illiquidity in the federal funds market”. *American Economic Review* vol. 97 (2), pp. 221–225.

Bookstaber, R. 2017. *The End of Theory*. 41 William Street, Princeton, New Jersey, Princeton University Press.

Boss, M., H. Elsinger, M. Summer, and S. Thurner 4. 2004. “Network topology of the interbank market”. *Quantitative finance* vol. 4 (6), pp. 677–684.

Carpenter, S., S. Demiralp, J. Ihrig, and E. Klee. 2015. “Analyzing Federal Reserve asset purchases: From whom does the Fed buy?”. *Journal of Banking & Finance* vol. 52, pp. 230–244.

Chakraborty, S., J. Gaeta, K. Dutta, and D. Berndt. 2017. "An Analysis of Stability of Inter-bank Loan Network: A Simulated Network Approach". In *Proceedings of the 50th Hawaii International Conference on System Sciences*.

Chalermchatvichien, P., S. Jumreornvong, P. Jiraporn, and M. Singh. 2014. "The effect of bank ownership concentration on capital adequacy, liquidity, and capital stability". *Journal of Financial Services Research* vol. 45 (2), pp. 219–240.

Cont, R., A. Moussa, and E. Santos. 2010. "Network structure and systemic risk in banking systems".

Elsinger, H., A. Lehar, and M. Summer. 2005. "Using market information for banking system risk assessment".

Furfine, C. H. 2003. "Interbank exposures: Quantifying the risk of contagion". *Journal of money, credit and banking*, pp. 111–128.

Haldane, A. G., and R. M. May. 2011. "Systemic risk in banking ecosystems". *Nature* vol. 469 (7330), pp. 351.

Huang, W.-Q., X.-T. Zhuang, S. Yao, and S. Uryasev. 2016. "A financial network perspective of financial institutions' systemic risk contributions". *Physica A: Statistical Mechanics and its Applications* vol. 456, pp. 183–196.

Jacobs, L. R., and D. S. King. 2016. *Fed Power: How Finance Wins*. Oxford University Press.

Markose, S., S. Giansante, and A. R. Shaghaghi. 2012. "'Too interconnected to fail'financial network of US CDS market: Topological fragility and systemic risk". *Journal of Economic Behavior & Organization* vol. 83 (3), pp. 627–646.

Nier, E., J. Yang, T. Yorulmazer, and A. Alentorn. 2008. "Network models and financial stability".

Pozsar, Z. 2014. "Shadow banking: The money view".

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