Data Visualization and Sonification for Financial Agent-Based Models

Emergent Research Forum Paper

Don Berndt
University of South Florida
dberndt@usf.edu

David Boogers
FinaMetrics
db@finametrics.com

Saurav Chakraborty
University of South Florida
sauravc@usf.edu

Ratish Dalvi
Indiana University
rdalvi@indiana.edu

Abstract

The corporate bond market is one of the areas that has witnessed profound changes since the last financial crisis, prompting regulators (and industry participants) to question its resilience under stress. We are building agent-based models to better understand bond market dynamics using simulations. Simulations offer an intriguing method of capturing the second-order feedback loops that can affect prices under conditions of stress. However, understanding all the data and emergent behaviors from these complex systems remains a difficult challenge. In this paper, we begin investigating visualization and sonification techniques that might help us meet this challenge at both agent (micro) and system-wide (macro) levels, with the goal of assembling an effective mixture of visual elements. Sonification offers a novel way to enrich our visualizations with sound, setting markets to music. An experiment assessing the impact of mutual fund market share on bond market stability provides an interesting context with meaningful outcomes.

Keywords

Agent-based modeling and simulation (ABMS), data sonification, data visualization, financial crises.

Introduction

Agent-based modeling and simulation (ABMS) is based on the interactions of a collection of different agents typically implemented with simple, but important behaviors encoded as algorithms. The challenge is uncovering the most appropriate behaviors in an application domain, then distilling those behaviors down to the most essential aspects. When done well, the interactions of many autonomous agents making simple but impactful decisions leads to interesting emergent outcomes. Agent-based modeling and simulation has been used to investigate a wide variety of phenomenon. Models have been explored in biology, health (including modeling epidemics), business, economics, technology, and aspects of organizational studies and social systems (Bonabeau 2002). Agent-based approaches are a natural fit with many financial phenomenon (Holland et al. 1991, Farmer 2009), which is the focus of our on-going research. However, our attention here is on the visualization and sonification of these agent-based models (Dorin 2014), or more accurately the data and behaviors generated by simulations. Understanding the potentially complex emergent outcomes of simulations is simply a challenging intellectual exercise (Sanchez et al. 2002). How can a researcher make sense of all those interacting agents over time? Data visualization is perhaps our best hope. We can “slice and dice,” drill down into the details, explore a network of relationships, and even replay key episodes. Using our model of the US corporate bond market to provide context, this paper reports on our early attempts to visualize (and even “sonify”) the simulation outcomes. Our approach can be characterized along two main dimensions.

1. Economic systems are often viewed at different levels of abstraction. Since our work is motivated in part by using simulations for assessing the effectiveness of financial regulation, it makes sense to draw a distinction between *macroprudential* (attempts to limit system-wide distress) and

microprudential regulation (firm-level interventions). So, our agent-based visualizations can usefully target both individual agents and the emergent behavior of the system.

2. Economic systems are also often analyzed statically (at points in time), as done in accounting reports and certain types of mathematical models, or as dynamic systems. Here again, our visualizations can focus on the state of an agent or market (snapshots), as well as depict the functioning system using active media such as audio and video.

Our research goal in this paper is to find a mixture of visualization (and sonification) techniques that can serve to highlight the important aspects of agent-based models and the complex emergent behaviors that typically arise during simulations.

Corporate Bond Market

Corporate bonds are an important means by which companies fund their business operations and expansion. Following the financial crisis of 2008, corporate bond markets have experienced significant change as the combined effects of monetary policy, regulatory reform and changing business models took hold. Persistently low yields caused the market to expand significantly (US corporate debt increased from 5.2 trillion in 2007 to 8.1 trillion in 2015). The declining rate environment herded investors into similar positions (or "crowded trades") leading to a significant decrease in investor heterogeneity. Collective investment vehicles (mutual funds, exchange traded funds, and others) witnessed extraordinary growth and have become significant players in corporate bond markets. Using Federal Reserve data, we estimate that mutual funds accounted for roughly 3% of the corporate bond market at the end of 1990, growing to nearly 20% by 2016. In addition, dealers have significantly reduced their commitments to making markets in corporate bonds as evidenced by the decline in dealer corporate bond holdings, leading to a potential imbalance between market size and the trading channel. These factors have contributed to a US corporate bond market much more at risk and makes this an area in need of research. Some observers argue that the lack of liquidity in the bond market may even trigger the next systemic crisis.

We have been developing an agent-based model of the bond market to investigate some of these issues. Through simulation, we can explore how future changes might affect the market and assess the impact of proposed regulatory policies. Simulation offers a way to capture some of the second-order feedback loops that affect prices in markets, often missed in more traditional economic models. We use a highly-targeted experiment to motivate our work in this paper based on concerns over the market share of mutual funds (potentially runnable investment vehicles) in the bond market (ECB 2016, Edwards et al. 2007). Essentially, we consider the impact of mutual fund market share (at 15%, 25%, and 35%) on the overall stability of the bond market.

Agent-Based Model

The bond market agent-based model implements a somewhat stylized investor ecology, with participants trading a limited universe of bonds through broker-dealers (there is no direct trading between investors). Broker-dealers provide immediacy services on a principal basis using a request-for-quote (RFQ) protocol. This mirrors the bilateral trading that characterizes the real US corporate bond market. The market model includes three types of buy-side agents including mutual funds, insurance companies and hedge funds (Berndt et al. 2016). In selecting this set of agents, we aim to model representative corporate bond investor heterogeneity. While there are multiple ways to segment the investor base, we guided our selection of buy-side agents by the nature of their liabilities (leveraged versus non-leveraged, presence of inflows/outflows) and their investment mandate (passive versus active, long only versus long/short).

1. **Mutual funds:** The mutual fund acts as a real money investor who aims to replicate the performance of a defined benchmark index. The mutual fund is long-only and does not leverage positions. The fund also maintains a dynamic cash balance as a buffer against investor redemptions (limiting forced sales). The mutual fund's trading activity is entirely driven by fund inflows and outflows, which in turn are primarily driven by the historical performance of the fund (Chen et al. 2016). As new money is invested, the mutual fund must put that money to work by buying bonds based on a pre-defined index. In the opposite direction, the mutual fund must liquidate a portion of the portfolio to meet redemptions that cannot be paid out of available cash.

2. **Insurance companies:** The insurance company agent implements a long-term value investor with a liability driven investment strategy. This agent manages an investment portfolio across equity and fixed income markets and changes the allocation between markets depending on overall market conditions. Trading activity for the insurance company results from changes in portfolio allocation between equity and fixed income markets.
3. **Hedge funds:** The hedge fund agent acts as a short-term tactical trader who follows a relative value trading strategy. As such, the hedge fund maintains both long and short positions and makes active use of leverage. The hedge fund agent is not subject to external inflows (basically a closed end fund) or redemptions (assume investor lock up); its trading capacity is constrained only by the availability of secured financing (leverage) from broker-dealer agents.
4. **Broker-dealers:** Broker-dealer agents only trade in response to requests from the buy-side agents. There is no inter-dealer market. Asset owners must trade with the broker-dealer offering the lowest price. The initial model includes three broker-dealer agents, each with somewhat of a specialization based on bond maturity, though with the freedom to trade as desired. These dealers can maintain long and short positions. Broker-dealers are the price setters in the model.

Data Visualization

At the microprudential level, the focus is on individual agents, in this case the mutual fund *Foo0* (each agent class has a different metasyntactic variable as a prefix followed a sequential number). This is certainly an informative perspective since you can drill into the details of each agent to better understand their trajectory during a simulation. Here, we look at the overall wealth of mutual fund *Foo0* captured at the end of each day (EOD) or tick. Figure 2 tells a dramatic story. The simulation proceeds normally for quite a while, with wealth increasing slightly as bond prices rise a bit because agents are trading. At tick 50, an interest rate shock is delivered causing an immediate and precipitous drop in all bond prices. The effect is different based on bond maturity, but overall prices drop significantly across the board (see also Figures 3 and 4 further below). The destruction of wealth impacts all agents since their bond portfolios are re-priced (that is the steepest drop in this figure). That first price drop is a direct effect of a rise in interest rates and can be computed as a change in fundamental value.

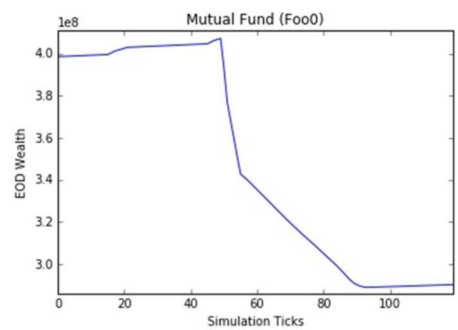

Figure 1: Individual Agent Wealth

Following that first drop, there is another somewhat slower price decline (over 30 ticks or so). This secondary drop in wealth is caused by feedback loops. As noted above, mutual fund agents are driven by the flow of funds. Investors withdraw funds when returns are poor (and returns are very bad following the shock), forcing mutual funds to sell assets to cover the redemptions. Forced sales lead to further price drops, more redemptions, and another round of wealth destruction. Eventually, the sales slow and the market stabilizes at a new, much lower level. Finally, there is a bit of an upward climb as the market rebounds amid a more normal flow of funds.

Treemaps (Micro)

Treemaps are a very interesting way to visualize hierarchical information, along with related attributes. Figure 2 is a treemap of a simple market with one mutual fund (*Foo0*), three broker-dealers (*Bar0-2*). Treemaps convey a lot of information and really are well-suited to agent-based models. Here the size of the rectangles is based on wealth, while the color conveys information about the daily return on investments. This treemap is

Figure 2: Agent-Level Market Treemap

essentially a snapshot, capturing the state of the model at a specific tick. Moving through time (tick-by-tick) can show patterns of behavior unfolding, while the whole simulation could be re-played as a video. We plan on using interactive treemaps to move between levels of analysis, as well as animate interesting portions of the simulations.

Market Outcomes (Macro)

The preliminary experimental results are quite dramatic. Figure 3 depicts bond prices at a mutual fund market share of 15%, somewhat below the real market share, but a reasonable starting point. An economic shock is delivered at tick 50 in the form of a 100 basis-point rise in the interest rate. The corresponding price drops across all five bonds is easily seen. The small but noticeable drop in prices for the next 10 to 20 ticks is due to the redemption-driven feedback loop. These are the dynamic aspects captured by the agent-based approach. After the market stabilizes, more normal trading activity returns (in the form of sporadic price increases as investor inflows add funds).

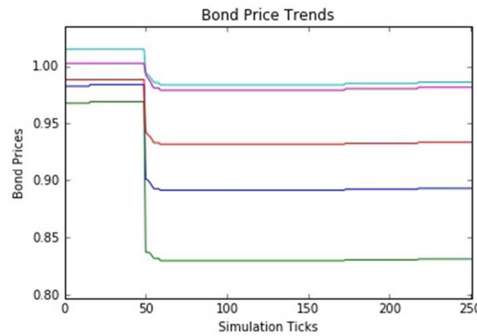

Figure 3: 15% Market Share

Figure 4 depicts a simulation with a mutual fund market share of 35%, a substantial increase over the current real-life situation. Again, a 100 basis-point interest rate shock is delivered at tick 50. The interest rate hike causes the expected price drops across all five bonds as before. However, after that the simulations take a different path. After these shock-induced drops, the prices fall off a cliff. For the next 50 clicks the redemption-driven feedback loop causes a spiral of decreasing prices. In fact, the concave curve means that the price drops accelerate with correspondingly dramatic wealth destruction. The price drops are more pronounced from the outset, but reach an inflection point with precipitous price drops until available dealer capacity is consumed (and the market flat lines). In these simulations, the redemption-driven price drops dwarf the initial interest rate shock effects. The feedback loop causes price drops in the 35% to 44% range, as compared to the shock-induced drops of roughly 1% to 14%. The compelling narrative is echoed by this high-level market outcome. The dynamic nature of these simulations is reflected in the figures, but would clearly benefit from both audio and video enhancements.

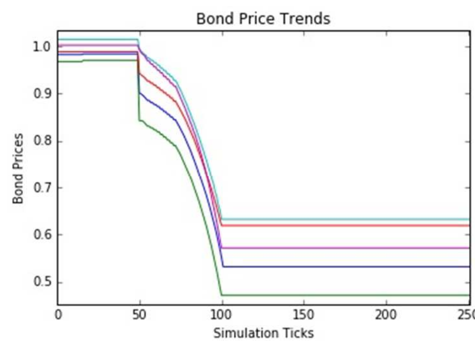

Figure 4: 35% Market Share

Data Sonification

Anecdotally, traders tend to refer to the state of a given market using the terms "market color" and "market buzz." The importance of auditory signals is evidenced by the layout of a typical trading room. Traders tend to co-locate in the same physical space without any partitioning or walls between desks, thereby allowing auditory signals to flow freely between trading desks. Fast moving asset classes (such as currencies, which react quickly to macro-economic and geopolitical news) tend

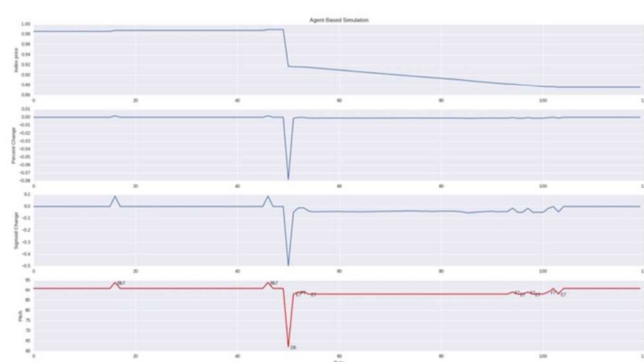

Figure 5: Transformations for Sonification

to be located at the center, with closely connected asset classes (e.g. short-term money markets) being placed next to each other. John Coates, a Cambridge neuroscientist (and former trader at Goldman Sachs), who works on the physiology of risk taking, notes that: "An experienced manager can sense a change in the market, tell how the floor is doing, just from the sight and sound of it" (Coates 2012). Practitioners value auditory signals to capture important changes in the dynamics of a complex ecosystem like a trading floor. We argue that these auditory representations of the dynamics of markets potentially hold value for prudential oversight as well.

Real market outcomes, as well as agent-based simulations, can chart some rather dramatic courses (see Figure 4). Music – as a rich auditory scheme – is certainly one way to express such drama. How do we set markets to music? As a preliminary effort, we captured some bond index time series data, such as individual bond prices, volatility and other measures. Transforms were applied to restrict the ranges and map the quantitative data to musical notes (see Figure 5). These early sonifications already express some of the drama in market moves. The absolute index price is replaced with relative changes, then transformed using a sigmoid function to accentuate small changes and mitigate large changes), so all the values fit on the same musical scale. To listen to this preliminary audio track, visit bit.ly/djb_sonify.

Conclusion

This paper presents a limited set of visualizations (and a start on some sonifications) that seem helpful in understanding agent-based simulations at both micro and macro levels. A focused experiment on bond market stability with varying mutual fund market shares provides the context and some interesting outcomes, including crisis-like behaviors. Mutual funds are "runnable" investment vehicles since investors can withdraw funds on demand, which can lead to redemption-driven feedback loops. It is exactly such feedback mechanisms that we hope to capture using agent-based approaches. While we start with some standard visualizations, such as trend lines and treemaps, the goal is to continue adding other elements along with animations and interactive designs that bring the simulations to life. For instance, the interaction of agents is easily expressed as a graph with the edges characterizing the trading relationships. Finally, sonifications offer an avenue for enriching visualizations with sound, setting market behaviors to music and adding a powerful communication channel.

Acknowledgements

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

Bonabeau, E. 2002. "Agent-Based Modeling: Methods and Techniques for Simulating Human Systems," *Proceedings of the National Academy of Sciences of the USA* (99:3), pp. 7280-7287.

Berndt, D. J., Boogers, D., and McCart J. 2016. "Agent-Based Models of the Corporate Bond Market," DSMM *Workshop*, *ACM SIGMOD/PODS Conference*, San Francisco, CA.

Chen, Y., Qin, N. 2016. "The Behavior of Investor Flows in Corporate Bond Mutual Funds". Management Science, Articles in Advance.

Coates, J. 2012. *The Hour Between Dog and Wolf: How Risk Taking Transforms Us, Body and Mind*, Penguin USA.

Dorin, A., and Geard, N. 2014. "The Practice of Agent-Based Model Visualization," *Artificial Life* (20), pp. 271-289.

European Central Bank (ECB). 2016. "Shadow Banking in the Euro Area: Risks and Vulnerabilities in the Investment Fund Sector". ECB Occasional Paper 174.

Edwards, A. K., Harris, L. and Piwowar, M. S. 2007. "Corporate Bond Market Transaction Costs and Transparency". *Journal of Finance*, Vol. 62, No. 3.

Farmer, J. D. 2009. "The Economy Needs Agent-Based Modeling," *Nature* (460:7256), pp. 685-686.

Holland, J. H., and Miller, J. H. 1991. "Artificial Adaptive Agents in Economic Theory," *American Economic Review* (81: 2), pp. 365-371.

Sanchez, S. M., and Lucas, T. W. 2002. "Exploring the World of Agent-Based Simulations: Simple Models, Complex Analyses," *Proceedings of the Winter Simulation Conference*, pp. 116-126.