Agent-Based Models of the Corporate Bond Market

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ABSTRACT

The paper presents an Agent-based modeling approach for the analysis of liquidity in corporate bond markets. Bond market liquidity is hard to measure empirically and its evolution is hard to predict due to its non-linear nature, with significant feedback loops between asset, funding and collateral markets. We discuss the applicability of Agent-based modeling and present an initial model using a stylized market microstructure.

CCS Concepts

• **Applied computing~Economics**

Keywords

Agent-Based Modeling; Corporate Bond Market; Liquidity Risk; Systemic Risk

1. INTRODUCTION

Following the financial crisis of 2008, the combined effects of monetary policy, regulatory reform and changing business models have fundamentally altered the US fixed income landscape. Persistent low yields caused the market to expand significantly (US corporate debt increased from 5.2 trillion (2007) to 8.1 trillion (Q2 2015)) and the declining rate environment herded investors into similar "long only" positions. Increased holdings of fixed income positions by pooled investment vehicles (mutual funds, ETFs, etc.) exacerbate systemic risk concerns, due to the imbalance between the immediacy of fund redemptions and the liquidity of its holdings.

These on-going concerns make the bond market a natural choice for experimenting with computational approaches to assessing systemic risk. As part of the Granular Systemic Risk Project (GSRisk.org), we are applying agent-based modeling to gain an understanding of the dynamics of liquidity under stress, one of the most widely discussed issues facing financial markets today. As noted above, the corporate bond market size has increased significantly along with fundamental changes in market ecology (including reduced investor heterogeneity and dealer intermediation capacity), leading to potential systemic imbalances. The analysis of market liquidity lends itself to simulation approaches, since liquidity is typically ample in normal (steady state) operation but tends to evaporate under conditions of stress. To that end, we are experimenting with agent-based models of a simplified corporate bond market. Our initial model includes three classes of investors: two classes represent "real money" investors, while the third investor class maintains leveraged positions. Real money investors are long only, with the two classes represented by a pension fund (value investor) and a mutual fund (using passive index tracking). The leveraged investor represents an unconstrained participant (such as a hedge fund) who can maintain long and short positions. All trading in our model occurs between the investors and a network of dealers using a simple request-for-quote (RFQ) mechanism. Using our agent based models we aim to provide insights into the behavior of price and liquidity under a variety of stress conditions.

2. LIQUIDITY IN CORPORATE BOND MARKETS

Over the past year, the liquidity conundrum in corporate bond markets has been one of the most widely discussed issues across major financial markets, with some observers arguing that illiquidity in this sector may trigger the next systemic risk event.

Trading in corporate bonds is conducted through bilateral (OTC) negotiations between investors and the dealer community. Recently, dealers have significantly decreased their commitments to making markets in fixed income (as evidenced by the decline in dealer balance sheets) leading to an imbalance between market size and the trading channel.

Regulators and market participants have repeatedly voiced concerns around fixed income market microstructure. In his speech to participants at the 4th Annual Fixed Income Conference at the University of South Carolina, SEC Commissioner Piwowar addressed the issue of bond market liquidity and noted that "these are the types of issues that merit further study by academic researchers, and which would be of enormous value to the SEC and other financial regulators".

Recognizing the issue of illiquidity, the SEC furthermore proposed new regulations that could significantly affect market functioning (for example, see proposed rule 22e-4, addressing liquidity concerns in open-end mutual funds and ETFs).

Following the 2002 introduction of FINRA TRACE (Trade Reporting and Compliance Engine), a significant amount of historical transaction level information is now available to academic researchers. The availability of granular time series

data makes the corporate bond market an ideal candidate for our granular systemic risk analyses.

3. AGENT-BASED MODELING

The agent-based modeling paradigm (ABM) provides a natural fit with our approach to modeling systemic risk using granular data. It is particularly well suited to the analysis of liquidity dynamics under stress.

The Office of Financial Research (OFR) published various papers discussing the value of ABM in the analysis of financial systemic risk, for example see Bookstaber (2012) and Bookstaber et Al (2014). The European Commission furthermore sponsored a major research initiative (CRISIS, the Complexity Research Initiative for Systemic Instabilities), which aims to analyze systemic risks to the financial sector and the wider economy using ABM. As noted by D. Farmer, agent-based approaches have not been applied nearly as widely as DSGE and econometric models.
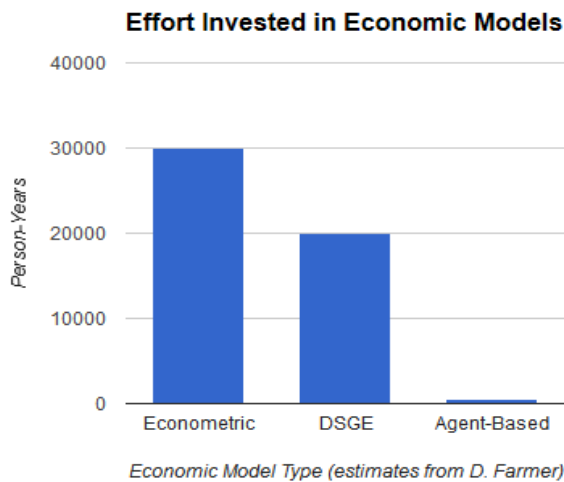

Figure 1: Economic Model Types

While most of the existing literature around the application of ABM to finance is focused on equity markets (with some interesting applications to currency and housing markets), we aim to analyze the liquidity conundrum in the US corporate bond market using ABM. We intend to provide some insights into the liquidity implications of changes in dealer intermediation capacity, the introduction of new trading protocols and electronic marketplaces, the reduction of investor heterogeneity and the increasing importance of collective investment vehicles such as mutual funds.

4. MODEL 0: MARKET MICROSTRUCTURE

The first iteration of our agent-based models (Model 0) includes a somewhat stylized investor ecology who trade a limited universe of bonds through broker/dealers (there is no direct trading between investors). Broker/Dealers provide immediacy services on a principal basis (dealers cannot handle orders in a riskless principal or agency capacity) using a Request-For-Quote (RFQ) protocol.

While our overall goal for Model 0 is simply to verify that realistic market behaviors emerge from the interactions between agents with succinctly defined internal rules, the design already incorporates essential elements of contagion and feedback loops.

Recent analysis from the Office of Financial Research (OFR) highlights the importance of financial networks in understanding contagion risk and presents a model of the financial system as a multilayer network (see Figure 2).
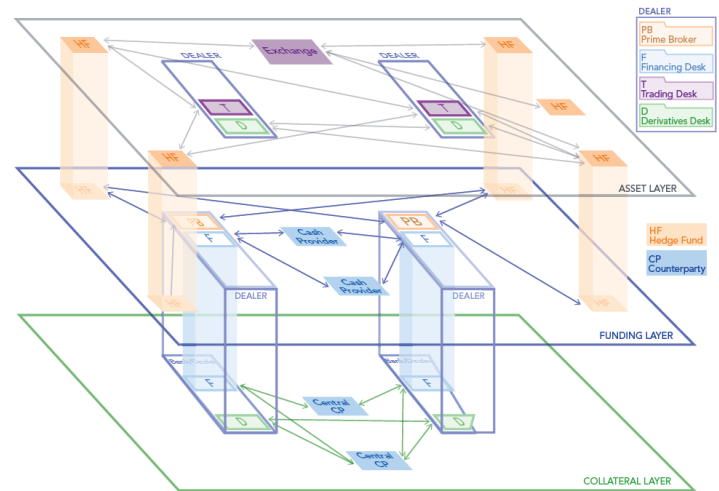
Figure 2: The Financial System as a Multilayer Network (Source: Office of Financial Research, 2015 Annual Report to Congress)

In line with the multilayer network view, we structured Model 0 to incorporate elements of the funding and collateral layers (in addition to the asset layer itself). The funding layer focuses on the role of leverage and its role in fire sales (including feedback loops and cross-asset contagion). It includes key leverage constraints for the Hedge Fund and the Broker/Dealers.

In the collateral layer, Model 0 assumes limited constraints on the availability and flow of collateral. All bonds in the experimental market are available as collateral against secured financing transactions and can be borrowed for delivery against short sales. Model 0 includes security-specific haircuts which can be adjusted by the lenders.

In addition to the three layers of the bond market, Model 0 includes a few direct and indirect linkages with other asset 'verticals', including equities and government bond markets. Equity markets impact the model through the behavior of one of the buy-side agents (an insurance company), who rebalances positions between equities and fixed income based on equity market volatility (as well as absolute yield levels). Government bond markets furthermore provide the 'risk free' yield curve which is used as input to the bond pricing equation.

4.1 Meet the Buy-side Agents

Model 0 includes three buy-side agents representative of a mutual fund, an insurance company and a hedge fund. In selecting the initial 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). The agents in Model 0 manage towards different investment horizons as highlighted in Figure 3.

Model 0: Agents

Source: Adapted from the Tabb Group, Liquidity Ladder in Transition
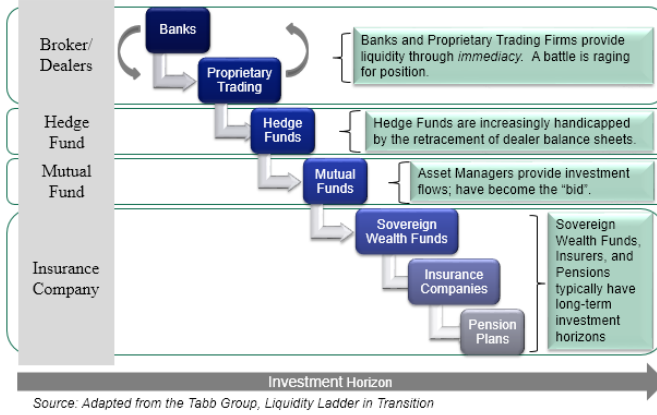
Figure 3: Model 0 Agents (Adapted from the Tabb Group, Liquidity Ladder in Transition)

4.1.1 Mutual Fund

The mutual fund is among the simplest buy-side agents, acting as a real money investor who aims to replicate the performance of a defined benchmark. The agent is implemented as a passively managed bond index fund. The fund is long only and does not leverage positions. Leverage is introduced through other agents in our initial model and will be more widely implemented in the future, including derivative-based leverage.

The fund's benchmark index includes the full universe of bonds available in the initial model and assumes static index weights (no periodic re-balancing of the index). The fund also maintains a dynamic cash balance as a buffer against investor redemptions (limiting forced sales) and to minimize transaction costs by parking cash until sizable orders can be made. The cash balance is managed to a target cash-to-assets ratio of 5% with a lower bound of 3% and an upper bound of 8%. Any dividends or capital gains distributions are assumed to be re-invested.

In this constellation, 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. 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 must liquidate a portion of the portfolio to meet redemptions that cannot be paid out of the available cash balance.

We keep track of the agent's wealth and cash balances and calculate historical returns over select time periods (returns are a key driver of fund inflows and outflows). The Mutual Fund's wealth and cash balances are calculated as:

$$W_t = W_{t-1} + NetContributions_t + Dividends_t + CapitalGainsLosses_t$$

with:

$$W_t = Wealth\ at\ the\ end\ of\ period_t$$
$$NetContributions_t = Inflows_t - Outflows_t$$
$$CapitalGainsLosses_t = MarketValue_{bonds_t} - MarketValue_{bonds_{t-1}} + Sales_t - Purchases_t$$

The cash position of the fund (C_t: cash at end of period$_t$) can then be calculated as:

$$C_t = C_{t-1} + NetContributions_t + Dividends_t + Sales_t - Purchases_t$$

4.1.2 Insurance Company

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 allocation between markets depending on overall market conditions.

The insurance company is a "long only" investor with additional constraints limiting the concentration of risk in any specific bond. In the initial model, leveraged positions cannot be established (another real money investor) and we assume there are no external inflows or outflows in the form of premiums or claims.

Trading activity for the insurance company results from changes in portfolio allocation between equity and fixed income markets. Macro allocation decisions are driven by a number of variables, including equity market volatility as well as the current level and slope of the yield curve.

4.1.3 Hedge Fund

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 (fixed income relative value hedge funds have historically been among the most leveraged market participants).

The hedge fund 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. In model 0 we assume the hedge fund finances all positions on margin through prime-brokerage style arrangements with the Broker/Dealers. Broker/Dealers limit leverage using security-specific haircuts which can be dynamically adjusted depending on market conditions.

All margining is assumed to occur on an overnight basis. At the start of each trading day (a tick in the agent-based simulation), margin requirements are calculated based on current market prices and security-specific haircuts as set by the broker-dealer agents. The difference between margin requirements and current wealth determines the trading capacity. If the new margin requirements exceed current wealth, the hedge fund is forced to liquidate positions (deleverage) to meet margin calls. Any excess wealth is free to be invested.

4.2 Broker-Dealers and RFQ protocol

In the initial model (Model 0), 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. Model 0 includes three dealer agents, each with somewhat of a specialization based on bond maturity (short term, medium term, and long term), though with overlapping ranges and the freedom to trade as desired. These dealers can maintain both long and short positions.

Dealers are the price setters in our initial model. Dealer behavior is limited through regulatory constraints and market discipline, the

latter expressed through a constraint on Value-at-Risk (VaR) relative to capital.

Given the intent to trade, asset owners make a request-for-quote (RFQ) to all dealers. Dealers must respond with "no quote" or a full quote for the requested order size (no partial order fills are allowed). Requests are handled as follows:

- Request to sell (dealer buys): Dealer responds with "no quote" if their long position limit would be breached. If not, a full quote or bid is provided with a spread determined by the dealer's current position (including age of the inventory), the risk associated with a new position (based on factors affecting hedging costs), distance from any position limit, and price momentum (aligned with the notion that dealers avoid "catching a falling knife").
- Request to buy (dealer sells): Dealer responds with "no quote" if their short position limit would be breached. If not, a full quote or ask is provided with a spread determined by the factors described above, with an analysis that reverses much of the logic.

4.3 Market Microstructure Evolution and Model Iterations

Recognizing the potential impact of recent market and regulatory developments on liquidity in these markets, the private sector is responding with a multitude of new initiatives (example initiatives include Electronifie, Trumid, Liquidnet FI, MarketAxess all-to-all trading, BondChain, Deplhx, MTS B2Scan, and Algomi Honeycomb). As new trading technologies get introduced, the marketplace will undergo structural change while at the same time adapting to new regulatory initiatives (including the existing Volcker rule and proposed new regulation such as the SEC proposed rule 22e-4). We closely monitor new initiatives and plan to analyze market impact through our agent based modeling efforts.

In reviewing bond market microstructure, we held informal discussions with several market participants, including major investment-grade issuers (primary markets) and buy-side participants. As we work on iterations of our agent-based models, we plan to intensify and formalize our outreach to market participants in order to validate inputs to our model and syndicate results.

5. MARKET UNIVERSE

The simple market universe for our initial model consists of five tradable bonds. The bonds are identical with respect to structure, form and major covenants including issuer, redemption (bullet redemption at maturity without optionality clauses) and rate provisions (fixed coupon). The bonds differ along only three dimensions:

1. Outstanding nominal amount ranges from 500M to 2B.
2. Maturities cover major points on the yield curve (1, 2, 5, 10 and 25 years).
3. Coupon rates range from 1.75% to 4.00%.

Table 1. Tradable Bond Characteristics

	bond 1	bond 2	bond 3	bond 4	bond 5
Nominal	500 M	500 M	1 B	2 B	1 B
Maturity	1Y	2Y	5Y	10Y	25Y
Coupon	1.75%	2.5%	2.25%	2.4%	4%

5.1 Asset Value Dynamics

At any point in time, all asset owners (the "buy side") perceive the same fundamental value for a specific bond. That is, all asset owners use the same valuation model and observe the same input prices (maintaining homogenous beliefs). The value for the above five bonds is fully reflected in five data points (a par yield curve with five rates), with a simple calculation of any given bond's price given its par yield. The asset owners' assessment of value changes over time based on the supply and demand for each bond and exogenous factors such as monetary policy. Our initial model will consider two shocks: 1) parallel shifts of the entire yield curve (by 25, 50, and 100 basis points), and 2) point moves such as a 50 basis point move in the 10 year yield (simulating QE-style impact of buying pressure on specific points on the curve).

5.2 Starting Conditions (Time Zero)

The starting conditions for the agent-based simulation include:

- Bond index composition with (static) weights based on nominal amount (Table 2. Bond Index Composition).
- Initial par yield curve and bond prices (Table 3. Initial Yield Curve and Bond Prices).
- Bond positions are allocated to buy-side agents and dealers reflecting an overall split of 40% (Mutual Fund), 50% (Insurance Company) and 10% (Dealers). The Mutual Fund is invested across the 5 bonds based on the index weights. Maturity preferences and sector specialization drive the allocation of starting positions for the Insurance Company and the Dealers. Table 4 summarizes the opening bond positions.
- Haircuts are set uniformly across all 5 bonds.
- Initial endowments for the buy-side agents include:
  - Mutual Fund: in addition to its bond holdings, the Fund has an opening cash position reflecting a 5% cash-to-assets ratio.
  - Insurance Company: initial portfolio allocation includes a 60/40 split between fixed income and equity markets. Equity positions are assumed to be invested in a broad market index (such as the S&P 500).
  - Hedge Fund: initial equity (held as cash) is 150M. The opening equity position is set to ensure leverage constraints (using realistic haircuts) become binding when the Hedge Fund accumulates a specific market share.

Table 2. Bond Index Composition

	bond 1	bond 2	bond 3	bond 4	bond 5
Nominal	500	500	1000	2000	1000
Index weight	10%	10%	20%	40%	20%

Table 3. Initial Yield Curve and Bond Prices

Yields	1Y	2Y	5Y	10Y	25Y
	1.50%	1.75%	2.50%	2.60%	4.21%
Prices	bond 1	bond 2	bond 3	bond 4	bond 5
	100.247	101.468	98.832	98.249	96.772

Table 4. Opening Bond Positions

	bond 1	bond 2	bond 3	bond 4	bond 5
Mutual F.	200	200	400	800	400
Ins. Cpy.	0	250	500	875	500
Hedge F.	0	0	0	0	0
Dealer 1	300	50	0	100	0
Dealer 2	0	0	50	125	0
Dealer 3	0	0	50	100	100

5.3 Preliminary Model Performance

Two of the challenges in agent-based modeling are: 1) to ensure that the approach is a good fit to the problem and 2) that the agent-based model is rigorously applied. As noted above, complex financial markets are a natural fit for agent-based models and simulation. Additionally, Rand and Rust (2011) propose guidelines for rigor in agent-based modeling that can be used to organize this research into issues of verification and validation.

Verification focuses on how well the agent-based model corresponds to the conceptual model. Documentation, programmatic testing (such as unit testing and code walkthroughs), test cases and scenarios are all tools for verification. The corporate bond market model used in this research was fully specified at a detailed level, with each agent implementation grounded in the financial research literature. Our goal is to release this detailed specification, along with the model itself. In addition, unit testing, code walkthroughs, and model-level test cases have been used during development.

Validation assesses how well the agent-based model corresponds to reality. Tools here include micro-face validation, macro-face validation, and empirical testing. Micro-face validation looks at how well individual elements of the model correspond "at face value" to the real world. Again, each agent was specified and implemented using key factors identified in the financial literature. Macro-face validation considers how well "processes and patterns" correspond to the real world. The initial model implements bilateral trading arrangements based on request-for-quote (RFQ) mechanism, mirroring the real bond market. With regard to patterns, simple exogenous shocks based on actual events, such as quantitative easing, are being used to assess how well the model responses correspond with real world events. Finally, empirical validation can be used to assess how the model corresponds to both real world input and output data. The model is being validated using historical input data, such as interest rates and equity prices, along with comparisons based on the bond trading activities and prices as output.

As an example, experiments based on trading patterns have been used as part of the micro-face validation of the mutual fund agent. Recall that the basic mutual fund agent trades only in response to inflows and outflows (from investors). The mutual fund buys and sells using an index following behavior, so additional funds are allocated across the available bonds according to static index weights. Investor outflows force liquidations, again across the bond index. A cash balance is maintained to cushion against outflows, as well as make new investments in meaningful amounts. Therefore, the cash-to-asset ratio is a reasonable metric for assessing mutual fund agent behavior. Mutual fund agent ash-to-asset ratios vary between 3-8% of the portfolio value (excluding cash), with an optimal target of 5%. Prolonged periods

of inflows or outflows should drive the cash-to-asset ratio in a single direction. As an experiment, four distinct phases were simulated. Phase 1 had small randomly generated inflows and outflows (in the symmetrical range of +/- 1 million dollars) that should have resulted in small changes in the cash-to-asset ratio (see Figure 2). The second phase had larger inflows and outflows (+/- 10 million dollars) that resulted in correspondingly larger swings in the cash-to-asset ratio.

The next two phases had asymmetrical ranges that generated either more inflows or outflows. In the case of inflows, the expectation would be that the continued addition of funds would cause repeated cycles of new investment, cushioned by the buildup of cash. Outflows would result in a similar pattern of repeated liquidations, again cushioned by cash reserves. As seen in Figure 2, the last two phases have distinctive "saw tooth" patterns. Phase 3 had randomly generated inflows and outflows, skewed toward outflows (in the range -10 to +2 million). These investor redemptions forced the mutual fund to deplete cash reserves until repeated liquidation events became necessary for the continued servicing of outflows. The cycle of cash depletion and liquidations to replenish the reserves is quite apparent. Similarly, in phase 4 the situation is reversed with randomly generated inflows and outflows (in the range of -2 to +10 million) giving rise to more inflows. Continued inflows result in cash reserves repeatedly reaching a point that requires new investment based on the benchmark index. Each investment draws down cash, which then builds up again over time. The last panel in Figure 2 clearly shows a similar cyclical pattern. These types of experiments are being used to validate the agent behaviors in our preliminary model.
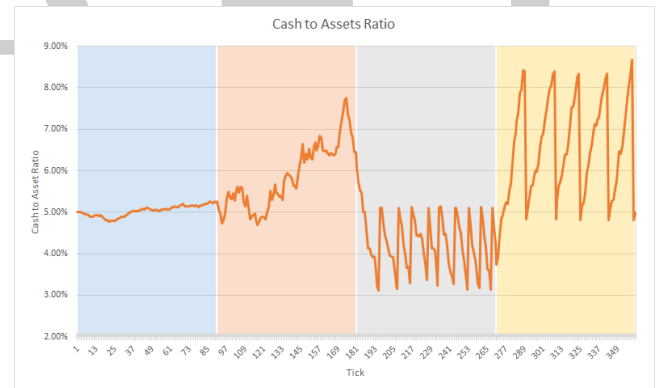
Figure 4. Mutual Fund Cash-to-Asset Ratio Changes

6. CONCLUSION

In this paper, we introduce an initial agent-based model of the corporate bond market. This minimal model includes three buy-side agents. The mutual fund agent is a real money investor that implements a passive index tracking strategy. The insurance company agent is another real money investor with a longer-term focus that allocates a portfolio between bonds and equities. Finally, the hedge fund agent is relative value tactical trader with the ability to use leverage. These three agents provide a nice breadth of different investment approaches that makes even this first model fairly realistic.

The sell side includes three broker-dealer agents that can hold both long and short positions. Each dealer agent has loosely defined specialization based on maturity (short term, medium term, and long term). These dealers serve as the price setters in

the model, responding to request-for-quote (RFQ) messages from the buy-side agents. This simple six-agent model is being used to refine agent behaviors and assess the model response to some basic exogenous factor such as yield curve shifts and monetary policies.

7. ACKNOWLEDGMENTS

8. REFERENCES

[1] Goldstein, I., Jiang, H. and Ng, D.T. 2015. Investor Flows and Fragility in Corporate Bond Funds. Working Paper. DOI= http://dx.doi.org/10.2139/ssrn.2596948.

[2] Y. Chen, Y. and Qin, N. 2015. The Behavior of Investor Flows in Corporate Bond Mutual Funds. *Management Science, Forthcoming*. DOI= http://dx.doi.org/10.2139/ssrn.2022059

[3] Edwards, A. K., Harris, L. and Piwowar, M. S. 2007. Corporate Bond Market Transaction Costs and Transparency". *Journal of Finance*, Vol. 62, No. 3 (Jun. 2007), DOI= http://dx.doi.org/10.1111/j.1540-6261.2007.01240.x

[4] Committee on the Global Financial System (CGFS). 2011. Fixed Income Strategies of Insurance Companies and Pension Funds. *CGFS papers* No. 44.

[5] Brunnermeier, M. K. and Pedersen, L. H. 2009. Market Liquidity and Funding Liquidity. *Review of Financial Studies* Vol. 22 Issue 6: 2201-2238 (2009). DOI= http://dx.doi.org/hhn098

[6] Ang, A., Gorovyy, S. and van Invwegen, G. B. 2011. Hedge Fund Leverage. *Journal of Financial Economics* Vol. 102(1): 102-126. (Oct. 2011) DOI= http://dx.doi.org/10.3386/w16801

[7] Rand, W. Rust, R. 2011. Agent-Based Modeling in Marketing: Guidelines for Rigor. *International Journal of Research in Marketing*, 28: 181-193 (Jun. 2011).

[8] Bookstaber, R., 2012. Using Agent-Based Models for Analyzing Threats to Financial Stability. *Office of Financial Research Working Paper* #0003 (Dec. 2012)

[9] Flood, M. D., Liechty, J. C., Piontek T., Systemwide Commonalities in Market Liquidity. *Office of Financial Research Working Paper* (May 2015)

[10] Office of Financial Research, 2015 Annual Report to Congress (Jan. 2016)

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