Simulating Blockchain Applications in Large-Value Payment Systems through Agent-Based Modeling

Demonstration Track

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ABSTRACT

We introduce an interactive Large-Value Payment System simulator designed to explore potential blockchain-based designs via agent-based modeling. Two hypothetical blockchain-based scenarios are used to demonstrate the simulator's capabilities. This tool supports financial institutions and policymakers in assessing blockchain's practical applications and in making informed design decisions for future enhancements in Large-Value Payment Systems. Our demo video can be found at this link: http://bit.ly/4aSBpWS.

KEYWORDS

Blockchain; Simulation; RTGS; CBDC; Agent-Based Modeling

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1 INTRODUCTION

Large-Value Payment Systems (LVPSs) are critical infrastructures for transferring high-value, priority payments between financial institutions and supporting global financial stability [11]. Due to their systemic importance, LVPSs are often operated or overseen by central banks to ensure reliability, security, and robustness [6]. For instance, during the disruptions of September 11, 2001, central bank intervention helped prevent broader financial contagion [15]. Even so, LVPSs remain vulnerable to payment delays from strategic bank behavior, operational disruptions, or unintended consequences of banks' business models [1, 7].

Central banks continuously seek to improve LVPSs, with system liquidity as a primary concern. Sufficient liquidity helps prevent systemic issues like gridlocks and cascading failures within the financial network [3, 8]. Simulations are useful in evaluating LVPS design, yet many models treat bank behavior as static. Given that banks act strategically [3, 17], agent-based models (ABMs) provide valuable insights into how these behaviors affect systemic risk. Prior work has proposed using ABMs to model banks as strategic agents [8]. We extend this approach by also modeling key LVPS components as agents—specifically, the Settlement Agent, Queue Agent, and Credit Facility Agent. Figure 1 illustrates these agent interactions. Potential strategic behaviors include the System Agent dynamically adjusting throughput rules based on historical transaction volume, the Queue Agent determining dequeuing priority based on some liquidity-saving mechanism algorithm, and the Credit Facility Agent determining credit eligibility based on credit risk factors.

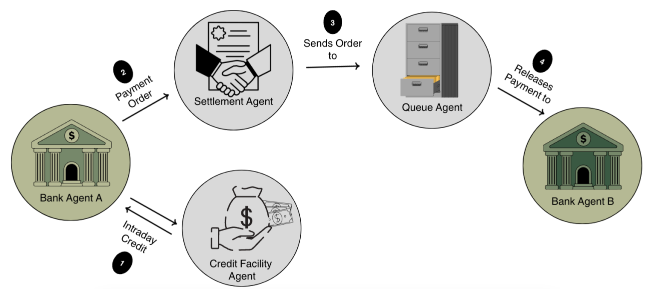

Figure 1: Agent Interactions for a Single Transaction

2 BLOCKCHAIN IN LVPS

Central banks are increasingly exploring wholesale Central Bank Digital Currencies (wCBDCs) [2, 16, 20] and the application of blockchain technology (loosely defined to include distributed ledger technology and smart contracts) to LVPSs [19]. Blockchain offers potential enhancements to payment systems through features like decentralization, transparency, and improved security. However, the discourse on exactly which blockchain features can most benefit LVPSs is just beginning to emerge.

Blockchain technology can alter information dynamics within financial systems, influencing agents' actions and strategies [5]. It enables validation of agents' claims through transparent and immutable transaction records [9]. Additionally, smart contracts can facilitate delivery-versus-payment (DvP) processes, automating settlements and reducing counterparty risk [4]. In this paper, we identify potential blockchain implementations in LVPSs and demonstrate how they can be simulated using agent-based models.

3 THE SIMULATOR APPLICATION

3.1 Simulator Overview

We built an interactive web application using the Python Streamlit framework, where users can create and simulate ABMs of LVPSs by configuring the parameters and the agents' behaviors. The application takes the user-defined input and fits them into *PSSimPy* [22], the simulator engine built for this LVPS simulation purposes.

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3.2 Demonstration of Blockchain Scenarios

We simulate two scenarios, with the transaction flow illustrated in Figure 1, and focus on two metrics to demonstrate how the outputs from our simulator can inform blockchain-based design considerations. The Turnover Ratio [18] ($\frac{\sum_{i=1}^{N} \text{Payment Value}_i}{\text{Average Intraday Liquidity}}$) measures the liquidity efficiency within the system, while the Average Payment Delay [14] ($\frac{\sum_{i=1}^{N} (\text{Settlement Time}_i - \text{Start Time}_i)}{N}$) evaluates system efficiency and operational stability. In this context, the start time typically refers to the payment submission time, making this metric an indicator of system congestion. Alternatively, defining the start time as the transaction arrival time would enable this metric to also capture strategic payment delays, which could occur when a bank decides to withhold payment despite having sufficient liquidity-a phenomenon known as liquidity hoarding [10].

3.2.1 Scenario 1: Unification of Asset Delivery and Payment Settlement Systems. In this scenario, we examine the influence on bank behavior when blockchain's transparency features enable targeted penalties for payment delays.

Traditional LVPSs manage only the settlement of cash payments, while the delivery of corresponding assets, such as securities, occurs through separate systems. Smart contracts allow DvP to be atomic and unified in a single system [2, 23]. Within a blockchain-based DvP framework, the timestamps of both the asset delivery and cash settlement are transparently recorded by the smart contract, allowing for targeted delay penalties to be imposed on the bank with the cash obligation. We assume that a well-designed blockchain infrastructure can mitigate legitimate payment delays caused by temporary network connectivity issues [13].

In our simulation, we model delay penalties by enabling the Settlement Agent to impose variable transaction fees. Bank Agents incorporate expected delay penalties into their payment timing strategies, influencing their approach to managing transaction delays. From Figure 2, we see that strategic delays can be countered if sufficient delay penalties are levied.

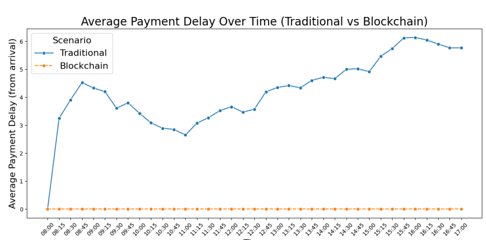

Figure 2: Comparison of Average Payment Delay Between Traditional LVPS and Blockchain-Based LVPS with Targeted Delay Costs

3.2.2 Scenario 2: Tokenizing Incoming Transactions. Here, we examine the impact on settlement delays and credit utilization when a Credit Facility Agent accepts incoming transactions as an alternative form of collateral.

Blockchain technologies offer potential benefits in tokenizing IOUs (promises to pay) [12, 21], which can be extended to LVPS by enabling the Credit Facility to accept tokenized incoming transactions from banks as collateral for intraday credit, alongside tokenized financial securities.

To simulate this, we design a Credit Facility Agent that functions similarly to a traditional intraday credit facility within a collateral-based framework but also allows for incoming transactions to serve as collateral. The Queue Agent in this setup aims to expedite transactions through the queue, subject to the constraint that the payer bank must maintain a positive balance after initiating a settlement. Consequently, certain transactions may experience delays if the payer bank has insufficient funds and cannot secure the necessary intraday credit to complete the settlement. For simplicity, we assume all Bank Agents are reliable and fulfill payment obligations on time. Figure 3 displays the combined indicator output of the traditional and blockchain-based scenarios.

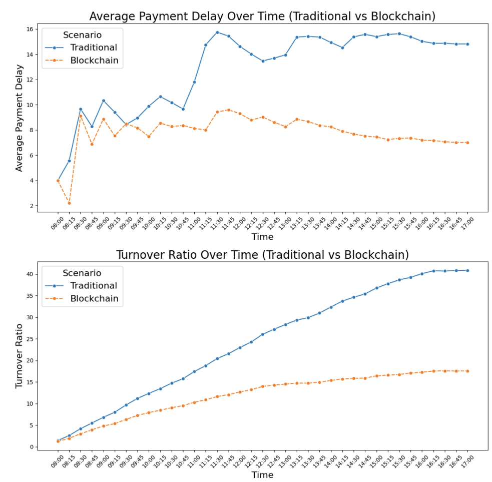

Figure 3: Comparison of Turnover Ratio and Average Payment Delay between Traditional and Blockchain-Based LVPS Utilizing Tokenized Incoming Transactions for Intraday Credit

Here, we observe that blockchain implementation leads to reduced payment delays but results in a lower Turnover Ratio over time. This highlights the inherent trade-offs involved in design decisions for blockchain-enabled LVPS and reinforces the importance of thorough simulation-based testing to assess potential impacts comprehensively before finalizing a blockchain system design.

4 CONCLUSION

We contribute to the study of LVPS by: (i) modeling LVPS as a multiagent system (ii) developing an interactive and customizable LVPS simulator compatible with ABM (iii) demonstrating the potential for blockchain applications in LVPS through configurable scenarios in our simulator. These contributions support policymakers and researchers to make data-driven design decisions.

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