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journal homepage: www.elsevier.com/locate/jedcAn agent-based model of payment systems[☆]Marco Galbiati^{a,*}, Kimmo Soramäki^b^a Bank of England, United Kingdom^b Aalto University School of Science and Technology, Helsinki, Finland

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ABSTRACT

We lay out and simulate a multi-agent, multi-period model of an RTGS payment system. At the beginning of the day, banks choose how much costly liquidity to allocate to the settlement process. Then, they use it to execute an exogenous, random stream of payment orders. If a bank's liquidity stock is depleted, payments are queued until new liquidity arrives from other banks, imposing costs on the delaying bank. We study the equilibrium level of liquidity posted in the system, performing some comparative statics and obtaining insights on the efficiency of alternative system configurations.

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1. Introduction

Virtually all economic activity is facilitated by transfers of claims by financial institutions. In turn, these claim transfers generate payments between banks whenever they are not settled across the books of a same bank. These payments are settled in interbank payment systems. In 2006, the annual value of interbank payments made in the European system TARGET totalled €675 trillion (\approx \$880 tr). In the corresponding US system Fedwire, the amount was \$670 trillion, while the UK system CHAPS processed transactions for a value of €68 trillion (\approx \$129 tr)—BIS (2009). In perspective, these transfers amounted to 24–40 times the value of the respective countries' GDPs. The sheer size of the transfers, and their pivotal role in the functioning of financial markets and the implementation of monetary policy, make payment systems a central issue for policy makers and regulators.

At present, most interbank payment systems work on a real-time gross settlement (RTGS) modality. That is, settlement takes place as soon as a payment is submitted into the system (real time); also, a payment can be settled only if the paying bank has enough funds to deliver the full amount in central bank money (*gross settlement*). Because no netting takes place

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offsetting payments, RTGS modality imposes high liquidity demands on the banks, making RTGS systems vulnerable to *liquidity risk*, i.e. to the risk that liquidity-short banks are unable to send their own payments. This may create delays and possibly cause gridlocks in the system (see e.g. [Bech and Soramäki, 2002](#)). The 2007–09 global financial crisis has stressed the importance of liquidity, prompting a lively debate on this issue at central banks and financial regulators. At the time of writing, new regulation is being designed throughout the world, to ensure that liquidity is present in sufficient amounts in key financial infrastructures: first of all, in interbank payment systems.

This paper aims at contributing to this knowledge, offering a model of liquidity demand and circulation in an RTGS system. To our knowledge, this is the first paper that explores this question using an “agent-based” approach. As [Ehrentreich \(2007\)](#) put it, a “major advantage [of such approach] is that [it] allows the removal of many restrictive assumptions that are required by analytical models for tractability”. As we will explain in a moment, this is our main reason to adopt such approach.

The amount and the distribution of liquidity in a payment system is the result of a complex interaction the system’s participants. Indeed, during the day, each bank has to make a stream of payments, that can only be partly predicted. To cover the liquidity needs generated by these payments, banks typically rely on two sources: (a) reserve balances or credit acquired from the central bank and (b) funds received from other settlement banks during the course of the day. The first source can be seen as providing *external* (to the system) *liquidity*, while the second is a source of *internal liquidity*. In normal conditions a bank can draw freely on external liquidity. This, however, has a cost, which gives incentives to economize on its use.² Internal liquidity on the other hand carries no cost, but its arrival is out of the bank’s control. Hence, reliance on internal liquidity exposes the bank to the risk of having to delay its own payment activity—something which also is costly.³ As a consequence, a bank has to optimally decide how much external liquidity to acquire, trying to forecast when and how much internal liquidity it will receive, trading off external liquidity costs against (expected) delay costs. The fact that banks (i) delay some payments, and yet (ii) do not wait till the very end of the day to make all their payments, shows that this tradeoff indeed exists.

Two main difficulties emerge when studying the behaviour of banks in a payment system. First, when modelled in sufficient detail, liquidity flows in RTGS systems follow complex dynamics (see [Soramäki et al., 2007](#)), making the bank’s liquidity management problem anything but trivial. Indeed, recent work by [Beyeler et al. \(2007\)](#) shows that, when the level of external liquidity is low, payments lose correlation with the arrival of payment orders; as a consequence, it is difficult to gauge the precise relationship liquidity and delays, making it hard to determine the optimal usage of external funds. Second, the actions of each bank produce spillover effects on the rest of the system, so no system participant can solve its optimal liquidity demand problem in isolation. As strategic interactions are widespread, banks interact in a fully fledged “game”, jointly determining the performance of the system.

This paper studies this liquidity game, putting particular effort into modelling liquidity flows. We thus build a payments model where external liquidity is continuously recycled among many banks, with delays and costs generated in a non-trivial way by a realistic settlement process. Such realism will force us to abandon a purely analytical approach, and to use simulations to find some elements of the game; in particular, the payoff function, that is the relationship the liquidity choices of each bank, and the resulting settlement delays and costs. We are interested in the equilibria of the liquidity game, or in the choices that banks may be seen to adopt in a consistent fashion. To do so we solve the model adopting a dynamic approach. That is, we assume that banks change their actions over time, using an adaptive process whereby actions are chosen on the basis of past experience. We then simulate the resulting dynamics and we look at the limit, or equilibrium, behaviour. The limit clearly depends on the specific form of the adaptive rule, which we therefore choose in such a way that: (a) it is consistent with some rationality on the part of the banks, in the spirit of the “agent-based” approach and (b) it leads to a meaningful equilibrium. In particular, a convergence point of our dynamics will be a Nash equilibrium of the liquidity game. Given that the outcome of our model is a Nash equilibrium, we could have followed the more traditional approach of directly looking for mutual best replies in the liquidity game. This approach would have lead to the same conclusions.⁴ However, it is interesting to see that the equilibrium as an emergent property of the system, a hallmark of agent-based models ([Tsfatsion, 2001](#); [Axelrod and Tsfatsion, 2006](#); [Herbert, 2007](#)).

Given its game-theoretic approach, this paper is related to recent work by [Angelini \(1998\)](#), [Bech and Garratt \(2003, 2006\)](#), [Buckle and Campbell \(2003\)](#). Our model differ from these contributions in two dimensions.

First, we consider a related but different issue. Previous works look at the *timing* decisions of banks: the liquidity management game played by the banks consists in deciding when to make a payment. Instead we concentrate on the decision of *how much liquidity* to post in a ‘collateralized’ RTGS system.⁵ That is, in a system where banks must pre-fund their accounts by pledging collateral with the central bank. Incidentally, most systems nowadays use the collateralized modality, with just

² The costs of acquiring liquidity are opportunity costs (returns that the bank would obtain if it could employ this liquidity differently), and interest costs (costs from borrowing the liquidity itself).

³ Delays usually carry two types of cost. First, formal agreements often penalize late delivery; if a delay extends over the end of the due day, penalties may apply. Second, delays may entail reputational costs, which are difficult to quantify but potentially large.

⁴ A technical aside: the fact that the liquidity game has multiple equilibria, and thus it is not clear *a priori* which one is selected by the learning process, is taken care of by our analytical result of Theorem 1.

⁵ [Chakravorti \(2000\)](#) looks at the choice of reserve holdings. However, he looks at a net settlement systems which are, as commented in the introduction, radically different RTGS systems.

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