Systemic Risk and Liquidity in Payment Systems

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Abstract

We study liquidity and systemic risk in high-value payment systems. Flows in high-value systems are characterized by high velocity, meaning that the total amount paid and received is high relative to the stock of reserves. In such systems, banks rely heavily on incoming funds to finance outgoing payments, necessitating a high degree of coordination and synchronization. We use lattice-theoretic methods to solve for the unique fixed point of an equilibrium mapping and conduct comparative statics analyses on changes to the environment. We find that banks attempting to conserve liquidity cause an increase in the demand for intraday credit and, ultimately, a disruption of payments. Additionally, we find that when a bank is identified as vulnerable to failure and other banks choose to cancel payments to that bank, there are systemic repercussions for the whole financial system.

1 Introduction

Since the credit market turmoil began in August 2007, financial institutions have become seriously preoccupied with their liquidity. These institutions have attempted to conserve cash holdings concerned about the possibility that they might face large draws on the standby liquidity facilities and credit enhancements of the special-purpose investment vehicles (SIVs) they sponsored. Moreover, as some of these SIVs were in danger of failing, banks came under raising pressure to rescue them by taking the assets of these off-balance sheet entities onto their own balance sheets. Greenlaw et al. (2008) and Brunnermeier (2008) present a detailed analysis of this on-going episode in financial markets.

As financial tension intensifies and banks become concerned about liquidity, they attempt to target more liquid balances. However, as banks increase their precautionary demand for liquid balances, they become less willing to lend to others. As a result, interbank funding rates have been showing clear signs of distress since August 2007. This has been highlighted by Fed Chairman Ben S. Bernanke in a speech last January[1]

> ... these developments have prompted banks to become protective of their liquidity and balance sheet capacity and thus to become less willing to provide funding to other market participants, including other banks. As a result, both overnight and term interbank funding markets have periodically come under considerable pressure, with spreads on interbank lending rates over various benchmark rates rising notably.

[1]'Financial Markets, the Economic Outlook, and Monetary Policy', speech by Ben S. Bernanke, 10 January 2008 (Bernanke (2008)).

A shorter, but perhaps an even sharper episode of the systemic implications of the gridlock in payments came in the interbank payment system following the September 11, 2001 attacks. The interbank payment system processes very large sums of transactions between banks and other financial institutions. Moreover, one of the reasons for the large volumes of flows is due to the two-way flow that could potentially be netted between the set of banks. That is, the large flows leaving bank A is matched by a similarly large flow into bank A over the course of the day. However, the fact that the flows are not exactly synchronized means that payments flow backward and forward in gross terms, generating the large overall volume of flows.

The nettable nature of the flows allows a particular bank to rely heavily on the inflows from other banks to fund its outflows. McAndrews and Potter (2002) notes that banks typically hold only a very small amount of cash and other reserves to fund their payments. The cash and reserve holdings of banks amount to only around 1% of their total daily payment volume. The rest of the funding comes from the inflows from the payments made by the other banks. To put it another way, one dollar held by a particular bank at the beginning of the day changes hands around one hundred times during the course of the day. Such high velocities of circulation have been necessitated by the trend toward tighter liquidity management by banks, as they seek to lend out spare funds to earn income, and to calculate fine tolerance bounds for spare funds.

There is, however, a drawback to such high velocities that come from the fragility of overall payment flows to disruptions to the system. There are two issues. There is, first, the issue of the resilience of the physical infrastructure, such as the robustness

of the communication channels and the degree of redundancy built into the system against the number of physical failures that the system can cope with.

However, much more important than the physical robustness of the system is the endogenous, mutually reinforcing responses from the constituents of the payment system itself. Even if the physical infrastructure is very robust, if the constituents begin to act more cautiously in their dealings with others, then the potential for a sharp decline in the total volume of payments is much greater in a high velocity payment system. The degree of strategic interaction is much higher in a high velocity payment system. In effect, a high velocity payment system is much more reliant on the virtuous circle of coordinated actions by the constituents. However, just as a high willingness to make payments will create a virtuous circle of high payment volumes, the decline in the willingness to pay will create a vicious circle of a downward spiral in the payment volume.

In what follows, our focus is on this second, endogenous response of the constituents of the payment system. We will show that even a small step change in the desired precautionary balances targeted by the banks may cause very large changes in the total volume of payments in the system. A foretaste of such effects was seen after the September 11 attacks, when banks attempted to conserve their cash balances as a response to the greater uncertainty. Given the high velocity of funds, even a small change in target reserve balances had a marked effect on overall payment volumes. The events of September 11 illustrate these effects vividly, as shown by McAndrews and Potter (2002) in their study of the US Fedwire payment system following the September 11 attacks.

Our paper addresses the issue of liquidity in a flow system. The focus is on the

interdependence of the agents in the system, and the manner in which equilibrium payments are determined and how the aggregate outcome changes with shifts in the parameters describing the environment. In keeping with the systemic perspective, we model the interdependence of flows and show how the equilibrium flows correspond to the (unique) fixed point of a well-defined equilibrium mapping. The usefulness of our approach rests on the fact that our model abstracts away from specific institutional details, and rests only of the robust features of system interaction. The comparative statics exercise draws on methods on lattice theory, developed by Topkis (1978) and Milgrom and Roberts (1994), and allows us to analyze the repercussions on the financial system of a change in precautionary demand for liquid balances and of a reduction in the value of transfers sent to one member of the payment system. Specifically, we aim at better understanding the systemic implications of a shift towards more conservative balance sheets targeted by one or a small set of market participants[2] as well as the consequences of delay and cancelation of payment orders directed to one member of the payment system[3].

We find that a reduction in outgoing payments to conserve cash holdings translates into lesser incoming funds to other banks, but lesser incoming funds will then affect outgoing transfers. Our findings show that if few banks targeted more liquid balances, there will be an increase in the demand for intraday liquidity provided by the Federal Reserve System and it could even lead to a full disruption of payments.

[2]See Ashcraft et al. (2008) for empirical evidence on banks holdings of large precautionary balances in the fed funds market during the 2007-08 financial crisis.

[3]Shifts in the timing of payments to later in the day have been observed in large-value payments since the market turmoil began in August 2007. Halsally et al. (2008) presents an interesting study of the interest rate volatility and the timing of activity in the Sterling unsecured overnight money market during the 2003-2008 period. They find significant delay in payment activity during turbulent times as lenders take a more cautious approach by making their funds available later in the trading day.

In the scenario where a bank is identified as vulnerable to failure by the other members of the payment system, which then decide to cancel payments to this bank, we find that the bank that does not receive any incoming funds demands an increased amount of intraday credit and reaches the end of the operating day with a significant negative balance and unable to settle queued payments. Also, our results show that the decision to cancel payments causes a reduction in the overall value of payments transferred over the whole payment system.

The outline of the paper is as follows. In the next section we introduce a theoretical framework for the role of interlocking claims and obligations in a flow system. An application to the interbank payment system then follows. Section 3 briefly reviews the US payment system paying special attention to the Fedwire Funds Service. Section 4 presents numerical simulations based on a stylized payment system and describes a standard business day in this payment system. Two more interesting scenarios are then considered in Sections 5 and 6. Section 5 analyzes the response of payment systems to a change in precautionary balances and Section 6 studies the systemic repercussions of banks' decision to cancel payments to a specific member of the payment system. Miscoordination in payments and a potential policy intended to economize on the use of intraday credit are discussed in Section 7. Section 8 concludes.

2 The Model

There are n agents in the payment system, whom we will refer to as "banks". Every member of the payment system maintains an account to make payments. This

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account contains all balances including its credit capacity.

Banks in a payment system rely heavily on incoming funds to make their payments. Let us denote by y_t^i the time t payments bank i sends to other members in the payment system. These payments are increasing in the total funds x_t^i bank i receives from other members during some period of time (from $t-1$ to t). We do not need to impose a specific functional form on this relationship. In particular, we will allow each bank to respond differently to incoming funds. The only condition we impose is that each bank only pays out a proportion of its incoming funds. Formally, it entails that transfers do not decrease as incoming payments rise and that its slope is bounded above by 1 everywhere. Then, outgoing transfers made by bank i at time t are given by:

$$y_t^i = f^i(x_t^i, \theta_t)$$

where $\theta_t = (b_t, c_t)$ and b_t represents the profile of balances b_t^i and c_t is the profile of remaining credit c_t^i. Outgoing payments made by bank i will depend on incoming funds, which in turn depends on all payments sent over the payment system. Then, for every member in the payment system we have:

$$y_t^i = f^i(x_t^i(y_{t-1}), \theta_t) \qquad i = 1, \ldots, n$$

This system can be written as:

$$y_t = F(y_{t-1}, \theta_t)$$

where $y_t = [y_t^1, y_t^2, \ldots, y_t^n]^\top$ and $F = [f^1, f^2, \ldots, f^n]^\top$.

The task of determining payment flows in a financial system thus entails solving for a consistent set of payments - that is, solving a fixed point problem of the mapping F. We will show that our problem has a well-defined solution and that the set of payments can be determined uniquely as a function of the underlying parameters of the payment system. We will organize the proof in two steps. Step 1 shows the existence of at least one fixed point of the mapping F. We will show uniqueness in Step 2.

Step 1. *Existence of a fixed point of the mapping F.*

LEMMA 1. *(Tarski (1955) Fixed Point Theorem) Let $(Y, \leq)$ be a complete lattice and F be a non-decreasing function on Y. Then there are y^* and y_* such that $F(y^*) = y^*$, $F(y_*) = y_*$, and for any fixed point y, we have $y_* \leq y \leq y^*$.*

A *complete lattice* is a partially ordered set $(Y, \leq)$ which satisfies that every non-empty subset $S \subseteq Y$ has both a least upper bound (join), $\sup(S)$, and a greatest lower bound (meet), $\inf(S)$. In our payments setting, we can define a complete lattice $(Y, \leq)$ as formed by a non-empty set of outgoing payments Y and the ordering $\leq$. Every subset S of the payment flows Y has a greatest lower bound (flows are non-negative) and a least upper bound which we will denote by $\overline{y}_i$. $\overline{y}_i$ represents the maximum flow of payments bank i can send through the payment system. This condition can be understood as a maximum flow capacity due to some technological limitations of the networks and communication systems used by the banks to receive and process transfer orders. We have:

$$Y = [0, \overline{y}_1] \times [0, \overline{y}_2] \times \ldots \times [0, \overline{y}_n]$$

The relation $\leq$ formalizes the notion of an ordering of the elements of Y such that $y \leq y'$ when $y_i \leq y'_i$ for all the components i and $y_k < y'_k$ for some component k.

In our payments problem, $(Y, \leq)$ is a complete lattice and since outgoing payments made by bank i do not decrease as incoming funds rise, i.e. f^i is a non-decreasing function, then $F = [f^1, f^2, \ldots f^n]^\top$ is non-decreasing on Y. Our setting hence satisfies the conditions of the Tarski's Theorem and as a result there exists *at least* one fixed point of the mapping F. Moreover, in Step 2 we will show that the fixed point is unique.

Step 2. *Uniqueness of the fixed point of the mapping F.*

THEOREM 1. *There exists a unique profile of payments flows y_t that solves $y_t = F(y_{t-1}, \theta_t)$.*

Proof. F is a non-decreasing function on a complete lattice $(Y, \leq)$. Then, by Tarski's Fixed Point Theorem (Lemma 1), F has a largest y^* and a smallest y_* fixed point. Let us consider, contrary to Theorem 1, that there exist two distinct fixed points such that $y_i^* \geq y_{i*}$ for all components i and $y_k^* > y_{k*}$ for some component k. Denote by x_i^* the payments received by bank i evaluated at y_i^* and by x_{i*} the payments received by bank i evaluated at y_{i*}. By the Mean Value Theorem, for any differentiable function f on $[x_{i*}, x_i^*]$, there exists a point $z \in (x_{i*}, x_i^*)$ such that

$$f(x_i^*) - f(x_{i*}) = f'(z)(x_i^* - x_{i*})$$

We have assumed that the slope of the outgoing payments is bounded above by 1 everywhere ($\frac{\partial f^i}{\partial x_i} < 1$ everywhere). Hence,

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$$
\begin{cases}
y_1^* - y_{1*} = f^1(\overline{y}_1, x_1^*) - f^1(\overline{y}_1, x_{1*}) \le x_1^* - x_{1*} \\[2mm]
y_2^* - y_{2*} = f^2(\overline{y}_2, x_2^*) - f^2(\overline{y}_2, x_{2*}) \le x_2^* - x_{2*} \\[2mm]
\vdots \\[2mm]
y_k^* - y_{k*} = f^k(\overline{y}_k, x_k^*) - f^k(\overline{y}_k, x_{k*}) < x_k^* - x_{k*} \\[2mm]
\vdots \\[2mm]
y_n^* - y_{n*} = f^n(\overline{y}_n, x_n^*) - f^n(\overline{y}_n, x_{n*}) \le x_n^* - x_{n*}
\end{cases}
$$

Re-arranging the previous system of equations we get

$$
\begin{cases}
x_{1*} - y_{1*} \le x_1^* - y_1^* \\[2mm]
x_{2*} - y_{2*} \le x_2^* - y_2^* \\[2mm]
\vdots \\[2mm]
x_{k*} - y_{k*} < x_k^* - y_k^* \\[2mm]
\vdots \\[2mm]
x_{n*} - y_{n*} \le x_n^* - y_n^*
\end{cases}
$$

Summing across banks we have

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\sum_{i=1}^{n} x_{i*} - \sum_{i=1}^{n} y_{i*} < \sum_{i=1}^{n} x_i^* - \sum_{i=1}^{n} y_i^*
$$

so that the total value of the balances including credit capacity is strictly larger under y^*, which is impossible. Therefore, there cannot exist two distinct fixed points and as a result $y^* = y_*$. $\qquad\square$

Although uniqueness is relevant to our analysis of payment systems, our key insights stem from the comparative statics results due to Milgrom and Roberts (1994).

2.1 Comparative Statics

THEOREM 2. *Let $y_t^*(\theta_t)$ be the unique fixed point of the mapping F. If for all $y_t \in Y$, F is increasing in θ_t, then $y_t^*(\theta_t)$ is increasing in θ_t.*

Proof. Let F be monotone non-decreasing and Y a complete lattice. From Tarski's Fixed Point Theorem (Lemma 1) and Theorem 1 there exists a unique fixed point $y_t^*(\theta_t)$ of the mapping F. For the simplicity of the argument, let us suppress the subscript t. Define the set $S(\theta)$ as

$$S(\theta) = \{y | F(y, \theta) \leq y\}$$

and define $y^*(\theta) = \inf S(\theta)$. Since F is non-decreasing in θ, the set $S(\theta)$ becomes more exclusive as θ increases. Hence, $y^*(\theta)$ is a non-decreasing function of θ. Formally, if F is increasing in θ, then for $\theta' > \theta$, $F(\theta') > F(\theta)$ and

$$S(\theta') = \{y | F(y, \theta') \leq y\} \subset S(\theta)$$

Thus,

$$y^*(\theta') = \inf S(\theta') > \inf S(\theta) = y^*(\theta)$$

Therefore, if F is increasing in θ, the fixed point $y^*(\theta)$ is increasing in θ too. $\square$

3 Payment Systems

Payment and securities settlement systems are essential components of the financial systems and vital to the stability of any economy. A key element of the payment system is the interbank payment system that allows funds transfers between entities[4]. Large-value (or wholesale) funds transfer systems are usually distinguished from retail systems. Retail funds systems transfer large volumes of payments of relatively low value while wholesale systems are used to process large-value payments. Interbank funds transfer systems can also be classified according to their settlement process. The settlement of funds can occur on a net basis (net settlement systems) or on a transaction-by-transaction basis[5] (gross settlement systems). The timing of the settlement allows another classification of these systems depending on whether they settle at some pre-specified settlement times (designated-time (or deferred) settlement systems) or on a continuous basis during the processing day (real-time settlement systems).

A central aspect of the design of large-value payment systems is the trade-off between liquidity and settlement risk. Real-time gross settlement systems are in constant need of liquidity to settle payments in real time while net settlement systems are very liquid but vulnerable to settlement failure[6]. In the last twenty years, large-value payments systems have evolved rapidly towards greater control of credit risk[7].

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[4]See Kahn and Roberds (2009) for a survey of the literature on payments economics.

[5]Kahn and Roberds (1998) studies the trade-offs between the cost and benefits associated with net relative to gross settlement of interbank payments.

[6]Zhou (2000) discusses the provision of intraday liquidity by a central bank in a real-time gross settlement system and some policy measures to limit the potential credit risk.

[7]Martin (2005) analyzes the recent evolution of large-value payment systems and the compromise between providing liquidity and settlement risk. See also Bech and Hobijn (2006) for a study on the history and determinants of adoption of real-time gross settlement payment systems by central banks across the world.

In the United States, the two largest large-value payment systems are the Federal Reserve Funds and Securities Services (Fedwire) and the Clearing House Interbank Payments System (CHIPS). CHIPS, launched in 1970, is a real-time, final payment system for US dollars that uses bi-lateral and multi-lateral netting to clear and settle business-to-business transactions. CHIPS is a bank-owned payment system operated by the Clearing House Interbank Payments Company L.L.C. whose members consist of 46 of the world's largest financial institutions. It processes over 300,000 payments on an average day with a gross value of $1.5 trillion.

Fedwire is a large-dollar funds and securities transfer system that links the twelve Banks of the Federal Reserve System[8]. The Fedwire funds transfer system, which we will discuss in more detail below, is a real-time gross settlement system, developed in 1918, that settles transactions individually on an order-by-order basis without netting. The average daily value of transactions exceeded $2 trillion in 2005 with a volume of approximately 527,000 daily payments. Settlement of most US government securities occurs over the Fedwire book-entry security system, a real-time delivery-versus-payment gross settlement system that allows the immediate and simultaneous transfer of securities against payments. More than 9,100 participants hold and transfer US Treasury, US government agency securities and securities issued by international organizations such as the World Bank. In 2005 it processed over 89,000 transfers a day with an average daily value of $1.5 trillion. Figure 1 depicts the evolution of the average daily value and volume of transfers sent over CHIPS and Fedwire.

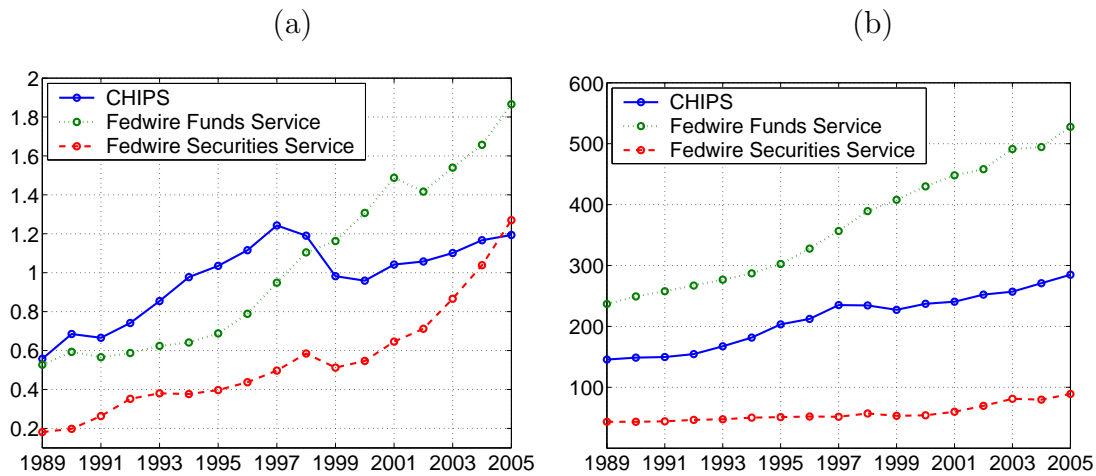[8]See Gilbert et al. (1997) for an overview of the origins and evolution of Fedwire.

Figure 1: Average daily value (a) ($ trillion) and volume (b) (thousands) of transactions over CHIPS, Fedwire Funds Service and Fedwire Securities Service, 1989-2005. Source: The Federal Reserve Board and CHIPS.

3.1   Fedwire Funds Service

Fedwire Funds Service, owned and operated by the Federal Reserve Banks, is an electronic payment system that allows participants to make same-day final payments in central bank money. An institution that maintains an account at a Reserve Bank can generally become a Fedwire participant. Approximately 9,400 participants are able to initiate and receive funds transfers over Fedwire. When using the Fedwire Funds Service, a sender instructs a Federal Reserve Bank to debit its own Federal Reserve account for the amount of the transfer and to credit the Federal Reserve account of another participant.

The Fedwire Funds Service operates 21.5 hours each business day (Monday through Friday), from 9.00 p.m. Eastern Time (ET) on the preceding calendar day to 6.30 p.m. ET[9]. It was expanded in December 1997 from ten hours to eigh-

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[9]A detailed description of Fedwire Funds Service operating hours can be found at

teen hours (12:30 a.m. - 6:30 p.m.) and again in May 2004 to accommodate the twenty-one and a half operating hours. This change increased overlap of Fedwire's operating hours with foreign markets and helped reduce foreign exchange settlement risk.

A Fedwire participant sending payments is required to have sufficient funds, either in the form of account balance or overdraft capacity, or the payment order may be rejected. The Federal Reserve imposes a minimum level of reserves, which can be satisfied with vault cash[10] and balances deposited in Federal Reserve accounts, neither of which earn interest[11]. A Fedwire participant may also commit itself or be required to hold balances in addition to any reserve balance requirement (clearing balances). Clearing balances earn no explicit interest but implicit credits that may offset the cost of Federal Reserve services. Fedwire participants thus tend to optimize the size of the balances in their Federal Reserve accounts[12].

When an institution has insufficient funds in its Federal Reserve account to cover

www.frbservices.org/Wholesale/FedwireOperatingHours.html.

[10]Vault cash refers to U.S. currency and coin owned and held by a depository institution.

[11]The Financial Services Regulatory Relief Act of 2006 authorizes the Federal Reserve to pay interest on reserve balances and on excess balances beginning October 1, 2011. The effective date of this authority was advanced to October 1, 2008 by the Emergency Economic Stabilization Act of 2008. Initially, the interest rate paid on required reserve balances was 10 basis points below the average target federal funds rate over a reserve maintenance period while the rate for excess balances was set at 75 basis points below the lowest target federal funds rate for a reserve maintenance period. The Federal Reserve began to pay interest for the maintenance periods beginning on October 9, 2008 (Federal Reserve (2008a)). The interest rate paid on required reserve balances was modified to 35 basis points below the lowest target federal funds rate. This new rate became effective on October 23, 2008 (Federal Reserve (2008b)). Since November 6, 2008, the rate paid on required reserve balances is equal to the average target federal funds rate over the reserve maintenance period while the interest rate on excess balances is equal to the lowest target federal funds rate in effect during the reserve maintenance period (Federal Reserve (2008c)). See Keister et al. (2008) for an analysis of the implications of paying interest on these balances.

[12]Bennett and Peristiani (2002) find that required reserve balances in Federal Reserve accounts have declined sharply while vault cash applied against reserve requirements has increased. They argue that reserve requirements have become less binding for US commercial banks and depository institutions.

its debits, the institution runs a negative balance or *daylight overdraft.* Daylight over-drafts result because of a mismatch in timing between incoming funds and outgoing payments (McAndrews and Rajan (2000)). Each Fedwire participant may establish (or is assigned) a maximum amount of daylight overdraft known as *net debit cap*[13]. An institution's net debit cap is a function of its capital measure. Specifically, it is defined as a cap multiple times its capital measure, where the cap multiple is determined by the institution's cap category. An institution's capital measure varies over time while its cap category does not normally change within a one-year period. Each institution's cap category is considered confidential information and hence it is unknown to other Fedwire participants (Federal Reserve (2005), Federal Reserve (2006d)).

In 2000 the Federal Reverse Board's analysis of overdraft levels, liquidity patterns, and payment system developments revealed that although approximately 97 percent of depository institutions with positive net debit caps use less than 50 percent of their daylight overdraft capacity, a small number of institutions found their net debit caps constraining (Federal Reserve (2001)). To provide additional liquidity, the Federal Reserve now allows certain institutions to pledge collateral to gain access to daylight overdraft capacity above their net debit caps. The maximum daylight overdraft capacity is thus defined as the sum of the institution's net debit cap and its collateralized capacity.

To control the use of intraday credit, the Federal Reserve began charging day-light overdraft fees in April 1994. The fee was initially set at an annual rate of 24 basis points and it was increased to 36 basis points in 1995[14]. At the end of each

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[13]Appendix A.1 briefly reviews the evolution of net debit caps and describes the different cap categories and associated cap multiples.

[14]Fedwire operates 21.5 hours a day, hence the effective annual rate is 32.25 basis points ($36 \times \frac{21.5}{24}$)

Fedwire operating day the end-of-minute account balances are calculated. The average overdraft is obtained by adding all negative end-of-minute balances and dividing this amount by the total number of minutes in an operating day (1291 minutes). An institution's daylight overdraft charge is defined as its average overdraft multiplied by the effective daily rate (minus a deductible). Table 4 presents an example of the calculation of a daylight overdraft charge. An institution incurring daylight overdrafts of approximately $3 million every minute during a Fedwire operating day would face an overdraft charge of $6.58.

At the end of the operating day, a Fedwire participant with a negative closing balance incurs overnight overdraft. An overnight overdraft is considered an unauthorized extension of credit. The rate charged on overnight overdrafts is generally 400 basis points over the effective federal funds rate. If an overnight overdraft occurs, the institution will be contacted by the Reserve Bank, it will be required to hold extra reserves to make up reserve balance deficiencies and the penalty fee will be increased by 100 basis points if there have been more than three overnight overdraft occurrences in a year. The Reserve Bank will also take other actions to minimize continued overnight overdrafts (Federal Reserve (2006a)).

4   An Example of Payment System

In this section we present numerical simulations of a stylized payment system reminiscent of Fedwire. We first describe the payment system and next we introduce the characteristics of a standard day of transactions in this payment system.

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and the effective daily rate is 0.089 basis points ($32.25 \times \frac{1}{360}$).

4.1 The Payment System

Consider a network of four banks. Each bank sends and receives payments from other members of the payment system. The payment system opens at 9.00 p.m. on the preceding calendar day and closes at 6.30 p.m. Every bank begins the business day with a positive balance at its central bank account and may incur daylight overdrafts to cover negative balances up to its net debit cap. For simplicity we assume initial balances and net debit caps of equal size. The expected value of bank i's outgoing payments equals the expected value of its incoming funds to guarantee that no bank is systematically worse off. Each member of the payment system is subject to idiosyncratic shocks which determine its final payments.

Following McAndrews and Potter (2002) we define outgoing transfers as a linear function of the payments a bank receives from all other banks. Specifically, at every minute of the operational day, bank i pays at most 80 percent of its cumulative receipts and is able to commit reserves and credit capacity up to the bank's own net debit cap. We assume banks settle obligations whenever they have sufficient funds. When the value of payments exceeds 80 percent of a bank's incoming funds and its available reserves and intraday credit, payments are placed in queue. Queued payments are settled as soon as sufficient funds become available[15].

When banks use more than 50 percent of their own daylight overdraft capacity[16], they become concerned about liquidity shortages and reduce the value of their

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[15]To avoid excessive fluctuations we consider that if bank i has spare reserves and/or intraday credit, it will devote this spare capacity to settle queued payments. Otherwise, payments will remain in queue.

[16]According to a Federal Reserve Board's review, in 2000, 97 percent of depository institutions with positive net debit caps use less than 50 percent of their daylight overdraft capacity (Federal Reserve (2001)).

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outgoing transfers. Inspired by McAndrews and Potter's estimates of the slope of the reaction function of banks during the September 11, 2001, events, we assume that banks would then pay at most 20 percent of their incoming funds. Table 1 summarizes how banks organize their payments.

Banks pay at most:	
NORMAL CONDITIONS	CAUTIOUS CONDITIONS
80% of its cumulative receipts	20% of its cumulative receipts
and	and
reserves and intraday credit up to bank's net debit cap	reserves and intraday credit up to 5% of bank's net debit cap

Table 1: Outgoing payments.

Once bank i becomes concerned about a liquidity shortage and reduces the slope of its reaction function, it faces one of two possible scenarios. Its balance may become positive (it has been receiving funds from all other banks according to the 80 percent rule while it has been paying out only 20 percent of its incoming transfers). The "episode" would be over and bank i would return to normal conditions. However, it may also be possible that despite reducing the amount of outgoing payments its demand for daylight overdraft continues to rise. Bank i would incur negative balances up to its net debit cap. At that time, it would stop using intraday credit to make payments and any incoming funds would be devoted to settle queued payments and to satisfy outgoing transfers at the 20 percent rate per minute.

Let us summarize the time-t decisions faced by bank i. Box 1(a) introduces these decisions while Box 1(b) explicitly presents the decision rules based on bank

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i's payments, balance and credit capacity. At any time t, bank i first verifies the conditions under which payments were sent to other banks at the previous minute of the operating day, i.e. at $t - 1$. If previous payment conditions were "normal" (we define "normal" below), then bank i focuses attention on its remaining credit capacity. If bank i has not reached half of its own daylight overdraft capacity, it continues organizing payments following the "normal conditions" rule. Under "normal conditions", bank i pays at most 80 percent of its cumulative receipts and up to its remaining reserves and credit capacity. If at a given time, outgoing payments exceed this amount, payments are placed in queue.
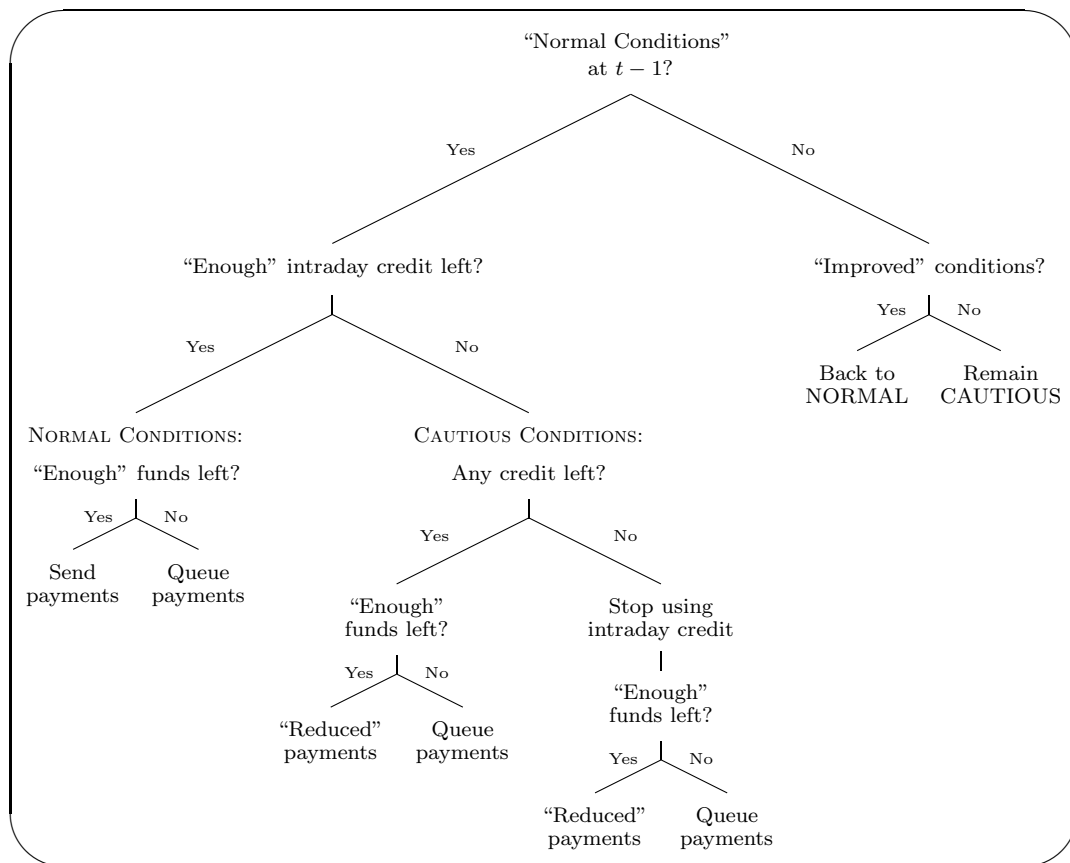
Box 1(a): Bank i's payment decisions at time t.

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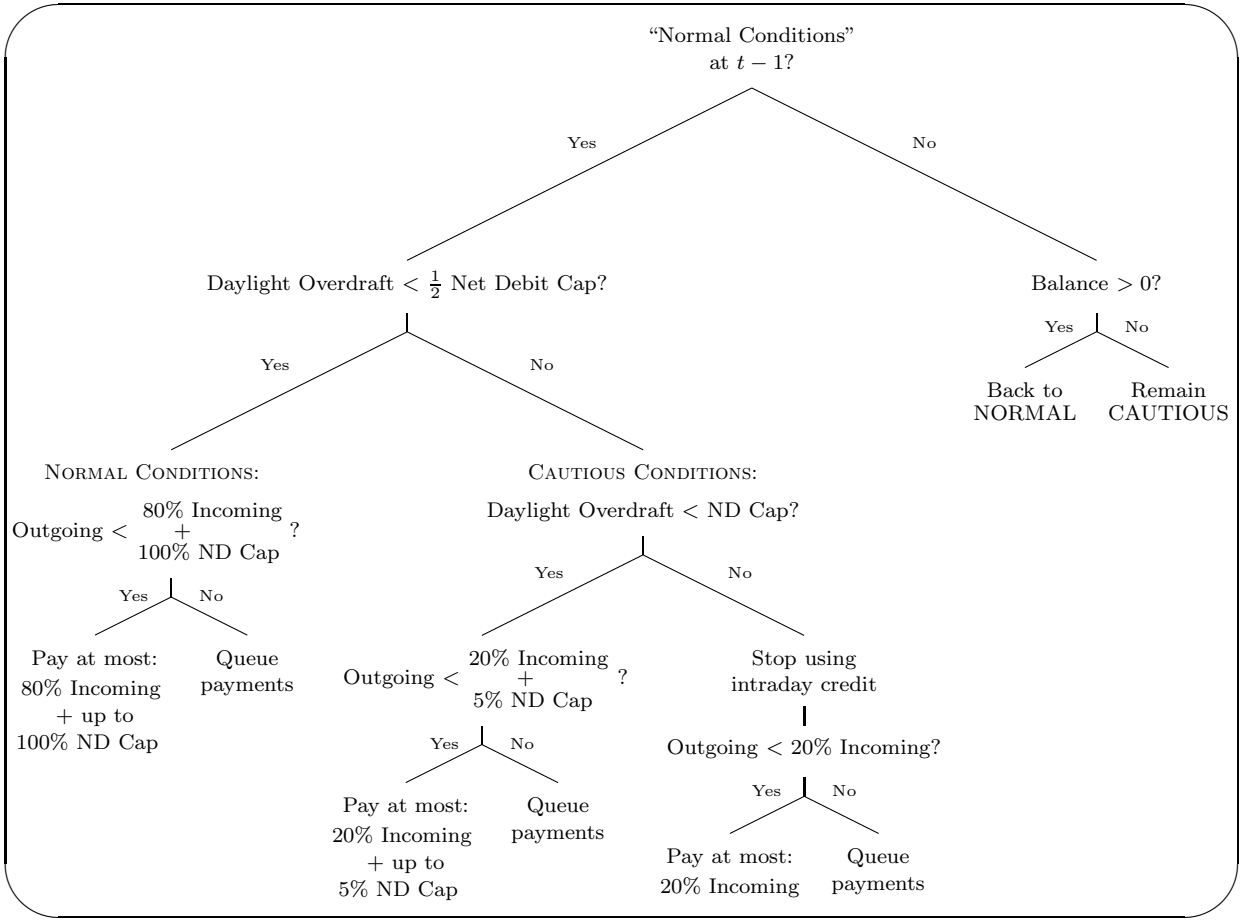
Box 1(b): Bank i's payment decisions at time t.

On the contrary, if at time t bank i has already used half of its daylight over-draft capacity, it becomes concerned about liquidity shortages and decides to make payments according to the "cautious conditions" rule. Under "cautious conditions", bank i considers two alternative scenarios. First, if bank i still has some intraday credit capacity left, i.e. if its daylight overdrafts have not reached its net debit cap, bank i pays out at most 20 percent of its incoming funds and up to 5 percent of its own net debit cap. Payments exceeding this condition are placed in queue. Second, if bank i's daylight overdrafts have already reached its net debit cap, bank i is no

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longer authorized to use daylight overdrafts. It pays out at most 20 percent of its cumulative receipts and queues other payments.

Finally, if at time $t-1$ payments were made under "cautious conditions", bank i faces two possibilities. If at time t, its balance has become positive, bank i has overcome the liquidity shortage and returns to organizing payments according to the "normal conditions" rule. However, if its balance is still negative, it remains "cautious".

To determine the initial and terminal payments, we assume the market opens under "normal conditions" and every bank has a positive net debit cap and thus begins the day with "enough" intraday credit. Once the market closes at 6.30 p.m. banks are required to satisfy reserve and clearing balance requirements. Banks can borrow from other participants before the market closes. For simplicity, we abstract away from the process to meet these requirements.

4.2 Standard Functioning of the Payment System

We consider a payment system as the one just described above and focus on the functioning of the payment system during one business day. The value of payments by time of the day is depicted in Figure 2(a). Payments are defined to follow the pattern of the average value of transactions sent over the Fedwire Funds Service[17]. Thus, as in the case of Fedwire, the market opens at 9.00 p.m. on the preceding calendar day, there is almost no payment activity before 8 a.m. and from then on the value of payments increases steadily and it peaks around 4.30 p.m. and again

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[17]See McAndrews and Rajan (2000) (Chart 3) and Coleman (2002) (Chart 1).

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around 5.15 p.m.[18] The market closes at 6.30 p.m.

Each bank starts the operating day with a positive balance in their Federal Reserve accounts, which we assume equal to 10. Figure 2(b) plots the balances at the central bank account of each member of the payment system during this business day. Before 8 a.m. all balances remain close to the opening balance because of the low payment activity. Let us focus our attention on banks B and C, for instance. Bank C initially receives more payment orders than transfers requests. Bank B represents the opposite case. Just after 1.30 p.m. bank C starts running negative balances and thus incurring daylight overdrafts as illustrated in Figure 2(c). Overdrafts peak at 5.13 p.m. Shortly after that, bank C begins receiving more payments than payment orders. At 5.25 p.m. it runs a positive balance and ends the day with a positive balance (its closing balance more than doubles its opening balance).

As shown in Figures 2(c) and the top panel of 2(d), all four banks incur daylight overdrafts but they do not place payments in queue. As in the case of bank C, banks A and D reach the end of the operating day with positive balances while B runs a negative closing balance and it will need to "sweep" deposits from another account to its account at the central bank to avoid an overnight overdraft charge (Figure 2(b)).

In this exercise, we set net debit caps equal to 100. During this business day, none of the four banks have reached half of their net debit caps (their balances never fall below -50 (50 percent of their cap)) and hence every bank sends out payments according to the "normal conditions" rule. The slope of their reaction functions is

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[18]The average value of Fedwire funds peaks at 4.30 p.m. and at 5.15 p.m. most likely from settlement at the Depositary Trust Company and from institutions funding their end-of-day positions in CHIPS respectively (Coleman (2002)).
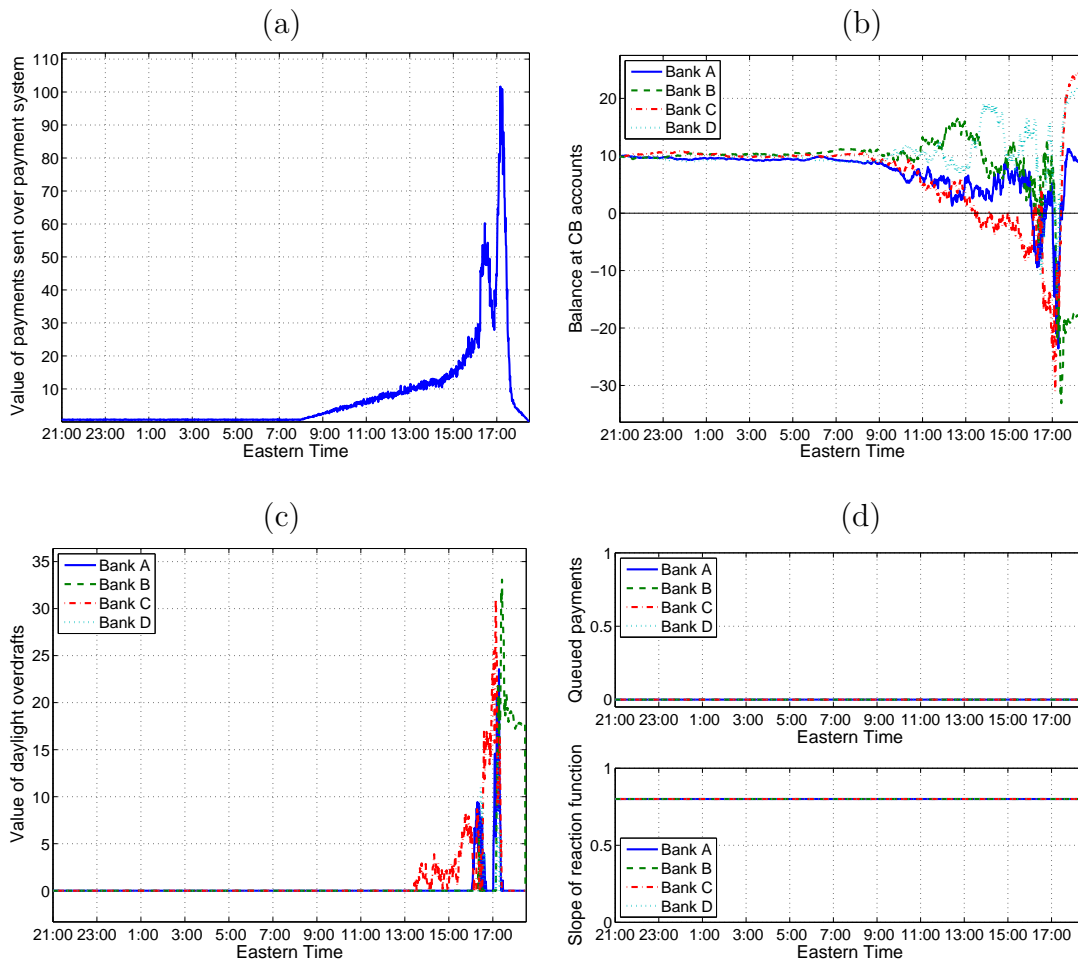
Figure 2: STANDARD FUNCTIONING OF THE PAYMENT SYSTEM - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

thus 0.8 as depicted in the bottom panel of Figure 2(d).

Overall, this example pictures the smooth functioning of the payment system. Let us now introduce more interesting scenarios. In Section 5 we discuss what happens when a bank attempts to conserve cash holdings. Then, in Section 6, we analyze the sequence of events following banks' decision to cancel transfers to a specific member of the payment system.

5 Increased Precautionary Demand

Consider a member of the payment system becomes suddenly concerned about a liquidity shortage. Suppose, for instance, this bank wants to conserve cash holdings because the conduits, SIVs or other off-balance sheet vehicles that it is sponsoring have drawn on credit lines as experienced in credit markets during the recent market turmoil.

We are interested in the consequences of an increase in the liquid balances targeted by one bank (or a small group of banks) in our payment system. Specifically, we assume bank A is the one concerned about a liquidity shortage. To preserve cash, bank A begins to make payments according to the "cautious conditions" rule. Hence, bank A decides to pay only 20 percent of the funds it receives (and up to 5 percent of its net debit cap per minute). Banks B, C and D initially behave as in the baseline scenario, i.e. they send out payments following the "normal conditions" rule (they pay at most 80 percent of incoming funds and up to their net debit caps).

Figure 3 summarizes the main results. Let us first focus our attention on the evolution of the balances hold at the central bank accounts depicted in Figure 3(b). Before 8 a.m. banks' balances are close to the opening balances due to the low level of activity in the payment system. Between 8 a.m. and approximately 4 p.m. the value of payment orders increases modestly and the payment system functions smoothly even though bank A is targeting a more conservative balance. During this period of time, no payments are delayed (top panel of Figure 3(d)) and only bank C incurs in daylight overdraft at around 1.30 p.m. (Figure 3(c)) as it balance becomes negative.
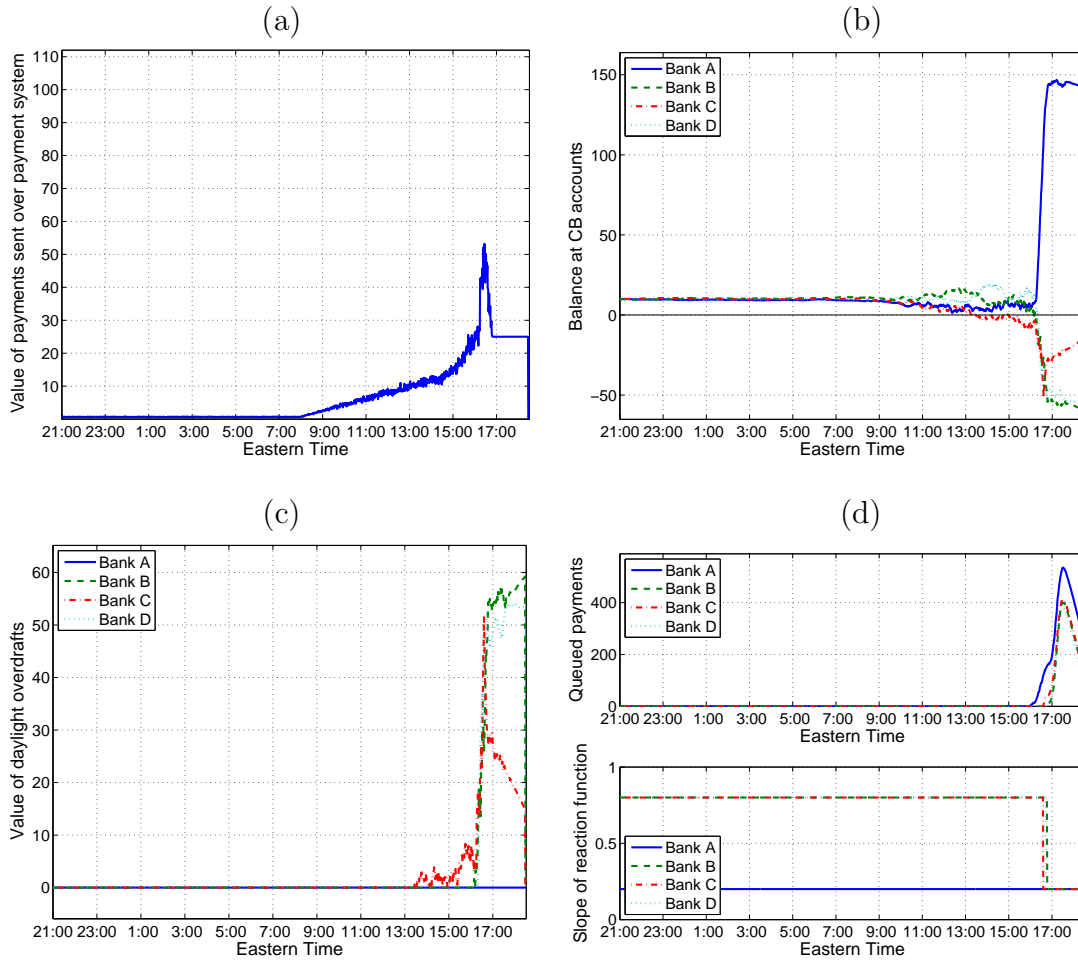
Figure 3: INCREASED PRECAUTIONARY DEMAND - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

The situation changes dramatically as the bulk of payment orders arrive after 4 p.m. Initially, banks B, C and D still make payments following the "normal conditions" rule while bank A sends out reduced payments. The size of bank A's balance thus increases enormously as it receives transfers at the 80 percent rate while paying out at most 20 percent of the funds it receives (Figure 3(b)). Also, as payment orders arrive, bank A begins to delay payments that exceed 20 percent of its cumulative receipts and 5 percent of its net debit cap. This is shown in the

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top panel of Figure 3(d). Meanwhile, banks B, C and D try to settle payments using the reduced incoming funds, their reserves and then intraday credit. Balances of these three banks become negative shortly after 4.20 p.m. (Figure 3(b)) and hence they begin to incur in overdrafts to make payments (Figure 3(c)). Just after 5 p.m. overdrafts reached half of the banks' net debit caps. Banks B, C and D now become concerned about a liquidity shortage and decide to organize their payments following the 20 percent rule as illustrated in the bottom panel of Figure 3(d). Under "cautious conditions", these banks make reduced payments and consequently they begin to place payments in queue (top panel of Figure 3(d)). At that time, there is disruption of payments (Figure 3(a)). The four banks are now making reduced payments and as a result they reach the end of the operating day unable to settle pending payments orders. Overall, comparing Figure 3(a) to 2(a) and Figure 3(b) to 2(b) clearly shows that both the value of payments and the size and pattern of the balances differ from the standard functioning of the payment system described in Subsection 4.2.

It is important to highlight that a change in preferences of a member of the payment system towards more liquid balances induces the following effects. First, it causes disruption of payments. Payment activity is disrupted as soon as all members organize payments according to "cautious conditions". When every bank sends only reduced payments, the payment system freezes and banks cannot settle payments before the market closes. Second, the size of banks' balances hold at the Federal Reserve increases compared to the standard functioning of the payment system. Third, a raise in precautionary demand leads to an enormous use of intraday credit.

We could think this abrupt change in payments, balances and the intraday credit

demanded by banks is determined by our choice of the rate at which bank A sends out transfers as it attempts to conserve cash holdings. This is not necessary the case. In Subsection 5.1 we present a sensitivity analysis and show how the pattern evolves as bank A varies its payment rule.

5.1   Sensitivity Analysis

In this subsection we present three alternative "cautious conditions" rules to analyze how bank A's choice of the proportion of incoming funds used to make payments affects the functioning the payment system. Specifically, we assume three different scenarios where bank A pays at most 30, 40 or 60 percent of its cumulative receipts (and up to 5 percent of its net debit cap). We also include the standard results when bank A pays at most 20 percent of the funds it receives to facilitate the comparison.

Figures 4 and 5 illustrate the main findings. Figure 4 shows the total value of payments sent over the payment system when bank A decides to conserve cash holdings and makes payments according to these four "cautious conditions" rules and Figure 5 depicts the value of delayed payments and the different rates at which banks send out payments during a business day. In Appendix A.3, we also present banks' balances (Figures 10(b), 11(b), 12(b) and 13(b)) and the value of daylight overdrafts (Figures 10(c), 11(c), 12(c) and 13(c)) for each rule respectively.

In the first two scenarios there is disruption of payments (Figure 4(a) and (b)) and some delayed payments cannot be settled before the market closes at 6.30 p.m. (Figure 5(a) and (b)). In particular, when bank A chooses to pay at the 30 percent rate, banks B, C and D use intraday credit heavily to make payments. Once they
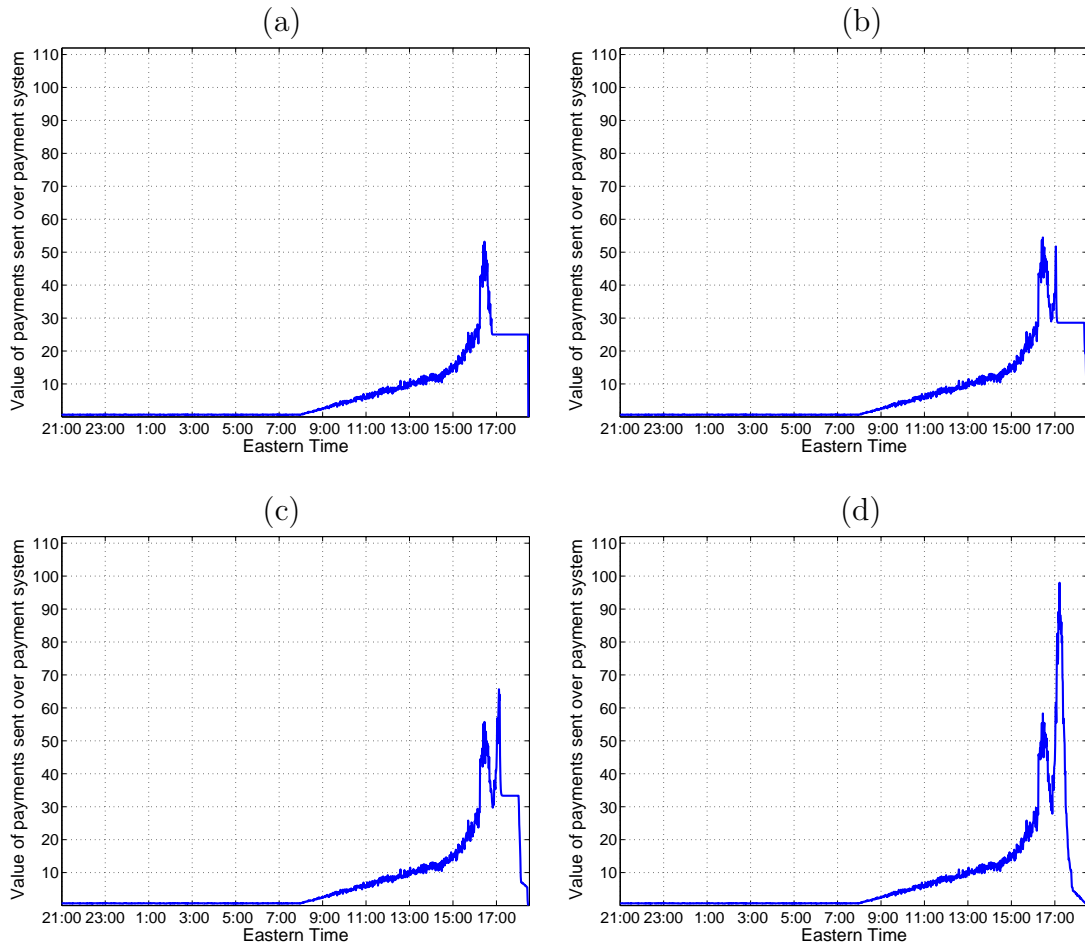
Figure 4: TOTAL VALUE OF PAYMENTS SENT OVER THE PAYMENT SYSTEM: Bank *A* pays out at most 20% (a), 30% (b), 40% (c) or 60% (d) of incoming funds.

reach half of their net debit caps, they also follow the 30 percent rule in an attempt to conserve cash and as a result they begin to place payments in queue. Bank *A* then receives reduced payments from all other members of the payment system and is forced to delay more payments. In this exercise banks *B*, *C* and *D* manage to settle all their delayed payments but bank A still has pending payment orders when the market closes (Figure 5(b)).
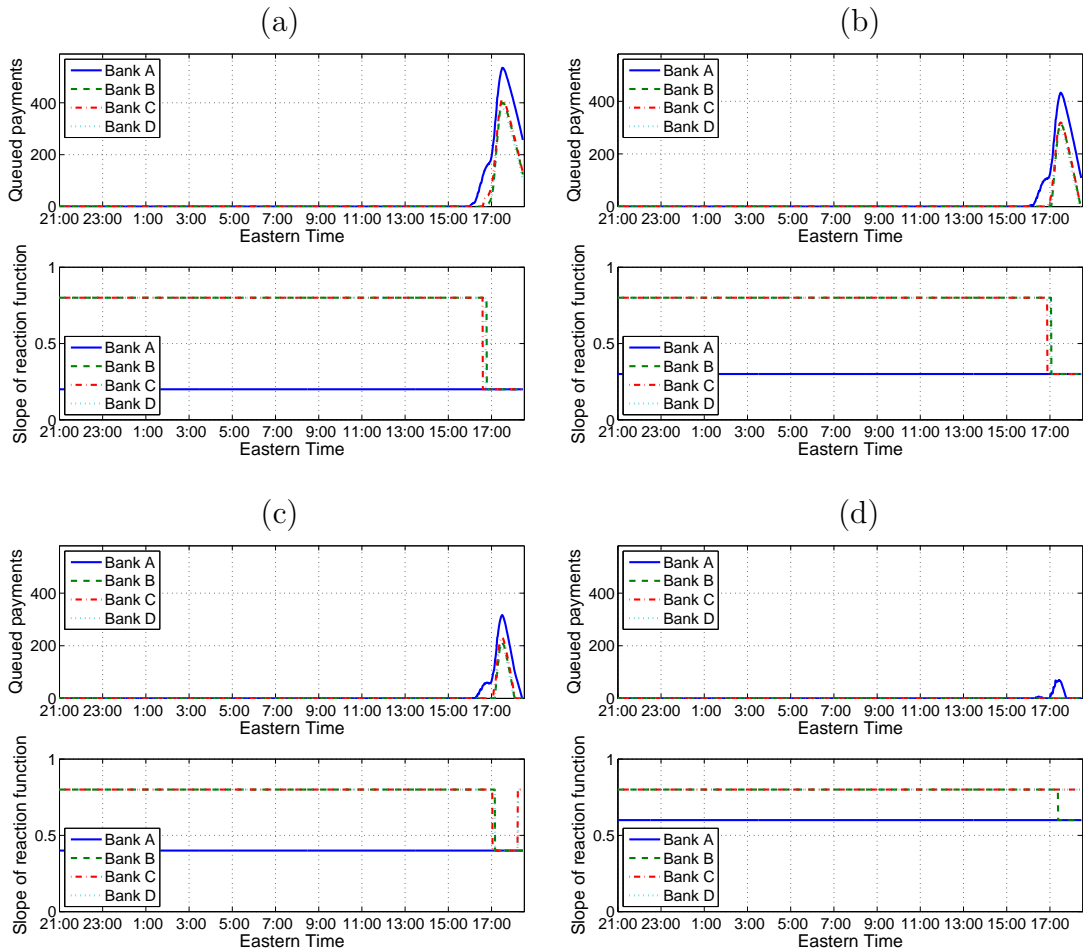
Figure 5: VALUE OF QUEUED PAYMENTS AND RATE OF PAYMENTS: Bank A pays out at most 20% (a), 30% (b), 40% (c) or 60% (d) of incoming funds.

If bank A were to pay out 40 percent of its cumulative receipts (and up to 5 percent of its net debit cap), the distribution of the value transferred across the day over the payment system would change but all payments would be settled before the end of the operating day as illustrated in Figure 4(c) and the top panel of Figure 5(c) respectively. As in the previous case, once banks B, C and D have used half of their credit capacity, they also follow the 40 percent rule and begin to delay payments. Bank A then receives reduced payments and places more payments in

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queue. The main difference is that now banks can take advantage of the reduction on the incoming payment orders after 5.30 p.m. to settle delayed payments.

The last scenario corresponds to the case where bank A follows the 60 percent rule. Bank A's preference for more liquid balances induces delays in payments within the operating day, larger balances and higher demand for intraday credit. These delays in payments cause a shift in activity to later in the day, consistent with the trend observed in the time distribution of value transferred over the Fedwire Funds Services[19].

Overall, it is relevant to point out that variations in outgoing payments to conserve cash holdings lead to delays in payments, an increase in the size of banks' balances at their central bank accounts (bank A's balance increases at the expense of the other banks), an enormous use of intraday credit and, in case of large changes, disruption of payments and unsettled payments at the end of the operating day.

6 Sudden Inflows Dry-up

In this section we discuss the possibility that banks delay and cancel payments to a specific member of the payment system. Suppose, for instance, that news or even rumors about a bank's financial position lead to an increasing lack of confidence in one member. Banks may then decide to postpone payments to this bank. Specifically, we assume bank A is the one hit by the rumor. Banks B, C and D queue and cancel payment orders to bank A while making transfers among them as usual. Initially, bank A sends out payments to every other bank. Our main results are presented in
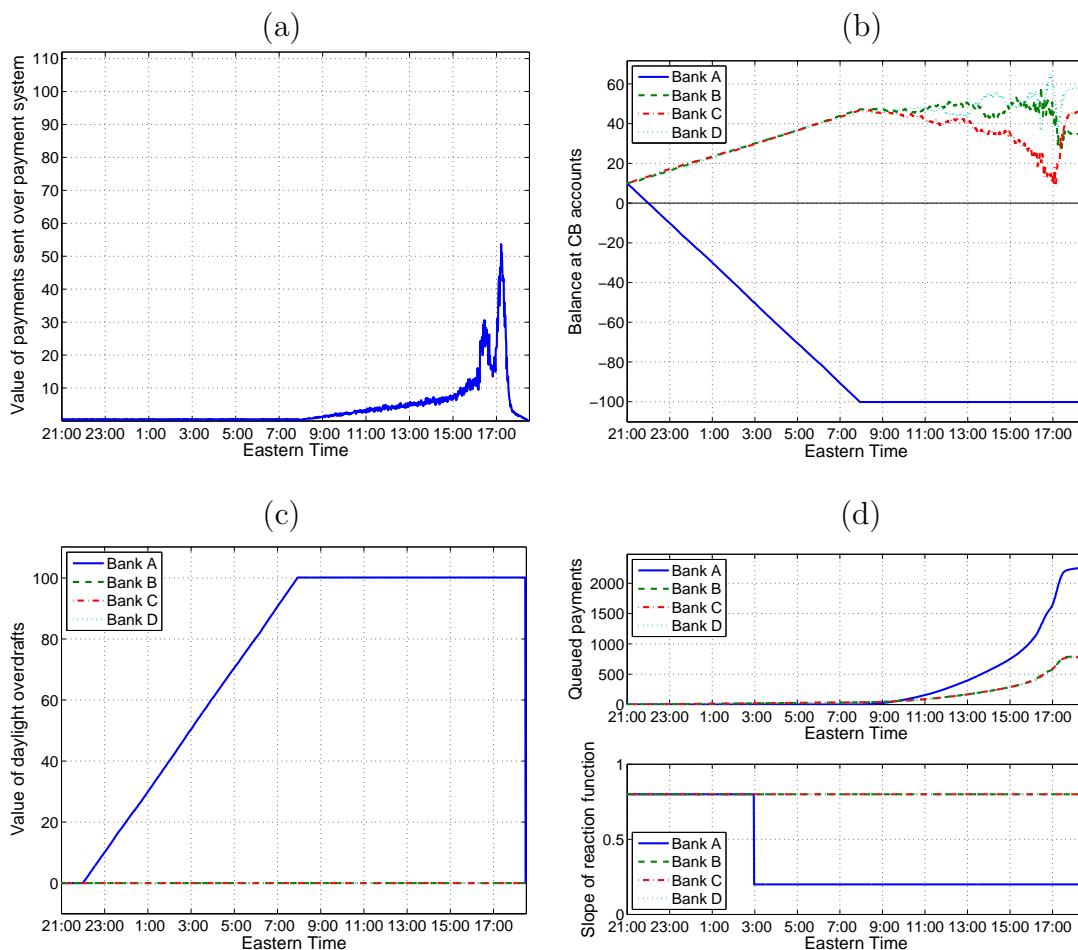
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[19]See Armantier et al. (2008).

Figure 6.

Figure 6: INFLOWS DRY-UP - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day when banks B, C and D cancel payments to bank A.

As shown in Figure 6 (b), bank A's balance decreases steadily until bank A exhausts its credit capacity. Since it does not receive any payments from other banks, bank A first uses its reserves to settle payments and then its intraday credit (Figure 6 (c)). At around 3 a.m. bank A's overdrafts reach half of its credit capacity. At that time, concerned about finding itself short of liquidity, it begins to send out

reduced payments (bottom panel of Figure 6 (d)). Shortly after 8 a.m., bank A runs out of credit and is forced to queue payments. Bank A ends the operating day with a large negative balance and pending payment orders.

Banks' decision to cancel payments to another bank causes a reduction in the overall value of payments transferred over the payment system and an increase in queued and unsettled payments. Also, the bank which receives no payments demands an enormous amount of intraday credit and ends the business day with a significant negative balance.

7 Miscoordination and Multiple Settlements

In this section we analyze, first, if the payment system is sensitive to timing miscoordination. Second, we discuss the possibility of having two synchronization periods (instead of having only one late in the afternoon).

7.1 Timing Miscoordination

In the U.S. payment system[20], banks in aggregate make payments that exceed their deposits at the Federal Reserve Banks by a factor of more than 100. To achieve such velocities a high degree of coordination and synchronization is required. In the standard functioning of the payment system, introduced in Subsection 4.2, we assumed banks could synchronize their payment activity perfectly, i.e., we considered the value of the payments made by every bank exhibited exactly the same pattern. In

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[20]See McAndrews and Potter (2002).

the next example, we examine the response of the payment system to miscoordination in the timing of payments. Specifically, suppose that banks experience a five-minute delay with respect to each others. Figure 7 summarizes our findings.
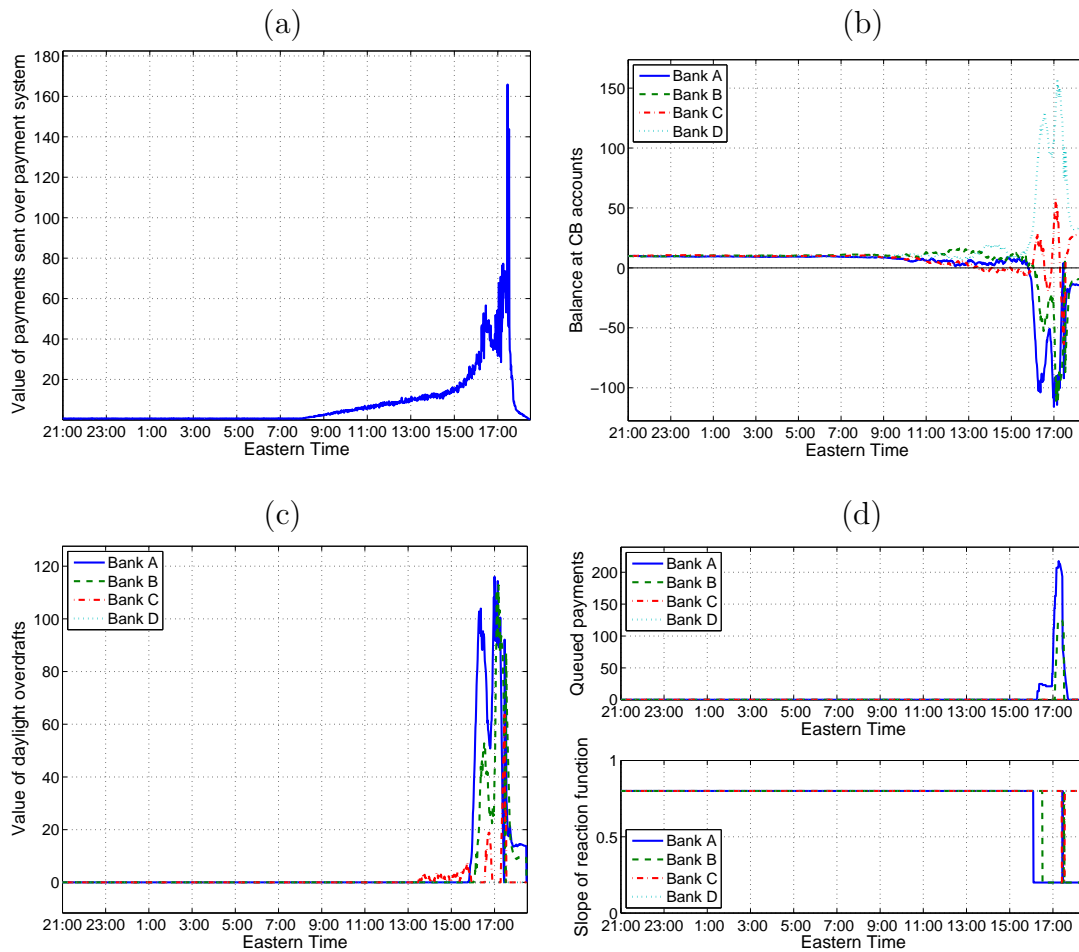

Figure 7: TIMING MISCOORDINATION - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

Payments are organized as follows. Bank A starts sending out payments first. B begins five minutes after A, then C after B and D is the last one. As a result, there is a mismatch in timing between the settlement of payments owned and the

settlement of payments due. Initially, bank A makes more payments that it receives (Figure 7(b)) and hence it incurs daylight overdrafts as shown in Figure 7(c). The bank that pays first will demand the largest amount of intraday credit. Then, the bank after the first one and so on (Figure 7(c)). This pattern persists across business days (simulations). Once a bank has used half of its credit capacity, it starts making payments according to the 20 percent rule. This is depicted in the bottom panel of Figure 7(d). The top panel of Figure 7(d) reports the payments placed in queue.

Banks A and B end the operating day with a negative balance while banks C and D run positive closing balances. We could think this is a consequence of the time mismatch. However, this is not the case. In this exercise, payments are delayed but the expected value of outgoing funds and incoming payments is still the same. To emphasize this result we present a different business day in Figure 8. Now, banks A and B hold a positive closing balance while banks C and D will need to "sweep" deposits to avoid the overnight overdraft penalty rate.

A five-minute miscoordination in payments thus induces an increase in the size of balances at the central bank accounts and a more intense use of the intraday credit compared to the standard functioning of the payment system.

7.2   Multiple Settlement Periods

To economize on the use of intraday credit, a potential operational change in settlement systems which is being considered (Federal Reserve (2006b)) is the possibility of developing multiple settlement periods. An example of such policy could be the establishment of two synchronization periods, one late in the morning and then an-
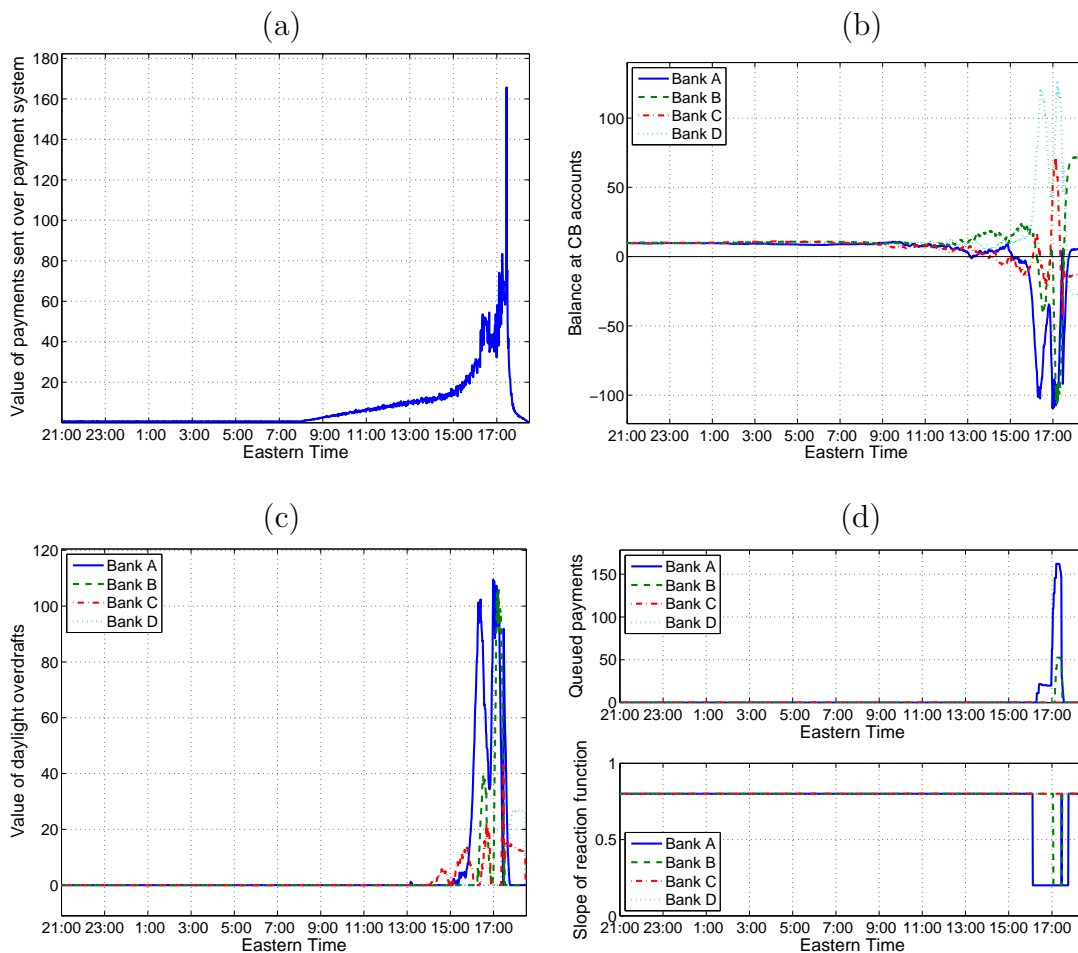
Figure 8: TIMING MISCOORDINATION (Different business day)

other early in the afternoon peak, as proposed by McAndrews and Rajan (2000).

Assume there is an additional synchronization period around noon such that the value of payments sent over the payment system follows the pattern in Figure 9(a). Let us discuss the response of the payment system to such policy. Our results are reported in Figure 9.

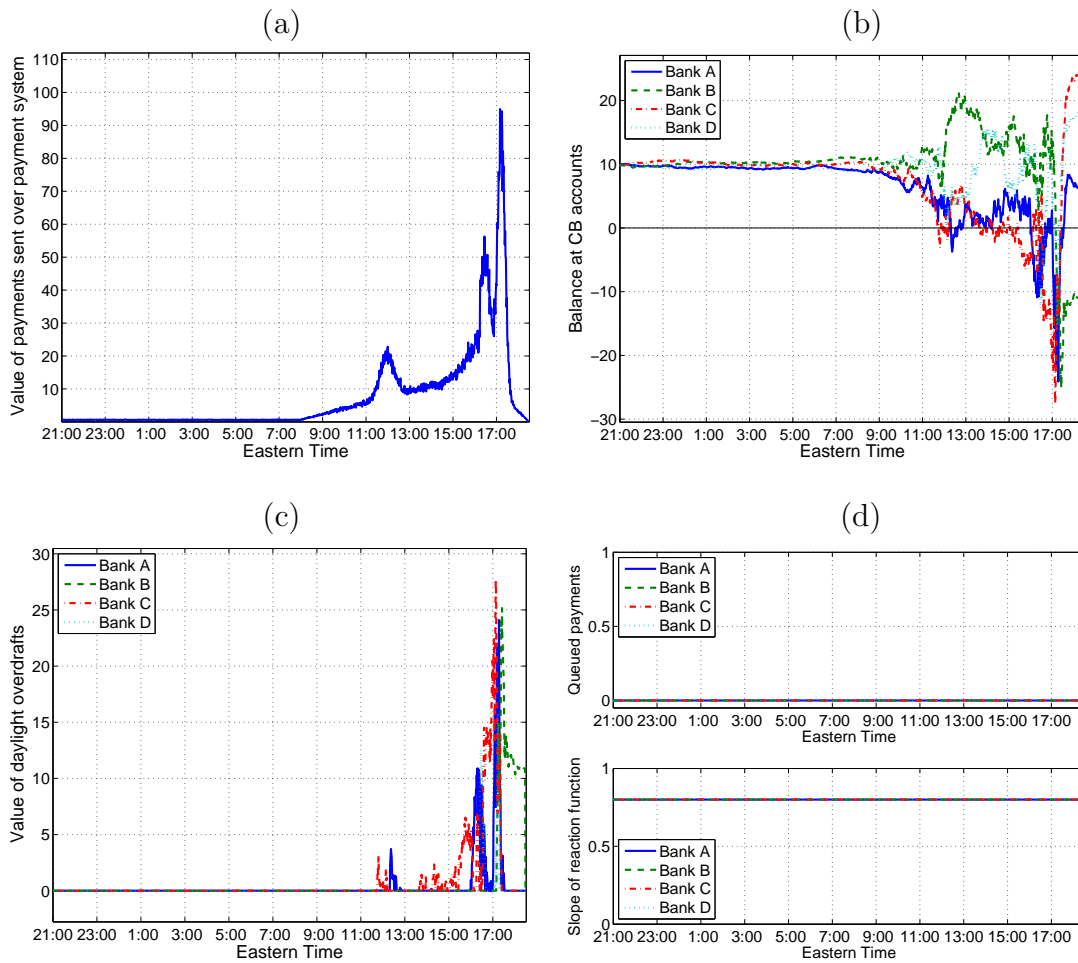Relative to the standard functioning, we find that introducing multiple synchro-

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Figure 9: MULTIPLE SYNCHRONIZATION PERIODS - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

nization periods does not alter significantly the size of banks' balances at their central bank accounts or the ratio between outgoing and incoming funds. This can be seen by comparing Figures 2(b) to 9(b) and the bottom panels of Figures 2(d) to 9(d). On the contrary, it reduces the use of daylight overdraft (Figures 2(c) and 9(c)) and the amount of payments in queue (top panel of Figures 2(d) and 9(d)).

We conclude that having two synchronization periods does economize on the use of intraday credit.

8   Concluding Remarks

The focus of the paper is on the role of liquidity in a flow system. We argue for the importance of the interdependence of the flows in high-value payment systems. High-value payment systems such as the interbank payment systems that constitute the backbone of the modern financial system, link banks and other financial institutions together into a tightly knit system. Financial institutions rely heavily on incoming funds to make their payments and as such, their ability to execute payments will affect other participants' capability to send out funds. Changes in outgoing transfers will affect incoming funds and incoming funds changes will affect outgoing transfers. The loop thus created may generate amplified responses to any shocks to the high-value payment system.

We draw from the literature on lattice-theoretic methods to solve for the unique fixed point of an equilibrium mapping in high-value payment systems. Using numerical simulations based on simple decision rules which replicate the observed data on the Fedwire payment system in the U.S., we then perform comparative statics analysis on changes to the environment of this payment system. We find that changes in preferences towards more conservative balances by one bank in the payment system lead to disruption of payments, increased balances at the Federal Reserve accounts and an immense use of intraday credit.

Our framework also allows simulations of counterfactual "what if" scenarios of disturbances that may lead to gridlock and systemic breakdown, as well as the consequences of potential policies such as the possibility of multiple settlement periods. We show that canceling payments to a bank which is identified as vulnerable to failure

leads to a reduction in the overall value of payments sent over the payment system. Also, introducing a second synchronization period late in the morning economizes on the demand for intraday credit.

Appendix

A.1 Net Debit Caps

In 1985, the Federal Reserve Board developed a payment system risk policy on risks in large-dollar wire transfer systems. The policy introduced four categories of limits (net debit caps) on the maximum amount of daylight overdraft credit that the Reserve Banks extended to depository institutions: *high*, *above average*, *average* and *zero*. In 1987 a new net debit cap (*de minimis*) was approved. It was intended for depository institutions that incur relatively small overdrafts. The Board incorporated a sixth cap class (*exempt-from-filing*) and modified the existing *de minimis* cap multiple in 1990. The *de minimis* cap multiple was then increased in 1994 when daylight overdraft fees were introduced[21]. A brief summary[22] of the actual cap categories and their associated cap multiples for maximum overdrafts on any day (single-day cap) and for the daily maximum level averaged over a two-week period (two-week average cap) are presented in Tables 2 and 3.

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[21] For a comprehensive study of the history of Federal Reserve daylight credit see Coleman (2002). See also Federal Reserve (2005).

[22] For a detailed reference, see Federal Reserve (2006c).

Table 2: Brief definition of cap categories.

Cap Category	Chosen by institutions that	Requirements
High *Above Average* *Average*	Regularly incur daylight overdrafts in excess of 40 percent of their capital. They are referred to as "self-assessed".	Self-assessment of own creditworthiness, intraday funds management, customer credit and operating controls and contingency procedures. Each institution's board of directors must review the self-assessment and recommend a cap category at least once in each twelve-month period.
De minimis	Incur relatively small daylight overdrafts.	Board-of-directors resolution approving use of daylight credit up to de minimis cap at least once in each 12-month period.
Exempt-from-filing	Only rarely incur daylight overdrafts.	Exempt from performing self-assessments and filing board-of-directors resolutions.
Zero	Do not want to incur daylight overdrafts and associated fees. A Reserve Bank may assign a zero cap to institutions that may pose special risks.	

Table 3: Net debit cap multiples of capital measure.

Cap Category	Single Day	Two-week Average
High	2.25	1.50
Above Average	1.875	1.125
Average	1.125	0.75
De minimis	0.4	0.4
Exempt-from-filing[a]	min{$10 million,0.2}	min{$10 million,0.2}
Zero	0.0	0.0

[a]The net debit cap for the *exempt-from-filing* category is equal to the lesser of $10 million or 0.20 multiplied by a capital measure.

A.2 Example Daylight Overdraft Charge Calculation

Table 4 contains an example of the calculation of a daylight overdraft charge.

Table 4: Daylight Overdraft Charge

Example of Daylight Overdraft Charge Calculation[a]

Policy parameters
Official Fedwire day = 21.5 hours
Deductible percentage of capital = 10%
Rate charged for overdrafts = 36 basis points (annual rate)

Institution's parameters
Risk-based capital = $50 million
Sum of end-of-minute overdrafts for one day = $4 billion

Daily Charge calculation
Effective daily rate = .0036 x (21.5/24) x (1/360) = .0000089
Average overdraft = $4,000,000,000 / 1291 minutes = $3,098,373
Gross overdraft charge = $3,098,373 x .0000089 = $27.58
Effective daily rate for deductible = .0036 x (10/24) x (1/360) = .0000042
Value of the deductible = .10 x $50,000,000 x .0000042 = $21.00
Overdraft charge = 27.58 - 21.00 = $6.58

[a]Federal Reserve (2006d).

A.3 Sensitivity Analysis

A.3.1 Bank A follows 'cautious conditions' (20% rule)
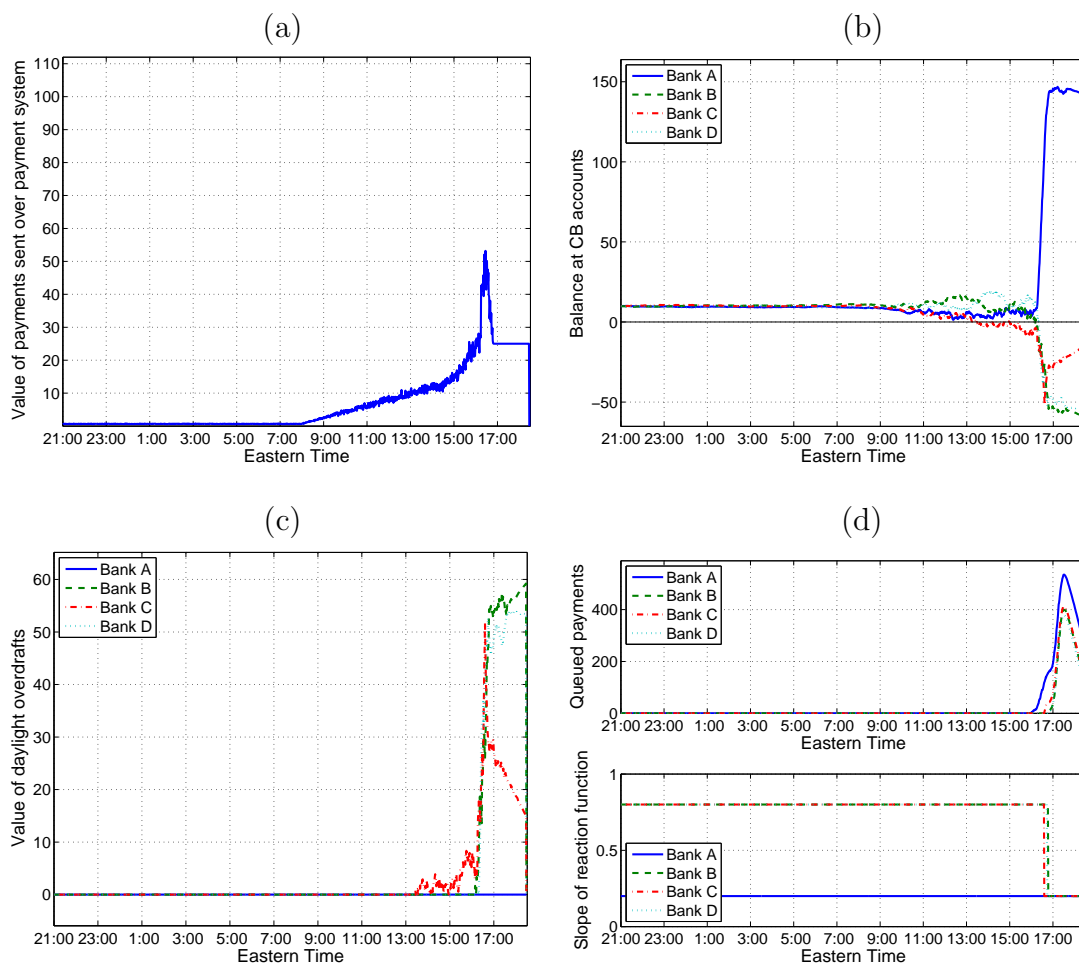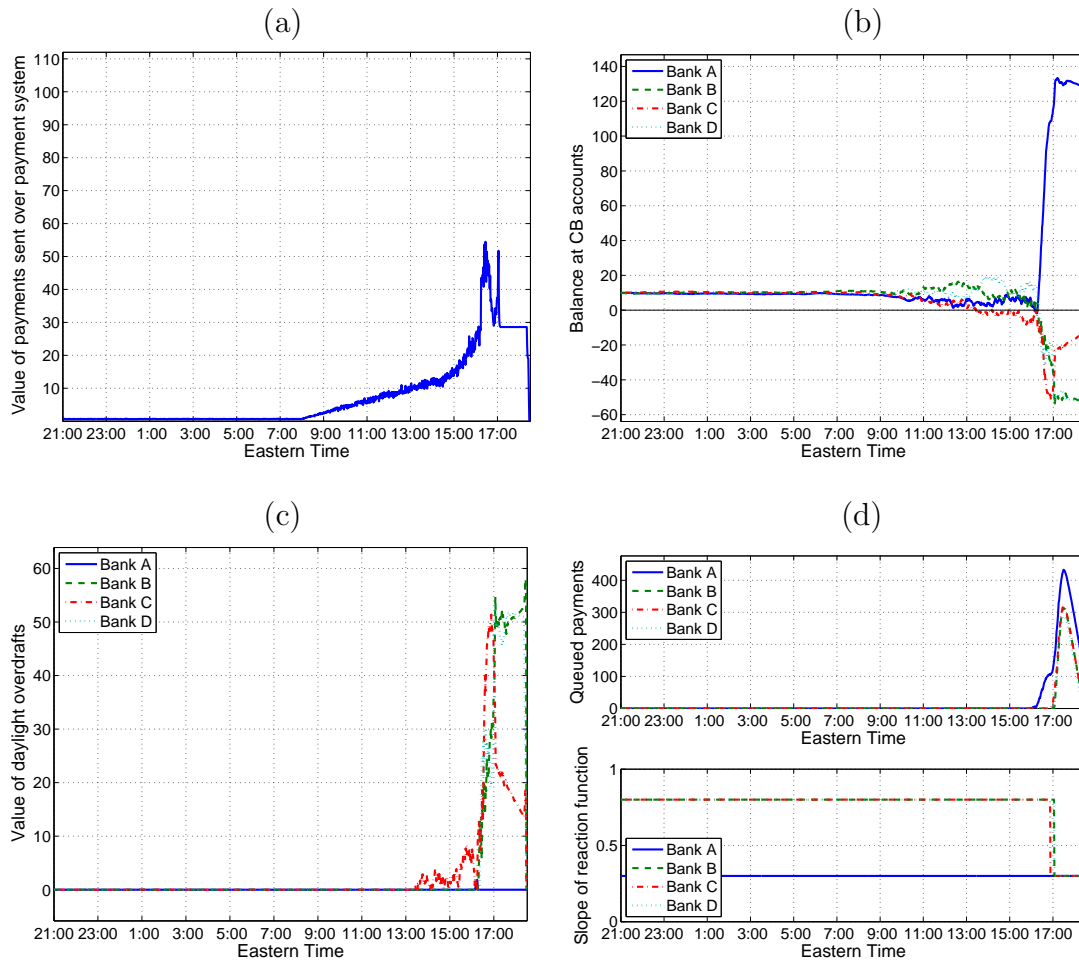

Figure 10: INCREASED PRECAUTIONARY DEMAND: Bank *A* pays out at most 20% of incoming funds - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

A.3.2 Bank A follows 'cautious conditions' (30% rule)

Figure 11: INCREASED PRECAUTIONARY DEMAND: Bank *A* pays out at most 30% of incoming funds - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

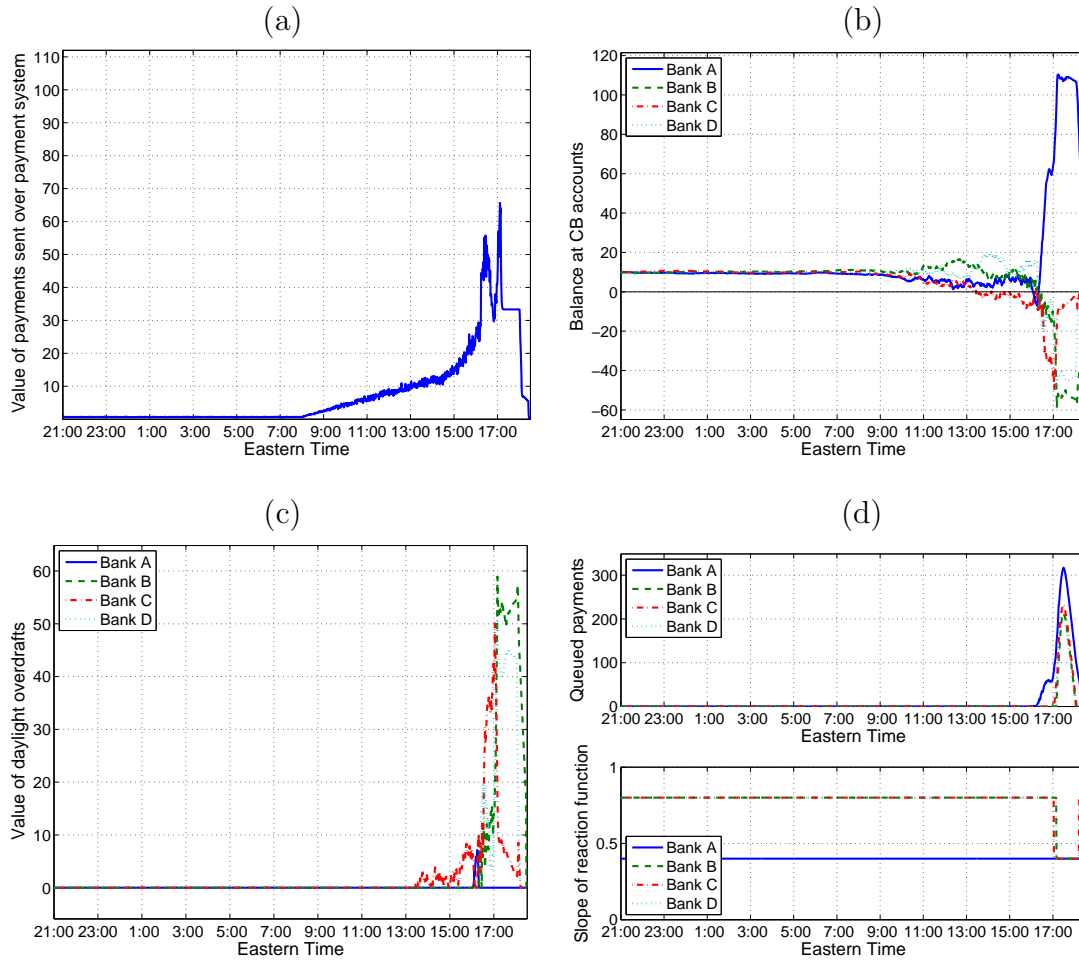## A.3.3 Bank A follows 'cautious conditions' (40% rule)

Figure 12: INCREASED PRECAUTIONARY DEMAND: Bank *A* pays out at most 40% of incoming funds - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

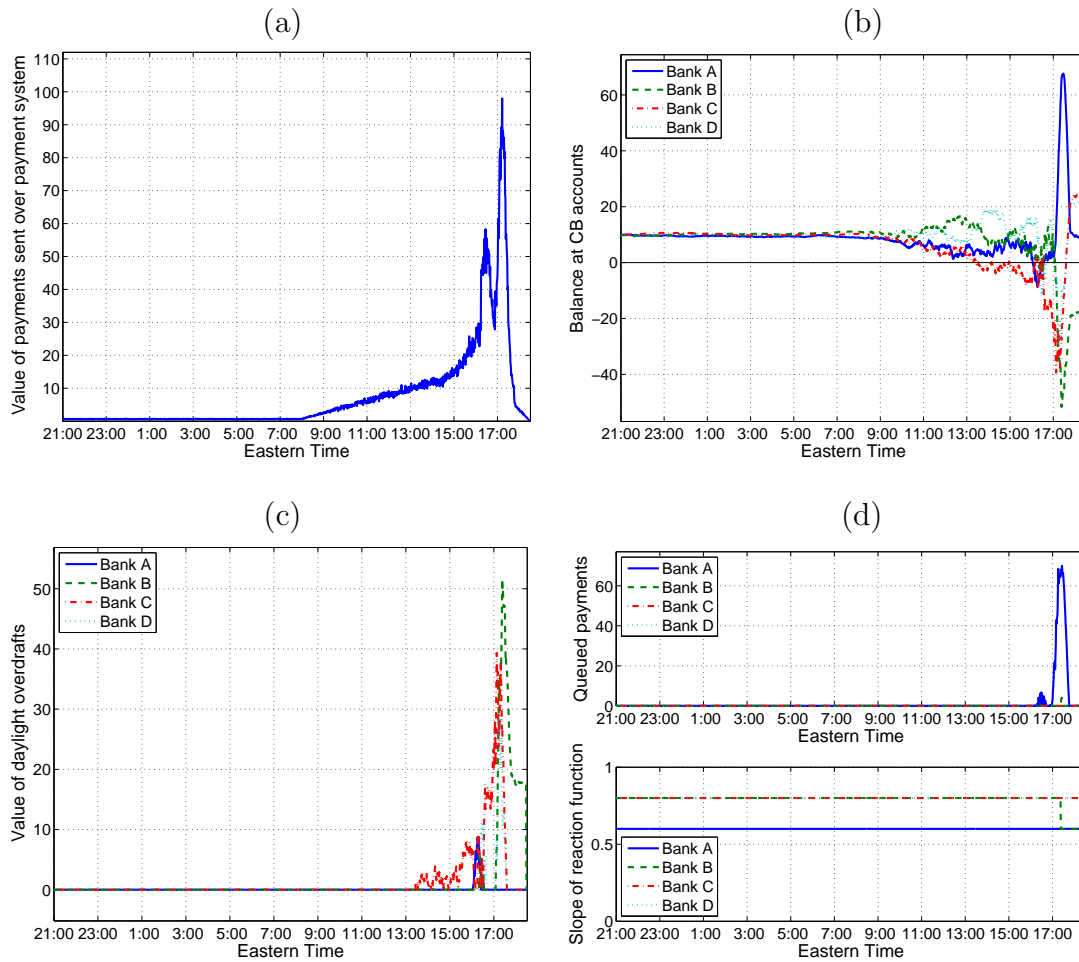## A.3.4 Bank A follows 'cautious conditions' (60% rule)

Figure 13: INCREASED PRECAUTIONARY DEMAND: Bank A pays out at most 60% of incoming funds - Total value of payments sent over the payment system (a), banks' balances (b), value of daylight overdrafts (c), queued payments and slopes of reaction functions (d) by time of the day.

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