Federal Reserve Bank of New York
Staff Reports

Precautionary Demand and Liquidity in Payment Systems

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Staff Report no. 352
October 2008
Revised August 2010

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JEL classification: E58, G21, D85, E44

Abstract

In large-value real-time gross settlement payment systems, banks rely heavily on incoming funds to finance outgoing payments. Such reliance necessitates a high degree of coordination and synchronization. We construct a model of a payment system calibrated for the U.S. Fedwire system and examine the impact of realistic disruptions motivated by the recent financial crisis. In such settings, individually cautious behavior can have a significant and detrimental impact on the overall functioning of the payment system through a multiplier effect. Our results quantify the mutually reinforcing nature of greater caution, and allow comparative statics analysis of shifts in key parameters.

Key words: systemic risk, financial networks, high-value payment systems, precautionary demand

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1 Introduction

The complex web of transactions in the economy is mirrored by the payment flows that settle those transactions, and the smooth functioning of the payment system is an essential part of the infrastructure of a well-functioning economy. Although issues regarding the payment and settlement system are relegated to the background as being merely the "plumbing" of the financial system, we are reminded of their importance in those rare occasions when problems emerge their smooth functioning.

A principal reason for giving the payment and settlement systems greater attention from policy makers is the potential for the amplification of problems in the system arising from the mutually reinforcing effect of actions that are entirely reasonable and prudent from the point of view of individual members of the system, but whose collective consequence can be disastrous. The interbank payment system processes very large sums due to the asynchronous nature of payments. One of the reasons for the large volumes of flows is due to the nettable nature of most day to day flows in the system between the core member banks. That is, the large flows leaving bank A is often 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 observed in the data.

The nettable nature of the flows enables a particular bank to rely heavily on the inflows from other banks to fund its own outflows. For this reason, banks typically hold only a very small amount of cash and other reserves to fund their payments. Before the current financial crisis, the cash and reserve holdings of banks amounted 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 were further spurred on by the trend toward tighter liquidity management by banks, as they sought 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 even small disruptions to the system. A key ingredient in the story is the endogenous onset of freezes in the payment system coming from the step change in the desired precautionary balances targeted by the constituent banks. An early lesson in such fragility came after the 9/11 attacks in September 2001 when banks attempted to conserve liquidity and raise their precautionary cash balances as a response to the greater uncertainty. Given the high degree of reliance on inflows in order to finance outflows, the onset of greater caution by constituent banks set off a spiral of falling payment volumes where greater caution by one bank undermined the ability of other banks triggering greater caution on their part, giving a further downward twist to the spiral. McAndrews and Potter (2002) give a detailed account of the events following the 9/11 attacks.

Our paper constructs a model of a payment system that is structurally rich enough for the purpose of quantifying the potential impact of shocks and their endogenous propagation within the system. Our model is constructed to mirror closely the US Fedwire system. We calibrate the key parameters so as to mimic the stylized facts during normal times, and then examine the impact of shocks as they spread through the system.

Our model is a network of 50 banks, with a size distribution calibrated to match the known densities within the Fedwire system. The top 50 banks within the Fedwire system is responsible for roughly 90% of the total value of payments within the system, and almost 80% of all payments within Fedwire are between the top 50 banks. We review the detailed numbers in a later section. Given the dominant position of the largest 50 banks, our numerical exercises are designed to capture faithfully the workings of the core of the system.

The key ingredient of our numerical analysis is the potential shift in the reaction functions of constituent banks from that observed in normal times to a more cautious stance in times of stress. Our calibration of the normally functioning payment system uses observed payment rates and build in the feature that constituent banks pay out a substantial fraction of incoming payments. However, our main interest is on capturing the endogenous propagation of shock that pushes the system into an illiquidity spiral when individual banks shift to a more cautious stance triggered by liquidity indicators within the bank.

The core of our paper consist of two sets of numerical experiments based on a network model with fully endogenous transitions in the reaction function of banks. The numerical experiments are designed to illustrate and quantify the damaging spillover effects when an exogenous disruption to the system sets off an increasingly destructive spiral. In our first set of numerical experiments we consider the emergence of a particular bank that is the subject of a rumor of potential distress, leading to a drying up of fund flows to that bank. However, due to network externalities and the potential for the shift toward the cautious regime by other healthy banks, the endogenous impact can be sizeable. Our second set of numerical experiments consider a shock where one or more banks shift to the cautious stance, perhaps due to an idiosyncractic shock due to discovery of fraud. In this instance, also, the endogenous propagation can be sizeable.

Our model is calibrated in order to match the payment flows observed in normal times. However, much more important than the ability to mimic the observed patterns in the data is the ability to conduct "what if" type exercises where we can address the counterfactual questions of how the payment system would behave in the face of specific changes in the environment, or the failure of one or more nodes in the system. The fact that the aggregate outcome takes account of the spillover effects gives us hope of capturing the potential consequences of systemic failure in the real world.

Although our paper is not the first to conduct a quantitative study of a payment system using real world data (a literature survey follows in Section 3 below), the main feature of our exercise that sets our work apart from previous studies is the incorporation of endogenous transitions in the reaction functions of constituent banks. The transitions are determined as a function of liquidity indicators within the bank itself. As we will see, it is this endogenous reaction of the constituents of the payment system that has the largest impact on the results. In contrast, many of the existing studies postulate a fixed reaction function and the numerical experiments vary just the inputs. To our knowledge, our paper is the first to incorporate endogenous transitions in the reaction function, thereby being able to capture more realistically the full force of the spillovers.

The outline of the paper is as follows. In the next section we provide a detailed description of the features of the Fedwire system in order that our model of the payment system can be faithful to the key institutional and quantitative features. We then present our theoretical framework and describe the workings of the quantitative model that serves as the engine of the numerical simulation exercises. The simulations and the comparative statics results that follow constitute the core of our paper.

2 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.[1] 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[2] (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).

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

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

A central aspect of the design of large-value payment systems is the trade-off between liquidity and settlement risk. Real-time gross settlement (RTGS) systems are in constant need of cash balances to settle payments in real time while net settlement systems can economize on cash but are vulnerable to settlement failure.[3] In the last twenty years, large-value payments systems have evolved to address credit risk.[4]

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 in US dollars that uses bilateral 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 48 of the world's largest financial institutions.[5] It processes over 365,000 payments on an average day with a gross value of $2 trillion.

Fedwire is a large dollar funds and securities transfer system that links the twelve Banks of the Federal Reserve System.[6] 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 reached $3 trillion in 2008 with a volume of approximately 521,000 daily payments. Settlement of most US gov-

[3]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.

[4]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 (2007) for a study on the history and determinants of adoption of real-time gross settlement payment systems by central banks across the world.

[5]See http://www.chips.org/about/pages/033742.php for a list of members.

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

ernment 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 7,000 participants hold and transfer US Treasury, US government agency securities and securities issued by international organizations such as the World Bank. In 2008 Fedwire Securities Services processed over 99,000 transfers a day with an average daily value of $1.6 trillion. Figure 1 depicts the evolution of the average daily value and volume of transfers sent over CHIPS and Fedwire.

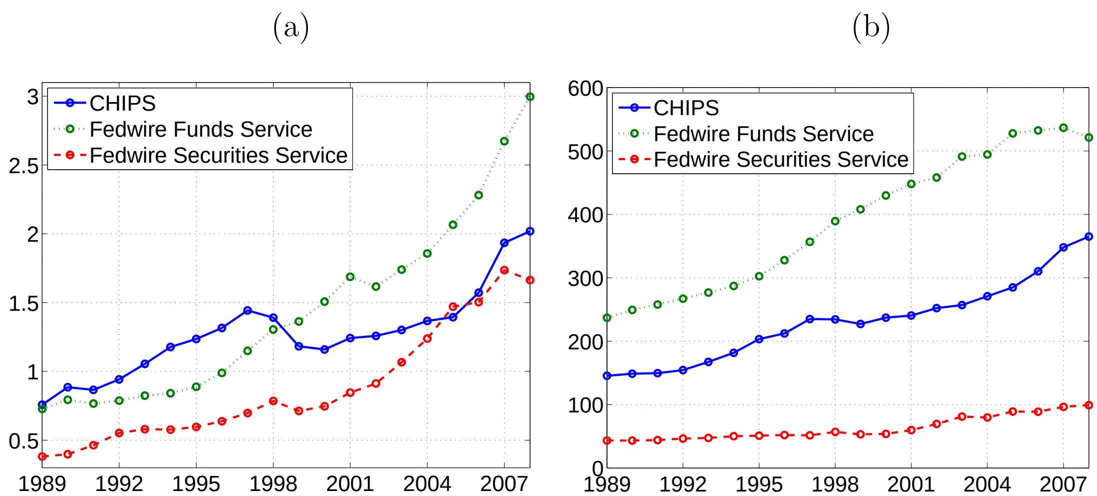


Figure 1: Average daily value (a) ($ trillion) and volume (b) (thousands) of transactions over CHIPS, Fedwire Funds Service and Fedwire Securities Service, 1989-2008. Source: The Federal Reserve Board and CHIPS.

2.1 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 (i.e. transfers across accounts held at the Fed). 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. 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.

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.[7] It was extended in December 1997 from ten hours to eighteen 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,[8] that earns no interest, and balances deposited in Federal Reserve accounts.[9] A Fedwire participant may also commit itself or be required to

[7]A detailed description of Fedwire Funds Service operating hours can be found at www.frbservices.org/Wholesale/FedwireOperatingHours.html.

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

[9]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 (2008b)). The interest rate paid on required reserve balances was then modified to 35 basis points below the lowest target federal funds rate. This new rate became effective on October 23, 2008 (Federal Reserve (2008c)). On November 6, 2008, the rate paid on required reserve balances was set equal to the average target federal funds rate over the reserve maintenance period while the interest rate on excess balances was equal to the lowest target federal funds rate in effect during the reserve maintenance period (Federal Reserve (2008d)). Since December 18, 2008 the interest rate on required reserve balances and excess balances is 25 basis points (Federal

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.[10]

When an institution has insufficient funds in its Federal Reserve account to cover its debits, the institution runs a negative balance or *daylight overdraft*. Figure 2 shows the evolution of the daily average daylight overdraft:

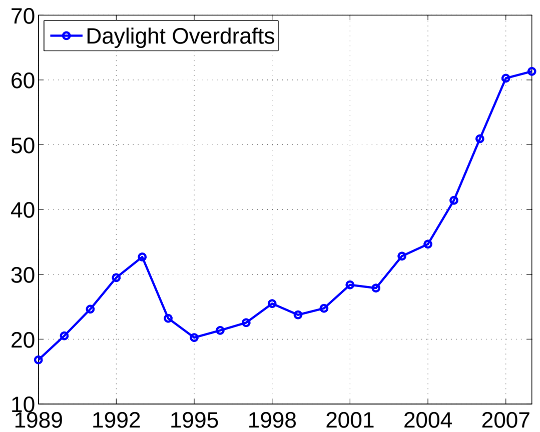


Figure 2: Daily average daylight overdraft ($ billions) in Fedwire Funds Service, 1989-2008. Source: Federal Reserve Board.

Daylight overdrafts 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*. An institution's net debit cap is a fixed multiple of its capital mea-

Reserve (2008e)). See Keister et al. (2008) for an analysis of the implications of paying interest on these balances.

[10]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.

sure depending on its "cap category". Each institution's cap category is considered confidential information and is not disclosed to other Fedwire participants (Federal Reserve (2005), Federal Reserve (2009)).

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.[11]

To control the use of intraday credit, the Federal Reserve began charging daylight 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.[12,13] At the end of each 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

[11] On December 19, 2008 the Federal Reserve Board announced revisions to its Payment System Risk (PSR) policy. The revised PSR policy explicitly recognizes the role of collateralized daylight overdrafts. Other modifications include an increase in the fee for uncollateralized daylight overdrafts to 50 basis points (annual rate), adjustments to net debit caps, elimination of the current deductible for daylight overdraft fees, and a raise in the penalty daylight overdraft fee for ineligible institutions to 150 basis points (annual rate). The implementation of the revised PSR policy will take effect either in the fourth quarter of 2010 or the first quarter of 2011 (Federal Reserve (2008f)). See Martin and Mills (2008) for a study of the benefits and costs of the increased use of collateral as a credit risk management tool.

[12] Fedwire operates 21.5 hours a day, hence the effective annual rate is 32.25 basis points ($36\times\frac{21.5}{24}$) and the effective daily rate is 0.089 basis points ($32.25 \times \frac{1}{360}$).

[13] The revised Payment System Risk (PSR) policy sets the annual rate at 50 basis points (Federal Reserve (2008f)). See footnote 11.

institution's daylight overdraft charge is defined as its average overdraft multiplied by the effective daily rate (minus a deductible). Table 3, in Appendix A, 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 an overnight overdraft, which is considered as 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 (2006)).

3 A Stylized Payment System

We now proceed to describe the formal model that underpins our numerical experiments. The earlier working paper version of this paper (Afonso and Shin (2009)) gives the full theoretical model, including proofs of existence and comparative statics. Here, we provide a sketch of the main ingredients of the formal framework.

Our framework is a network model consisting of n agents in the payment system, whom we will refer to as "banks" for convenience. In practice, the Fedwire system contains non-banks also, such as the government sponsored enterprises (GSEs). Every member of the payment system maintains an account to make payments. This account contains all balances including its credit capacity.

Banks in a payment system rely on incoming funds to make part of their outgoing payments. Time is discrete and indexed by t, which we may interpret as a short interval, such as one minute. We denote by y_t^i the time t payments bank i sends to other members in the payment system. These payments are defined as a function of the incoming payments received in the previous time interval. We denote by x_t^i the total funds received by bank i from other members during the previous interval of time to date t. We may allow a wide variety of reaction functions, but we do impose the condition that outflows are an increasing function of the inflows, but where the slope of the reaction function is bounded above by 1.

Formally, outgoing transfers made by bank i at time t are given by:

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

where f^i is an increasing function of its first argument, but where the partial derivative is bounded above by 1. The parameter θ_t is the pair (b_t, c_t) where 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 $F = [f^1, f^2, \ldots, f^n]^\top$.

In this way, the outgoing payments y_t are a function of the previous period's payments y_{t-1}, giving rise to the possibility of feedback effects. In steady state, solving for the profile payment flows entails finding a consistent set of payments - that is, solving for a fixed point y of the mapping F. The fixed point turns out to be well-behaved in our framework. It can be shown by lattice-theoretical arguments that there is a unique fixed point of the mapping F, and the comparative statics of the unique fixed point can be characterized cleanly. We refer the reader to our earlier working paper Afonso and Shin (2009) for details.

In the following subsections we present numerical simulations of a stylized payment system calibrated to mimic the main features of the US Fedwire system. Before we do so, we give a brief overview of the existing literature on numerical simulations of payment systems, mainly coming from the central banks. Bakšys and Sakalauskas (2009) presents simulations of the European Trans-European Automated Real-time Gross Settlement Express Transfer system (TARGET2[14]) system, with a focus on the efficiency of settlement algorithms for the queue. For the U.K., James and Willison (2004) studies the role of collateral in the CHAPS Sterling system.[15] The

[14]TARGET2 is the Real-Time Gross Settlement (RTGS) system for the euro, offered by the Eurosystem. It started operations on 19 November 2007 and is used for the settlement of central bank operations, large-value euro interbank transfers and other euro payments. It provides real-time processing, settlement in central bank money and immediate finality. In 2008, TARGET2 processed a daily average of 369,966 payments, representing a daily average value of € 2,667 billion.

[15]CHAPS (the Clearing House Automated Payment System) Sterling, the UK's main large-value

authors conclude CHAPS Sterling should be robust to operational incidents that temporarily prevent a member bank from making payments. Through numerical simulations, Bedford et al. (2004) finds that CHAPS is resilient to operational disruptions, but the simulations are based on fixed reaction functions. Harry Leinonen (ed.) (2009) offers a collection of simulation-based papers on operational and liquidity disruptions in some European payment systems. Simulations are frequently used by central banks to assess the impact of potential policy changes as well as to test and evaluate the effect of implemented measures. Bank of Japan (2009) analyzes the payment activity in the BOJ-NET[16] during the first six months after the implementation of Phase 1 of the Next-Generation RTGS to determine the repercussion on the safety and efficiency of large-value payments in Japan. Also, using simulation analysis in BOJ-NET, Imakubo and McAndrews (2006) studies optimal funding levels to examine how changes in a level of initial balances affect the value of payments settled, the amounts left unsettled after a particular time, and the average time of settlement.

As noted above, our study has the feature that the reaction functions of the banks undergo endogenous transitions in reaction to the triggering of liquidity indicators within the bank. As we see below, this endogenous transition of reaction functions play a key role. To our knowledge, our paper is the first to incorporate such endoge-

payment system, is a Real-Time Gross Settlement (RTGS) payment system operated by the bank-owned CHAPS Clearing Company. CHAPS Sterling has 15 members and allows banks to make real-time sterling payments on their own behalf or on behalf of their customers. Member banks can borrow intraday against collateral from the Bank of England. Nearly £70 trillion was processed through the system in 2007.

[16]BOJ-NET, the Bank of Japan Financial Network System, is a Real-Time Gross Settlement (RTGS) payment system owned and operated by the Bank of Japan. BOJ-NET Funds Transfer System is used to process money-market transactions, the cash legs of Japanese Government Bond (JGB) and other securities transactions, and net positions arising from private-sector deferred net settlement (DNS) systems. The average daily value and volume settled in the first six months of 2008 reached 125 JPY trillion and 29,000 transactions respectively.

nous transitions. We attribute the starkly different findings of our paper compared to previous studies to such endogenous transitions.

3.1 The Payment System

Consider a network of 50 institutions, which we will refer to as a network of "banks" for convenience. Although more than 9,400 participants are able to initiate transfers over Fedwire Funds Service (Fedwire), 50 of them were responsible for 87.27% of the total value transferred over Fedwire in 2008. The value of payments sent only within this network of 50 banks represents 78.27% of the total value sent over Fedwire in 2008. For tractability we examine a payment system comprising of 50 institutions that are closely modeled on the top 50 real world institutions in Fedwire.

Each bank can send and receive payments from other members of the payment system.[17] 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. The distribution of balances in the first half of 2008 corresponding to the top 50 institutions (by value transferred over Fedwire) is presented in Figure 3. We limit our choice of balances to the first half of 2008 so as to leave out the unusual reserve levels in the period of severe crisis from September 2008.[18] Opening balances are proxied by the average of banks' total balances due

[17]From a payment processing perspective, Fedwire Funds Service is a complete network as all participants (nodes) can send and receive payments from each other (Soramäki et al. (2007)).

[18]The quantity of reserves in the U.S. banking system has grown dramatically since September 2008. Prior to the onset of the financial crisis, required reserves were about $40 billion and excess reserves were roughly $1.5 billion. Following the collapse of Lehman Brothers, required reserves rose from $44 billion to $60 billion. Excess reserves exceeded $850 billion by January 2009 (Keister and McAndrews (2009)).

from the Federal Reserve Bank reported in the Report of Condition and Income (Call Report) in the first two quarters of 2008.

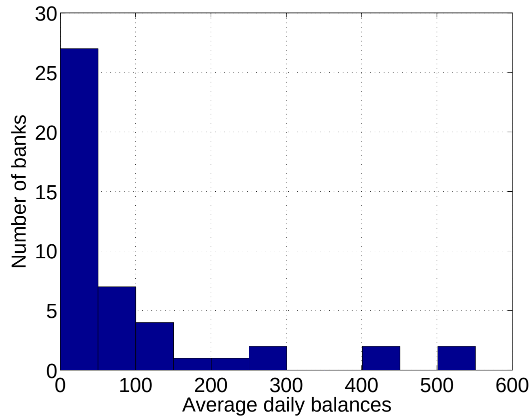


Figure 3: Distribution of the average daily balances ($ million) of 47 (of the 50) institutions in the first half of 2008. The balances of the top three institutions ($1.7 billion, $2.9 billion and $6.0 billion) have been omitted from the histogram to better illustrate the overall distribution of balances. Source: Report of Condition and Income (Call Report).

Net debit caps are defined as an institution's cap multiple times its capital measure. The capital measure refers to those capital instruments that can be used to satisfy risk-based capital standards, i.e., "risk-based" capital in the case of US commercial banks, savings banks, and savings associations and total regulatory reserves for credit unions (Federal Reserve (2008f)). For most U.S. banks, risk-based capital is calculated as Tier 1 plus Tier 2 capital. For U.S. branches and agencies of foreign banks, risk-based capital is captured by a U.S. capital equivalency measure. This U.S. capital equivalency measure corresponds to 35 percent of the capital when the foreign banking organization's is a financial holding company.[19]

There are six possible cap categories and caps multiples including a *zero* category

[19]For a detailed description of the capital measures used for daylight overdraft cap and fee calculation, see Appendix C in Federal Reserve (2009).

for institutions that do not want to incur daylight overdrafts.[20] Table 1 summarizes these categories and their corresponding cap multiples.[21]

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.

Table 1: Cap categories and net debit cap multiples of capital measure.

Some Fedwire participants, such as the government sponsored enterprises (GSEs), have no access to intraday credit.[22] Self-assessed cap levels (the *high*, *above average* and *average* categories) are considered confidential. Figure 4 depicts the distribution of net debit caps used in our analysis, where we have assumed that banks select the intermediate of the three self-assessed categories (i.e. the *above average* cap category), that foreign banks are financial holding companies and that GSEs and other special institutions have a *zero* cap.

Payment activity over Fedwire exhibits a very specific pattern over the course of the day. Payments, especially large ones, are concentrated in the late afternoon as banks attempt to synchronize outgoing payments with payment inflows and to reduce the amount and duration of daylight overdrafts from the Federal Reserve System. Such concentration of large payments late in the day amplifies the potential

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

[21]See Federal Reserve (2008a) for a detailed reference.

[22]In July 2006, the Federal Reserve ended its provision of daylight credit to government sponsored enterprises (McAndrews (2006)).

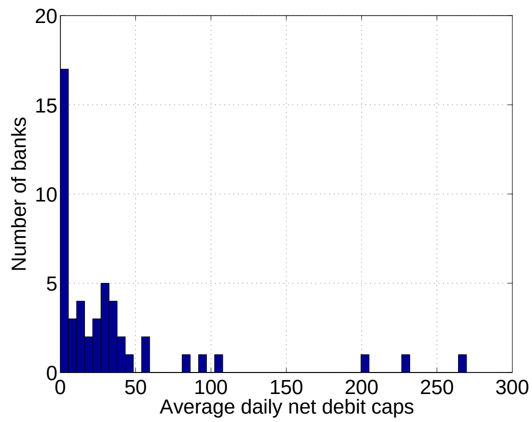


Figure 4: Distribution of the average daily net debit caps ($ billion) of the 50 institutions in 2008. Source: Report of Condition and Income (Call Report) and Capital IQ.

of liquidity dislocation and risk if operational disruptions occur.[23] To capture the importance of the timing of payments in Fedwire, we assume that the value of payments transferred over our payment system by time of the day mimics the pattern of transactions sent over Fedwire. Specifically, we consider that payment orders each institution receives from its clients are comprised of two components: a common factor, $\overline{y}_t^i$, and an idiosyncratic shock, ϵ_t^i. For simplicity, the common factor, $\overline{y}_t^i$, is defined as proportional to the pattern of Fedwire payments,[24] where the constant multiple is determined by each institution's average daily balance presented in Figure 3. The idiosyncratic shock is normally distributed with zero mean and standard deviation equal to $\overline{y}_t^i$.

Drawing on the empirical evidence from McAndrews and Potter (2002) we posit reaction functions where outgoing transfers are a linear function of the payments a

[23]For a detailed study of the distribution of Fedwire payments, see McAndrews and Rajan (2000) and Armantier et al. (2008).

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

bank receives in the previous period. Specifically, at every minute of the operational day in normal times, bank i pays at most 80 percent of its cumulative receipts and is able to commit reserves and credit up to half of 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 half of its available balance (including intraday credit) payments are placed in queue. Queued payments are settled as soon as sufficient funds become available.[25]

When banks use more than 50 percent of their own daylight overdraft capacity[26], we assume that a transition occurs when they become concerned about liquidity shortages and reduce the value of their outgoing transfers. Drawing on the empirical estimates given by McAndrews and Potter of the slope of the reaction function of banks during September 11, 2001, we assume that banks transition to a more cautious state where they pay at most 20 percent of their incoming funds. Table 2 summarizes how decision rules govern payments.

These decision rules attempt to capture key features of the liquidity queue banks use in real life to organize their payments. The process varies across banks but in general is based on a two-queue system. First, any outgoing payment must clear an internal credit queue which holds a payment if a client does not have sufficient balance or credit capacity. To ease exposition and analysis, we assume clients only request payments when they have sufficient funds. Second, even if the client has sufficient

[25] 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.

[26] 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)).

Banks pay at most:	
NORMAL CONDITIONS	CAUTIOUS CONDITIONS
80% of its cumulative receipts and reserves and intraday credit up to 50% bank's net debit cap	20% of its cumulative receipts and reserves and intraday credit up to 0.5% of bank's net debit cap

Table 2: Outgoing payments.

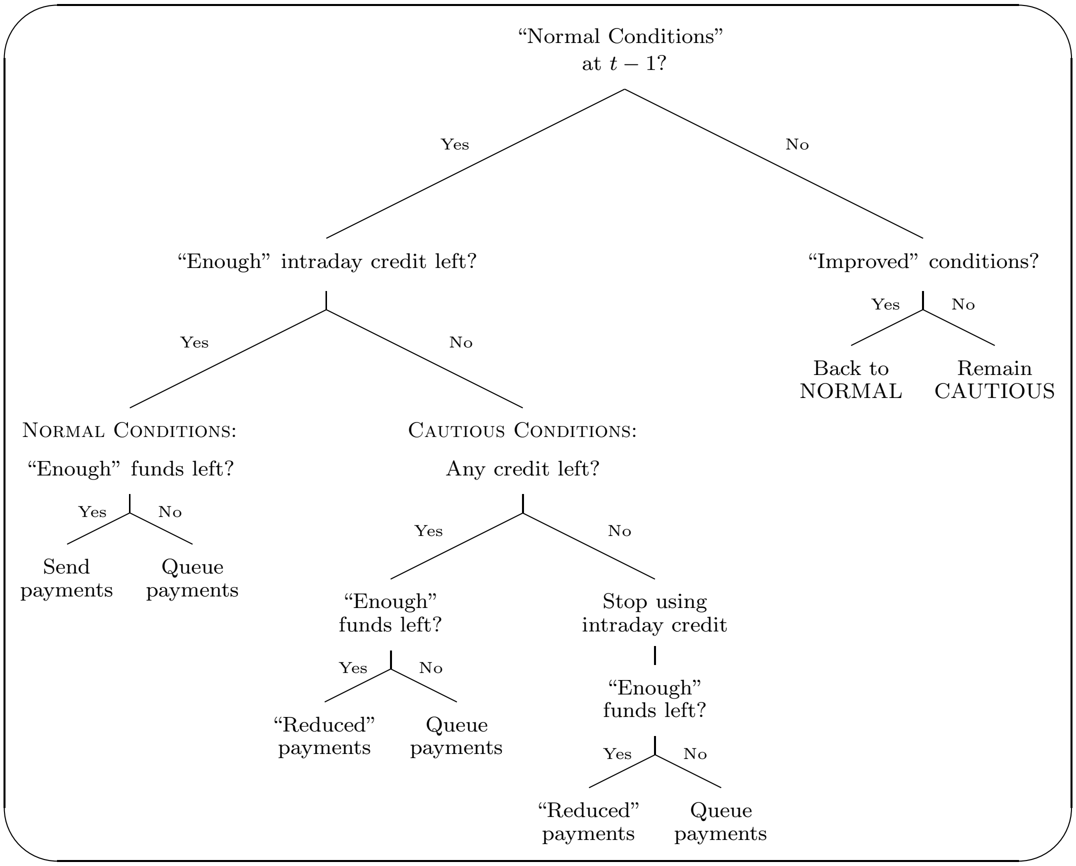
funds, the payment needs to clear an internal liquidity queue. This liquidity queue holds large-value payments that reach an internal net debit cap, which the bank establishes and adjusts throughout the day. For simplicity, we keep this cap constant and equal to half of the bank's credit capacity.[27] Under these conditions, payments are made until overdrafts reach the cap. At that time, banks become cautious and hold large-value 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

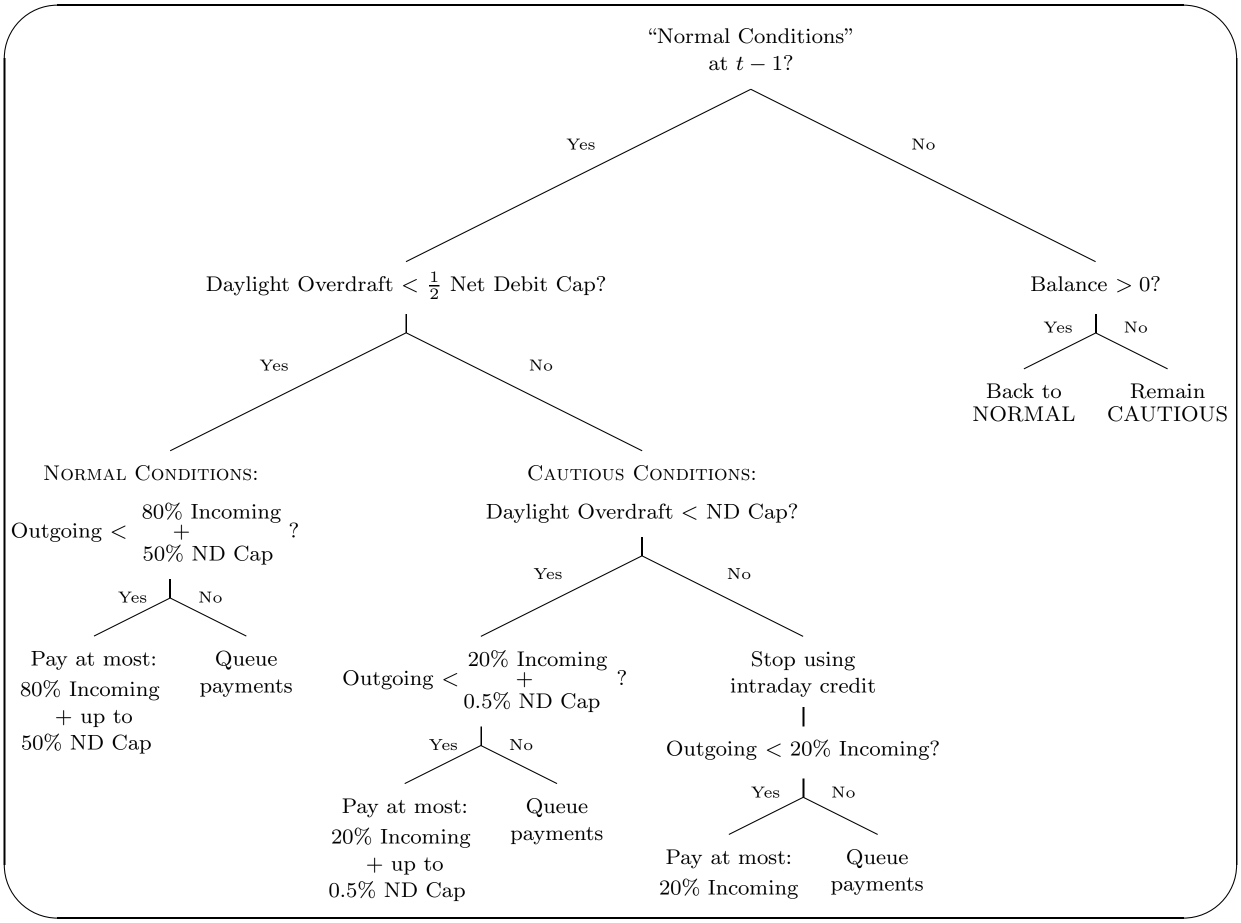
[27] See footnote 26.

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 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 half of 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.



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 overdraft capacity, it becomes concerned about liquidity shortages and makes a transition 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 0.5 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 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 non-negative 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. To meet these requirements, banks could borrow from other participants before the market closes in the federal funds market.[28] For simplicity, we abstract away from the process to satisfy these requirements.

3.2 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 specific business day.[29] The total value of payments made by the 50 members of the payment system by time of the day is depicted in Figure 5(a). As discussed in Subsection 3.1, payments are defined to follow the pattern of the average value of transactions sent over the Fedwire

[28]See Furfine (1999), Afonso et al. (2010) and Ashcraft and Duffie (2007) among others.

[29]Our analysis considers a single time series of idiosyncratic shocks rather an average over runs of Monte Carlo simulations. We thus represent a specific day in the payment system instead of an average day.

Funds Service. 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 around 5.15 p.m.[30] The market closes at 6.30 p.m.

Each bank starts the operating day with a non-negative balance in their Federal Reserve accounts. The distribution of these opening balances is depicted in Figure 3. Figure 5(b) plots the balances at the central bank account of each of the 50 members of the payment system during this given business day. Before 8 a.m. all balances remain close to the opening balance because of the low payment activity.

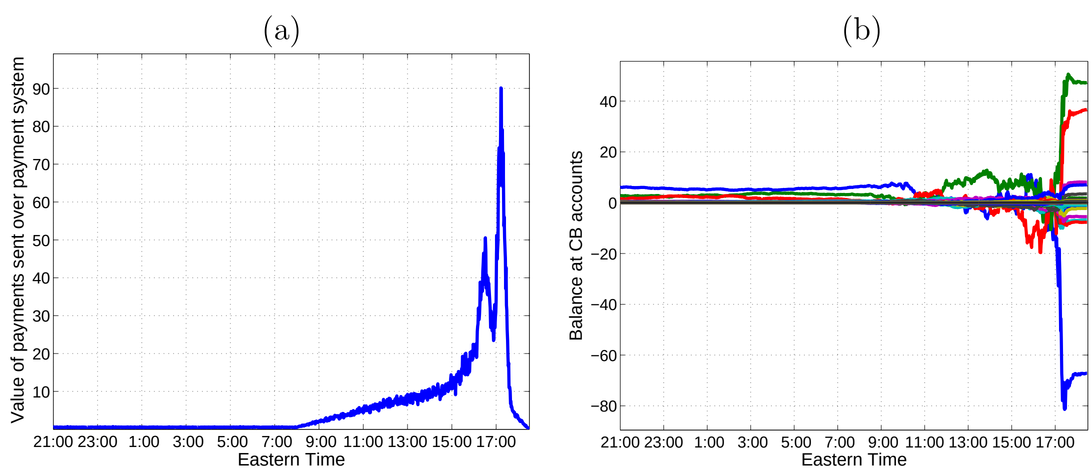


Figure 5: STANDARD FUNCTIONING OF THE PAYMENT SYSTEM - Total value of payments (a) and balances of the 50 institutions (b) by time of the day. Payments and balances correspond to a specific business day where the payment system functions smoothly.

Due to the large number of institutions in our analysis and the heterogeneity of the payment system, it is not easy to identify the balances and other variables of

[30] 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)).

interest for the 50 institutions when plotted in a single figure. For example, even though Figure 5(b) represents the balances of all 50 institutions, it is visually hard to track the evolution of each of them. Heterogeneity in balances makes it particularly difficult in our exercise, since a single figure needs to accommodate institutions with average daily balances of less than \$1million and no access to intraday credit as well as institutions whose average daily balances exceed a \$1billion and their net debit caps are in excess of \$200 billion. To easy understanding, we focus our attention on three institutions: banks A, B and C, which in Figure 6 are represented by a diamond ($\diamondsuit$), a square ($\square$) and a circle ($\bigcirc$), respectively. Specifically, Figure 6 plots the balance at the central bank accounts, daylight overdrafts, the slope of the relationship between incoming and outgoing payments and the value of queued payments corresponding to these three banks. Even though Figure 6 only shows results for a reduced group of banks, our analysis is performed using the whole network of 50 banks. Figure 13 in Appendix B.1 presents the same variables for the system of 50 banks during this business day. Figure 6 can thus be understood as a zoom in on Figure 13, where only three banks are plotted.

Let us first describe a standard day for bank A ($\diamondsuit$). As depicted in Figure 6(a), bank A's balance remains very close to its opening balance until approximately 5.00 a.m. At that time, bank A starts receiving more transfer requests than payments. This can be seen more clearly in Figure 6(b), which presents the value of intraday credit borrowed from the central bank to satisfy payments. Just after 5.00 a.m. bank A starts running negative balances and thus incurring daylight overdrafts as illustrated in Figure 6(b). Overdrafts peak at 12.04 p.m. Shortly after that, bank A begins receiving more payments than payment orders. At 12.35 p.m. it runs a positive balance as shown in Figure 6(a) and ends the day with a positive balance

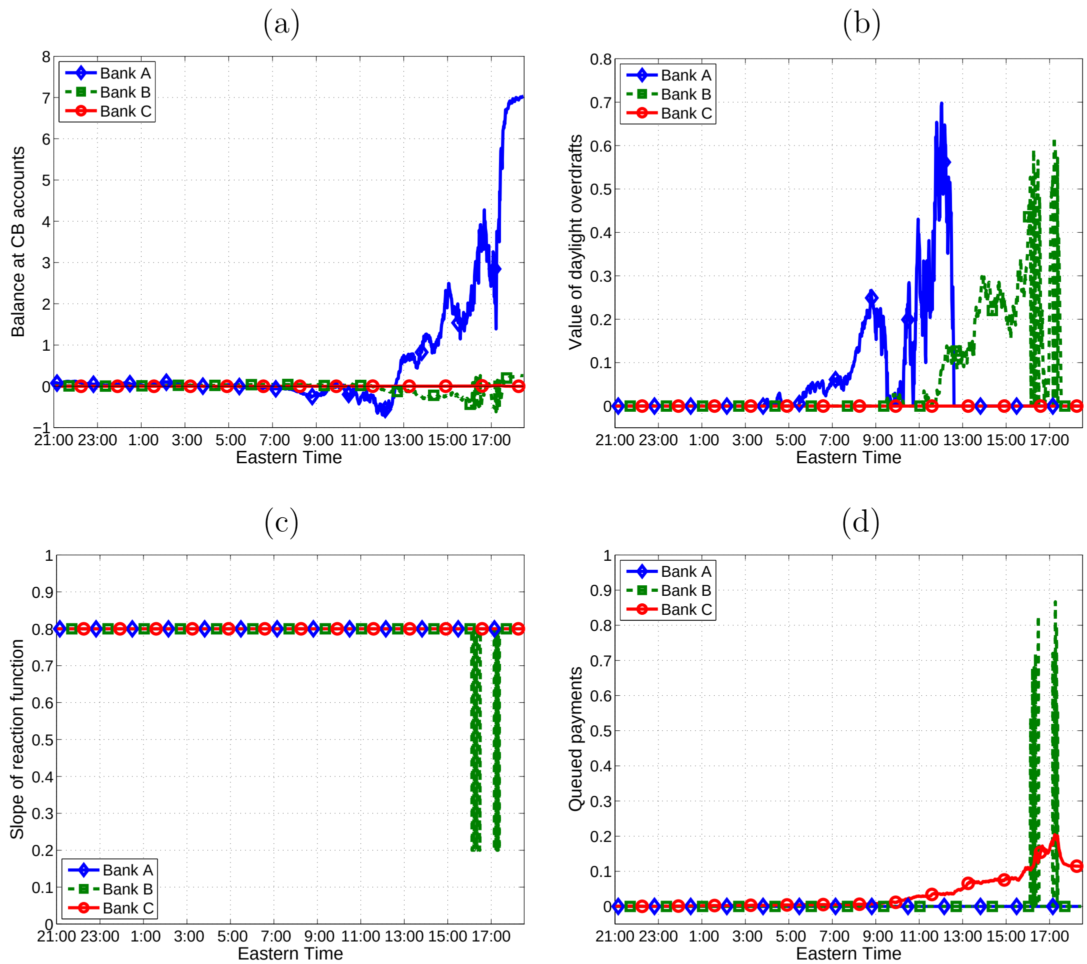


Figure 6: Standard functioning of the payment system - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where the payment system functions smoothly. Variables of interest are shown only for three banks: A ($\Diamond$), B ($\Box$) and C ($\bigcirc$), but analysis is performed for the whole payment system. Same variables corresponding to the 50 members of the payment system (including banks A, B and C) for the same business day are depicted in Figure 13 in Appendix B.1.

(its closing balance being significantly larger than its opening balance).

During this business day, bank A organizes its payments following the "normal conditions" described in Subsection 3.1 and hence the slope of the relationship between incoming and outgoing payments is set equal to 0.8 throughout this operating day. This is shown in Figure 6(c). Also, on this given day, bank A places no payments in queue (Figure 6(d)).

As in the case of bank A, bank B ($\square$) initially holds a balance close to its opening balance until it starts receiving more transfer orders than incoming payments just before 9.30 a.m. (Figure 6(a)). Soon bank B runs out of balances and starts using intraday credit to make payments (Figure 6(b)). In this exercise, net debit caps follow the distribution in Figure 4. Interestingly, during this business day, bank B, which has significantly lower access to intraday credit from the central bank than bank A, reaches half of its net debit cap twice at 4.30 p.m. and 5.15 p.m. At those times, bank B becomes concerned about a liquidity shortage and temporarily reduces the slope of the reaction function to 0.2 (Figure 6(c)) and consequently some payments are placed in queued as shown in Figure 6(d). Bank B soon realizes it has overcome the liquidity shortage and returns to organizing payments following the "normal conditions" rule.

Bank C ($\bigcirc$) represents an institution with a small opening balance (Figure 6(a)) and a zero net debit cap (Figure 6(b)). Just after 9.00 a.m., bank C receives more payment orders than incoming funds and, as it cannot borrow intraday from the central bank, it starts placing payments in queue (Figure 6(d)). Bank C ends the business day with a zero balance and queued payments and it will have to bring in funds from another account to its account at the central bank to satisfy the pending payments before market closure.

Overall, this example pictures the smooth functioning of the payment system. Let us now introduce more interesting scenarios. In Section 4 we analyze the sequence of events following banks' decision to cancel transfers to a specific member of the payment system. Then, in Section 5, we discuss what happens when a group of banks attempts to conserve cash holdings.

4 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 D is the one hit by the rumor. All other banks queue and cancel payment orders to bank D while making transfers among themselves as usual. Initially, bank D sends out payments to every other bank. Let us here consider the case where bank D is a large player in the payment system (measured both by asset size and by value of payments transferred).[31]

Figure 7 depicts the value of payments and balances of the 50 banks during the same business day described in Subsection 3.2 but where we now assume that payments to one bank are canceled. The vertical axis in Figure 7(a) has been rescaled

[31] An analysis for the case of bank D being a small bank has also been performed. The consequences to a smaller bank D are qualitatively similar to the ones described in this section. However, the magnitude of the distortion to total payments is attenuated. These results are available upon request.

to facilitate the comparison with the baseline case discussed in Subsection 3.2 (Figure 5(a)). Compared to an average day, the total value of payments sent by all members of the payment system is reduced (Figure 7(a)) while the size of balances hold at the central bank experiences a vast increase (Figure 7(b)).

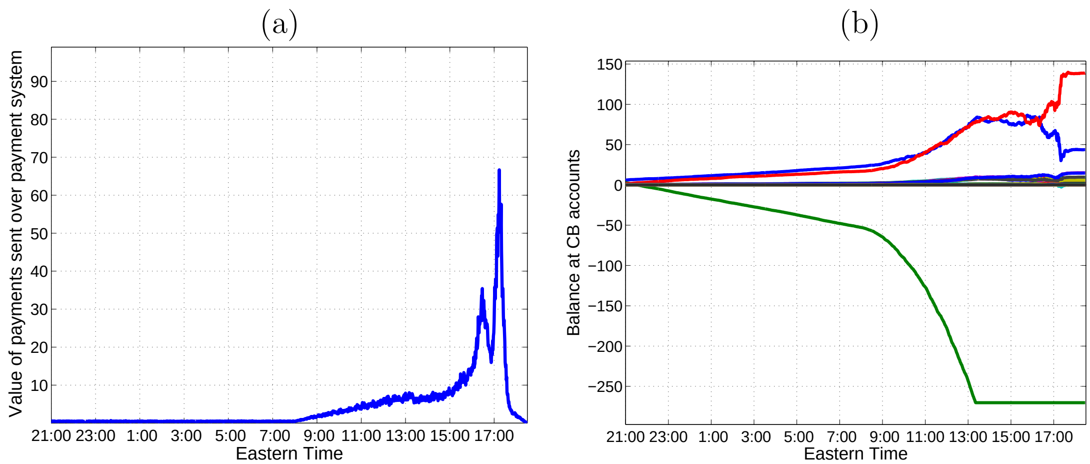


Figure 7: Inflows dry-up - Total value of payments (a) and balances of the 50 institutions (b) by time of the day. Payments and balances correspond to a specific business day where institutions cancel all payments to one bank identified as vulnerable to failure.

As in the baseline case, let us focus our attention on a reduced group of banks. Banks A, B and C are the same three banks introduced in Subsection 3.2 and, as before, are represented by a diamond ($\diamondsuit$), a square ($\square$) and a circle ($\bigcirc$), respectively. Bank D is the one identified as vulnerable to failure by the other members of the payment system and represented by a star ($\star$). Our main results are presented in Figure 8, which to facilitate the graphical representation, shows bank's balances, daylight overdrafts, slopes of the relationship between incoming and outgoing payments and queued payments only for these four banks. However, it is important to highlight that the analysis is performed for the whole payment system. The same variables for the 50 institutions are plotted in Figure 14 in Appendix B.2.

Let us center out attention on the bank identified as vulnerable to failure: bank D ($\star$). As shown in Figure 8(a), bank D's balance decreases steadily until bank D exhausts its credit capacity. Even though bank D receives no payments from other institutions, it keeps sending out payments to signal that its financial position is strong and hoping other members regain confidence in it and finally restore payments. Since it does not receive any payments from other banks, bank D first uses its reserves to settle payments and then its intraday credit (Figure 8(b)). At around 11.00 a.m. bank D'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 and sets the slope of the reaction function to 0.2 (Figure 8(c)). Shortly after 1.00 p.m., bank D runs out of credit and is forced to queue payments (Figure 8(d)). Bank D 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 that receives no payments demands an enormous amount of intraday credit and ends the business day with a significant negative balance.

5 Increased Precautionary Demand

Let us now consider the following situation. A small group of banks in our payment system becomes suddenly concerned about a liquidity shortage. Suppose, for instance, that these banks want to conserve cash holdings because the conduits, SIVs

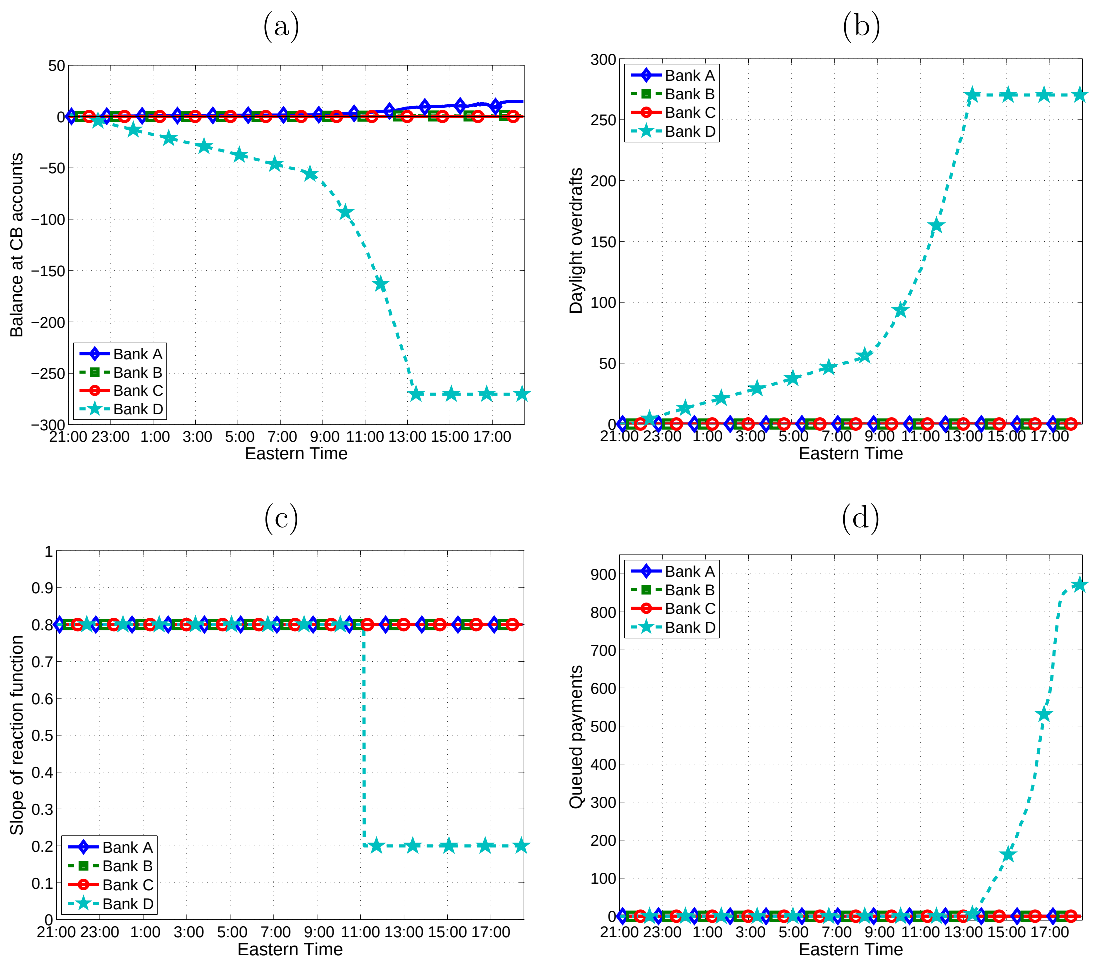


Figure 8: INFLOWS DRY-UP - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where institutions cancel all payments to one institution identified as vulnerable to failure: Bank D. Variables of interest are shown only for four banks: A ($\diamondsuit$), B ($\square$), C ($\bigcirc$) and D ($\star$), but analysis is performed for the whole payment system. Same variables corresponding to the 50 members of the payment system for the same business day are depicted in Figure 14 in Appendix B.2.

or other off-balance sheet vehicles that they are 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 some members of our payment system. Specifically, we assume that a group of six institutions (banks, for convenience) becomes concerned about a liquidity shortage. This group is comprised of at least a large domestic bank, a small domestic bank, a foreign financial holding company and a government sponsored enterprise to capture the heterogeneity in our payment system.[32] To preserve cash, these banks make payments according to the "cautious conditions" rule, i.e. they pay only 20 percent of the funds they receive and up to 0.5 percent of their net debit caps per minute. All other banks initially behave as in the baseline scenario described in Subsection 3.2 and they send out payments following the "normal conditions" rule (they pay at most 80 percent of incoming funds and up to half of their net debit caps).

Figure 9(a) depicts the total value of payments transferred over the payment system by time of the day during a specific business day where six institutions become concerned about a liquidity shortage. The vertical axis has been rescaled to facilitate the comparison with the baseline case in Figure 5(a). Figure 9(b) shows the balances at the central bank accounts of the 50 members of the payment system.

As shown in Figure 9(a), when a group of banks targets more liquid balances,

[32]Two complementary analyses have also been performed. First, we examine the case of an idiosyncratic liquidity shock to study a business day when only one bank is hit by a liquidity shock and decides to hoard cash. The second analysis considers the other limiting case, i.e. the scenario where all banks decide to send out reduced payments to conserve cash holdings (a common shock). Findings are quantitatively different but consistent with those explained in this subsection: in the case of a shock to only one bank, the impact to the payment system is attenuated while in the case of a common shock payments are disrupted rapidly and the market freezes. Results are available upon request.

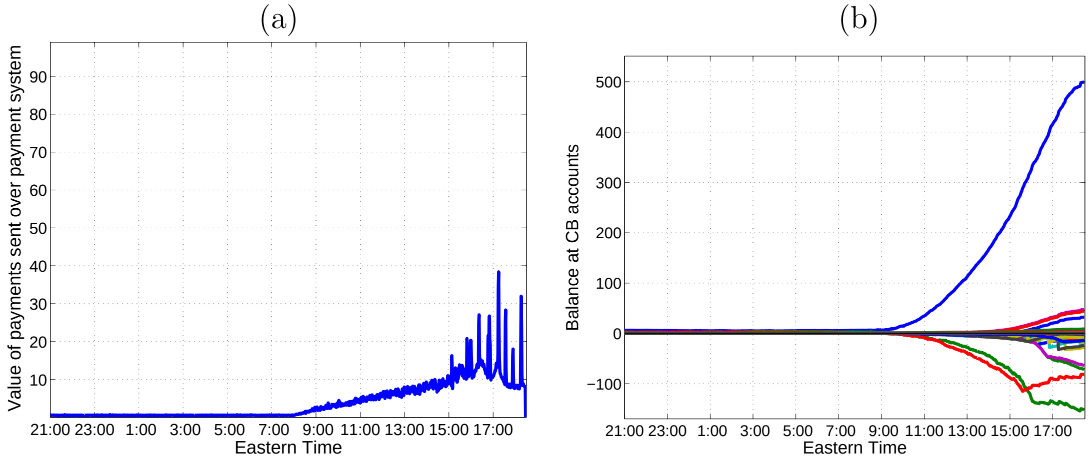


Figure 9: Increased precautionary demand - Total value of payments (a) and balances of the 50 institutions (b) by time of the day. Payments and balances correspond to a specific business day where a group of six institutions attempts to conserve cash holdings.

the pattern and value of payments transferred over the payment system is severely disrupted. Balances held at the central bank (Figure 9(b)) increase significantly compared to the standard functioning of the payment system described in Subsection 3.2 (Figure 5(b)).

Let us focus our attention on the group of six banks: M, N, O, P, Q and R, which in Figure 10 are identified by a diamond ($\diamondsuit$), a square ($\square$), a circle ($\bigcirc$), a star ($\star$), a triangle ($\triangle$) and an inverted triangle ($\bigtriangledown$), respectively. As in previous sections, the analysis is performed for the whole payment system although, to facilitate graphical representation, Figure 10 only depicts bank's balances, daylight overdrafts, slopes of the relationship between incoming and outgoing payments and queued payments for these six banks. The same variables for the 50 institutions are illustrated in Figure 15 in Appendix B.3.

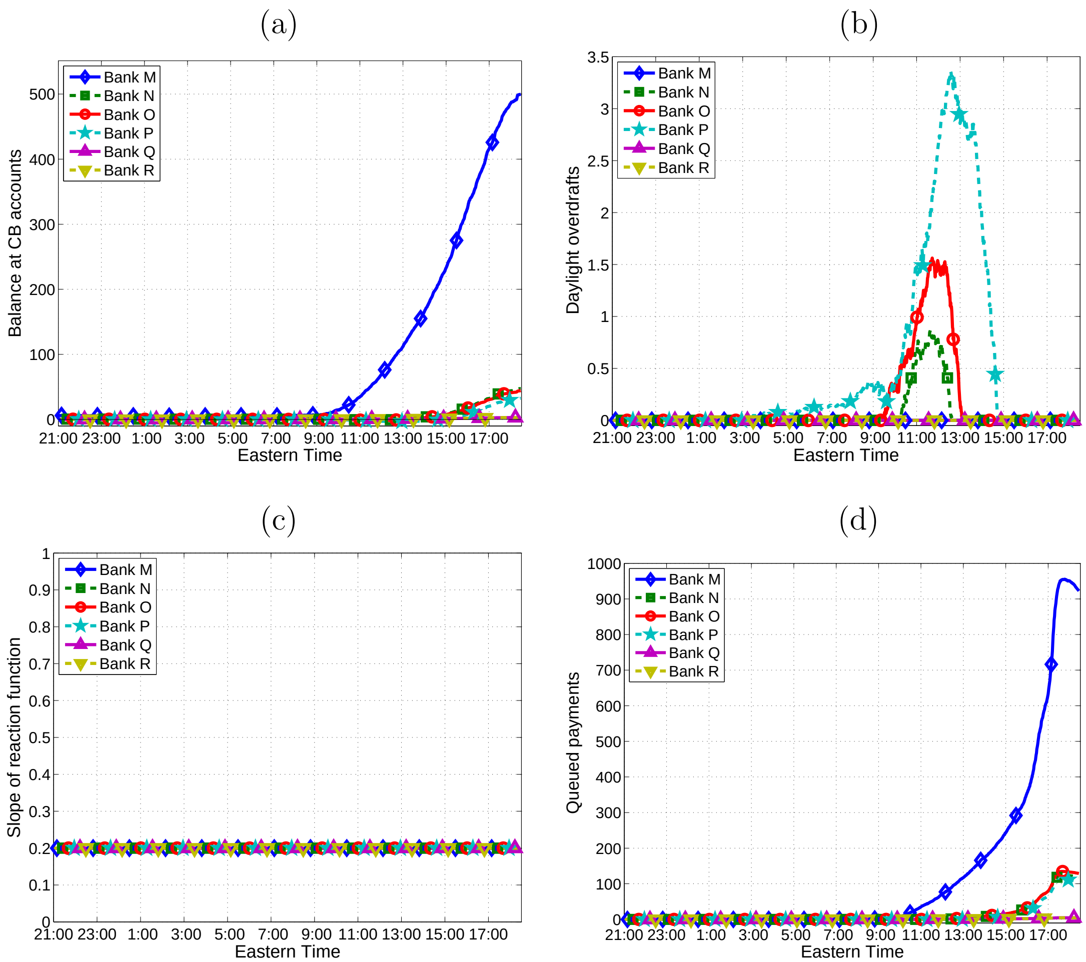


Figure 10: Increased precautionary demand - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where a group of six institutions attempts to conserve cash holdings. Variables of interest are shown only for these six banks: M ($\diamondsuit$), N ($\square$), O ($\bigcirc$), P ($\star$), Q ($\triangle$) and R ($\bigtriangledown$) but analysis is performed for the whole payment system. Same variables corresponding to the 50 members of the payment system for the same business day are depicted in Figure 15 in Appendix B.3.

During this business day all six banks send out reduced payments to conserve cash holdings. This is clearly shown in Figure 10(c). Let us fist focus on bank M ($\diamondsuit$). Before 8 a.m. bank M's balance is close to its opening balance due to the low level of activity in the payment system, but as payment activity takes off, the size of bank M's balance starts to increase steadily as it receives transfers at the 80 percent rate while paying out at most 20 percent of the funds it receives (Figure 10(a)). Of all the banks in this group with a positive net debit cap, bank M is the one with the largest credit capacity and as a result it does not need to borrow intraday from the central bank as illustrated in Figure 10(b). However, as payment orders arrive, bank M receives transfer requests that exceed its cautious payment rule and starts placing payments in queue. The value of payments queued by bank M is identified in Figure 10(d) by diamonds.

Similarly, although later in the day as shown in Figure 10(a), banks N ($\square$), O ($\bigcirc$), P ($\star$), Q ($\triangle$) and R's ($\bigtriangledown$) balances begin to increase as they receive payments at the 80 percent rule while sending out only reduced payments. Banks Q ($\triangle$) and R ($\bigtriangledown$) are institutions with no access to intraday credit (Figure 10(b)) and that place no payments in queue during this business day. On the contrary, banks N ($\square$), O ($\bigcirc$) and P ($\star$) borrow from the central bank to make payments as depicted in Figure 10(b) and queue some large-value payments (Figure 10(d)).

Initially, other members of the payment system behave as in the baseline scenario discussed in Subsection 3.2 and may temporarily incur in daylight overdrafts to compensate for the reduced payments they receive from this group of six institutions. Overdrafts by time of the day for the 50 institutions are shown in Figure 15(b) in Appendix B.3. During the day, some banks reach their internal caps and become also concerned about a liquidity shortage and thus set the slope of its reaction function to 0.2 (Figure 15(c)) and start sending out only reduced payments. As a result, even more institutions receive reduced payments and may also reach their internal overdraft limits. Once a significant number of banks sends out reduced payments, the market freezes.

Overall, it is important to highlight that a change in preferences of a group of members of the payment system towards more liquid balances induces the following effects. First, it causes disruption of payments. When a sufficiently large number of banks 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 central bank increases compared to the standard functioning of the payment system. Third, a raise in precautionary demand leads to an enormous use of intraday credit.

5.1 Sensitivity Analysis

In this subsection we present three alternative "cautious conditions" rules to analyze how banks' choice of the proportion of incoming funds used to make payments affects the functioning of the payment system. Specifically, we assume three different scenarios where banks concerned about a liquidity shortage ("cautious banks") pay at most 30, 40 or 60 percent of their cumulative receipts (and up to 0.5 percent of its net debit cap). We also include the standard results when cautious banks pay at most 20 percent of the funds they receive to facilitate the comparison.

Figures 11 and 12 illustrate the main findings. Figure 11 shows the total value of payments sent over the payment system when cautious banks decide to conserve cash holdings and make payments according to these four "cautious conditions" rules and Figure 12 depicts the value of delayed payments and the different rates at which banks send out payments during a business day.

In all four scenarios there is disruption of payments (Figure 11) and some delayed payments cannot be settled before the market closes at 6.30 p.m. (Figure 12). Results are thus robust to the choice of percent rule banks adopt when sending reduced payments.

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 (cautious banks' balances increase at the expense of the other banks), an enormous use of intraday credit and disruption of payments and unsettled payments at the end of the operating day.

6 Concluding Remarks

High-value payment systems such as the Fedwire system constitutes the backbone of the modern financial system, linking banks and other financial institutions together into a tightly knit system. Our results amply demonstrate the interdependence of the flows in such high-value payment systems. 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

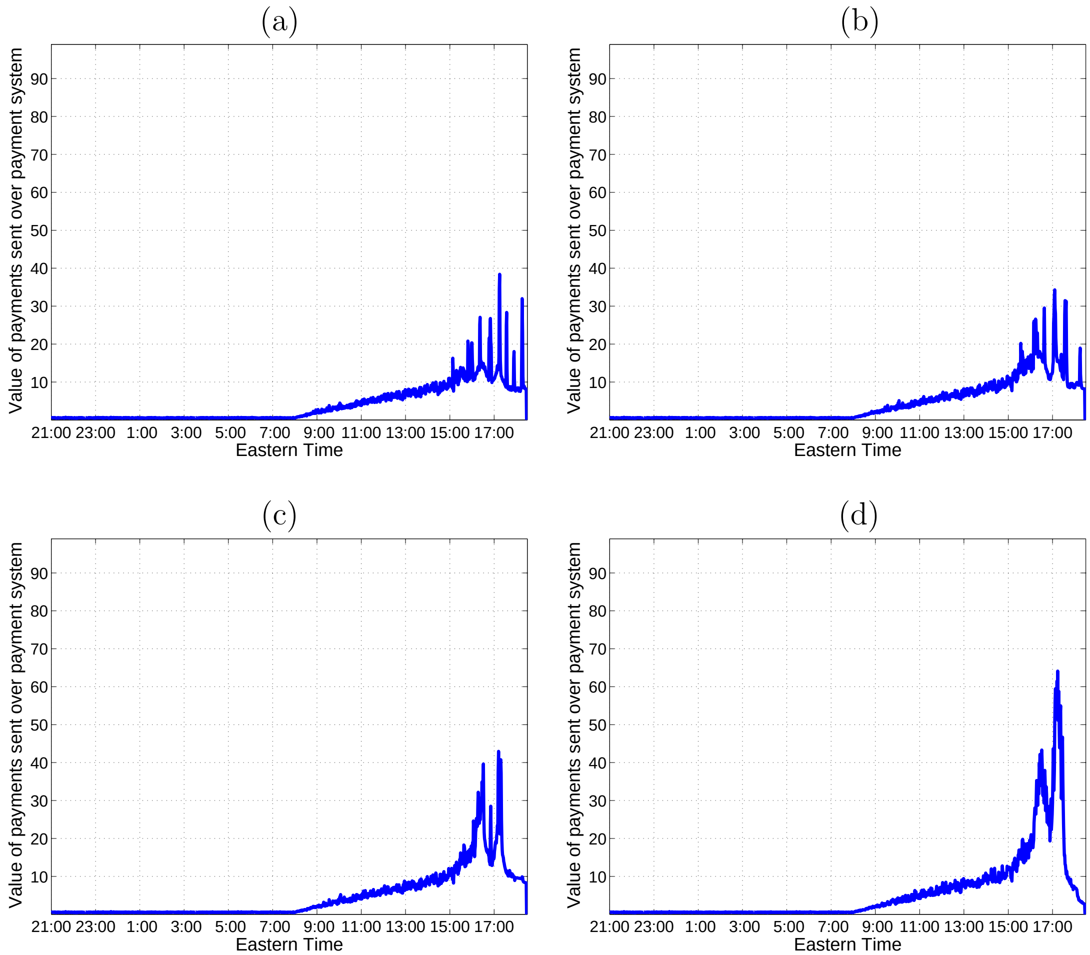


Figure 11: Sensitivity Analysis - Value of payments: Total value of payments transferred over the payment system by the 50 institutions by time of the day during a specific business day where banks concerned about a liquidity shortage pay at most 20% (a), 30% (b), 40% (c) or 60% (d) of incoming funds. Payments correspond to the same business day under alternative payment rules.

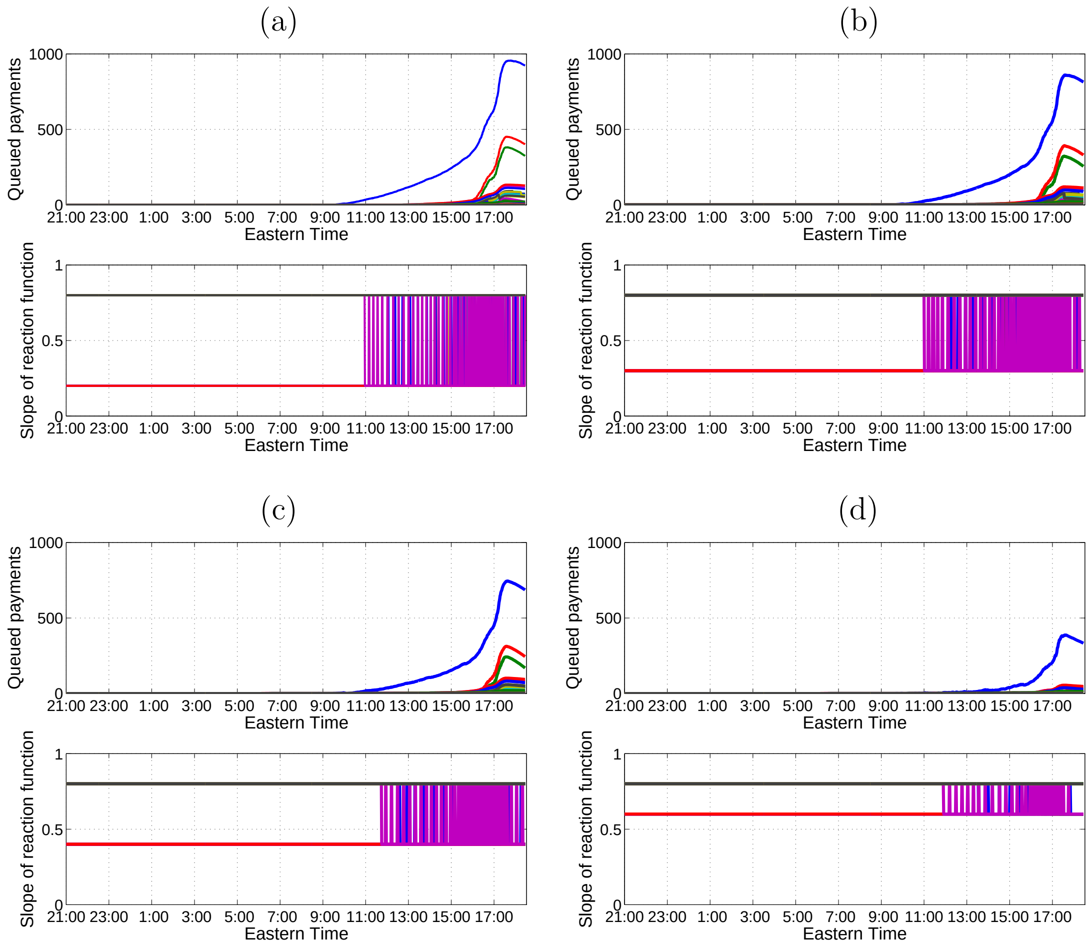


Figure 12: SENSITIVITY ANALYSIS - VALUE OF QUEUED PAYMENTS AND RATE OF PAYMENTS: Total value of payments queued (top) and slopes of reaction functions (bottom) of the 50 institutions by time of the day during a specific business day where banks concerned about a liquidity shortage pay at most 20% (a), 30% (b), 40% (c) or 60% (d) of incoming funds. Queued payments and slopes correspond to the same business day under alternative payment rules.

shocks to the high-value payment system.

Our framework has allowed simulations of counterfactual “what if” scenarios with the key feature that they have incorporated potential shifts in the stance of individual banks’ behavior between a normal mode and a more cautious liquidity hoarding mode. Building in the possibility of such a shift gives some hope that the full force of the endogenous reactions of the constituent banks in the system can be captured faithfully. As seen in our numerical results, the potential impact of even small disruptions can be large - indeed, sometimes catastrophic in extreme cases.

Our numerical results form the basis for potentially more ambitious studies of richer networks that incorporate greater detail of the real world networks, and developments that provide detailed microfoundations of the risk management systems within the constituent banks that refine the criteria used by banks in their stance toward other banks and the system at large. Our paper is a first step in this direction, but even with this first step, we have seen a rich seam of results that can inform our thinking about this important component of our financial system.

Appendix

A Daylight Overdraft Charge Calculation

Table 3 contains an example of the calculation of a 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 (2009).

Table 3: Daylight Overdraft Charge

B Further Analysis

B.1 Standard Functioning of the Payment System

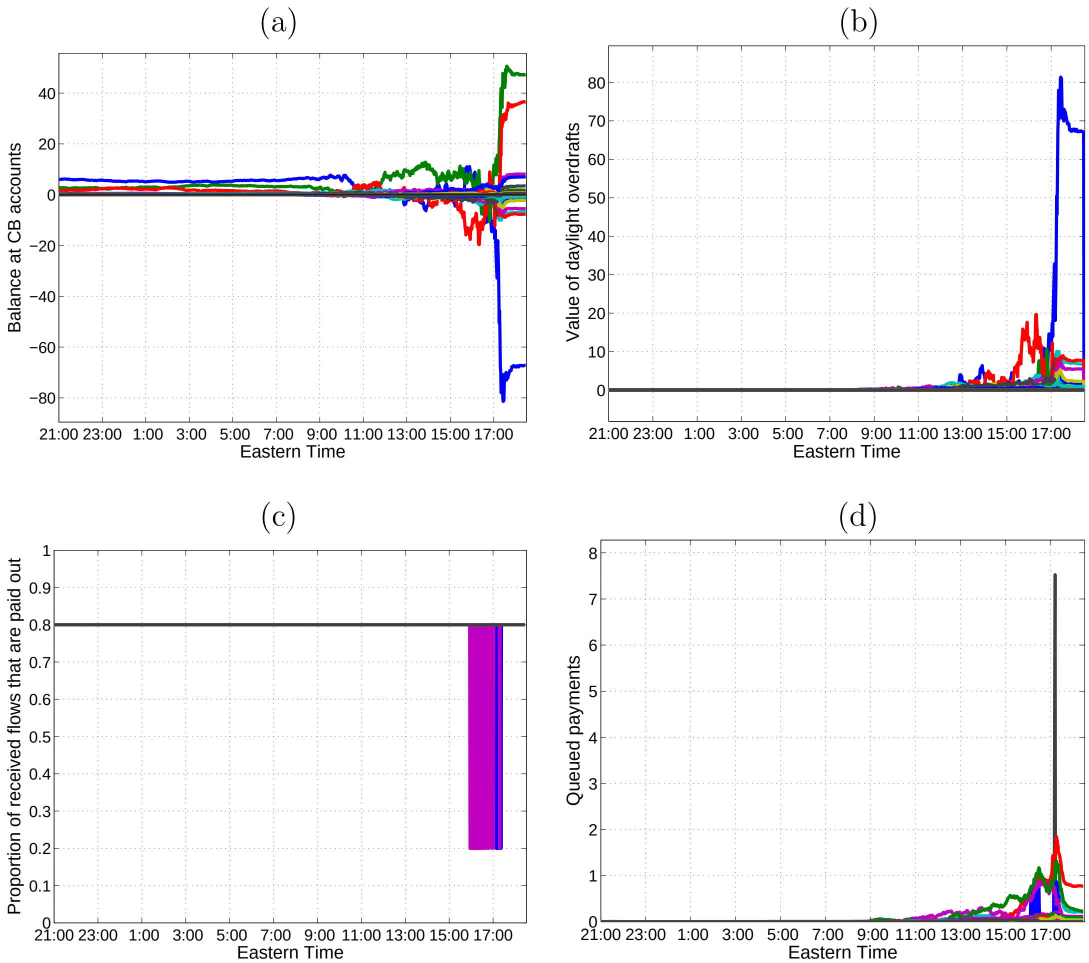


Figure 13: Standard functioning of the payment system - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where the payment system functions smoothly. Variables of interest are depicted for the system of 50 banks corresponding to the same business day shown in Figure 6.

B.2 Sudden Inflows Dry-up

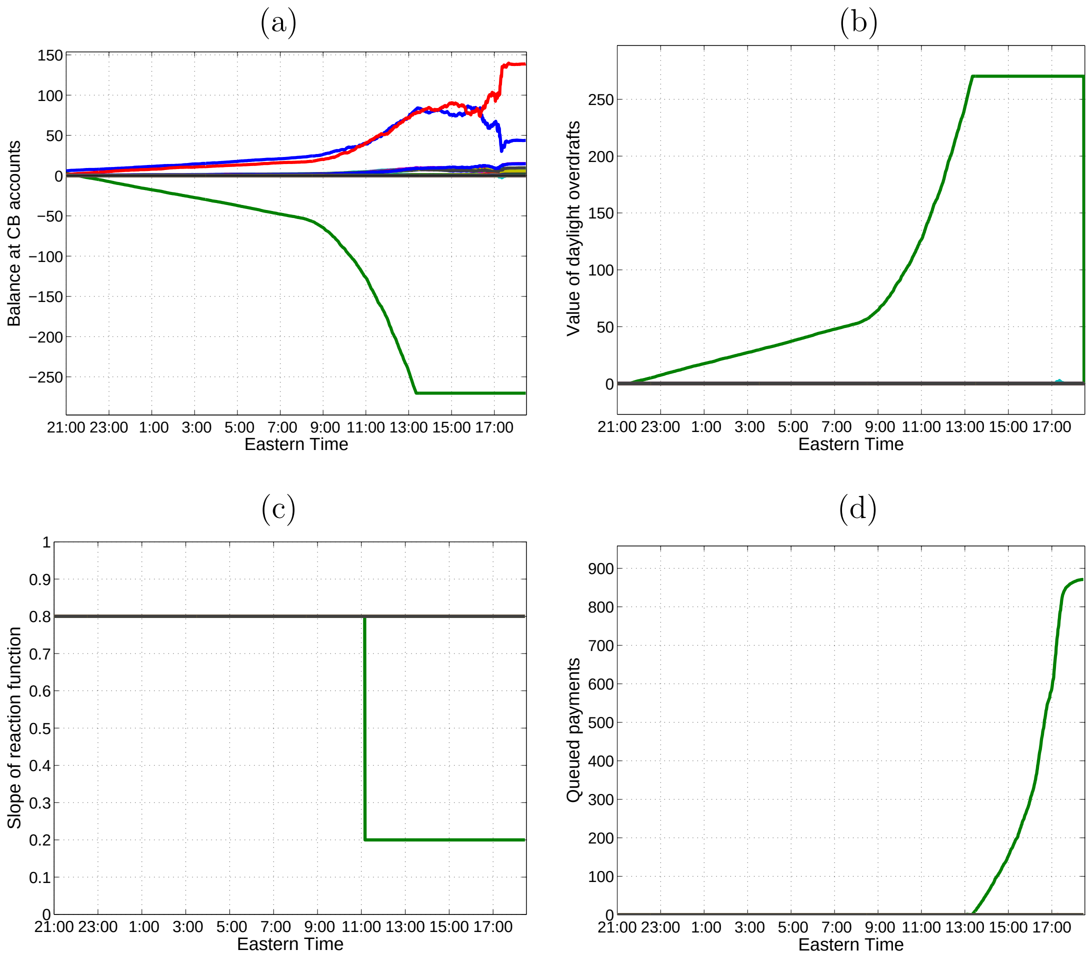


Figure 14: Inflows dry-up - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where banks cancel all payments to bank D. Variables of interest are depicted for the system of 50 banks corresponding to the same business day shown in Figure 8.

B.3 Increased Precautionary Demand

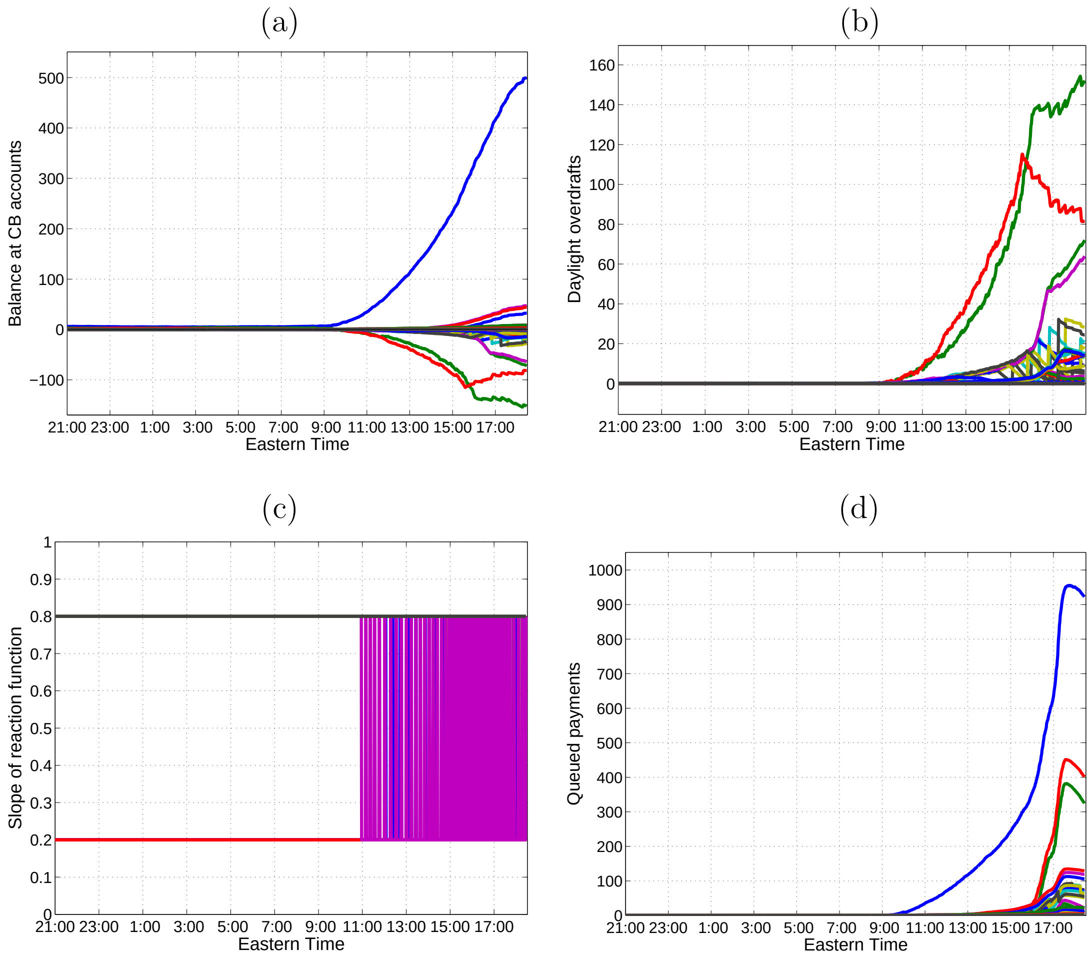


Figure 15: Increased precautionary demand - Value of banks' balances (a), daylight overdrafts (b), slopes of reaction functions (c), and queued payments (d) by time of the day during a specific business day where a group of six institutions attempts to conserve cash holdings. Variables of interest are depicted for the system of 50 banks corresponding to the same business day shown in Figure 10.

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