The Microstructure of Japan's Interbank Money Market: Simulating Contagion of Intraday Flow of Funds Using BOJ-NET Payment Data

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Under a real-time gross settlement (RTGS) system, there is an incentive for system participants to delay making their outgoing payments to facilitate their funding, and this creates the risk of settlement delays spreading throughout the entire system. Intraday credit facility and market practices have been established to avoid the risk and led to settlement concentration in the morning, as well as concentrations at the specific times due to other deferred net settlement (DNS) systems. The heterogeneity of intraday progress of settlements causes intraday fluctuation in interest rates. In this paper, we analyze and run simulations on the payment network to understand the intraday flow of funds within Japan's interbank money market, especially recycling of the "receipt-driven payments." We find that (1) the shape of the payment network changes with the time of day, and payment recycling becomes more likely when the density of the network is high; (2) patterns of intraday payment flow differ across the three RTGS systems of the United States, the United Kingdom, and Japan, reflecting differences in each country's system for, and underlying approach to, settlement and funding; and (3) participants comprising the hub of the payment network function as absorbers of contagion under a condition sufficiently stressful to cause a cascade of settlement delays.

Keywords: Real-time gross settlement; Payment recycling; BOJ-NET
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I. Introduction

Interbank money markets, such as Japan's call money market, used by financial institutions for their final funding, exhibit a unique intraday pattern of interest rate fluctuations. Bartolini *et al.* (2005) reports a clear tendency in the federal funds (FF) market in the United States, whereby the FF rate is high from the market opening until the early afternoon, and then gradually declines approaching the market closing. The interest rates in Japan's call money markets also tend to be higher in the morning session, and are likely to decline gradually during the afternoon session (Bank of Japan [2007a]). These intraday changes in the interest rates can be interpreted as resulting from a mismatch of intraday transaction needs between borrowers and lenders of funds. It seems that market participants with a funds surplus are flexible with the timing of making their outgoing payments, whereas those short of funds are in a hurry in terms of funding immediately after the market opening to obtain the funds they need for that day.

This behavior in lending/borrowing funds is also strongly influenced by the underlying payment system. For example, the BOJ-NET Funds Transfer System (BOJ-NET), which handles payments in Japan's call money market, adopted a deferred net settlement (DNS) system until the end of 2000. Under DNS, in which payments are settled in batches at designated times during the day, the timing of funding and investments has some specific patterns due to the designated times. Hayashi (2001), which analyzes intraday changes in the interest rates under DNS, finds a statistically significant liquidity effect at the designated times and a declining trend in the interest rate for afternoon half-day transactions after 13:00, the time for the interim settlement of net clearing positions. Another observation by Saito *et al.* (2001) is that there was a consistent prediction-error in the unsecured overnight interest rate over the end of each quarter, caused by the business practice of concentrating settlement then.

In January 2001, BOJ-NET was converted to a full-fledged real-time gross settlement (RTGS) system, under which individual payments are settled immediately throughout the day. Under the RTGS system, participants' strategic behavior aims at economizing settlement funds, and market practices introduced to prevent such behavior have an impact on intraday changes in the interest rates. These factors cause concentrations of settlements at several timings during the day and increase temporary demand for settlement funds immediately prior to that, thereby putting upward pressure on the interest rates.

In this paper, we perform network analysis and simulations using BOJ-NET payment data, and analyze the intraday flow of funds among participants—intraday changes in relationship between senders and receivers of funds including both initial payments and repayments of the call market transactions. An analysis of the microstructure of the payment system is of value in an *ex ante* examination of the contagion of settlement delays under stress conditions. It is also useful for investigating the function and role that should be played by participants and facilities introduced in conjunction with RTGS in the system-wide contagion triggered by "receipt-driven payments." This should provide a clue to examine the impact on the pricing of the interest rates, particularly the overnight call rate, during the day.

This paper is organized as follows. Section II summarizes differences between the two primary types of settlement modes, DNS and RTGS, and provides an overview of the literature on the settlement behavior of participants in an RTGS system. Section III compares BOJ-NET with the RTGS systems of the United States and the United Kingdom to shed light on BOJ-NET's systemic characteristics. From a network perspective, Section IV examines BOJ-NET's payment network in the morning and afternoon, respectively, to confirm how the network's shape is affected by non-time-homogeneous settlement behavior. Section V uses the fundamental information collected in the previous section to simulate a liquidity-shock contagion. This allows an experimental examination of the impact on intraday flow of funds if there is a change in settlement behavior. We end with our conclusion in Section VI.

II. Settlement Behavior

A. Shift from DNS to RTGS

The payment systems operated by central banks in advanced economies used to adopt DNS, in which payments are settled on a net basis in a manner of batch. DNS can minimize the total funds needed to settle a given amount of payments and is therefore the most efficient settlement mode. On the other hand, it provides no settlement finality until predetermined settlement times. Because all transactions are unsettled until those times and remain revocable and conditional,[1] the exposure, which is indicated as the product of settlement value and its duration, mounts during the day, and thus creates a risk management problem. As central banks have become more aware of the issue of settlement risk since the late 1980s, they have begun to shift from DNS to RTGS in their payment systems to avoid the accumulation of intraday settlement exposure.

Under RTGS, payments are settled on a transaction-by-transaction basis immediately after they are accepted in the payment system. This makes it possible to achieve settlement finality continuously throughout the day depending on the timing of submission of the payment instruction. Under DNS, if only a single participant fails to settle its net position, all settlements of other participants involved in the netting calculation are forced to be unwound. Under RTGS, in contrast, the only the counterparties for the defaulting participant are directly affected. However, if a participant plans to use an incoming payment to fund its outgoing payment, such settlement behavior of one participant can have an indirect impact on that of other participants. It is this characteristic that we refer to as payment recycling under RTGS. For example, if an incoming payment from a counterparty comes in promptly, the funds can be used to promptly make an outgoing payment. If the incoming payment does not come in promptly, however, the outgoing payment will be delayed until it comes, barring resort to other funding sources including the existing account balance.

1. This means there is still a possibility left of revoking or unwinding a status for which settlement has been final.

Table 1 Simultaneous-Move Game under RTGS

		Bank Y	
		Move early	Move late
Bank X	Move early	C, C	$2C$, D
	Move late	D, $2C$	$C+D$, $C+D$

B. Theoretical Research on RTGS

In step with the rapid adoption of RTGS mode, there has been a substantial body of theoretical and empirical literature written, primarily by central bank staff, on settlement behavior under RTGS.

The mainstream thought on the theoretical side, such as by Kobayakawa (1997), Angelini (1998), Roberds (1999), and Bech and Garratt (2003), uses game theory analysis on participants' strategic behavior.[2] Although the terminology differs depending on the model, all of these papers construct a theoretical model that assumes participants make payments subject to the trade-off between their funding cost and settlement delay cost, while simultaneously taking account of the settlement behavior of their counterparties. Because the need for additional funding declines as the number of opportunities to receive payments from counterparties increases, these models assume that the funding cost is a decreasing function of time, while the settlement delay cost, representing here a loss of confidence from counterparties when settlement is late, is an increasing function of time. Participants are assumed to time their outgoing payments so as to minimize their own settlement costs, the total of these two costs, with respect to time.

When there is an opportunity to save on settlement costs by making payments late, participants have an incentive to delay their own outgoing payments.[3] For example, assume that Banks X and Y each have one same-value outgoing payment instruction to another. Table 1 shows the payoff matrix in a simultaneous-move game between the two banks. Each bank has a choice of strategies: making a payment either in the first period (move early) or in the second period (move late). If both banks choose to move early, they each only bear the funding cost, C (> 0). If both choose to move late, they must bear the settlement delay cost, D (> 0), in addition to the funding cost. If one bank moves early and the other bank moves late, the early-moving bank bears the funding cost in the first period as well as the opportunity cost of settlement funds, C, in the second period. Because the late-moving bank can recycle the funds received from the early-moving bank in the first period to make its outgoing payment, it only bears the settlement delay cost. When $C > D$, the opportunity to reduce settlement costs by moving late creates an incentive to pursue the move-late strategy.

2. For an overview of settlement games under RTGS, see Imakubo (2005).
3. Because the settlement time under DNS is predetermined, participants do not have an alternative strategy except settlements at that time. Strictly speaking, they could also pursue a strategy of purposefully not making a payment, that is, strategic defaults. It is not a realistic strategy, however, especially in a repeated game because of the large penalty that would incur.

Following McAndrews and Potter (2002), we can simplify participant i's reaction function, derived from the minimization problem of settlement costs, that determines the gross payment amount, $P_{i,t}$, as

$$P_{i,t} = \alpha_i IB_i + \beta_i R_{i,t-1}, \quad 0 \leq \alpha_i, \beta_i \leq 1. \tag{1}$$

The first term on the right-hand side of the equation (1) is the receipt-independent payment that does not rely on incoming payments from counterparties, and IB_t is funded either by the banks' own balances at central bank accounts or by the intraday credit facility offered by the central bank. The second term on the right-hand side represents the receipt-driven payment using $R_{i,t-1}$, reserved funds of incoming payments from counterparties at the time $t-1$. The development in the funds is affected by the pace of both incoming and outgoing payments. Parameters of α_i and β_i depend on the costs of funding and settlement delay, with α_i and β_i becoming smaller as both the costs increase.

This strategic settlement behavior of one participant recycles payments and then sequentially affects the settlement behavior of other participants. Once a participant makes a payment, a receiver of the payment makes a receipt-driven payment, and then a subsequent receiver of the payment makes another receipt-driven payment, with incoming and outgoing payments occurring sequentially. If β_i is large enough, payments are recycled one after another through receipt-driven payments. As long as these funds circulate efficiently among participants, smooth flow of payments is achieved in the entire system while each participant does its best to hold down its additional funding cost. This is a positive aspect of payment recycling.

There is also a negative aspect, however. RTGS, under which each payment is settled on a transaction-by-transaction basis, is basically a sender-driven system, that is, the timing of settlement is determined by senders of payments.[4] Participants with a strong incentive to hold down their funding cost are likely to attempt to delay making payments so that they can fund them with incoming payments. This increases uncertainty of the timing of receipts for the receiver side. McAndrews (2006) refers to this uncertainty as timing friction. RTGS itself does not have any mechanism to eliminate the moral hazard deriving from excessive dependence on incoming payments to secure funds, as well as the intentional restriction on receipt-independent payments to save funding cost. Consequently, if the funding environment becomes tight or the opportunity cost of securing funds in advance becomes high, and one participant slows its pace of settlement as a way to save its funding cost, the first-round effect will be delays in both receipt-independent and receipt-driven payments. This would be followed by the second-round effect in which participants expecting to receive the payments would reduce their own receipt-driven payments. When these second-round effects become persistent and spread among participants one after another, they can result in system-wide gridlock.[5] The transmission mechanism of second-round effects caused by payment recycling will depend on the value of payments and which participants

4. As in the case of a direct debit contrary to sender-driven payment, settlement can be initiated by the receiver instead of the sender.
5. This refers to a situation in which there are enough funds available to settle net positions of unsettled payments, but not enough funds available to settle their gross positions.

make or receive the payments, as well as on the initially scheduled order of settlement. Of these two, the former set of relationships can be dealt with in a concept of payment network, wherein the flow of funds is described using the vector information of direction and value. The latter factor can also be expressed in terms of network structure if the scheduled order is added to the vector information.

The positive and negative aspects of payment recycling are really two sides of the same coin. The side of the coin that appears depends on the participants' incentives. Payment recycling thus creates a very strong interconnectedness among participants, that is, externality, and leads to strategy-dependency among participants' settlement behavior. Consequently, it affects the timing of settlements, which depends on their incentive to settle with and without settlement delay.

C. Empirical Research on RTGS

There are also empirical studies that analyze settlement activity from the perspective of payment recycling. The literature on a statistical examination of the intraday distribution of payment value and volume includes McAndrews and Rajan (2000), McAndrews and Potter (2002), and Lacker (2004), all of which look at the Fedwire funds transfer system in the United States, and James (2003), which looks at the Clearinghouse Automated Payment System (CHAPS) in the United Kingdom. The results of these papers support the theoretical argument that when funding cost is high relative to settlement delay cost, the pace of settlement is reduced because each participant delays making its outgoing payments. The literature also notes the presence of spontaneous cooperative action to concentrate settlement at around exogenous settlement events so as to minimize funding cost. In the case of BOJ-NET, the concentration of settlement is observed at around the scheduled time of settlements of clearing balances for ancillary systems such as the Zengin System, which handles domestic retail credit transfers.

A different empirical approach is to combine network analysis with simulation analysis. Network analysis views the participants as nodes and the interconnectedness between these senders and receivers of payments as links, statically analyzing the payment recycling among them. In contrast, simulation analysis generates a sequence of settlements as a result of participants' decisions on when and how much they fund subject to funding liquidity constraints such as their position limits and the timing according to which they proceed with their payments under the predetermined payment framework. This allows for a dynamic assessment of payment recycling.

The network approach has become possible with the emergence of social network analysis techniques, the wider use of software, and the settlement simulators developed by central banks. Examples of social network analysis include introductory texts by Barabási (2002) and Watts (2003), and a software-based description by De Nooy, Mrvar, and Batagelj (2005). Examples of simulators include the Bank of Finland Payment System Simulator, an overview of which is given by Koponen and Soramäki (2005).

Empirical research using network analysis includes Inaoka *et al.* (2004), which looks at the characteristics of the payment network using BOJ-NET's settlement log; Imakubo and Soejima (2010), which analyzes the interbank funding network by extracting call money transactions from the same settlement log; Soramäki *et al.* (2006), which analyzes the payment network using the U.S. Fedwire settlement log; Iori *et al.* (2007), which is an analysis of the funding network using the transaction log for Italy's interbank electronic broking system; and Müller (2006), an examination of large-value bilateral exposures among Swiss financial institutions.[6] Empirical research that uses a settlement simulator includes Schmitz *et al.* (2006), a study of the Austrian Real Time Interbank Settlement System (ARTIS); Bedford, Millard, and Yang (2004), an examination of the U.K. CHAPS; and Beyeler *et al.* (2006), which uses hypothetical data.[7]

Payment data are not ordinarily disclosed because of their confidential nature. Consequently, most empirical research using either approach has thus far been done by analysts who work for organizations that operate payment systems.

III. International Comparison of RTGS Systems

Unless specific measures are taken under RTGS, there is a risk of system-wide settlement delays and social welfare inefficiencies due to the incentive to delay making payments. At the extreme, it is conceivable that no payment would be completed during the day, but rather that all payments would be concentrated immediately prior to the system closing. In fact, as explained later, in some countries the settlement is concentrated in the evening. Normally, a variety of precautionary measures are taken in both direct and indirect manners to prevent such a potential problem in RTGS systems. These measures can make RTGS systems effectively more stable. In this section, we compare Japan's BOJ-NET with U.S. Fedwire and U.K. CHAPS,[8] examine the mechanisms built in BOJ-NET RTGS, and consider how well these mechanisms have functioned. Fedwire, the RTGS system operated by the U.S. Federal Reserve, handles the settlement of transactions denominated in U.S. dollars. CHAPS, the RTGS system jointly operated by the Bank of England (BOE) and a private-sector institution, handles the settlement of transactions denominated in pounds sterling. The international comparison is conducted by focusing on five factors: (1) reserve requirements that ensure settlement funds *ex ante*; (2) an intraday credit facility provided by a central bank to cover temporary liquidity shortages during the day; (3) market practices that clearly specify the timing of settlement; (4) the funds turnover ratio, which is the ratio of a total payment value to settlement funds balances; and (5) the intraday settlement activity that reflects these factors.

A. Reserve Requirements and Intraday Credit Facility

Access to settlement funds under an RTGS system is given by the reserve requirement, which is one of the frameworks for money market operations, and the intraday credit facility, which is specific to an RTGS system (Table 2). Current account balances under the reserve requirement can be directly used as settlement funds. The demand for settlement funds by financial institutions varies day by day, but the reserve requirements are designed to stabilize reserve balances at the central bank.

6. For a survey of the literature, see Imakubo and Soejima (2010).
7. See Leinonen and Soramäki (2004) for an overview of settlement simulation analysis.
8. See Bank for International Settlements (2005) for details of the basic design of both systems.

Table 2 Funding Sources of Settlement Funds

	Fedwire	CHAPS	BOJ-NET
Reserve requirements	Yes	No	Yes
Other requirements	Clearing balances	Reserve averaging scheme Cash ratio deposits Stock liquidity regime	No
Intraday credit facilities			
Form of credit	Unsecured overdrafts	Intraday repos	Secured overdrafts
Limits of credit	Yes	No	No
Fee	Charged	Not charged	Not charged

While the reserve requirements have been established by law in the United States and Japan, other requirements of current account reserves with a central bank in the United States and the United Kingdom are made on a contractual basis, referred to as the clearing balances and the reserve averaging scheme, respectively. In addition, the cash ratio deposits held at the BOE by depository institutions can also be used during the day as settlement funds in the United Kingdom. A number of these accounts pay interest, which helps to lower the opportunity cost of maintaining current account balances at a central bank. For example, in the United Kingdom, interest is paid on the amount up to the required reserves under the reserve averaging scheme. In the United States, interest is also paid on the clearing balances in the form of points that can be used to pay various fees incurred under the Federal Reserve System.[9]

Direct participants in Fedwire and CHAPS are in principle subject to reserve controls, but many BOJ-NET participants are not subject to the reserve requirement, namely, private-sector non-depository institutions that are able to settle directly within BOJ-NET. These institutions are expected to keep current account balances and/or maintain collateral for intraday overdrafts.

All three RTGS systems have intraday credit facilities. Common to all three is a requirement to make repayments before the system closing on that day and a mechanism to complement the market's function to allocate any intraday fund imbalance caused by institutional reasons. The specifics of these facilities vary by central bank, however. Both Fedwire and BOJ-NET take the form of overdrafts, and CHAPS uses intraday repos.[10] Users of intraday credit under CHAPS and BOJ-NET, which are predicated on secured transactions, are subject to collateral restrictions.[11]

Reserve requirements and intraday credit facilities provide a source of funds for receipt-independent payments. Accordingly, the lower the cost of funding from these sources, the greater the contribution of receipt-independent payments to payments

9. In October 2008, central banks changed their deposit facilities in response to the market turmoil. The BOE replaced the existing Standing Lending Facility with a new Operational Standing Lending Facility. The Fed began to pay interest on required and excess reserve balances. The BOJ introduced the complementary deposit facility as a temporary measure, under which it pays interest on excess reserve balances.
10. See Zhou (2000) for a detailed survey of the literature on forms of intraday credit.
11. BOJ-NET offers no specific measures for re-hypothecation of collateral assets, but CHAPS allows for reuse of liquid assets posted under the stock liquidity regime to fund via the intraday repo facility.

Table 3 Market Practices

	Fedwire	CHAPS	BOJ-NET
Minimum balance	No	No	No
Early settlement	No	Throughput guidelines	One-hour rule Repayment-first rule
Gridlock countermeasures	No	Circle operations Position limits	No
Liquidity sink countermeasures	No	SBLS	No

overall, which contributes to receipt-driven payments and accelerates payments as a whole. Realistically, however, either not all payment system participants have access to these funds, as is the case in Japan's reserve requirements, or it is not always possible for participants to time their use of intraday credit as they please, because some participants may face collateral restrictions, as with the intraday credit facilities in both the United Kingdom and Japan. In this case, participants must either depend on incoming payments or procure new funds in the market, and the latter option would put upward pressure on interest rates during the day.

In one respect, unsecured intraday call money transactions in Japan marginally ease the upward pressure on the unsecured overnight call rate. The intraday money market works through the function of *tanshi* companies (money market brokers), which play the role as both the money center and the center of information on the intraday imbalance among money markets. Specifically, a lender provides its intraday surplus funds to the brokers, which then allocate the funds to a borrower through their dealing account. If the lender and the borrower of funds do not agree on the desired transaction timing in terms of the start and the end, the brokers repay the lender of funds on behalf of the borrower and temporarily bridge the gap, thereby overcoming this mismatch of trading timing. Intraday call money transactions provide an important source of liquidity for participants who do not have sufficient collateral but tend to have a large amount of intraday multilateral net debit positions.

B. Market Practices

We look next at the market practices associated with RTGS systems (Table 3).

While no rules have been introduced regarding minimum balances of settlement funds, the RTGS systems in Japan and the United Kingdom do have a number of rules aimed at preventing participants from delaying settlement. The throughput guidelines for CHAPS require completion of 50 percent of a day's settlement by noon and 75 percent by 14:30.[12] CHAPS has also introduced measures to prevent and solve gridlock. The position limits are set bilaterally between counterparties so that their intraday bilateral net positions are not overly biased, which mitigates the risk of gridlock. The circle operation initiates multilateral netting if gridlock does occur. In addition, CHAPS has the Stricken Bank Liquidity Scheme (SBLS) to deal with liquidity sinks, which occur when a hoarding of funds by certain participants momentarily reduces liquidity

12. Buckle and Campbell (2003) carry out a theoretical analysis of the impact of the throughput guidelines on participants' strategic settlement behavior.

Table 4 Funds Turnover Ratios

Daily averages, US$ billions

	Fedwire	CHAPS	BOJ-NET
Current account balances (A)	17.5 (—)	5.8 (3.4)	213.1 (25.1)
Intraday credit (B)	116.5 (—)	24.6 (13.6)	136.3 (16.2)
Settlement value (C)	2,074.2 (—)	377.2 (207.6)	785.8 (86.6)
$C/(A+B)$	15	12	2
C/A	119	65	4
C/B	18	15	6

Notes: 1. Figures as of December 2006.
2. Figures in parentheses are denominated in local currency. CHAPS is in units of billions of pounds, and BOJ-NET in units of trillions of yen.

Source: Bank for International Settlements (2008).

available within the system. Under SBLS, a participant that for whatever reason is temporarily unable to make a payment has its incoming payments suspended. This is one mechanism aimed at keeping settlement on track under unusual conditions.

Under BOJ-NET, the timing of most settlement is controlled through the one-hour rule, which encourages lenders in a same-day-start transaction to release their funds within one hour after the contract, and through the repayment-first rule, which encourages borrowers to make repayments immediately after 9:00 (the opening time of BOJ-NET) and no later than 10:00. By establishing clear-cut time limits, it appears that both rules go beyond simply alleviating the uncertainty associated with the timing of receipts and actually help to prevent gridlock to some extent. These market practices result in both the repayments and the initial payments contracted in that morning being concentrated from 9:00 to 10:00. During this time period of concentrated funds flow, there is a large level of market funding activity, particularly for the settlement of repayments, and this puts upward pressure on interest rates.

Without any rules regarding the timing of settlement, there would be no way for participants in an RTGS system to gain *ex ante* knowledge of when on the settlement day the counterparty will execute payments. Consequently, the more dependent a participant is on receipt-driven payments, the more easily it is affected by uncertainty over settlement timing. If market practices share the information on settlement timing and participants can easily forecast and confirm their own intraday funds balances, they should be able to efficiently use incoming payments to fund their outgoing payments and minimize the impact from such timing uncertainty.

C. Funds Turnover Ratio and Settlement Activity

Table 4 shows a comparison of the funds turnover ratios that are achieved under the systems and rules described above. The funds turnover ratio is the ratio of the total value settled to the amount of system liquidity, and is a simple measure of the efficiency of that liquidity. Note, however, that it measures the efficiency of the entire system's liquidity, and provides no indication of the efficiency of each participant's funding liquidity.

The turnover ratio for the sum of current account balances and intraday credit is generally highest at Fedwire, followed by CHAPS and then BOJ-NET. Interest rate levels, which are critical to measuring opportunity cost, vary by country, making a simple comparison of turnover ratios difficult. A look at BOJ-NET's overall settlement environment including its related facilities shows that it requires a greater amount of liquidity for a given settlement value than the other systems. From the opposite standpoint, BOJ-NET seems to be more robust to liquidity shocks, and therefore the upward pressure on interest rates caused by liquidity shocks should be relatively lower within BOJ-NET.

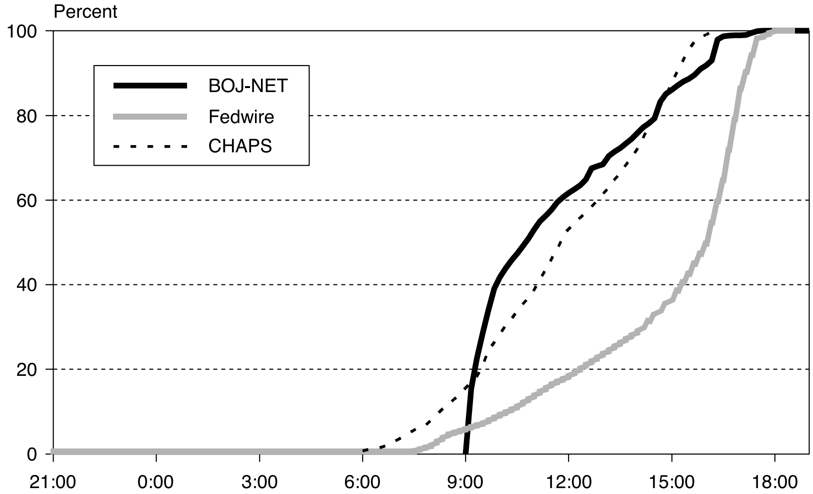
Both CHAPS and BOJ-NET are designed so that intraday credit can be received for an amount greater than that needed for settlement, and thus there are constantly a number of participants receiving greater intraday credit than their settlement needs. At BOJ-NET, for example, to simplify operations for settlement during the course of the day, it is possible for participants to obtain an intraday overdraft from the system opening, by pledging Japanese government securities (JGSs) as collateral not otherwise planned for use that day, through the simultaneous processing of delivery-versus-payment and collateralization facility (SPDC).[13] This explains why the amount of intraday credit drawn under both CHAPS and BOJ-NET tends to be higher than the total value settled. This is not observed for intraday overdrafts in Fedwire, which in principle incur a fee. Instead, any Fedwire overdraft repaid within one minute is not counted nor charged the overdraft fee. This creates an incentive to take advantage of super short-term, one minute or less, overdrafts, and thus, as explained below, during specific time periods there are numerous very short-term overdrafts repeatedly used at a high frequency (McAndrews and Rajan [2000]).

Figure 1 shows that differences in facilities and rules among the three systems result in different settlement progress, measured by the intraday cumulative distribution of settlement value. Fedwire does not have any rules regarding the timing of settlement, and this creates a strong incentive to delay making payments. Consequently, the intraday cumulative distribution shows a sharp increase immediately before the end of the system's operating hours, which run from 21:00 on the previous day until 18:30 on the day.[14] Since the 1990s, settlements have become increasingly delayed, and thus concentrated more heavily toward the system closing. Under these extreme conditions, there is a risk that system operational problems or other emergencies will prevent all settlements from being completed during the day, and the monetary authority also sees this as an issue (Board of Governors of the Federal Reserve System [2006]). The concentration of payments flow, however, does not necessarily lead directly to upward

13. The SPDC facility refers to the simultaneous processing of JGS delivery and its payment. It allows a receiver of JGSs to pledge the incoming securities as collateral for intraday overdrafts from the BOJ, while using the overdrafts to pay for those incoming securities (likewise in the opposite direction).

14. For securities settlement at the Depository Trust Company (DTC) and payment settlement at the Clearing House Interbank Payment System (CHIPS), a certain amount of funds is locked up during the day in dedicated accounts. The momentary decline in usable funds over Fedwire until these settlements are completed has been identified as one reason why Fedwire settlements are concentrated in the period just before the system closing. For details, see McAndrews and Rajan (2000).

Figure 1 Intraday Settlement Activity



Note: Horizontal axis shows local time, and vertical axis shows the rate of cumulative value settled.

Sources: Federal Reserve; Bank of England; Bank of Japan.

pressure on interest rates, unlike the other RTGS systems. Because intraday overdrafts repaid within a minute are not recorded, Fedwire could be viewed as having the same economic impact as an RTGS system with an offsetting mechanism.[15]

In contrast, for interbank funds transfers under BOJ-NET, a large amount of settlement is completed immediately after the system opening at 9:00 because of the repayment-first rule, and then the rest of settlement proceeds in order according to the one-hour rule, resulting in a decreasing pace of settlement approaching the system closing at 17:00. Consequently, the cumulative distribution of value settled in BOJ-NET has a shape symmetrical to that of Fedwire. The rapid progress in settlement means minimizing intraday exposure of settlement. Settlements on CHAPS occur at a fairly even pace throughout the business day, from the system opening at 6:00 to the system closing at 16:20, and thus the figure is fairly linear. The timing of settlement for each participant under the throughput guidelines determines the pace of settlement for the overall system.

15. The offsetting mechanism searches for a set of payment instructions that may not be settled one by one because of insufficient balances but can be settled when taking into account incoming payments from counterparties as a source of liquidity. It then settles the selected set of payment instructions simultaneously. For details, see Imakubo (2005).

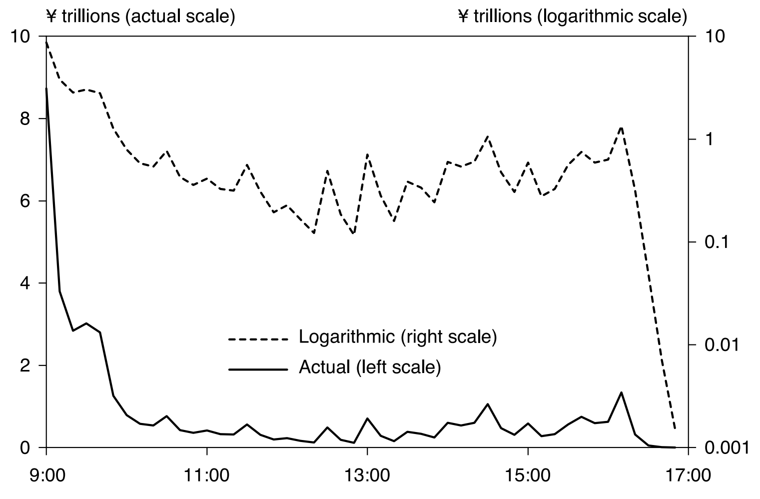
IV. Payment Network

In this section, we show that the pace of settlement under BOJ-NET varies during the course of the day, and we express this as a change in the shape of the payment network. Unless specifically stated otherwise, our analysis focuses only on interbank funds transfers (primarily the settlement of call loans), a subset of BOJ-NET funds transfers. For more on the relationship between the interbank funds transfers and overall BOJ-NET funds transfers, see the Appendix.

The content of interbank funds transfers changes throughout the day according to the type of transactions and the relationship between counterparties. These transactions include the repayment of call loans made until the day prior, the short-term investment by investment trusts in response to fluctuations in their cash positions, the supply of intraday surplus funds in the intraday call market, and the supply of banks' overnight surplus funds after they confirm their net positions for that day's domestic retail credit transfers in the ancillary DNS system. Consequently, the pairings of senders and receivers of funds, as well as the settlement value and volume, vary greatly depending on the time of day.

The distribution of settlement value for the interbank funds transfers every 10 minutes is shown in Figure 2. In the morning, roughly half of the value settled in a single day is completed during the one hour starting at 9:00 because of the repayment-first rule, the concentration of call money transactions for that day's funding in the early hours, and the early settlement of those transactions subject to the one-hour rule. Settlements

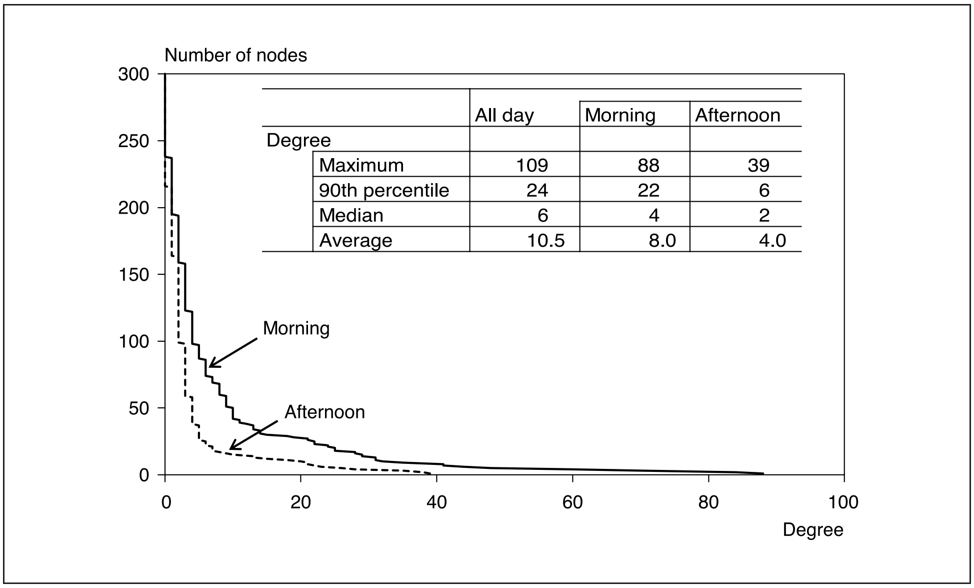
Figure 2 Intraday Settlement Activity



Note: Daily average value of interbank funds transfers settled in December 2006.

Source: Bank of Japan.

Figure 3 Distribution of the Degree (Number of Nodes Linked)



	All day	Morning	Afternoon
Degree			
Maximum	109	88	39
90th percentile	24	22	6
Median	6	4	2
Average	10.5	8.0	4.0

Note: Daily average of interbank funds transfers settled in December 2006 for transactions valued at ¥10 million or higher.

Source: Bank of Japan.

from 10:00, in contrast, are primarily of transactions for adjustments of cash positions. Specifically, the settlements of net positions for some clearing systems occur one after another: the bill and check clearing system at 12:30, the foreign exchange yen clearing system at 14:30, and the domestic retail credit transfers at 16:15. The distribution across time, therefore, shows a tendency for settlement value to reach local peaks immediately after those clearing settlements. These intraday changes can be viewed as changes in the shape of the payment network. Although the network shape changes throughout the day, for simplicity we compare network shapes for just two periods, morning and afternoon.

Network analysis investigates nodes and their links. The number of nodes to which a node links is called its degree, and their quantitative information is called the strength of these links. Within a payment network, the participants are the nodes, the outgoing-incoming pairing of payments is the link, the number of counterparties a participant links to is the degree, and the value and volume of settlements in a link corresponds to the strength of the link.[16]

Figure 3 shows a distribution of the degree, that is, the number of counterparties with which a participant settled interbank funds transfers. In both the morning and the afternoon, the most common level of degree is one, but the number of nodes with

16. In addition to the statistics dealt with in this paper, there are various statistics such as the distance between two nodes, the influence domain that measures the range possibly affected, and the core and cluster coefficients that measure the network density. See Imakubo and Soejima (2010) for definitions of these statistics.

the degree of zero is rather limited even for low-degree nodes (the zero degree is not shown in the figure). There are very few high-degree nodes. This sort of long-tailed distribution is observed in many types of networks, and often follows a power law distribution.[17] Imakubo and Soejima (2010), a study of Japan's call money transaction network, find these high-degree nodes that have functioned as the hub for the entire network, consisting of money brokers, city banks, asset management trusts, central financing organizations for financial cooperatives, major securities firms, trust banks, and major regional banks. They also suggest that the hub institutions are very densely linked to each other as in a complete network.

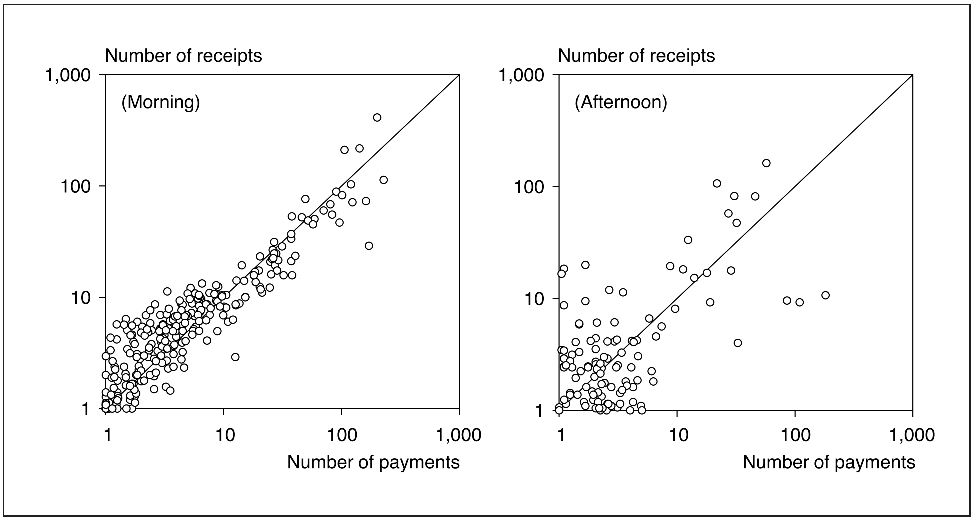
Imakubo and Soejima (2010) look only at the network's average structure over a specific month, without respect to changes throughout a day. As noted above, because the settlement pace is not homogenous, there are substantial differences in both concentration and distribution of the degree depending on the time of day. Figure 3 shows that the degree in the morning is higher than in the afternoon. This indicates that the network has greater link density in the morning, and clearly reflects that funding transactions are concentrated in the morning, and a smaller value of transactions for adjustments of cash positions are settled in the afternoon. For low-degree participants, however, there is virtually no difference between the morning and the afternoon. The majority of these participants have only a few links in both the morning and the afternoon and are likely to settle with the same counterparties such as money brokers. On the other hand, in the morning there are participants with the high degree of more than 40, but not in the afternoon. In addition, the number of participants with the degree of at least 10 decreases from 50 in the morning to only 15 in the afternoon. This indicates that as the network becomes sparser in the afternoon, the number of participants functioning as the hub declines, and the number of nodes linked with the hub institutions also declines. The high-degree participants in the morning are primarily money brokers, city banks, trust banks, asset management trusts, major securities firms, central financing organizations for financial cooperatives, and major regional banks. In the afternoon, the degree declines as a whole, especially among major securities firms. This is attributed to two factors: the banks handling the foreign exchange yen transactions and domestic retail credit transfers still have a larger number of nodes linked in the afternoon owing to the adjustments for cash position; contrarily, the major securities firms largely complete their settlement including securities settlement during the morning.

Figure 4 plots in a scatter diagram the volume of outgoing and incoming payments for each node in the morning and the afternoon. The volume of payments indicates the strength of links with other nodes. In the morning, the majority of nodes have a distribution approaching a 45-degree line, implying roughly an equal frequency of outgoing and incoming payments. This is attributed to a concentration of rollover payments caused by the repayment-first rule. The large number of nodes in the upper right area of the diagram indicates a considerable flow of payments to/from the participants. The subset of the nodes with a large payment volume largely equates with the subset of the

17. When following a power law distribution, the probability of node i having the degree x_i, $p(x_i)$, is given as $p(x_i) = \alpha x_i^{-\gamma}$.

For a simple explanation of how power law distributions relate to a network, see Barabási (2002) and Watts (2003).

Figure 4 Payment Frequency per Node



Note: Daily average of interbank funds transfers settled in December 2006 for transactions valued at ¥10 million or higher. Both axes are on a logarithmic scale.

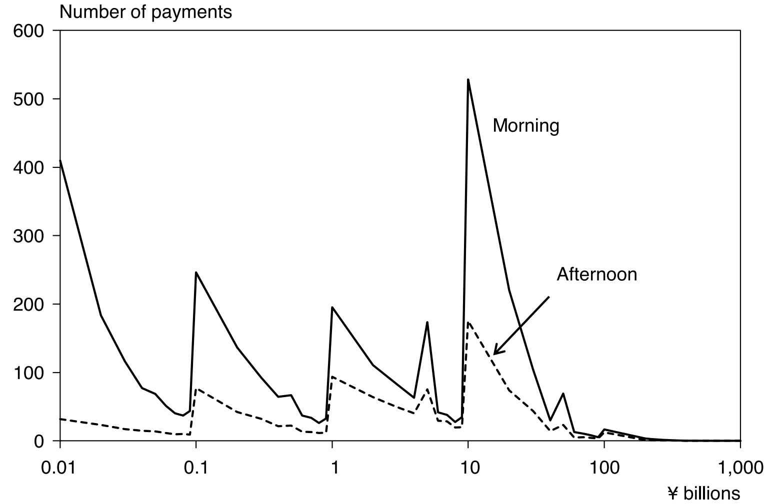
Source: Bank of Japan.

hub institutions described above, namely, the institutions that make frequent payments with multiple counterparties. Under RTGS, hub institutions serve as intermediaries that facilitate the flow of funds, but can suddenly have an adverse impact on a wide range of payments if they fall behind in making their payments.

In the afternoon, the distribution is weighted toward the lower left area, indicating that the majority of nodes have fewer than 10 outgoing/incoming payments, and there is a decline in not only the link density of the network but also the overall volume of payments. Unlike in the morning, payments are only made between limited node pairs, and there is substantial deviation from the 45-degree line, implying that many nodes are weighted toward either outgoing or incoming payments. As opposed to the morning when the concentration of that day's funding transactions including rollovers occurs immediately after the system opening, the transactions for position adjustments in the afternoon are mostly made up of either additional funding or investment. This explains the decline in payment volume and the dispersion toward outgoing or incoming payments.

Lastly, we look at the distribution of interbank funds transfers by value. In a payment network, the significance of any one link varies depending on whether it represents a payment value of ¥10 million or ¥10 billion. Payment value, like payment volume, contains critical information on the strength of a link. Figure 5 shows that in both the morning and the afternoon, payments in nice round numbers (such as ¥10 million or ¥10 billion) are the most frequent. As shown by Brown, Laux, and Schachter (1991), business practices tend to result in most transactions becoming specific sizes in order to minimize transaction costs between counterparties and increase the speed of contract

Figure 5 Distribution of Interbank Funds Transfers by Value



Note: The daily average value of interbank funds transfers settled in December 2006 for transactions valued at ¥10 million or higher.

Source: Bank of Japan.

execution. In the morning, payments with a value of either ¥10 million or ¥10 billion are overwhelmingly the most frequent. Because secured call money transactions are most frequently valued at ¥10 million and unsecured transactions at ¥10 billion in the morning, the respective distribution peaks are indicative of the types of transactions. In the afternoon, there are still a fairly large number of unsecured call money transactions valued at ¥10 billion, whereas the volume of payments corresponding to secured transactions is low. This is because the position adjustments in the afternoon are based more on unsecured call money transactions than on secured transactions.

As seen above, the links between nodes are stronger in the morning, whether measured in degree, value, and volume of payments. In other words, the payment network is more densely linked, and each link's strength is on average higher in terms of both value and volume, during the morning. This is attributed to a greater extent of payment recycling in the morning owing to the market practices and intraday credit facility introduced with the conversion to full-fledged RTGS. Greater payment recycling makes funding liquidity more efficient, but also may increase the possibility of a negative contagion when payment delays or liquidity sinks occur. In addition, if severe gridlock takes place within the hub, it is conceivable that an adverse shock can be propagated widely across the network. With this in mind, in the next section we quantitatively examine the extent of payment recycling by running a simulation to measure the impact of an exogenous shock.

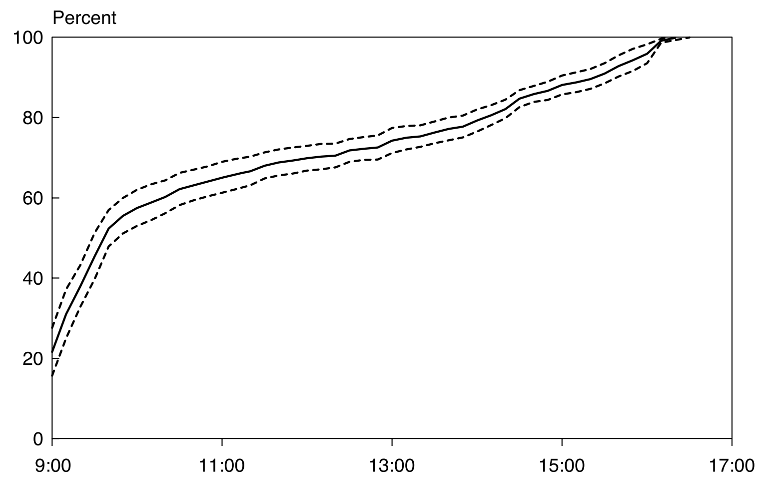
V. Payment Recycling

As shown in the previous section, the extent of payment recycling appears to vary depending on the time of day. Consequently, even when assuming the same reaction function for every participant, the pace of settlement for the system overall is also going to vary by time of day.

Figure 6, the cumulative distribution of the intraday settlement (in value terms) shown previously in Figure 2, makes it clear that more than 20 percent of that day's payment value is concentrated within the first 10 minutes of the business day, from 9:00 to 9:10. The pace of settlement remains quite fast until 9:50, after which it starts to gradually slow. In the afternoon, the settlement pattern reflects a response to the settlements for ancillary DNS systems. As evident from the standard deviation, this settlement pace is quite stable, showing very little deviation during the observed period.

One way to measure the impact of payment recycling on the full day's settlement activity for the system overall is to run a behavioral simulation, using certain assumptions for participants' settlement behavior. Our simulation makes the natural assumption that when insufficient funds are available to make a payment, the payment is delayed until incoming payments increase the account balance sufficiently to enable settlement. We also assume that when a participant faces a rise in intraday multilateral net debit above a certain threshold at any time of day, that participant will exhibit more cautious settlement behavior. The participant delays payments and then maintains a given level of available funds to avoid a temporary liquidity shortage due to the possibility

Figure 6 Cumulative Distribution of Intraday Settlement



Note: The value of interbank funds transfers settled in December 2006. The solid line is the daily average, and the dotted lines show the average plus or minus two standard deviations.

Source: Bank of Japan.

of incoming payments from counterparties being delayed. To examine the extent to which this cascading of settlement delays occurs when there is no constraint on payment delaying behavior, we examine the simulation without the repayment-first and one-hour rules.

We perform a stress test on interbank funds transfers assuming rule-based reactions shown above.[18] While simulation results are very dependent on the assumptions we use for the behavior of participants, we do not aim to predict what will happen under stress conditions, but rather to understand the complex interconnectedness of a payment network.

Our assumptions of the participant behavior use upper bound liquidity, which we define here as the minimum initial balance to enable a participant to pay the same amount at the same timing as in the historical record of its settlements. For the amount of outgoing payments, $P_{i,t}$, and the amount of incoming payments, $R_{i,t}$, by participant i at time t, the net debit amount at time t, $DL_{i,t}$, can be given by

$$DL_{i,t} = \max\left\{\sum_{s=0}^{t}(P_{i,s} - R_{i,s}), 0\right\}, \quad 0 \leq t \leq T, \tag{2}$$

where T is the time at the system closing. In this case, the upper bound liquidity for that participant, UL_i, is given by

$$UL_i = \max_t DL_{i,t}. \tag{3}$$

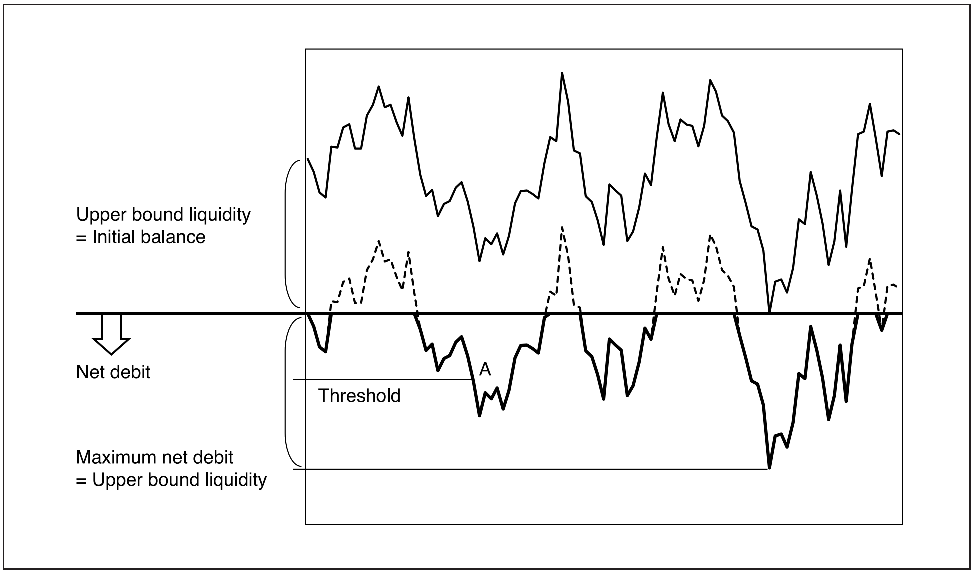
That is to say, the upper bound liquidity is equal to the maximum amount of intraday net debit with no delayed payments. This is each participant's initial balance. Figure 7 gives an example of relationship between the net debit and the upper bound liquidity.

Participants start with their initial balances, and make an outgoing payment each time a recorded settlement time arrives, as long as their balances are positive. Incoming payments received are automatically added to the receivers' balances. Under this condition alone, all payments are settled without delay as smoothly as recorded. Payments are delayed when adding a second condition, however, which is that when the level of net debit rises above a certain threshold, the participants will delay making payments because of the possibility of a temporary shortage of liquidity due to the slower pace of incoming payments. In Figure 7, the payment begins to delay at point A where the net debit is over the threshold. Participant a's settlement delay may have an impact on the next settlement of participant b, the counterparty expecting to receive a's payment. This recycling of receipt-driven payments could further impact participant c, and if this impact is fed back to participant a and results in unexpected delay in incoming payments for a, the scheduled path starting from point A in Figure 7 would break down.

Consequently, payment-delaying behavior would be enhanced not only by the second condition expressing concern for future shortages of liquidity, but also by the first condition of insufficient balance for settlement when an initial delay is triggered by the second condition. Because of the difficulty in understanding these complex forms of

18. Our simulation uses the Bank of Finland Payment System Simulator.

Figure 7 Net Debit and Upper Bound Liquidity



Note: Net positive debit $DL_{i,t}$ is plotted downward. The dotted line shows fluctuations before applying the max function.

interconnectedness, we assess the extent of system-wide settlement delays relative to the actual pace of settlement in value terms.

We first provide an overview of the payment data used in our simulation (Table 5). Our simulation examines the occurrence of settlement delays, using the interbank funds transfers settled on December 15, 2006, the last day of the reserve maintenance period. A single payment has four data points: sender, receiver, payment amount, and time of instruction issuance/settlement. A total of 4,400 transactions valued at ¥45 trillion were settled. The distribution of value across participants, based on the average, median, and top decile, is heavily skewed to the right. More than half of all participants had a relatively low value of both outgoing payments (below ¥15.9 billion) and incoming payments (below ¥18.2 billion), and much of the large-value payments was concentrated among a small number of participants. The largest sender, for example, accounted for 7.3 percent of the total value of all payments. The same tendency is evident with the distribution of the upper bound liquidity across participants.

The results of the simulation in Figure 8 show for each stress scenario the deviation in percentage points from the baseline cumulative percentage of settlement value measured by real data. A scenario with no settlement delays (payments settled at the same timing as the baseline) would follow the horizontal line passing through zero on the vertical axis. The threshold values are set progressively smaller for scenarios (1) through (4), with (1) at 4/5 of each participant's upper bound liquidity, (2) at 3/5, (3) at 2/5, and (4) at 1/5. The smaller threshold, the more frequently settlement delays occur.

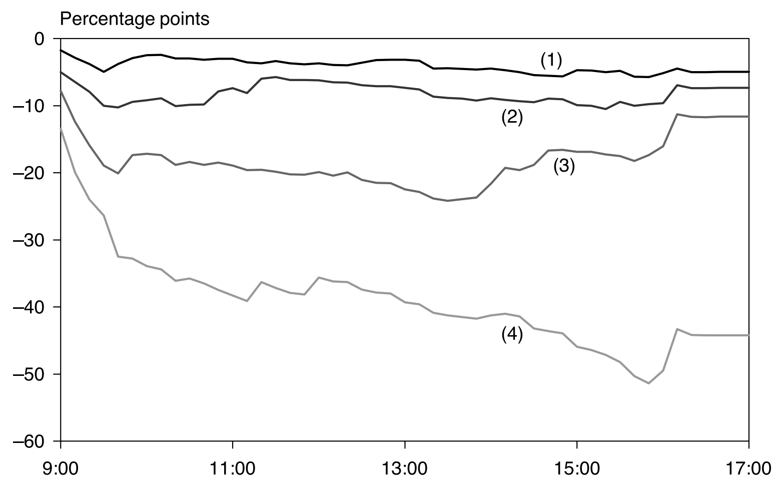
Table 5 Summary Statistics for Simulation Data

¥ billions

	Outgoing payments	Incoming payments	Upper bound liquidity
Total	45,200.1 (4,469)	45,200.1 (4,469)	15,861.7
Maximum	3,322.8 (370)	3,391.0 (366)	1,252.5
Top decile	229.8 (20)	362.0 (28)	93.0
Median	15.9 (3)	18.2 (5)	5.9
Average	118.9 (12)	157.4 (16)	40.5

Note: Figures in parentheses are the number of transactions.

Figure 8 Stress Tests; Scenarios (1) to (4)



Note: The rate of deviation from the baseline (actual) cumulative percentage of settlement value over time. The deviation rate at 17:00 is the percentage of that day's payments unsettled. The same is true for Figure 9.

The threshold levels are set at $4/5$ of each participant's upper bound liquidity for stress scenario (1), $3/5$ for (2), $2/5$ for (3), and $1/5$ for (4).

Our results confirm that delays become more pronounced as the threshold level decreases. We also see that each scenario has its own peculiarities in regard to how settlement delays increase over time. The level of deviation increases substantially for all scenarios in the hour starting at 9:00, particularly immediately after the system opening, but after that, the trends diverge. In scenarios (1) and (2), the deviation then either flattens out or shows a recovery of delay in some periods, while in scenario (3) it continues to show a moderate expansion of delay until 13:00, after which substantial recovery is observed. In scenario (4), the deviation increases at the fastest pace, and there is only a marginal recovery around 14:30, when there is DNS settling of foreign exchange yen transactions, and 16:15, when there is DNS settling of domestic retail credit transfers. This is attributed to the factors outlined below.

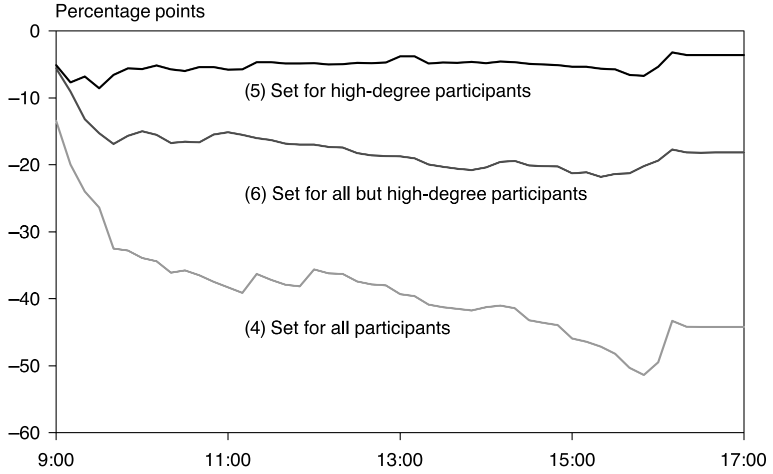
Settlement delays spread immediately and broadly in the morning, when the payment network has high density and high frequency of settlements. When participants have initial balances to clear the maximum amount of intraday net debit, that is, the upper bound liquidity, under the repayment-first rule, only a little payment delay makes it difficult to execute the large volume and value of payments concentrated immediately after system opening. For the hour starting at 9:00, settlement delays increase by at least 5 percentage points for stress scenarios (1) and (2), where settlement constraints causing the payment delay are smaller, and increase by 20 percentage points for scenario (3) and 30 percentage points for scenario (4), where those constraints are substantial.

In the afternoon, when the payment network is sparse, that is, it has relatively lower density and frequency, settlement delays are less likely to have a direct impact on subsequent payments. Except for stress scenario (4), additional delays are minor in the afternoon. As noted above, this is attributed to the payments' relative independence from each other partly because most transactions and payments are related to the DNS settlements. Stress scenarios (3) and (4) also confirm that after the DNS settlements are completed, surplus funds resulting from the settlements help recover the delay in payments. Nevertheless, under scenario (4) nearly half of all payments are unsettled by the system closing (the deviation rate at 17:00 in the graph is that day's percentage of unsettled payments). Scenario (3) shows some narrowing of delays toward the system closing, but scenario (4) does not. The results suggest the possibility that the threshold level, at which it becomes impossible for settlement delay contagion to autonomously recover from the peak of delay, lies somewhere between the two scenarios.

Our simulation assumes a strict first-in first-out (FIFO) constraint, which means that participants make payments in the order in which transactions were contracted. Under the FIFO, payments are not executed even if there are queued payments that meet the execution condition. These payments are not settled until the payments that come in earlier are settled. Accordingly, under a bypass FIFO constraint, which is weaker than strict FIFO and gives priority to payments that meet the execution condition, the degree of settlement delay contagion is less than the results shown in Figure 8.

Next, we run a simulation by changing each participant's threshold level according to their position in the payment network. Specifically, under scenario (5), we set a threshold to cause payment delay only for high-degree participants with at least 30 nodes linked and not for the others, while we do the opposite in scenario (6), not setting a threshold for high-degree participants and setting them for the rest. We use the same threshold level as in scenario (4), 1/5 of each participant's upper bound liquidity. High-degree participants account for only 10 percent of the total number of participants but account for more than 45 percent of all payment value, and thus function as the network hub.

Figure 9 Stress Tests; Scenarios (4) to (6)



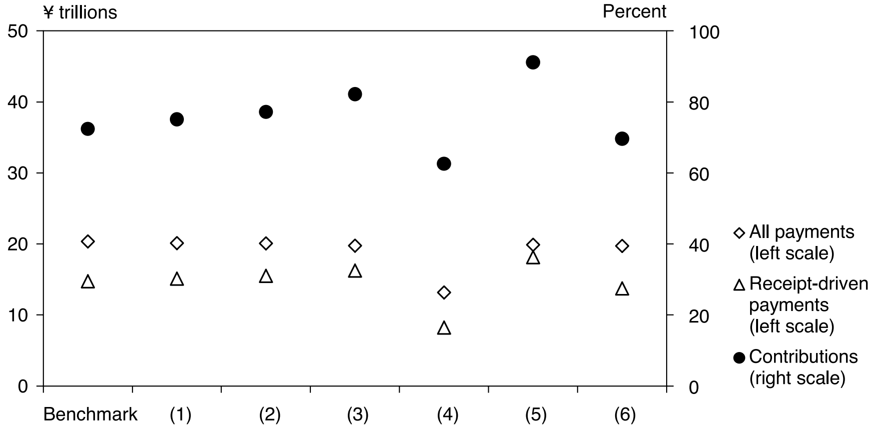
Note: A threshold level of 1/5 of each participant's upper bound liquidity is applied to all participants in scenario (4), only to high-degree participants in scenario (5), and only to low-degree participants (all but high-degree participants) in scenario (6).

The results of scenarios (4), (5), and (6) are shown in Figure 9. The differences observed in the way that settlement delays spread immediately after the system opening suggest the following hypotheses. The high-degree participants that act as a hub have a large volume and value of outgoing payments, and thus the absolute value of their intraday net debit tends to be large. Consequently, the upper bound liquidity corresponding to maximum intraday net debit tends to be larger than the average value of a single payment. In fact, participants often tap intraday credit to cover this amount initially.[19] The constraints of funds balances and net debit position become less binding on the settlement behavior of participants as the hub immediately after the system opening. As payments from the hub proceed, so do payments system-wide because of payment recycling. The opposite is true for low-degree participants. Because of the low value of their upper bound liquidity, the constraints of funds balances and net debit position tend to be more binding on their settlement behavior immediately after the system opening when they make a relatively large-value payment. In fact, the ratio of the threshold level (1/5 of the upper bound liquidity) to the average value of a single payment is a high 6.9 for high-degree participants, but only 0.6—below unity—for low-degree participants.[20]

19. When not withdrawn at the start, net debit is reduced through funding after 9:00.

20. Because low-degree participants do not need to raise a large amount of settlement funds, it follows that their upper bound liquidity can be lower, implying that when necessary they have plenty of scope to access new intraday credit or other sources of funding. We assume here no outside sources of additional funding even under stress conditions, although a resort to outside funding is likely in the real world.

Figure 10 High-Degree Participants' Receipt-Driven Payments



Note: A threshold level of $1/5$ of each participant's upper bound liquidity is applied to all participants in scenario (4), only to high-degree participants in scenario (5), and only to low-degree participants (all but high-degree participants) in scenario (6).

Finally, we check how the surplus funds held by high-degree participants could alleviate the settlement delay in the entire system.

Receipt-driven payments by high-degree participants are shown in Figure 10 for simulations (1) through (6). When planned settlement time t arrives, if the balance of receipts from the counterparties, $B_{i,t-1}$, is large enough, the outgoing payment, $P_{i,t}$, is funded by the balance of receipts from the counterparties. Then, a receipt-driven payment $P_{i,t}^{IP}$ is given by

$$P_{i,t}^{IP} = \begin{cases} 0 & \text{if } P_{i,t} > B_{i,t-1}, \\ P_{i,t} & \text{if } P_{i,t} \leq B_{i,t-1}, \end{cases} \quad \text{where } B_{i,t-1} = \sum_{s=0}^{t-1} (R_{i,s} - P_{i,s}^{IP}). \qquad (4)$$

It is noted that $P_{i,t}^{IP}$ does not mean a payment driven by a simultaneous receipt $R_{i,t}$.

If the threshold is lowered from (1) to (3), the fraction of receipt-driven payments increases, but if the threshold is changed from (3) to (4), the fraction of receipt-driven payments declines substantially. The result suggests one possible reason why the mechanism to mitigate the contagion of settlement delay does not work well enough in scenario (4) as in Figure 8. It seems that high-degree participants become unable to make receipt-driven payments in scenario (4). Conversely, as in scenario (3), if the contribution from receipt-driven payments is high, settlement delays can be largely improved. To keep settlement delays to a minimum in FIFO settlement system, it is important to settle large-value payments without any queuing at all. By definition, a severe threshold level as in scenario (4) increases the contribution from receipt-driven payments, but once the threshold exceeds a certain level, it becomes difficult to execute large-value payments without significant delay. Consequently, the contribution from receipt-driven payments also declines.

VI. Conclusion

We investigated the intraday flow of funds among participants in BOJ-NET using large-scale records of payments.

Settlements in BOJ-NET under full-fledged RTGS are intricately linked to a variety of systems, including the reserve requirements and the intraday overdraft facility. They are also significantly affected by market practices. These systems have built-in mechanisms to prevent the spread of settlement delays caused by participants' payment recycling, such as receipt-driven payments. One of them, the repayment-first rule, causes payments to agglomerate immediately after the system opening, and is not used in the RTGS systems of the major economies other than Japan.

Time-heterogeneous intraday settlement activity causes the shape of the payment network to vary through the day, which implies that the degree of payment recycling also varies through the day. To understand the time-variable nature of the payment network structure and its complex interconnectedness, we ran simulations under stress conditions, and found the following: (1) during the time of the day when payment recycling is active, particularly immediately after the system opening, it becomes easy for settlement delays to spread widely, therefore resulting in the gridlock of funds flow; and (2) participants functioning as the hub of the payment network are able, owing in part to their relatively high level of liquidity, to absorb and limit the contagion of settlement delays.

Acceptance of some settlement delays may also have the effect of moderating the funding pressure in the morning and stabilizing the money market rates. Behind the merit, it may accompany the repercussion that it could enlarge intraday unsettled exposure due to settlement delay. There are a number of conceivable ways to deal with the trade-off between stabilizing the intraday developments in the interest rates and minimizing intraday exposures.

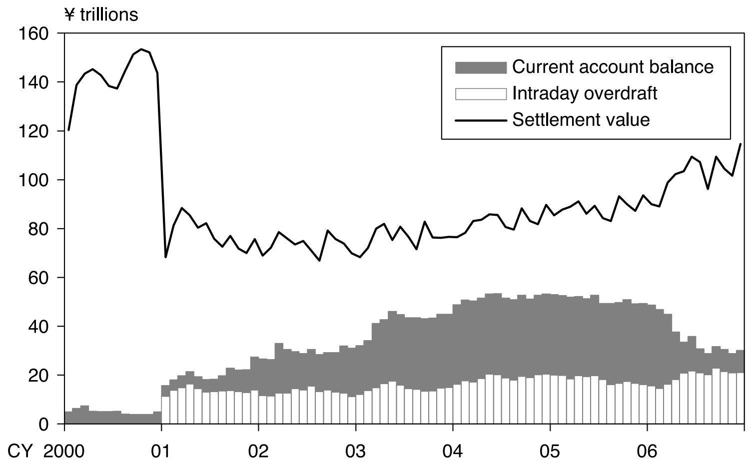
One is to exogenously reform the shape of the payment network by either selecting or tiering participants. As a matter of course, it is difficult to *a priori* specify the desirable network structure. Even if this could be done, it would be difficult to determine whether such a network shape were desirable from a social welfare perspective in terms of efficiency, safety, and convenience. Nevertheless, it is meaningful to examine a desirable payment network with consideration on positive and negative sides of payment recycling. For example, it may be possible to achieve a more efficient flow of intraday funds by further concentrating payments into participants functioning as the hub. This may hold down intraday exposures while stabilizing the intraday fluctuations in the interest rates caused by the demand for settlement funds.

Possibly a more realistic action would be to implement a supplementary facility to improve the trade-off. For example, the liquidity-saving features with offsetting mechanism implemented within BOJ-NET RTGS in 2008 are attempts to efficiently use the system liquidity while simultaneously achieving early settlement.[21] With these liquidity-saving features, payments that meet certain conditions would be settled even under settlement gridlock, making it possible to hold down participants' upper bound liquidity. This in turn would alleviate the early-morning upward pressure on the interest rates caused by the demand for settlement funds, while maintaining the same settlement pace as under RTGS with the repayment-first rule and the one-hour rule.

APPENDIX: BOJ-NET FUNDS TRANSFERS

Excluding a large decline caused by conversion to full-fledged RTGS in 2001, the daily average value settled under BOJ-NET has followed a moderate growth path, in step with the increase in settlements of Japanese government securities (JGS) repos and other transactions (Appendix Figure 1). Average annualized growth was 6 percent from 2001, when daily settlements averaged ¥77 trillion, to 2006, when they averaged ¥102 trillion. The level of liquidity available for settlements fluctuated widely during this period. The intraday overdraft facility, which was introduced with the conversion to RTGS, made

Appendix Figure 1 BOJ-NET Funds Transfers, Current Account Balances, and Intraday Overdrafts

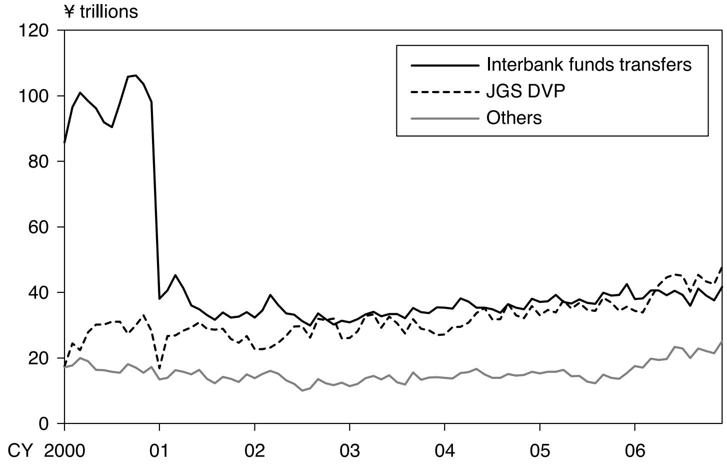


Note: Settlement value is the monthly average value settled under BOJ-NET, the current account balance is the average balance during the reserve maintenance period, and the intraday overdraft is the monthly average of daily peak amount used.

Source: Bank of Japan.

21. The next-generation RTGS project is built on two steps: (1) introducing liquidity-saving features to BOJ-NET RTGS; and (2) incorporating large-value payments currently handled by two private-sector DNS systems (the foreign exchange yen clearing system and the domestic retail credit transfer system) into the new RTGS with liquidity-saving features (Bank of Japan [2006]).

Appendix Figure 2 BOJ-NET Funds Transfers by Type of Transaction



Note: Interbank funds transfers are primarily for the settlement of call money transactions, JGS DVP is the cash legs of DVP for JGSs, and others include the cash legs of DVP for non-JGSs, the final settlement of net positions, and the settlement of transactions with the BOJ.

Source: Bank of Japan.

about ¥10–20 trillion of intraday liquidity available for RTGS. In addition, the level of balances kept in current accounts held at the BOJ was stepped up in accordance with the quantitative monetary easing policy, temporarily climbing above ¥30 trillion. Because current account balances declined sharply after the end of the quantitative easing, the ¥115 trillion of payments was settled with intraday overdrafts of ¥21 trillion and current account balances of ¥9 trillion at the end of 2006.

The value settled under BOJ-NET can be broadly categorized as interbank funds transfers, mostly call loans, the cash legs of securities settlements including JGS delivery-versus-payment (DVP), some DNSs of net positions including the domestic retail credit transfers, and transactions between participants and the BOJ (Bank of Japan [2007b]). The interbank funds transfers accounted for roughly one-third of all payments settled through BOJ-NET at the end of 2006, and thus are important for their overall size as well as because they represent the call money transactions for the final leg of funding transactions.

The conversion to RTGS was accompanied by a substantial decline in the interbank funds transfers, as evident from data showing the breakdown of BOJ-NET funds transfers (Appendix Figure 2). Prior to the introduction of BOJ-NET in 1988, participating financial institutions were in the practice of consolidating multiple payments to and from *tanshi* companies (money market brokers), and drawing a single check to present to the BOJ, to avoid the operational hassle of presenting a check to the BOJ for every transaction. Partly out of a reluctance to change, settlements of the transactions through *tanshi* companies' broking in BOJ-NET prior to the conversion to RTGS were done in two stages, passing through *tanshi* companies' current account with the BOJ, with the funds passing from the lender of funds to the *tanshi* companies and then to the borrower of funds. This system made the settlement value in BOJ-NET double the value of transactions. At the conversion to RTGS in 2001, direct settlement between the lender and borrower with bypass of the *tanshi* companies was introduced, which essentially cut the value of funds transfers in half.

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