Interlinkages between Payment and Securities Settlement Systems*

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Abstract

Payments systems involve a number of interconnected systems. These typically have at the center a large-value payment system (in many cases operated by a central bank) through which banks send funds to each other for various purposes. Of fundamental interest to central banks are the interlinkages among these types of systems. This paper builds on Mills and Nesmith (2008) to construct a relatively simple economic framework to begin to understand some of the different linkages of such systems with particular emphasis on the impact various disruptions may have. It looks at three alternative arrangements through which a funds transfer system and securities settlement system are linked. Each arrangement differs by the way the securities settlement system is designed. The main finding is that, although the different arrangements have different possible implications during a settlement shock ex ante, the equilibrium behavior

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of banks leads to the arrangements having similar implications ex post.
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1 Introduction

Payments systems involve a number of interconnected systems. These typically have at the center a large-value payment system (in many cases operated by a central bank) through which banks send funds to each other for various purposes. Some of these purposes include providing liquidity to complete transactions in any number of ancillary systems, such as other large value funds transfer systems, retail payment networks, securities settlement systems, and foreign exchange settlement systems. Of fundamental interest to central banks are the interlinkages among these types of systems. In particular, it is important to understand how disruptions in one system may affect the functioning of other systems. This paper provides a relatively simple economic framework to begin to understand some of the different linkages of such systems with particular emphasis on the impact various disruptions may have. The model can then be used to study implications for the timing of payment and securities settlement systems, the concentration of transactions and the impact on operational and systemic risk.

The model follows the literature of Bech and Garratt (2003) who formulated a simple game-theoretic model to compare alternative central bank credit policies and their impact on the timing and concentration of payments in a payments system. Mills and Nesmith (2008) extend that framework to securities settlement systems and use the model to explain a number of stylized facts about banks' responses to the introduction of and subsequent increase in the price of intraday overdrafts for the Federal Reserve's payment and securities settlement system, Fedwire. In that model, the payment and securities settlement systems were treated in isolation.

The model for this paper is a synthesized version of both the payment system and the securities settlement system as presented in Mills and Nesmith (2008). This allows for a relationship between the use of a funds transfer and securities settlement system for a banks' decision regarding when to send payments and securities transactions. The model follows Mills and Nesmith (2008) in that three factors are important in driving bank balances and behavior on the timing of payments: the cost of intraday liquidity, settlement risk, and the design of the systems.

This paper looks at three alternative arrangements through which a funds transfer system and securities settlement system are linked. The first arrangement is one in which the central bank operates both the funds and securities settlement systems. This allows the participating banks to use the same account for both funds and securities transactions. Each transaction is settled in real-time on a gross basis. This arrangement is a generalized version of the funds and securities models of Mills and Nesmith (2008). The second arrangement is one in which the central bank operates the funds system, but that a separate entity operates the securities settlement system. Although separate, the two systems are linked in such a way that securities transactions in the securities settlement system initiate a corresponding funds transfer in real time. The third arrangement is one in which the central bank operates the funds system, a separate entity operates the securities settlement system, and the securities settlement system nets the funds needed to complete securities transactions.

Our analysis shows that while there are some notable differences among the three systems, the equilibrium behavior of the banks suggest that there is little difference among the them. Without considering equilibrium behavior, the case where the central bank operates both systems through one account, a disruption necessarily impacts both funds and securities transactions that have not been settled before the disruption. In the case where the two systems are separate, but that the securities settlement system has securities settled on a gross basis, a shock in the securities settlement system is less disruptive than a shock to the funds transfer system. Crucial to this is the fact that the funds leg of securities settlement must go through the funds transfer system at the same time the securities settle in the securities settlement system. In the net securities settlement case, the fact that funds related to securities transactions net and settle at the end of the day mean there is a more targeted impact when one of the systems is disrupted.

However, when equilibrium behavior is considered, the timing strategies for sending payments and securities are the same across systems, as are the expected size of overdrafts. This suggests that strategic behavior is an important consideration in evaluating the severity of interconnectedness across systems and their impact on systemic risk.

The paper is organized as follows. Section 2 presents the model environment. Section 3 provides the notation that is more or less uniform for the three alternative arrangements. Sections 4, 5 and 6 present each alternative arrangement separately. Section 7 provides a summary comparison of the alternative arrangements. Section 8 concludes.

2 The Model

The model is a combined version of the funds and securities models in Mills and Nesmith (2008). There are three periods denoted $t = 1, 2, 3$ which can be interpreted as morning, afternoon and overnight, respectively. There are two agents called banks, indexed by $i \in \{1, 2\}$, whose objective is to minimize the expected cost of sending both funds and securities to one another.

In addition to the banks, there are two institutions. The first is a central bank that operates a funds transfer system over which the banks may send funds to one another.[1] The second is a securities settlement system over which the banks may send securities transfers. The two systems are linked (at a minimum) by the fact that funds required to settle securities are sent via the funds system. Each bank has an account with both systems. We consider the operation and design of the securities settlement system in more detail below.

At the beginning of period 1, banks know their payment and securities instructions for the day. However, they only have limited information about what they expect to receive. Banks know whether or not they expect to receive securities, but only know the probability of receiving funds. This captures the fact that banks can anticipate flows of securities and the coinciding funds more accurately than the more general flow of payments. Securities trades occur a few days before the actual settlement of those trades, whereas many funds instructions are received the same day they are expected to settle.

Specifically, bank $i \in \{1, 2\}$ knows that with probability p it will receive a funds transfer from bank $j \neq i$ valued at F dollars. The probability of receiving funds is i.i.d. between banks. Bank $i \in \{1, 2\}$ also knows with probability 1 whether it expects to receive securities valued at S dollars from bank $j \neq i$. It is assumed that $S > F$ to represent the fact that average securities transfers are typically higher than average funds transfers. There are six possible types of banks. A bank that expects to receive securities may need to send funds only, securities only, or both funds and securities. Likewise, a bank that expects not to receive securities may need to send funds only, securities only, or both funds and

[1] There is nothing in the model that suggests that these payment services should be provided by a central bank instead of a private clearinghouse. However, in practice, most central banks provide at least one critical payment system to which ancillary systems are connected.

securities. Because the most general case is when a bank expects to receive securities and must send both funds and securities, in what follows we assume that both banks expect to receive securities.

Once a bank knows its set of funds and securities settlement instructions, it then decides which instructions, if any, to carry out in the morning (period 1) and which to delay until the afternoon (period 2). It is assumed that banks do not strategically delay transfers until the overnight period (period 3). Thus, a bank that sends both funds and securities decides whether to send both in the morning, both in the afternoon, securities in the morning and funds in the afternoon, or funds in the morning and securities in the afternoon. As discussed in Mills and Nesmith (2008), three factors influence the timing of transactions: the cost of intraday liquidity, the extent of settlement risk and the overall design of the systems. We now describe each of these in turn.

2.1 Cost of Intraday Liquidity

The banks are able to access intraday liquidity from the central bank by overdrawing their account. Formally, banks can overdraw on their central bank accounts to settle transactions at a fee $r \geq 0$ for each period $t \in \{1, 2\}$ in which their account is in overdraft status. An account is in overdraft status whenever it has a negative funds balance at the end of a period. If a bank's account is in overdraft status at the end of period 2, it must borrow funds in the overnight market at interest rate $R > r$ to return to a zero balance. The assumption that the overnight interest rate R is greater than the price for intraday overdrafts r is consistent with the historical relationship between many central banks' price for intraday overdrafts and the target overnight rate, and serves as an upper bound on the policy choice of r.[2]

[2] Indeed, many central banks have $r = 0$. It should be noted that during the recent financial crisis, the U.S. target rate has at certain times been below the rate for intraday overdrafts. Our view is that such an arrangement is temporary, but worth further study that

Central banks may also require collateral for a bank to overdraw on its account. Collateral may carry an opportunity cost to pledge but is typically a sunk cost that is pledged up front at the beginning of the day. Because it is sunk, it will not have a strategic impact on the timing of settlement and we ignore it.[3]

2.2 Settlement Shocks

In addition to the cost of intraday liquidity, the banks also consider settlement risk. At the beginning of period 2, a bank may receive a settlement shock. With a small probability $\epsilon_f > 0$, bank i cannot receive a funds payment from bank j during period 2, but will receive it in period 3. With a small probability $\epsilon_s > 0$, bank i cannot receive a securities transaction from bank j during period 2, but will receive it in period 3. The realization of the settlement shocks are independent across banks and systems. Moreover, the realization of the settlement shocks is common information among the banks, but the realization of whether a bank is to receive a payment from the affected bank remains private. Thus if a bank finds out that it cannot receive a payment from the other bank, it can delay any outstanding payments that must be sent to the affected bank until the overnight period (period 3).

As in Mills and Nesmith (2008), the settlement shock represents a certain type of settlement risk to the receiving bank—defined as the risk that a payment is not sent by the expected time, in this case by the end of the intraday period. Such a shock could occur, for example, when the sending bank has an operational disruption or has a lack of available liquidity to send a payment at a particular point in time. This

goes beyond the scope of this paper. Also, one notable exception to this set-up is the Reserve Bank of New Zealand which does not permit overdrafts but pays interest on banks' reserves at the central bank equal to the target overnight rate. See Nield (2006).

[3] Collateral is not always modeld as a sunk cost. See for example, Bech and Garratt (2003) where the fact that collateral is not a sunk cost is an important feature of their comparison of central bank intraday credit policies.

restricts a receiving bank's incoming source of liquidity that could offset outgoing payments and reduce their own costs of sending payments. The settlement shock can be thought of as a proxy for uncertainty regarding incoming funds to offset outgoing funds. More severe types of settlement shocks, such as those arising from insolvency, would have the effect of strengthening this cost.

2.3 Alternative Designs of the Securities Settlement System

Finally, we consider three alternative system designs. In each of the designs, the central bank operated payment system is a real-time gross settlement (RTGS) system where funds transactions are made one at a time with finality. Further, securities transactions settle individually on a delivery-versus-payment (DVP) basis. What differentiates the alternatives are the way in which the funds system and the securities settlement system are linked, and the specific nature of the DVP design of the securities settlement system.

The funds and securities settlement systems can be linked in one of two ways. The first way has the central bank operating both types of systems. In this way, banks essentially use one account for both types of transactions. An example of such a model is Fedwire Funds and Securities in the U.S. The second way has the securities settlement system operated by another institution.

We also consider two types of DVP design.[4] In the first design, consistent with Fedwire Securities in the U.S. and CREST in the U.K., the securities and funds are exchanged between counterparties simultaneously with finality. Such a design is sometimes referred to as DVP Model 1. In the second design, consistent with DTC in the U.S., securities transfers

[4] See Committe on Payment and Settlement Systems (1992). There is also a DVP Model 3, in which there are cumulative account balances for both funds and securities. The mechanics for such a model are the same as the DVP Model 2 for this paper.

are exchanged in real time with finality, but the net balance of funds related to securities are exchanged at system-designated times, which in our model occur at the end of period 2. This design is sometimes referred to as DVP Model 2.

3 Notation

Before proceeding to each specific arrangement in the sections that follow, we set up some common notation. Recall that the objective of a participating bank is to minimize the expected cost of sending both funds and securities across the overall payment system. A bank's strategy is based on when to send a particular transaction. In this paper we only consider pure strategies. It will be convenient to think about a bank's strategy in terms of its decision to send funds or securities in the morning. Let $\sigma_i^f \in \{0,1\}$ denote the strategy of bank i to send a funds payment in the morning where if $\sigma_i^f = 1$ the bank sends funds in the morning (period 1), and if $\sigma_i^f = 0$ then the bank sends funds in the afternoon (period 2). Similarly, let $\sigma_i^s \in \{0,1\}$ denote the strategy of bank i to send securities where 1 and 0 represent morning and afternoon, respectively. Then, the set of possible pure strategies for bank i is $\Sigma_i = (\sigma_i^f, \sigma_i^s) \in \{(1,1),(1,0),(0,1),(0,0)\}$.

We are interested in how a bank's funds balances are affected by the different combinations of strategies, as well as different states of the world regarding settlement shocks. In general there are four states of the world regarding settlement shocks. The first state is when there are no settlement shocks at all and occurs with probability $(1-\epsilon_s)(1-\epsilon_f)$. The second is when there is a settlement shock in the securities settlement system but not in the funds settlement system and occurs with probability $\epsilon_s(1-\epsilon_f)$. The third is when there is a settlement shock in the funds settlement system but not in the securities settlement system and occurs with probability $(1-\epsilon_s)\epsilon_f$. The fourth is when there is a settlement shock in both systems and occurs with probability $\epsilon_s \epsilon_f$.

Let $\delta_s \in \{0, 1\}$ denote the occurrence of a settlement shock in the securities settlement system where $\delta_s = 0$ indicates that no shock was realized, while $\delta_s = 1$ indicates that a shock was realized. Let $\delta_f \in \{0, 1\}$ denote the occurrence of a settlement shock in the funds settlement system with a similar interpretation. Then we can denote the three balances for bank i that are relevant for discussion: end of morning balances, $m_i(\Sigma_i, \Sigma_j)$, end of afternoon balances, $a_i(\Sigma_i, \Sigma_j, \delta_s, \delta_f)$, and overnight balances, $o_i(\Sigma_i, \Sigma_j, \delta_s, \delta_f)$. Note that the morning balances are independent of the realizations of the settlement shock because they are determined before the shock is realized. The afternoon and overnight balances, however, do depend on the realization of the settlement shocks.

Finally, the realized cost of sending both funds and securities is a function of a banks own strategy Σ_i, and the timing strategy of the other bank Σ_j, the realization of settlement shocks, and the cost of intraday and overnight liquidity as determined by central bank policy. Let $c(\Sigma_i, \Sigma_j, \delta_s, \delta_f)$ denote bank i's realized cost of sending both funds and securities when it plays the strategy Σ_i while bank j plays the strategy Σ_j and the realizations of the settlement shocks are δ_s in the securities settlement system and δ_f in the funds settlement system. The expected cost at the beginning of the day, therefore is

$$\begin{aligned} c(\Sigma_i, \Sigma_j) \quad = \quad & (1 - \epsilon_s)(1 - \epsilon_f) c(\Sigma_i, \Sigma_j, 0, 0) + \epsilon_s (1 - \epsilon_f) c(\Sigma_i, \Sigma_j, 1, 0) \\ & + (1 - \epsilon_s) \epsilon_f c(\Sigma_i, \Sigma_j, 0, 1) + \epsilon_s \epsilon_f c(\Sigma_i, \Sigma_j, 1, 1). \end{aligned}$$

Of course, the central bank's policy for providing intraday liquidity will impact the expected cost to the banks. There are two policy parameters in the model: the choice of an overdraft fee, and whether or not collateral is required.

4 Central Bank Operated DVP 1 Securities Settlement System

This section focuses on a payments system where both the funds and securities settlement are operated by a central bank. Each participating bank has one central account through which funds and securities are settled.

Because there is only one system, there is no need to distinguish between a settlement shock in a securities settlement system and one in a funds transfer system. In terms of the notation, δ_s and δ_f are perfectly correlated such that $\delta_s = 1$ if and only if $\delta_f = 1$ and $\delta_s = 0$ if and only if $\delta_f = 0$. Thus, there are only two possible outcomes in the afternoon instead of four. For simplicity, we denote the probability of a settlement shock by ϵ so that the probability of no shock is $1 - \epsilon$.

4.1 Balances

First, consider the morning period. Because the settlement shock does not affect end of morning balances, we only distinguish between bank j's receipt or not of a payment instruction. The expected end of morning balance for bank i, is

$$m_i(\Sigma_i, \Sigma_j) = (\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F. \quad (1)$$

The first term in (1) represents the net inflow of funds related to securities transactions. Bank i receives S in funds if it sends securities in the morning (i.e. $\sigma_i^s = 1$) and sends S in funds to bank j if bank j sent securities in the morning (i.e. $\sigma_j^s = 1$). The second term represents the net expected outflow of funds related to funds transactions If bank i sends funds ($\sigma_i^f = 1$) then its central bank account is reduced by F. If bank j's strategy is to sends funds in the morning ($\sigma_j^f = 1$) then bank i will receive an incoming transfer of F with probability p.

Next, consider the afternoon period. Bank i's end of afternoon balance is

$$a_i(\Sigma_i, \Sigma_j, 0, 0) = -(1-p)F \tag{2}$$

when there is no settlement shock. This occurs with probability $1-\epsilon$ and all transactions are completed. If bank j received a payment instruction, all securities and funds offset each other. Otherwise, only securities offset and bank i ends the afternoon with a negative balance.

Bank i's end of afternoon balance is

$$a_i(\Sigma_i, \Sigma_j, 1, 1) = m_i(\Sigma_i, \Sigma_j) \tag{3}$$

when there is a settlement shock. This occurs with probability ϵ, and bank i is unable to send or receive funds and securities. Thus, its balances are unchanged from the morning so (3) is just (1).

Finally, in the overnight period, any transactions that were not able to be completed during the day are sent. However, it is not possible to offset funds or securities payments. The implication of this is that any negative account balance must return to zero via an overnight loan. We are interested in bank i's expected overnight balance before it receives any overnight transactions from bank j. This balance is

$$o_i(\Sigma_i, \Sigma_j, 0, 0) = -(1-p)F \tag{4}$$

when there is no settlement shock. In this case, overnight balances are simply the end of afternoon balances.

Equation (4) is just (2). The overnight balance when there is a settlement shock is

$$o_i(\Sigma_i, \Sigma_j, 1, 1) = m_i(\Sigma_i, \Sigma_j) - (1-\sigma_j^s)S - (1-\sigma_i^f)F. \tag{5}$$

Equation (5) reflects the fact that, in the event of a settlement shock, bank

i completes its outgoing transactions that were affected by the shock that involve a decrease in funds. These were funds transactions that were scheduled to be sent in the afternoon period and any receipt of securities (and withdrawal of funds) from bank j. What bank i is not able to include are any incoming transactions from bank j that increase its funds account balance and may have been affected.

4.2 Cost

We can now derive bank i's expected cost of sending both funds and securities. Recall that this cost is a function of a banks own timing strategy Σ_i, and the timing strategy of the other bank Σ_j, the realization of settlement shocks, and the cost of intraday and overnight liquidity as determined by central bank policy. We can express this expected cost as

$$\begin{aligned} c(\Sigma_i, \Sigma_j) &= \max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\ &+(1-\epsilon)\max\{-a_i(\Sigma_i, \Sigma_j, 0, 0), 0\}r \\ &+\epsilon\max\{-a_i(\Sigma_i, \Sigma_j, 1, 1), 0\}r \\ &+(1-\epsilon)\max\{-o_i(\Sigma_i, \Sigma_j, 0, 0), 0\}R \\ &+\epsilon\max\{-o_i(\Sigma_i, \Sigma_j, 1, 1), 0\}R. \end{aligned} \tag{6}$$

Equation (6) is essentially made up of three parts corresponding to the three periods. The expected cost in each period then is determined by whether or not the end-of-period balance is expected to be negative. If the expected balance is negative, the appropriate fee is charged. If the balance is nonnegative, then the fee is zero. Using (1) - (5) we can express

(6) as:

$$\begin{aligned} c(\Sigma_i, \Sigma_j) &= \max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\ &+(1-\epsilon)(1-p)Fr \\ &+\epsilon \max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\ &+(1-\epsilon)(1-p)FR \\ &+\epsilon \max\{(1-\sigma_i^s)S + (1-\sigma_j^f p)F, 0\}R. \end{aligned} \tag{7}$$

4.3 Equilibrium

We now solve for the equilibria of the payment coordination game. To do so, we shall eliminate weakly dominated strategies. We begin with the following lemma, which states that the expected morning balance for bank i is maximized when it sends securities in the morning, but delays funds in the afternoon.

Lemma 1 *$m_i[(0,1), \Sigma_j] > m_i[\Sigma_i, \Sigma_j]$ for all $\Sigma_i \neq (0,1)$ and all Σ_j. Moreover, $m_i[(0,1), \Sigma_j] \geq 0$ for all Σ_j.*

Proof. From (1), we have

$$\begin{aligned} m_i[(0,1), \Sigma_j] &= (1-\sigma_j^s)S + \sigma_j^f pF \\ m_i[(0,0), \Sigma_j] &= -\sigma_j^s S + \sigma_j^f pF \\ m_i[(1,0), \Sigma_j] &= -\sigma_j^s S - (1-\sigma_j^f p)F \\ m_i[(1,1), \Sigma_j] &= (1-\sigma_j^s)S - (1-\sigma_j^f p)F. \end{aligned}$$

As a result,

$$\begin{aligned} m_i[(0,1), \Sigma_j] - m_i[(0,0), \Sigma_j] &= S > 0 \\ m_i[(0,1), \Sigma_j] - m_i[(1,0), \Sigma_j] &= S + F > 0 \\ m_i[(0,1), \Sigma_j] - m_i[(1,1), \Sigma_j] &= F > 0. \end{aligned}$$

Finally, $m_i[(0,1),\Sigma_j] = 0$ when $\Sigma_j = (0,1)$. It is positive for any other Σ_j. ■

Lemma 1 states that sending securities in the morning and delaying funds in the afternoon will guarantee that bank i does not incur an overdraft charge in the morning.period. By playing this strategy, bank i will also avoid an overdraft in the afternoon period in the event of a disruption (the third term on the right-hand side of equation (7)). Moreover, because $m_i[(0,1),\Sigma_j] > m_i[\Sigma_i,\Sigma_j]$ for all $\Sigma_i \neq (0,1)$, no other strategy can guarantee that bank i avoids an overdraft charge in the morning period (and afternoon period during a disruption).

Bank i does expect to pay a fee in both the afternoon and overnight period whenever there is not a disruption (the second and fourth terms on the right-hand side of equation (7)), but those fees are independent of both banks' strategies. All that remains is the expected overnight cost in the event of a disruption (the final term on the right-hand side of equation (7)). For that term, we have the following lemma.

Lemma 2 *$o_i(\Sigma_i,\Sigma_j,1,1)$ is maximized for strategies $\Sigma_i = (0,1)$ and $\Sigma_i = (1,1)$.*

Proof. Because $o_i(\Sigma_i,\Sigma_j,1,1) = -(1-\sigma_i^s)S-(1-\sigma_j^f p)F$ depends only on bank i's decision to send securities and bank j's decision to send funds, it is obvious that bank i maximizes its expected overnight balance by choosing $\sigma_i^s = 1$. ■

An implication of Lemma 2 is that $\Sigma_i = (0,1)$ is one of the strategies that maximizes overnight balances and so minimizes the expected cost of the overnight period. Combine this with the fact that $\Sigma_i = (0,1)$ is the only strategy that also maximizes the morning and afternoon balances, and the symmetry of the two banks, we have proved the following main result.

Proposition 1 *For any $\epsilon > 0$, and $r, R > 0$, the strategy profile $(\Sigma_i,\Sigma_j) =$*

$\{(0,1),(0,1)\}$ *is the unique equilibrium via elimination of dominated strategies.*

An implication of Proposition 1 is that securities transactions occur early but funds transactions occur late. This is what is observed in Fedwire as documented in Mills and Nesmith (2008). Indeed, Proposition 1 is a generalization of the results of Mills and Nesmith (2008).

Another implication of Proposition 1 is that a disruption would impact funds transactions more than securities transactions. The late settlement of funds has been known to be of policy concern to central banks because of the increased impact of operational disruptions.[5] Finally, central banks are also concerned with their exposure to credit risk in the form of intraday overdrafts. Here expected intraday overdrafts associated with securities transactions is zero because banks are sending securities in the morning and offsetting each other quickly. This offsetting also applies to funds transactions in the afternoon, but because there is more uncertainty about whether or not banks send payments, expected overdrafts are just $p(1-p)F$ which is the probablilty that one bank sends a payment but the other does not and so offsetting cannot occur.

5 Privately Operated DVP 1 Securities Settlement System

This section focuses on a payments system where the funds transfer system is operated by a central bank, but the securities settlement is privately operated. The key distinction between this payment arrangement and that of the previous section, is that there are two separate systems. The way the arrangement works is as follows. Each bank has an account in both systems. The securities settlement system keeps track of each

[5] Reference needed here.

bank's balance of securities, while the funds system keeps track of funds balances at the central bank. The DVP 1 nature of the securities system implies that each securities transaction that is completed on the securities settlement system initiates a coinciding transaction for funds in the funds system at the central bank accounts. Thus, a bank's account at the securities settlement system is effectively only for securities. Funds are not explicitly transferred from one system to the other. Because we are primarily interested in funds balances, and those are only at the central bank, we only need to keep track of banks' account balances at the central bank.

The main notable difference between this arrangement and that of the previous section is that the two separate types of settlement shocks are now appropriate.

5.1 Balances

First, consider the morning period. Because the settlement shocks do not affect end of morning balances, we only distinguish between bank j's receipt or not of a payment instruction. Bank i's end of morning balance at the central bank, denoted by $m_i(\Sigma_i, \Sigma_j)$, is

$$m_i(\Sigma_i, \Sigma_j) = (\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F. \tag{8}$$

Note that this is the same equation as (1) from the previous arrangement and has the same interpretations.

Next, consider the afternoon period. In the event that there is no settlement shock in either system (which occurs with probability $(1 - \epsilon_s)(1 - \epsilon_f)$), bank i's end of afternoon balance is

$$a_i(\Sigma_i, \Sigma_j, 0, 0) = -(1 - p)F. \tag{9}$$

As in the previous arrangement, everything settles and a bank's expected end of afternoon balance is determined by whether or not bank j receives a payment instruction, and (9) is just (2).

In the event that there is a settlement shock in the securities settlement system but not the funds system (which occurs with probability $\epsilon_s(1-\epsilon_f)$, bank i's end of afternoon balance is

$$a_i(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - \sigma_j^s)S - (1-p)F. \tag{10}$$

Equation (10) reflects the fact that if there are no securities transactions in the afternoon, funds transactions are unaffected, but the portion of the afternoon balances related to securities settlement are only those that were sent in the morning.

In the event that there is a settlement shock in the funds system regardless of whether or not there is a settlement shock in the securities settlement system (which occurs with probability ϵ_f), bank i's end of afternoon balance is

$$a_i(\Sigma_i, \Sigma_j, \delta_s, 1) = m_i(\Sigma_i, \Sigma_j). \tag{11}$$

Note that a settlement shock in the funds system affects the settlement not only of funds transactions, but also the funds related to securities transactions. This is because of the DVP 1 nature of the arrangement. Securities cannot settle without the funds being transferred even if there is no settlement shock to the securities settlement system. Thus, end of afternoon balances in this state of the world are just end of morning balances and (11) compares with (3) from the previous section.

Finally, consider the overnight period where any transactions that were not able to be completed during the day are sent. For the event that there is no settlement shock in either system (which occurs with probability

$(1-\epsilon_s)(1-\epsilon_f)$), bank i's overnight balance is simply the afternoon balance:

$$o_i(\Sigma_i, \Sigma_j, 0, 0) = -(1-p)F \tag{12}$$

and is similar to (4) from the previous section. For the case where there is a settlement shock in the securities settlement system but not the funds system (which occurs with probability $\epsilon_s(1-\epsilon_f)$), bank i's overnight balance is

$$o_i(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - \sigma_j^s)S - (1-p)F - (1-\sigma_j^s)S \tag{13}$$

which is just the afternoon balance in such a scenario minus any funds sent to complete an affected securities transaction. Note that (10) does not have a counterpart in the pervious arrangement.

For the case where there is a settlement shock in the funds system (which occurs with probability ϵ_f), bank i's end of afternoon balance is

$$o_i(\Sigma_i, \Sigma_j) = m_i(\Sigma_i, \Sigma_j) - (1-\sigma_j^s)S - (1-\sigma_i^f)F \tag{14}$$

which is the afternoon balance in such a scenario minus any funds sent to complete any affected transactions which include both securities and funds settlement. Note that (14) is (5) from the previous section.

5.2 Cost

We can now derive bank i's expected cost of sending both funds and securities. Recall that this cost is a function of a banks own timing strategy Σ_i, and the timing strategy of the other bank Σ_j, the realization of settlement shocks, and the cost of intraday and overnight liquidity as determined by central bank policy. We can express this expected cost as

$$\begin{aligned}
c(\Sigma_i, \Sigma_j) &= \max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\
&+(1-\epsilon_s)(1-\epsilon_f)\max\{-a_i(\Sigma_i, \Sigma_j, 0, 0), 0\}r \\
&+\epsilon_s(1-\epsilon_f)\max\{-a_i(\Sigma_i, \Sigma_j, 1, 0), 0\}r \\
&+(1-\epsilon_s)\epsilon_f\max\{-a_i(\Sigma_i, \Sigma_j, 0, 1), 0\}r \\
&+\epsilon_s\epsilon_f\max\{-a_i(\Sigma_i, \Sigma_j, 1, 1), 0\}r \\
&+(1-\epsilon_s)(1-\epsilon_f)\max\{-o_i(\Sigma_i, \Sigma_j, 0, 0), 0\}R \\
&+\epsilon_s(1-\epsilon_f)\max\{-o_i(\Sigma_i, \Sigma_j, 1, 0), 0\}R \\
&+(1-\epsilon_s)\epsilon_f\max\{-o_i(\Sigma_i, \Sigma_j, 0, 1), 0\}R \\
&+\epsilon_s\epsilon_f\max\{-o_i(\Sigma_i, \Sigma_j, 1, 1), 0\}R. \qquad (15)
\end{aligned}$$

Equation (15) follows the logic of equation (6) but now has more terms to reflect the greater possible combinations of disruptions. The expected cost in each period then is determined by whether or not the end-of-period balance is expected to be negative. If the expected balance is negative, the appropriate fee is charged. If the balance is nonnegative, then the fee is zero. Using (8) - (14) we can simplify (15) as:

$$\begin{aligned}
c(\Sigma_i, \Sigma_j) &= \max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\
&+(1-\epsilon_s)(1-\epsilon_f)(1-p)Fr \\
&+\epsilon_s(1-\epsilon_f)\max\{(\sigma_j^s-\sigma_i^s)S+(1-p)F, 0\}r \\
&+\epsilon_f\max\{-m_i(\Sigma_i, \Sigma_j), 0\}r \\
&+(1-\epsilon_s)(1-\epsilon_f)(1-p)FR \\
&+\epsilon_s(1-\epsilon_f)\max\{(1-\sigma_i^s)S+(1-p)F, 0\}R \\
&+\epsilon_f\max\{(1-\sigma_i^s)S+(1-\sigma_j^f p)F, 0\}R. \qquad (16)
\end{aligned}$$

5.3 Equilibrium

We now solve for the equilibria of the payment coordination game. As before, we shall eliminate weakly dominated strategies. Note that Lemmas 1 and 2 still apply for the cost function (16). All that is new in (16) is

Lemma 3 $a_i(\Sigma_i, \Sigma_j, 1, 0)$ *and* $o_i(\Sigma_i, \Sigma_j, 1, 0)$ *are maximized for strategies* $\Sigma_i = (0, 1)$ *and* $\Sigma_i = (1, 1)$.

Proof. Because $a_i(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - \sigma_j^s)S - (1-p)F$ depends only on both banks' decision to send securities, it is obvious that bank i maximizes its expected afternoon balance by choosing $\sigma_i^s = 1$. Similarly, because $o_i(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - 1)S - (1-p)F$ depends only on bank i's decision to send securities, $\sigma_i^s = 1$ maximizes the expected overnight balance in this case. ■

As in the previous section, therefore, we have shown the following.

Proposition 2 *For any* $\epsilon_s, \epsilon_f > 0$*, and* $r, R > 0$*, the strategy profile* $(\Sigma_i, \Sigma_j) = \{(0, 1), (0, 1)\}$ *is the unique equilibrium via elimination of weakly dominated strategies.*

The fact that Propositions 1 and 5 are identical suggest that the timing of payment and securities settlement is independent of whether the central bank runs both systems or not. Also, the expected level of overdrafts is the same, $p(1-p)F$.

6 Privately Operated DVP 2 Securities Settlement System

This section focuses on a payments system where the funds settlement is operated by the central bank, the securities settlement system is operated privately, and the securities system is a DVP 2 system. A DVP 2 system is one that settles the securities leg of the transaction in real time, but nets the funds for one final payment.[6] The implication of this payments system is that there is a funds component to a bank's account with the operator of the securities settlement system. Thus, banks may need to send funds to the system from their central bank accounts at the end of the day. Conversely, banks may receive funds in their central bank accounts from positive end of day balances from the securities settlement system.

As a result, we need to keep track of the funds balances in both the funds settlement and securities settlement system. To do so, we amend our notation slightly to include both accounts. Specifically, bank i's end of morning, end of afternoon and overnight balances are denoted $m_i^k(\Sigma_i, \Sigma_j)$, $a_i^k(\Sigma_i, \Sigma_j, \delta_s, \delta_f)$, and $o_i^k(\Sigma_i, \Sigma_j, \delta_s, \delta_f)$, respectively, where $k \in (f, s)$ and f is for the funds settlement system and s represents the securities settlement system.

Finally, note that there are now two distinctions between the end of afternoon and overnight balances. In particular, any funds balances at the end of the afternoon in the securities settlement system are transferred to the funds account in the overnight period. The other distinction is the same as in the previous two arrangements. Overnight balances in a bank's funds account at the central bank reflect any transactions that involve outgoing funds that were not completed during the day.

6.1 Balances

First, consider the morning period. As in the previous two arrangements, the settlement shocks do not affect end of morning balances, so we only distinguish between bank j's receipt or not of a payment instruction.

[6] In a richer model, there may be opportunities or even requirements to pay in throughout the day. For simplicity, we assume that there is only one time when a pay-in may be needed, and that is at the end of the day.

Bank i's end of morning balances can be expressed as

$$m_i^f(\Sigma_i, \Sigma_j) = -(\sigma_i^f - \sigma_j^f p)F. \tag{17}$$

in bank i's funds account and

$$m_i^s(\Sigma_i, \Sigma_j) = 0 \tag{18}$$

for its securities settlement account. Equation (17) represents the net outflow of funds resulting from funds transactions that occur in the morning. Because the securities settlement system nets transactions, no funds need to be sent to that system in the morning. Therefore, the decision on when to send securities does not impact bank i's funds account at the central bank. Moreover, because no funds need to be sent, the funds balance at the securities settlement system is just zero.

Next, consider the end of afternoon and overnight balances for each state of the world. In the event that there is no settlement shock in either system bank i's end of afternoon balances are

$$a_i^f(\Sigma_i, \Sigma_j, 0, 0) = -(1-p)F \tag{19}$$

for the funds account and

$$a_i^s(\Sigma_i, \Sigma_j, 0, 0) = 0 \tag{20}$$

for the securities settlement system account. The overnight balance for bank i then is

$$o_i^f(\Sigma_i, \Sigma_j, 0, 0) = -(1-p)F. \tag{21}$$

Note that, if everything goes as intended, securities transactions perfectly net out so that each bank's securities account balance is zero at the end of the day and no transfers are made to or from it for the overnight period.

In the event that there is a settlement shock in the securities settlement system but not the funds system, bank i's end of afternoon balances are

$$a_i^f(\Sigma_i, \Sigma_j, 1, 0) = -(1-p)F \tag{22}$$

for the funds account and

$$a_i^s(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - \sigma_j^s)S \tag{23}$$

for the securities settlement account. In this case, it is possible to have a nonzero funds balance at the securities settlement system. This balance is then cleared to zero in the overnight period and moved to the funds balance. Thus, overnight balance for bank i is then

$$o_i^f(\Sigma_i, \Sigma_j, 1, 0) = (\sigma_i^s - \sigma_j^s)S - (1-p)F - (1-\sigma_j^s)S. \tag{24}$$

In the event that there is a settlement shock in the funds system but not in the securities settlement system, bank i's end of afternoon balances are

$$a_i^f(\Sigma_i, \Sigma_j, 0, 1) = -(\sigma_i^f - \sigma_j^f p)F \tag{25}$$

for the funds account and

$$a_i^s(\Sigma_i, \Sigma_j, 0, 1) = 0 \tag{26}$$

for the securities account. Equation (25) is just the end of morning balances for the funds account because no additional transactions take place. Equation (26) is a product of the fact that the securities settlement system nets transactions perfectly. Thus, there will be no transfer of funds to or from the securities settlement system in the overnight period and bank i's overnight balance is

$$o_i^f(\Sigma_i, \Sigma_j, 0, 1) = -(\sigma_i^f - \sigma_j^f p)F - (1-\sigma_i^f)F. \tag{27}$$

Finally, in the event that there is a settlement shock in both systems, bank i's end of afternoon balances are

$$a_i^f(\Sigma_i, \Sigma_j, 1, 1) = -(\sigma_i^f - \sigma_j^f p)F \tag{28}$$

for the funds account and

$$a_i^s(\Sigma_i, \Sigma_j, 1, 1) = (\sigma_i^s - \sigma_j^s)S \tag{29}$$

for the securities account. The right-hand side of equations (28) and (29) are just (25) and (23), respectively, and reflect the fact that settlement shocks in each system are independent of one another in the afternoon. In the overnight period, however, there is a possible transfer of a funds balance from the securities settlement system to the funds system, and bank i's overnight balance is

$$o_i^f(\Sigma_i, \Sigma_j, 1, 1) = (\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F - (1 - \sigma_i^f)F - (1 - \sigma_j^s)S. \tag{30}$$

6.2 Cost

We can now derive bank i's expected cost of sending both funds and securities. Recall that this cost is a function of a banks own timing strategy Σ_i, and the timing strategy of the other bank Σ_j, the realization of settlement shocks, and the cost of intraday and overnight liquidity as determined by central bank policy. We can express this expected cost as

$$\begin{aligned}
c(\Sigma_i, \Sigma_j) \quad = \quad & \max\{-m_i^f(\Sigma_i, \Sigma_j), 0\}r \\
& +(1-\epsilon_s)(1-\epsilon_f)\max\{-a_i^f(\Sigma_i, \Sigma_j, 0, 0), 0\}r \\
& +\epsilon_s(1-\epsilon_f)\max\{-a_i^f(\Sigma_i, \Sigma_j, 1, 0), 0\}r \\
& +(1-\epsilon_s)\epsilon_f\max\{-a_i^f(\Sigma_i, \Sigma_j, 0, 1), 0\}r \\
& +\epsilon_s\epsilon_f\max\{-a_i^f(\Sigma_i, \Sigma_j, 1, 1), 0\}r \\
& +(1-\epsilon_s)(1-\epsilon_f)\max\{-o_i^f(\Sigma_i, \Sigma_j, 0, 0), 0\}R \\
& +\epsilon_s(1-\epsilon_f)\max\{-o_i^f(\Sigma_i, \Sigma_j, 1, 0), 0\}R \\
& +(1-\epsilon_s)\epsilon_f\max\{-o_i^f(\Sigma_i, \Sigma_j, 0, 1), 0\}R \\
& +\epsilon_s\epsilon_f\max\{-o_i^f(\Sigma_i, \Sigma_j, 1, 1), 0\}R. \qquad (31)
\end{aligned}$$

Because the cost of intraday and overnight liquidity is determined solely by a bank's funds account balance at the central bank, only those funds balances are relevent. The expected cost in each period then is determined by whether or not the end-of-period balance of the funds account is expected to be negative. If the expected funds account balance is negative, the appropriate fee is charged. If the balance is nonnegative, then the fee is zero. Using (17) - (30) we can simplify (31) as:

$$\begin{aligned}
c(\Sigma_i, \Sigma_j) \quad = \quad & \max\{(\sigma_i^f - \sigma_j^f p)F, 0\}r \\
& +(1-\epsilon_f)(1-p)Fr \\
& +\epsilon_f\max\{(\sigma_i^f - \sigma_j^f p)F, 0\}r \\
& +(1-\epsilon_s)(1-\epsilon_f)(1-p)FR \\
& +\epsilon_s(1-\epsilon_f)\max\{(1-\sigma_i^s)S + (1-p)F, 0\}R \\
& +(1-\epsilon_s)\epsilon_f\max\{(1-\sigma_j^f p)F, 0\}R \\
& +\epsilon_s\epsilon_f\max\{(1-\sigma_i^s)S + (1-\sigma_j^f p)F, 0\}R. \qquad (32)
\end{aligned}$$

6.3 Equilibrium

We can now characterize equilibria for the payment coordination game. As before, we solve via the elimination of weakly dominated strategies. First note from equation (32) that securities only impact the overnight balances of each bank. Also note that a bank's strategy to send funds only impact morning balances, and afternoon balances if there is a disruption in the funds system. Our first result is similar to Lemma 1.

Lemma 4 $\sigma_i^f = 1$ *is a weakly dominated strategy.*

Proof. First note that σ_i^f impacts only the morning balance and the afternoon balance in the event of a funds disruption. Thus we only need to show that

$$\begin{aligned} \max\{(1-\sigma_j^f p)F, 0\}r &\geq \max\{(0-\sigma_j^f p)F, 0\}r \\ \max\{(1-\sigma_j^f p)F, 0\}r &\geq 0 \end{aligned}$$

which is satsified. ■

Our second result then pertains to σ_i^s.

Lemma 5 $\sigma_i^s = 0$ *is a weakly dominated strategy.*

Proof. The decision to send securities only impacts balances only if there is a shock to the securities settlement system as in lines 5 and 7 of equation (32). From those lines, it is easy to see that $\sigma_i^s = 1$ minimizes those balances. ■

Combining Lemmas 4 and 5 we get the following result, consistent with the other models.

Proposition 3 *For any* $\epsilon_s, \epsilon_f > 0$*, and* $r, R > 0$*, the strategy profile* $(\Sigma_i, \Sigma_j) = \{(0,1),(0,1)\}$ *is the unique equilibrium via elimination of weakly dominated strategies.*

The timing of decision for bank settlement of payments and securities, therefore, is the same over the various institutional structures. Further, the expected level of overdrafts is still $p(1-p)F$.

7 The Impact of Disruptions Across Systems

Given that the equilibria for the three types of institutional arrangements for the payment system are the same, we can now turn our attention to the impact that certain types of disruptions may have on the various systems. Table 1 summarizes balance information for each of the payment systems presented above. There are a number of similarities among the systems, but also a few important differences to point out.

First, note that when everything works well and there are no settlement shocks, the overnight balances are identical across all arrangements. The afternoon balances are nearly identical, with the DVP 2 system having two sources of funds balances instead of one.

Next, note that when there is a shock to both systems (or in the case of the central bank operated DVP 1 case, there is a shock to the only system), all three arrangements have identical overnight balances. This is the most disruptive case because it leaves both types of transactions affected regardless of the arrangement. Moreover, this state of the world leaves banks with the most negative balances overnight for which they must borrow funds at the overnight rate R. The afternoon balances for this state of the world are most pronounced for a bank in the DVP 2 arrangement. That is because the funds of the two accounts are separate and so any potential positive balance that comes from sending securities cannot be used to offset negative balances in the funds system. Thus, the DVP 2 system is, in certain situations, more costly for the banks than the other arrangements when there are multiple shocks.

The biggest differences across the three arrangements arise from the resulting balances when there is a shock to only one of the systems. For the central bank operated DVP 1 case, there is only one system and so the worst possible scenario results.

For the separate DVP 1 case, the worst possible scenario arises when there is a settlement shock in the funds system, but not as bad if there is a settlement shock in the securities system. Recall that a settlement shock to the funds system impacts both funds and securities in the separate DVP 1 case because of the close tie between the funds and the securities settlement system. This is driven by the DVP 1 nature of the securities settlement system. This impact is felt less when there is a settlement shock in the securities system for the separate DVP 1 case, because funds transactions are not affected by the settlement shock.

For the separate DVP 2 case, the fact that the two systems are separate means that a settlement shock in one system will not directly impact the other system. This is similar to the separate DVP 1 case when there is a settlement shock in the securities system, but less settlement shock than the DVP 1 case when there is a settlement shock in the funds system. Here the DVP 2 nature of the securities settlement system helps lessen the impact relative to the other systems.

Now given that the equilbirum strategies for banks in each of the payment systems is $(\Sigma_i, \Sigma_j) = \{(0,1),(0,1)\}$ we can check to see what the predicted impact of various disruptions may have in equilbirum. Table 2 shows the expected equilibrium balances at possible scenario for each of the three payment systems. As you can see, these balances are identical. So that even though there are potential differences in the balances given different disruptions, there are no realized differernces. This suggests that the design of the real-time gross settlement system is more important than that of the connected securities settlement system.

8 Conclusion

This paper provides a framework to begin to study how the interlinkages among different systems, particularly those between a real-time gross settlement large value funds transfer system and various types of securities settlement systems. The paper develops how balances are derived from the different institutional arrangements for the linkage of the two systems, and the type of settlement of the securities settlement system and notes how balances are affected under these different arrangements.

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Table 1: Comparison of Balances for the Different Payment Systems

	Central Bank DVP 1	Separate DVP 1	Separate DVP 2 (funds, securities)
Morning	$(\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F$	$(\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F$	$-(\sigma_i^f - \sigma_j^f p)F, 0$
No Shocks			
Afternoon	$-(1-p)F$	$-(1-p)F$	$-(1-p)F, 0$
Overnight	$-(1-p)F$	$-(1-p)F$	$-(1-p)F$
Shock to Securities			
Afternoon	nap	$(\sigma_i^s - \sigma_j^s)S - (1-p)F$	$-(1-p)F, (\sigma_i^s - \sigma_j^s)S$
Overnight	nap	$(\sigma_i^s - \sigma_j^s)S - (1-p)F - (1-\sigma_j^s)S$	$(\sigma_i^s - \sigma_j^s)S - (1-p)F - (1-\sigma_j^s)S$
Shock to Funds			
Afternoon	nap	$m_i(\Sigma_i, \Sigma_j)$	$-(\sigma_i^f - \sigma_j^f p)F, 0$
Overnight	nap	$m_i(\Sigma_i, \Sigma_j) - (1-\sigma_j^s)S - (1-\sigma_i^f)F$	$-(\sigma_i^f - \sigma_j^f p)F - (1-\sigma_i^f)F$
Shocks to Both			
Afternoon	$m_i(\Sigma_i, \Sigma_j)$	$m_i(\Sigma_i, \Sigma_j)$	$-(\sigma_i^f - \sigma_j^f p)F, (\sigma_i^s - \sigma_j^s)S$
Overnight	$m_i(\Sigma_i, \Sigma_j) - (1-\sigma_j^s)S - (1-\sigma_i^f)F$	$m_i(\Sigma_i, \Sigma_j) - (1-\sigma_j^s)S - (1-\sigma_i^f)F$	$(\sigma_i^s - \sigma_j^s)S - (\sigma_i^f - \sigma_j^f p)F - (1-\sigma_i^f)F - (1-\sigma_j^s)S$

Table 2: Comparison of Equilibrium Balances for the Different Payment Systems

	Central Bank DVP 1	Separate DVP 1	Separate DVP 2 (funds, securities)
Morning	0	0	$0, 0$
No Shocks			
Afternoon	$-(1-p)F$	$-(1-p)F$	$-(1-p)F, 0$
Overnight	$-(1-p)F$	$-(1-p)F$	$-(1-p)F$
Shock to Securities			
Afternoon	nap	$-(1-p)F$	$-(1-p)F, 0$
Overnight	nap	$-(1-p)F$	$-(1-p)F$
Shock to Funds			
Afternoon	nap	0	$0, 0$
Overnight	nap	$-F$	$-F$
Shocks to Both			
Afternoon	0	0	$0, 0$
Overnight	$-F$	$-F$	$-F$