Double duty and two-part tariff

Thomas Nellen*
Swiss National Bank†
Bundesplatz 1, P.O. Box, CH-3003 Bern
E-mail: thomas.nellen@snb.ch

April 4, 2012

Abstract

This paper analyses the intraday liquidity management game played in large-value payment systems. With settlement risk and free but collateralized intraday liquidity, the intraday liquidity facility's design is found to determine resulting settlement delay and the effectiveness of the two-part tariff to coordinate on early settlement. Stylised facts suggest that the opportunity cost of collateral is perceived to be fixed as a consequence of double duty on collateral required by Basle II liquidity regulations. Model predictions are consistent with stylised facts from a comparison between settlement behaviour in the Swiss Interbank Clearing (SIC) and Fedwire funds.

JEL classification: E58; G21; G28

Key words: interbank payments; intraday liquidity facility; collateralization; strategic games; bank behaviour; Basle II liquidity regulation

1 Introduction

This paper analyses the liquidity management game played by participants of real-time gross settlement (RTGS) payment systems. Settlement in RTGS systems requires costly intraday liquidity. To save liquidity participants delay payments to await incoming funds provided by other participants. Thus, settlement behaviour is determined by strategic interaction that results in multiple Pareto-ranked equilibria. Central banks as operators and overseers of such systems care about settlement behaviour as it influences safety and efficiency of the RTGS system. At the same time, settlement behaviour depends on diverse central bank policies. In particular, the terms and conditions of the provision of intraday liquidity stay at the center of attention.

*I would like to thank Andy Sturm for valuable comments.

†The views expressed in this paper are those of the author and do not necessarily represent those of the Swiss National Bank.

Intraday liquidity is either provided uncollateralised but priced or collateralised but free. The former facility is often referred to as a daylight overdraft facility while the latter is referred to as an intraday credit facility. Bech and Garratt (2003) investigate both facilities assuming a cost of delay to be the driving force of the liquidity management game. They assume a variable opportunity cost of collateralisation. Mills and Nesmith (2008) investigate priced but uncollateralised overdraft systems assuming settlement risk to be the driving force of the liquidity management game.

A crucial difference between the two facilities is that uncollateralised but priced overdrafts are not charged when offsetting payment requests are processed in the same period. Furthermore, it naturally gives rise to a variable liquidity cost.[1] In contrast, collateralised but free intraday credit always bears an opportunity cost of collateral as collateral has to be posted upfront to be granted a credit. This prefunding or collateralisation constraint motivates the analysis of collateralisation policy. The opportunity cost of collateral is crucially determined by the collateralisation policy of the central bank and bears correspoinding consequences for the settlement strategy played by banks.

The literature works with different assumptions on the opportunity cost of collateral for free but collateralised intraday liquidity facilities. For instance, Bech and Garratt (2003) and Martin and Jurgilas (2008) underlie a variable cost while Koboyakawa (1997) and Mills and Husain (2009) assume a fixed cost. While cost assumptions are usually not motivated, we provide empirical support and a justification for both assumptions. The cost crucially depends on the collateralisation policy a central bank applies. First, an intraday credit facility that allows to collateralise credits ad hoc exhibits a variable opportunity cost of collateral because collateral can be reused intraday. However, we will see that this is a necessary but not a sufficient condition for a variable cost. Second, an intraday liquidity facility that only accepts permanently prepledged collateral causes a fixed opportunity cost of collateral as collateral cannot be reused. This holds true for any permanently collateralised intraday liquidity facility whether based on credits or on overdrafts as permanent collateralisation is a sufficient condition for a fixed cost. This is in line with the empirical literature. For instance, Kränzlin and Nellen (2010) find a positive implicit intraday interest rate in the Swiss franc repo market, indicating a positive opportunity cost of collateral.

This paper contributes to the literature in three ways. First, to our knowledge nobody has investigated collateralised facilities assuming settlement risk to be the driving force. Second, to the analysis of the standard collateralised intraday credit facilities[2] we add a new facility that is based on collateralised overdrafts. While most central banks make use of intraday credit facilities, the Federal Reserve System introduced a free but collateralised overdraft facility in

[1] See Bech and Garratt (2003), Martin and McAndrews (2008) and Mills and Nesmith (2008) among others.

[2] This is relevant as worldwide RTGS systems predominately offer free but collateralised intraday liquidity facilities (see World Bank (2010)). Moreover, the Federal Reserve System introduced a collateralised overdraft facility on 24 March 2011.

March 2011.[3] With settlement risk and free but collateralized intraday liquidity, collateralisation policy is found to determine resulting settlement behaviour. Third, the use of instruments normally motivated with the implementation of early settlement is found to be essential to avoid multiplicity of equilibria that may hinder coordination. Thus, we introduce a two-part tariff into the liquidity management game. Finally, we find the effectiveness of the two-part tariff to coordinate payments and to induce early settlement to depend on the collateralisation policy.

Assuming a variable opportunity cost of collateral, late settlement results for systems with free but collateralised intraday credit. This is in line with Mills and Nesmith (2008) who find late settlement to result for systems with priced but uncollateralised overdrafts. While Mills and Nesmith (2008) and this paper rely on the settlement risk approach, Koboyakawa (1997) and Bech and Garratt (2003) rely on the delay cost approach. If the cost of intraday credit is variable, Bech and Garratt (2003) show that the resulting equilibrium depends on the relation between the cost of liquidity and delay for both type of systems. Assuming a fixed cost, Koboyakawa (1997) shows early settlement to result. This contrasts with our finding for a model with settlement risk. While incentives to settle late are reduced this does not imply early settlement but results in all strategy pairs to be equilibria and may, thus, hinder efficient payment coordination.

These findings motivate the use of further instruments to induce coordination on early settlement. Indeed, some central banks apply so-called through-put rules or two-part tariffs. While a through-put rule prescribes the settlement of fixed percentages of total settlement by prespecified times during the settlement day, a two-part tariff induces earlier settlement by making the settlement fee an increasing function of settlement time. Buckle and Campbell (2003) analyse a through-put rule that is applied to participants in CHAPS, the UK RTGS system. Ota (2011) compares resulting welfare if a through-put rule is applied with resulting welfare if a two-part tariff is applied.

Ota (2011), assuming a cost of delay, and this paper both find a two-part tariff to facilitate coordination on early settlement. We go beyond this result showing that the quality of coordination depends on the collateralisation policy. With a variable opportunity cost of collateral, the resulting settlement equilibrium depends on the steepness of the two-part tariff. In particular, the two-part tariff must be steep enough to neutralise the strategic dependence on the cost of intraday liquidity, payment uncertainty and settlement risk. Because the necessary information to impose the right tariff is private or simply unknown, the calibration of an effective two-part tariff is non-trivial and may hinder efficient coordination, making a through-put rule the preferable instrument. In contrast, given a fixed cost of intraday liquidity, the two-part tariff easily enforces coordination on early settlement. This comes as a result of a fixed opportunity cost of liquidity that eliminates strategic interaction driven by settlement risk. Thus,

[3] See http://www.federalreserve.gov/paymentsystems for further information on the new facility.

any positive two-part tariff enforces early settlement.

In 2011, the Federal Reserve System introduced a novel intraday liquidity facility. A free but collateralised daylight overdraft facility works on the basis of prepledged collateral. While this facility primarily aims at reducing the credit risk of uncollateralised overdrafts, it is interesting to consider its effect on settlement behaviour. As a consequence of free but permanently prepledged limit for collateralised overdraft, this type of intraday liquidity facility goes along with a fixed cost. However, free but collateralised daylight overdraft does not result in early settlement. We find late settlement to prevail as a consequence of settlement risk. A two-part tariff can induce early settlement, but needs to be calibrated in dependence of payment uncertainty, settlement risk and the cost of overnight liquidity.

Findings are validated by contrasting model predictions with stylised facts. The first stylised fact is gained by comparing settlement behaviour in Fedwire funds - the U.S. RTGS system - with settlement behaviour in the Swiss Interbank Clearing (SIC) - the Swiss RTGS system. The second stylised fact results from a change in the collateralisation policy of the Swiss National Bank (SNB) and liquidity regulation.

First, we find evidence that settlement takes place substantially earlier in SIC than in Fedwire funds. This is in line with model predictions. While Mills and Nesmith (2008) predict late settlement for Fedwire funds (a system with priced but uncollateralised daylight overdraft that implies a variable cost), we predict early settlement for SIC (a system with free but collateralised intraday credits - that implies a fixed cost - and with a two-part tariff).

Second, we find supportive evidence that collateralisation policy matters. In 2005, the SNB changed from its Lombard facility to a new 'liquidity-shortage financing facility' (LSFF).[4] Before the reform took place, intraday credits were collateralised ad hoc by means of repos. Since the regime shift, collateral prepledged for the LSFF can also be used to draw intraday repos. While the collateralisation policy before the regime shift suggests a variable opportunity cost of collateral, the regime based on prepledged collateral is associated with a fixed cost. However, the regime shift was not accompanied with effects associated with model predictions. Rather, the evidence found supports the view that banks have perceived opportunity cost of collateral as fixed both before and after the policy change took place. In line with Ball et al. (2011) we argue that this is related to the fact that regulatory required liquidity buffers can be used to draw intraday liquidity, a practice referred to as double duty. Because collateral prepledged for the LSFF is SNB eligible repo collateral and can be credited against Basle II liquidity buffers, the cost of intraday liquidity is fixed. Behaviour in SIC is in line with this view as neither settlement timing nor intraday credit demand has changed after the regime switch.

The paper is organised as follows. Section two presents the model. In section three settlement behaviour for systems with intraday credits and collateralised

[4] In the U.S. the discount window serves a similar role as the Lombard facility and the LSFF in Switzerland. See www.snb.ch for further information on LSFF.

daylight overdraft is analysed. Section four studies resulting effects of a two-part tariff and section five presents stylised facts. The final section concludes.

2 Model

The model is closely related to Mills and Nesmith (2008). There are three periods denoted by $t = 0, 1, 2$, for morning, afternoon and end-of-day.Two agents called banks indexed by $i \in \{1, 2\}$ populate the payment system. Their objective is to minimise the expected cost of making payments to one another. A third institution is present that can be interpreted either as a private clearinghouse or a central bank (hereinafter referred to as the central bank). Specifically, banks can send and receive payments by moving balances across accounts that they hold with the central bank. Banks are able to access liquidity from the central bank, such as overnight credits and intraday liquidity either provided as daylight overdraft or intraday credit.

We abstract from reserve requirements and precautionary motives for banks to hold balances with the central bank in order to focus on the intraday liquidity management game. This assumption allows us to describe the timing of events such that banks start period 0 with a zero account balance. Then, with probability p, bank $i \in \{1, 2\}$ receives an instruction to make a payment of value 1 to bank $j \neq i$.[5] The realisation of this payment shock is independent of whether the other bank also receives a payment instruction and it is private information to the bank receiving it. Mills and Nesmith (2008) interpret this as the inability of banks to communicate with one another. Thus, banks cannot engage in cooperatively coordinating payments in order to reduce expected costs. While this looks extreme in the case of two banks, such an assumption seems to be justifiable for systems such as SIC, CHAPS and Fedwire, where hundreds or thousands of banks participate.

We assume that banks are granted intraday liquidity by the central bank. In contrast to uncollateralised but priced overdrafts in Mills and Nesmith (2008), banks can get either collateralised but free intraday credits or collateralised but free overdrafts. It is assumed that the interest rate R forgone by holding overnight reserves on central bank accounts is greater than the opportunity cost banks incur if they draw a collateralized intraday credit.

Posting collateral comes either as a time of usage dependent (henceforth variable) opportunity cost ω ($R > \omega > 0$) that realises per period $t \in \{0, 1\}$, or as a fixed cost ψ ($R > \psi > 0$) per settlement day. The variable opportunity cost of collateral is born if and only if an intraday credit is drawn. The fixed opportunity cost of collateral is born in any case, whether or not and for whatever length intraday liquidity is drawn. This contrasts with uncollateralised but priced overdraft for which a fee is charged if and only if the negative account balance

[5] As in Mills and Nesmith (2008) this is a difference to the model by Bech and Garratt (2003) where banks receive a second payment instruction shock in the afternoon. As also Mills and Nesmith (2008) argue, a second shock would complicate the analysis without fundamentally changing the results.

remains until the end of a period $t \in \{0, 1\}$. In other words, no fee is charged if payments offset within a period.

Furthermore, if a bank has not paid back its intraday credit or overdraft by the end of period 1, it must borrow funds from the central bank at interest rate $R > \omega, \psi$ to bring back the account to zero. Also, during period 2 any outstanding payment is made and funded by borrowing overnight at interest rate R if necessary. While intraday credit cannot be drawn after period 1, i.e. banks immediately have to draw an overnight credit, daylight overdrafts are granted until the end of the day, i.e. offsetting transactions without any cost remain possible. Overdrafts not paid back to central bank until the end of the day are automatically replaced by overnight credits. These differences between intraday credit and overdraft liquidity are consistent with the assumptions by Bech and Garrett (2003) for intraday credits and by Mills and Nesmith (2008) for daylight overdraft.[6]

If bank i receives a payment instruction it can decide to make the payment either in period 0 or in period 1. As in Mills and Nesmith (2008) it is assumed that a bank does not strategically delay payments until the end-of-day (period 2) unless it receives information concerning the ability of the other bank to send payments. That is where settlement risk comes into play.

At the beginning of period 1, a bank may receive a settlement shock. Specifically, with a small probability $\varepsilon > 0$, bank i cannot receive a payment from the affected bank j during period 1, but will receive it in period 2. The realisation of the settlement shock is independent across banks and its realisation is common information. However, whether or not a bank is to receive a payment from the affected bank with probability p remains private information. 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 period 2. Thus, differences in the game will be driven by the difference between the intraday credit and the daylight overdraft, i.e. while the former does not allow for offsetting in any period, the latter allows for offsetting even in the last period. This difference affects the cost of borrowing overnight if payments are delayed.

The settlement shock represents a certain type of settlement risk to the receiving bank - defined as the risk that a payment is not sent and received as expected, in this case by the end of period 1. Such shocks occur when the sending bank suffers an operational disruption or lacks available liquidity to send a payment at a particular point in time. This restricts the receiving bank's incoming source of liquidity that could offset outgoing payments and reduce its own cost of sending payments. We can think of the settlement shock as a proxy for uncertainty regarding incoming funds. Even though we might think of the shock ε to be relatively small, it does have a cost in the model's setup as it raises the probability that a bank needs to borrow overnight.

The bank's objective function is taken to minimise the expected cost of

[6] Differences also mirror policies applied. For instance, SIC allows to draw intraday credits until 3 p.m., while the settlement day ends at 4.15 p.m. Fedwire funds allows overdrafts to be drawn until the end of the day.

making a payment. This objective becomes relevant only when a bank receives a payment shock at the beginning of period 0. Thus, we can simply focus on a bank's payment strategy in the state of the world in which it receives a payment instruction. The analysis is restricted to pure strategies. s_i denotes the strategy of bank i given that it receives a payment instruction. The set of possible pure strategies is $s_i \in \{m, a\}$, where m denotes a morning payment (period 0) and a denotes an afternoon payment (period 1). A strategy profile is a pair of timing strategies (s_i, s_j) for both banks. Thus, the expected cost c of making a payment is a function of a bank's payment timing strategy s_i, the timing strategy of the other bank s_j, the probability p that the bank is to receive a payment, the opportunity cost of intraday liquidity (either a variable cost - ω - or a fixed cost - ψ) and the probability of settlement risk ε. $c(s_i, s_j)$ denotes bank i's expected cost of making a payment when it plays the timing strategy s_i while bank j plays the timing strategy s_j. This setup generates four possible realisations of expected costs.

3 Collateralised intraday liquidity facilities

This section analyses collateralised intraday liquidity facilities. The first two subsections focus on collateralised intraday credit facilities. While the first subsection investigate the case of a variable opportunity cost of collateral, the second subsection analyses the case of a fixed opportunity cost of collateral. The third subsection is concerned with an overdraft facility that is collateralised insofar as banks can go into overdraft up to the value of prepleged collateral. Thus, this facility exhibits a fixed opportunity cost of collateral.

3.1 Variable opportunity cost of collateral

First, we assume a per-period opportunity cost $\omega > 0$ of pledging collateral. This per-period opportunity cost is incurred whenever a bank processes a payment request without having funds available in its settlement account to settle a payment. Because collateral must be posted before processing a request in order to obtain intraday liquidity, the morning cost of a bank depends solely on the action taken by the bank itself and not on the opponent's action. The cost is ω if the bank processes the request and zero if the bank decides to delay. If the intraday credit has not been paid back until the end of a period, it is automatically prolonged. Therefore, the opportunity cost of collateral has to be taken into account for another period. If a bank has not paid back its intraday credit by the end of period 1, it has to borrow in the overnight market at interest rate R.

The settlement shock takes place at the beginning of period 1. Banks decide on when to send payments and, accordingly, post collateral to receive an intraday credit in case of insufficient liquidity. Finally, during period 2 any outstanding payments are made. However, if no funds are available during period 2, the bank has to draw an overnight loan in order to process outstanding payments

even if the other banks needs to settle an offsetting payment.

Depending on the strategy pair considered, the game leads to the following four realisations of expected costs:

$$c(m,m) = \omega + (1-p)(\omega + R) \tag{1}$$

$$c(m,a) = \omega + p(1-\varepsilon)\omega + p\varepsilon(\omega + R) + (1-p)(\omega + R) \tag{2}$$

$$c(a,m) = (1-p)(1-\varepsilon)(\omega + R) + (1-p)\varepsilon R \tag{3}$$

$$c(a,a) = p(1-\varepsilon)\omega + p\varepsilon R + (1-p)(1-\varepsilon)(\omega + R) + (1-p)\varepsilon R \tag{4}$$

Suppose bank i receives a payment, then the first term in equations (1) and (2) mirrors the necessity for bank i to draw an intraday credit in order to settle early. The second term in equation (1) reflects the fact that, if bank j does not receive a payment order, bank i has to prolong the intraday credit and, additionally, it has to draw an overnight loan to bring the account balance back to zero. In equation (2) settlement risk matters. If bank j does receive a payment, the realisation of settlement risk may additionally force it not only to prolong the intraday credit but also to draw an overnight loan. In equation (3) and (4) the cost of bank i is analysed if its strategy is to settle late. Therefore, no intraday credit is drawn in the first period. The difference between cost functions (3) and (4) can be explained by the fact that in equation (3) we look at a situation where bank i with probability p has received a payment by bank j in the morning. Thus, given bank j receives a transaction, bank i does not incur a settlement cost since its payment is prefunded. Otherwise, bank i has to draw an intraday credit and, finally, an overnight loan to bring its account balance back to zero. If settlement risk realises, it can delay to period 2 in order to circumvent the nessecity of an intraday credit. The same holds true for the last two terms of cost function (4). In constrast to the previous situation, since both banks play afternoon, settlement risk also plays a role if bank j receives a payment instruction. As in cost function (4), the realisation of settlement risk forces bank i to draw an additional overnight loan.

The derivation of cost functions is set out in more detail in the appendix. Figure 1 represents the game in normal form with equations (1) to (4) simplified where appropriate.

Proposition 1 *Under a collateralised intraday credit regime with a per period opportunity cost of collateral $\omega > 0$ and a settlement shock $\varepsilon > 0$, the strategy profile (a,a) is the unique Bayesian Nash equilibrium. Furthermore, a is a strictly dominat strategy for each player.*
Proof. *It is easy to see that for bank i $c(a,m) < c(m,m)$ and $c(a,a) < c(m,a)$ and for bank j $c(m,a) < c(m,m)$ and $c(a,a) < c(a,m)$.* ■

We call an equilibrium efficient if it minimises the joint expected costs of the two banks. It is easily shown that this is the case for the strategy pair (a,a). Because a is a strictly dominant strategy, the strategy pair (a,a) is also Pareto-dominant. In comparison to an uncollateralised but priced overdraft regime - as

Figure 1: Intraday credit system with variable opportunity cost of collateralIntraday credit system with variable opportunity cost of collateral

	m	a
m	2ω-pω 2ω-pω	2ω+pεR (1-p)(1-ε)ω
a	(1-p)(1-ε)ω 2ω+pεR	(1-ε)ω+pεR (1-ε)ω+pεR

analysed in Mills and Nesmith (2008) - the intraday credit game with a variable opportunity cost of collateral results in even stronger incentives to settle late.

If $\omega = 0$ and $\varepsilon > 0$, all strategy pairs become Bayesian Nash equilibria. This is in contrast to Mills and Nesmith (2008) with free overdrafts for which (a, a) survives the elimination of weakly dominated strategies. This difference arises with intraday credits because banks cannot offsett payments in period 2. Thus, they are not only affected by settlement risk if they have opposing strategies but also if they both play a. The result is also in contrast to the delay cost approach. As a result of the cost of delay, Bech and Garratt (2003) find early settlement to be the unique equilibrium if intraday liquidity is for free (remember $\varepsilon = 0$ in their model).

If $\omega > 0$ and $\varepsilon = 0$, (a, a) results as the unique Bayesian Nash equilibrium. Because a being a strictly dominant strategy, (a, a) is both efficient and Pareto-dominant. Banks seek to avoid the cost of intraday liquidity by waiting for incoming payments from the other participants. This is in line with Mills and Nesmith (2008) and differs from the result in Bech and Garratt (2003). In the latter, a positive cost of delay induces banks to settle payments early if the cost of delay is lower than the intraday liquidity cost.

If $\omega = 0$ and $\varepsilon = 0$, all strategy pairs are Bayesian Nash and efficient. Again this is in line with Mills and Nesmith (2008) and clearly differs from the early settlement result in Bech and Garratt (2003).

3.2 A fixed opportunity cost of collateral

We assume banks to have permanently prepledged collateral of value 1 at the central bank. The opportunity cost of collateral ψ is considered to be lower than the overnight rate $R > \psi$. Banks use the possibility to draw an intraday credit either in the morning m or in the afternoon a, according to their settlement strategy. Again, if a bank's intraday credit has not been paid back by the end of period 1, it has to borrow overnight credit at a cost R.

The following cost functions result:

$$c(m, m) = \psi + (1 - p)R \tag{5}$$

Figure 2: Intraday credit system with a fixed cost

	m	a
m	0 0	pεR 0
a	0 pεR	pεR pεR

$$c(m,a) = \psi + p\varepsilon R + (1-p)R \tag{6}$$

$$c(a,m) = \psi + (1-p)R \tag{7}$$

$$c(a,a) = \psi + p\varepsilon R + (1-p)R \tag{8}$$

Whatever the payment strategy is and whether or not a bank actually receives a payment instruction, it incurs opportunity cost ψ since it has to prepledge collateral to the amount that covers its intraday liquidity needs. Therefore, its cost functions are determined by the fixed cost, the other bank's strategy, realising payment uncertainty and settlement risk. If bank j's strategy is to pay late, bank i's cost is affected by settlement risk. If settlement risk realises, bank i is urged to draw an overnight loan. Without realised settlement risk, bank i would not necessarily be required to do so since bank j's payment might just be delayed due to operational problems. In case bank j's strategy is to settle early, bank i's cost is not affected by settlement risk. Again, in contrast to an overdraft model, banks are also affected by settlement risk if both play a.

Again, the derivation of cost functions is explained in greater detail in the appendix. Figure 2 represents the game in normal form with equations (5-8) simplified where appropriate. By inspection of figures 1 and 2 it is easy to see that this resembles exactly the result obtained for $\omega = 0$ beforehand.

Proposition 2 *Under a collateralised intraday credit regime with a fixed opportunity cost of collateral $\psi > 0$ and a settlement shock $\varepsilon > 0$, all strategy profiles are Bayesian Nash equilibria.*
Proof. *It is easy to see that $c(m,m) = c(a,m)$ and $c(m,a) = c(a,a)$ for bank i and $c(m,m) = c(m,a)$ and $c(a,m) = c(a,a)$ for bank j hold true.* ■

From figure 10 it is easy to see that (m,m) is efficient as $c_i(m,m)+c_j(m,m) < c_i(s,s)+c_j(s,s)$ for all possible strategy pairs $(s,s) \neq (m,m)$. Furthermore, the strategy profile (m,m) is Pareto-dominant as $c_i(m,s) \leq c_i(a,s)$ and $c_j(s,m) \leq c_j(s,a)$ $\forall$ $s \in \{m,a\}$.

The fixed opportunity cost of collateral leaves all possibilities open because all strategy profiles are Bayesian Nash equilibria. This is a strong result. Acknowledging the incentive to delay strategically that results from settlement risk, a fixed opportunity cost of collateral neutralises strategic interaction.

Moreover, the strategy profile (m, m) is a Pareto-dominant equilibrium. Because all strategy profiles are Bayesian Nash equilibria, it is compelling to assume that (m, m) would be the effectively chosen equilibrium. However, a focal point argument may not convince as an argument for early settlement to result. This motivates the use of further instruments to ensure early settlement. For instance, many central banks relay on instruments such as a through-put rule or a two-part tariff. In essence, these instruments serve to coordinate payment activity in the morning.

Koboyakawa (1997) analyses a fixed opportunity cost of collateral in a framework with a delay cost and finds the strategy pair (m, m) to result as the chosen equilibrium. In a delay cost framework, a sunk opportunity cost of collateral results in the equivalent outcome to that obtained in a framework with free overdrafts. Saying this, it is evident that above conclusion does not change if $\psi = 0$. In contrast, in a framework with settlement risk Mills and Nesmith (2008) find late settlement to result also with free but uncollateralised overdraft. Even though we find a fixed opportunity cost to neutralise incentives to delay, (m, m) cannot be established as unique Baysesian Nash equilibrium.

Also, if $\varepsilon = 0$, all strategy pairs remain equilibria. In contrast to before, however, no particular equilibrium is Pareto-dominant. The same result is obtained by Mills and Nesmith (2008) for free overdrafts. In contrast, Bech and Garratt (2004) predict early settlement as a consequence of the delay cost.

3.3 A prepledged overdraft facility

A fixed opportunity cost of collateral invites to reflect on free but prepledged overdraft facility. On 24 March 2011, the Federal Reserve System introduced such a facility next to the priced but uncollateralised overdraft facility. Permanently prepledged collateral involves a fixed opportunity cost ψ. If banks on top of the prepledged amount of collateral have to rely on priced but uncollateralised overdraft, this results in a variable cost of intraday liquidity. As this new intraday liquidity facility is of interest in its own right, we assume banks to prepledge the full amount of collateral needed for overdrafts, i.e. 1\$.

The crucial difference to the game with a fixed opportunity cost of collateral is that the strategy pair (a, a) does not involve costs related to settlement risk. This is related to the assumption that an overdraft facility is open until the end of the day. In contrast, intraday credits are ususally open until a predetermined time before the end of the day. Thus, given intraday credits, we allow to draw intraday liquidity until period 1 and banks immediately have to draw overnight credit to settle payments in period 2. In contrast, given an overdraft facility, banks are able to offset payments in period 2 without having to draw overnight loans. This is why banks are only prone to settlement risk if they play different strategies. The derivation of cost functions are further discussed in the appendix.

The following cost functions result:

$$c(m, m) = \psi + (1 - p)R \tag{9}$$

Figure 3: Overdraft system

	m	a
m	0 0	pεR 0
a	0 pεR	0 0

$$c(m,a) = \psi + p\varepsilon R + (1-p)R \tag{10}$$

$$c(a,m) = \psi + (1-p)R \tag{11}$$

$$c(a,a) = \psi + (1-p)R \tag{12}$$

Figure 3 represents the game in normal form with equations (9-12) simplified where appropriate.

Proposition 3 *Under a collateralised overdraft regime with fixed opportunity cost of collateral $\psi > 0$ and a settlement shock $\varepsilon > 0$, the strategy profiles (m,m) and (a,a) are Bayesian Nash equilibria. The strategy profile (a,a) survives the elimination of weakly dominated strategies.*

Proof. *It is easy to see that $c(m,m) = c(a,m)$ and $c(a,a) > c(m,a)$ for bank i and $c(m,m) = c(a,m)$ and $c(a,a) > c(a,m)$ for bank j. Furthermore, it is also easy to see that $c(a,s) \geq c(m,s)$ and $c(s,a) \geq c(s,m)$ hold true $\forall\ s \in \{m,a\}$.* ■

Because the model setup is identical to Mills and Nesmith (2008), it does not come as a surprise that we find the same results for free overdrafts (i.e. $\psi = 0$). As a fixed cost of collateral is sunk, the game is played as if overdrafts are for free. Settlement risk determines the strategy pair (a,a) to be the surviving equilibrium even though a prepledged overdraft facility makes the cost of using intraday liquidity sunk and both Bayesian Nash equilibria - (m,m) and (a,a) - are efficient and Pareto-dominate the other strategy profiles. (a,a) is the chosen strategy pair because playing morning risks to be exposed to settlement risk. Letting $\varepsilon = 0$, it is easy to see that all strategy profiles become Bayesian Nash equilibria and no particular one suggests itself to be chosen.

Mills and Nesmith (2008) argue that a priced overdraft system in the presence of settlement risk results in late settlement. In the light of above proposition, the Federal Reserve System's introduction of a prepledged and free overdaft facility cannot be justified as an instrument to foster early settlement. Thus, the introduction of a prepledged and free overdraft facility without further instruments will not affect settlement timing.

The move towards earlier settlement in Fedwire funds that has been observed since late 2008 is related to the fact that overnight reserve holdings have been

showing peak values due to unconventional monetary policy at the zero lower bound (see figure 8). The fact that the same can be observed for SIC (see figure 9) confirms this view. In both Mills and Nesmith (2008) and Bech and Garratt (2003), this situation is mirrored by a free intraday liquidity that is caused by an unpreceded level of overnight reserves. However, as soon as unconventional monetary policy will be neutralised and reserve levels return to pre-crisis levels, incentives to delay payments return. The coordination later in the day is hard to change since keeping it assures that miscoordination does not result in higher overnight refinancing needs caused by settlement risk.

Given free choice of usage of either facility, we expect banks to opt for the less expensive solution to the greatest possible extent. Furfine (2001), Baglioni and Monticini (2008) and Kraenzlin and Nellen (2010) provide evidence that the implicit intraday interest rate as a proxy of the opportunity cost of collateralisation is lower than the overdraft fee charged to cover the credit risk of uncollateralised intraday liquidity.[7] In the same vain, Ball et al. (2011) argue that double duty makes the cost of collateralisation sunk, respectively understand this to be the reason why collateralised intraday liquidity is indeed less expensive than the currently charged overdraft fee in Fedwire funds. Thus, we would expect banks to reduce uncollateralised overdrafts as far as possible because the collateralised overdraft facility provides a less expensive source of intraday liquidity. Even though current numbers on the relative use of the two facilities from 24 March 2011 on have to be treated with caution due to the high reserve balances at the zero lower bound, the choice by banks seems to be clearcut. Out of total overdrafts on average almost 93%[8] have been collateralised.

4 Two-part tariff as a coordination device

A two-part tariff is often understood to incentivise early settlement, similarly to a through-put rule. Two-part tariff is applied by various RTGS systems, for instance SIC.Our model setup allows us to introduce a two-part tariff by simply adding a late settlement fee $\tau > 0$.[9] The central bank charges the late settlement fee whenever settlement occurs during the last two periods.[10] In the following subsections we analyse the effects on settlement behaviour if a two-part tariff is introduced in above analysed setups.

[7] Along with the introduction of the new facility, the Federal Reserve System incentivised the switch from priced to prepledged overdrafts with an increase of the overdraft fee from 36bp to 50bp.

[8] Data is available on http://www.federalreserve.gov/paymentsystems/psr_data.htm. Author's calculation.

[9] As set out in Ota (2011), one could well have an early settlement fee τ_m and a late settlement fee τ_a. $\tau_a - \tau_m = \tau > 0$ makes notation easier.

[10] Ota (2011) argues that a negative morning fee $\tau_m < 0$ in combination with a positive evening fee $\tau_a > 0$ allows to implement an overall cost-neutral tariff scheme with strong incentives to settle early. We completely abstract from such aspects as our focus lies on the incentive effects.

Figure 4: Intraday credit game with a variable cost and a two-part tariff

	m	a
m	2ω-pω 2ω-pω	2ω+pεR (1-p)(1-ε)ω+τ
a	(1-p)(1-ε)ω+τ 2ω+pεR	(1-ε)ω+pεR+τ (1-ε)ω+pεR+τ

4.1 A variable opportunity cost

Compared to cost functions (1) to (4), the only change is related to the late settlement fee:

$$c(m,m) = \omega + (1-p)(\omega + R) \tag{13}$$

$$c(m,a) = \omega + p(1-\varepsilon)\omega + p\varepsilon(\omega + R) + (1-p)(\omega + R) \tag{14}$$

$$c(a,m) = (1-p)(1-\varepsilon)(\omega + R) + (1-p)\varepsilon R + \tau \tag{15}$$

$$c(a,a) = p(1-\varepsilon)\omega + p\varepsilon R + (1-p)(1-\varepsilon)(\omega + R) + (1-p)\varepsilon R + \tau \tag{16}$$

Figure 4 represents the game in normal form with equations (13-16) simplified where appropriate.

Proposition 4 *Under a collateralised intraday credit regime with a per period opportunity cost of collateral $\omega > 0$, a settlement shock $\varepsilon > 0$ and a two-part tariff $\tau > 0$, the strategy profile (a,a) is efficient if $\tau < (1+\varepsilon-p)\omega - p\varepsilon R$. (a,a) and (m,m) are both efficient if $\tau = (1+\varepsilon-p)\omega - p\varepsilon R$. (m,m) is an efficient and Pareto-dominant strategy profile if $\tau > (1+\varepsilon-p)\omega - p\varepsilon R$. The following strategy profiles emerge as equilibria:*

1. *If $\tau < \omega(1+\varepsilon-p\varepsilon)$, (a,a) is the unique Bayesian Nash equilibrium. Furthermore, m is a strongly dominating strategy for each player;*

2. *If $\tau = \omega(1+\varepsilon-p\varepsilon)$, (m,m) and (a,a) are Bayesian Nash equilibria. Furthermore, the strategy profile (a,a) survives the elimination of weakly dominated strategies;*

3. *If $\omega(1+\varepsilon-p\varepsilon) > \tau > \omega(1+\varepsilon)$, (m,m) and (a,a) are Bayesian Nash equilibria;*

4. *If $\tau = \omega(1+\varepsilon)$, (m,m) and (a,a) are Bayesian Nash equilibria. The strategy profile (m,m) survives the elimination of weakly dominated strategies;*

5. *If $\tau > \omega(1+\varepsilon)$, (m,m) is the unique Bayesian Nash equilbrium. Furthermore, m is a strongly dominating strategy for each player.*

Proof. *It is easy to see that following inqualities hold true* $\omega(1-p+\varepsilon)-p\varepsilon R < \omega(1+\varepsilon-p\varepsilon) < \omega(1+\varepsilon)$ *(Figure 5). Let* $s, b, c \in \{m, a\}$. *If* $\tau > (1-p+\varepsilon)\omega - p\varepsilon R$, (m, m) *is efficient and Pareto-dominant as* $c(m, m) < c(b, c)$ *for any* $(b, c) \neq (m, m)$. *If* $\tau = (1-p+\varepsilon)-p\varepsilon R$, *both* (m, m) *and* (a, a) *are efficient as* $c(s, s) < c(b, c)$ *for any* (b, c) *for which* $b \neq c$. *If* $\tau < (1-p+\varepsilon)\omega - p\varepsilon R$, (a, a) *is efficient and Pareto-dominant because* $c(a, a) < c(b, c)$ *for any* $(b, c) \neq (a, a)$.

1. *If* $\tau < \omega(1+\varepsilon-p\varepsilon)$, $\forall\ s \in \{m, a\}$ *it holds true that* $c(a, s) < c(m, s)$ *and* $c(s, a) < c(s, m)$;

2. *If* $\tau = \omega(1+\varepsilon-p\varepsilon)$, *for bank i* $c(a, m) < c(m, m)$ *and* $c(a, a) = c(m, a)$ *and for bank j* $c(m, a) < c(m, m)$ *and* $c(a, a) = c(a, m)$. *Thus,* $\forall\ s \in \{m, a\}$ *it holds true that for bank i* $c(a, s) \leq c(m, s)$ *and for bank j* $c(s, a) \leq c(s, m)$;

3. *If* $\omega(1+\varepsilon-p\varepsilon) < \tau < \omega(1+\varepsilon)$, *it is easy to see that for bank i* $c(a, a) < c(m, a)$ *and* $c(a, a) < c(a, m)$ *and for bank j* $c(m, m) < c(m, a)$ *and* $c(m, m) < c(a, m)$;

4. *If* $\tau = \omega(1+\varepsilon)$, *it is easy to see that for bank i* $c(m, m) = c(a, m)$ *and for bank j* $c(m, m) = c(m, a)$. *Furthermore, for bank i* $c(a, a) < c(m, a)$ *and for bank j* $c(a, a) < c(a, m)$. *Thus, for bank i* $c(m, s) \leq c(a, s)$ *and for bank j* $c(s, m) \leq c(s, a)$;

5. *If* $\tau > (1+\varepsilon)\omega$, $\forall\ s \in \{m, a\}$ *it holds true that for bank i* $c(m, s) < c(a, s)$ *and for bank j* $c(s, m) < c(s, a)$.

■

Figure 5 illustrates the proposition. It is evident that steering settlement behaviour is a non-trivial undertaking if the opportunity cost of collateral is variable. While the opportunity cost of collateral may be publicly observable, at least on the basis of a market wide implicit intraday interest rate, other variables may not be so. Both settlement risk and the payment shock may be difficult to infer from payment data.

Ota (2011) concludes that a two-part tariff is able to reduce aggregate liquidity cost if banks incur delay cost and differ in their cost of liquidity. However, the conclusion is based on a model without payment uncertainty. We show that if payment uncertainty and settlement risk are present, for an effective calibration of the two-part tariff one must take into account the opportunity cost of collateral, payment uncertainty and settlement risk. Thus, given a variable opportunity cost of collateral, it is far from evident which two-part tariff implements early settlement and improves welfare.

It is interesting to do comparative statics. An increase in p widens the area of indeterminancy between point A and B by moving point A to the left. However, it does not increase the necessary level of τ to make early settlement the unique equilibrium. An increase in ε leaves the area of interderminancy the same but increases the necessary level of τ to make early settlement the unique equilibrium. An increase in ω widens the area of indeterminancy and increases the necessary level of τ to induce early settlement.

Figure 5: Resulting equilibria in dependence of τ

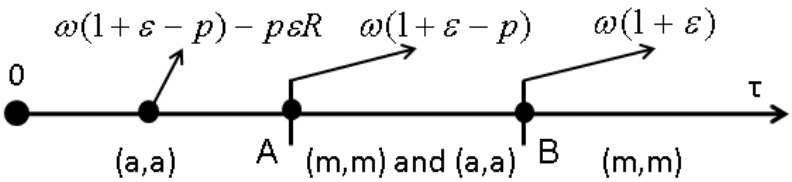


Figure 6: Intraday credit with a fixed cost and a two-part tariff

	m	a
m	0 0	pεR τ
a	τ pεR	pεR+τ pεR+τ

4.2 A fixed opportunity cost

Under a fixed cost of intraday credits early as well as late settlement are Bayesian Nash equilibria. We argued that banks choose the Pareto-dominant morning equilibrium. While this may not suffice as an equilibrium selection argument, the situation facilitates the elimination of the late settlement equilibrium. In particular, the introduction of a two-part tariff allows to change early settlement into a dominant strategy for both players.

The following cost functions result:

$$c(m,m) = \psi + (1-p)R \tag{17}$$

$$c(m,a) = \psi + p\varepsilon R + (1-p)R \tag{18}$$

$$c(a,m) = \psi + (1-p)R + \tau \tag{19}$$

$$c(a,a) = \psi + p\varepsilon R + (1-p)R + \tau \tag{20}$$

Figure 6 represents the game in normal form with equations (17-20) simplified where appropriate.

Proposition 5 *Under a collateralised intraday credit regime with a daily fixed opportunity cost of collateral $\psi > 0$, a settlement shock $\varepsilon > 0$ and a two-part tariff $\tau > 0$, (m,m) is the unique Bayesian Nash equilibrium. The strategy m is a strictly dominating strategy for each player.*

Proof. *It is easy to see that for bank i $c(m,m) > c(a,m)$ and $c(m,a) > c(a,a)$ and for bank j $c(m,m) > c(m,a)$ and $c(a,m) > c(a,a)$.* ■

Figure 7: Overdraft system with a two-part tariff

	m	a
m	0 0	pεR τ
a	τ pεR	τ τ

In contrast to a variable opportunity cost of collateral, with a fixed opportunity cost any level of τ allows to eliminate late settlement or areas of indeterminancy. In particular, the effect of the two-part tariff does not depend on payment uncertainty, settlement risk and interest rates as any $\tau > 0$ makes early settlement to be a strictly dominating strategy.

4.3 A prepledged overdraft facility

Again, with the exception that we add a positive fee $\tau > 0$ in case of late settlement, the same cost functions result as for the case without a two-part tariff:

$$c(m, m) = \psi + (1 - p)R \tag{21}$$

$$c(m, a) = \psi + p\varepsilon R + (1 - p)R \tag{22}$$

$$c(a, m) = \psi + (1 - p)R + \tau \tag{23}$$

$$c(a, a) = \psi + (1 - p)R + \tau \tag{24}$$

Figure 7 represents the game in normal form with equations (21-24) simplified where appropriate.

Proposition 6 *Under a collateralised overdraft regime with a daily fixed opportunity cost of collateral $\psi > 0$, a settlement shock $\varepsilon > 0$ and a two-part tariff $\tau > 0$, (m, m) is the efficient and Pareto-dominant strategy pair. Depending on τ, the following strategy profiles emerge as equilibria:*

1. if $\tau > p\varepsilon R$, (m, m) is the only Bayesian Nash equilibrium. The strategy m is a strictly dominating strategy for each player.;

2. if $\tau = p\varepsilon R$, the strategy pairs (m, m) and (a, a) are Bayesian Nash equilibria. The strategy pair (m, m) survives the elimination of weakly dominated strategies;

3. if $\tau < p\varepsilon R$, the strategy profiles (m, m) and (a, a) are Bayesian Nash equilibria.

Proof. It is easy to see that $c(m,m) < c(a,a)$, $2c(m,m) < c(m,a) + c(a,m)$. Furthermore, $c(m,m) < c(m,a)$ and $c(m,m) < c(a,m)$. Therefore, the strategy profile is both efficient and Pareto-dominant.

1. If $\tau > p\varepsilon R$, it is easy to see that for bank i $c(m,m) = c(a,m)$ and $c(m,a) > c(a,a)$ and for bank j $c(m,m) = c(m,a)$ and $c(a,m) > c(a,a)$. Furthermore, $\forall\ s \in \{m,a\}$ it holds true that for bank i $c(m,s) \geq c(a,s)$ and for bank j $c(s,m) \geq c(s,a)$;

2. If $\tau = p\varepsilon R$, for all strategy pairs (s_i, s_j) for which $s_i \neq s_j$ it holds true that $c(s_i,s_j) > c(m,m)$ and $c(s_i,s_j) > c(a,a)$;

3. If $\tau < p\varepsilon R$, it is easy to see that for bank i $c(a,m) = c(a,a)$ and $c(a,a) > c(m,a)$ and for bank j $c(m,a) = c(a,a)$ and $c(m,a) > c(m,m)$. Furthermore, for bank i $c(a,s) \geq c(m,s)$ and for bank j $c(m,s) \geq c(a,s)$ hold true.

■

The introduction of a two-part tariff makes the strategy pair (m,m) the efficient and Pareto-dominant equilibrium whatever value is chosen for $\tau > 0$. Thus, for any $\tau > 0$, it is compelling to believe in (m,m) as the strategy pair chosen. Thus, earlier settlement in a collateralised but free overdraft system can be induced by establishing a two-part tariff. However, for $\tau < p\varepsilon R$, (a,a) remains a Bayesian Nash equilibrium next to (m,m) and there is no assurance that (m,m) is effectively chosen. In particular, given one tries to move from a well-established late settlement to an early settlement equilibrium, stronger incentives may well have to be provided, i.e. $\tau \geq p\varepsilon R$. Again, the implementation of a two-part tariff requires careful calibration.

5 Stylised facts

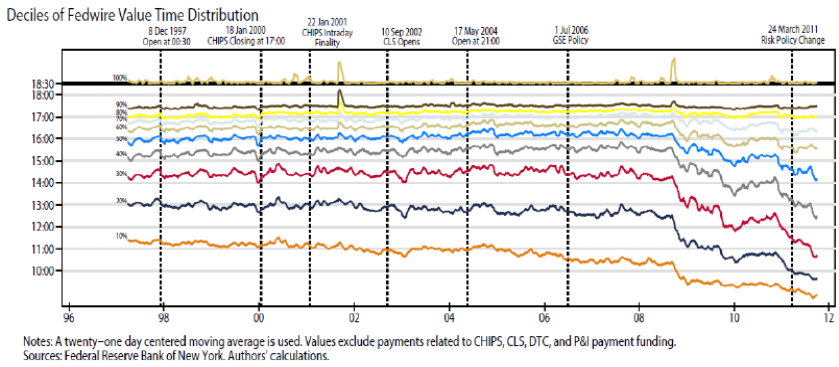
5.1 Comparing SIC and Fedwire funds

A comparison between SIC and Fedwire funds shows that settlement in SIC takes place earlier than in Fedwire funds. This is consistent with the prediction of Mills and Nesmith (2008) and this paper. An overdraft system with a variable liquidity cost predicts late settlement for Fedwire funds while a model for intraday credits with a fixed opportunity cost of collateral and a two-part tariff predicts early settlement for SIC.

Bech, Martin and McAndrews (2011) provide an empricial analysis of the timing of payments in Fedwire funds (see figure 8).[11] As they extract all payments to and from settlement institutions such as CLS, we remove similar payments from SIC data (see figure 9). This allows to focus on the non-settlement

[11] Reprint of figure *xy* was kindly permitted by Bech, Martin and McAndrews (2011) *(still has to be asked for!!!!)*.

Figure 8: Deciles of Fedwire Value Time Distribution



institutions' fund transfers that are subject to strategic decisions of the sending party.[12]

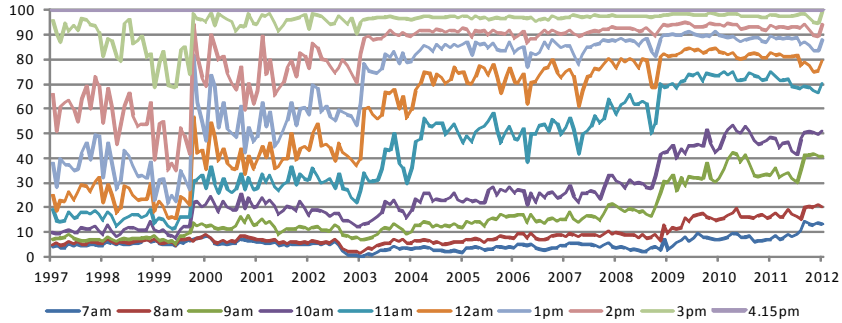
We are able to compare the last 2 1/2 (5 1/2) hours of the Fedwire funds settlement day with the last 2 1/4 (5 1/4) hours of the SIC settlement day.[13] We do so for the period from 2003 to mid 2007, i.e. the period after the introduction of Continuous Linked Settlement and before the financial crisis starting 2007. This period is unaffected by any responses to the financial crisis such as higher intraday liquidity demand (such as in the case of SIC - see figure 10) or unusually high overnight balances. However, the basic conclusion that SIC settles earlier than Fedwire funds remains valid for the time until the first quarter 2012. Bech, Martin and McAndrews (2011) show that around 50% of value is settled 2 1/2 hours before the system closes. Also, only 20% of the value is settled 5 1/2 hours before the system closes (see figure 5). Figure y shows that 2 1/4 hours before SIC closes more than 90% of turnover is settled. Furthermore, 5 1/4 hours before end of day 50% of turnover is settled in SIC.

Even though institutionalised payments with fixed settlement times are removed from the data analysed, many further issues may affect settlement behaviour. For instance, differring market structures could alter settlement behaviour (e.g. 8000 participants in Fedwire funds versus less than 400 in SIC). Armantier et al. (2008) argue that insitutionalised payment times stemming from CHIPS and DTC in particular serve as focal points for other payment activities. Due to the financial crisis tri-party repo in the US has found special attention. Armantier et al. (2008) find late settlement activity for this secured interbank money market. As pointed out in Kraenzlin and Nellen (2010) the

[12] In the case of SIC, institutionalised payments stem from CLS, payments that originate from securities and repo settlement or related services and several retail clearing houses. For Fedwire funds payments stemming from CHIPS, CLS and Depository Trust Company (DTC) are not considered.

[13] SNB's data base on SIC knows hourly data points only. This does not allow to reproduce the analysis for Fedwire funds based on deciles of value time distribution.

Figure 9: Monthly percentages of the value settled by a specific time of the SIC settlement day



secured money market in Switzerland settles the repurchase transaction early in the morning as delivery-versu-payment (DVP) transaction.[14] However, these institutionalised transactions are removed from the SIC data.

Mills and Nesmith (2008) mention that even though their model qualitatively explains the stylised facts concerning Fedwire, other factors such as late arriving payments may also contribute to the settlement patterns observed. Indeed, anecdotal evidence suggests that a substantial fraction of payments is known ahead of the settlement day. Most relevant in terms of value are interbank payments that originate from any form of interbank trading. Such trades are usually concluded some days ahead of the settlement day. However, another large fraction of payments originates on the settlement date itself. Such payments are related to customer payments and unsecured interbank money market transactions. Indeed, Bartolini et al. (2008) find evidence that same day money market transactions are subject to substantial strategic delay. There is also evidence for SIC that strategic delay is an issue. As reported in Nellen (2010), the experience with the introduction of a two-part tariff for SIC in April 1988 and its more progressive application from 1989 on is that - in terms of the number of payments, many more payments were released earlier than before as early release and settlement incurs lower fees. However, in terms of the value of transactions released and settled, a remarkable move towards later release and settlement can be noticed from 1990 onwards. Relating these facts makes clear that substantial payment management takes place in internal queues and is, thus, subject to strategic delay.

To summarise, for both categories of payments - those that are known ahead and those that are generated on the same day - strategic interaction is known

[14] Early settlement of repos in Switzerland is consistent with the prediction of early settlement timing for DVP transaction in Mills and Nesmith (2008). Early settlement would also result as equilibrium outcome for DVP transactions in systems with collateralised intraday liquidity facilities.

to be an issue. While the exact extent is hard to quantify, the phenomenon of strategic delay in payment systems is real. The period of quantitative easing starting end of 2008 has provided further evidence of strategic delay for both types of systems (see figures 8 and 9 show drastic reductions in delay due to bascially free and unlimitled supply of overnight reserve balances). Since differences in the timing of payments are substantial and settlement figures compared reflect payments that are not institutionalised, we believe that the difference in settlement timing stems from the fundamental factors.

5.2 Collateralisation policy and intraday credit demand

In 2005, collateralisation of intraday credit changed because the SNB introduced the liquidity-shortage financing facility (LSFF). This new facility replaced the former Lombard credit facility. Both facilities' objective is to allow banks to insure against potential liquidity shortages by means of a liquidity facility that is priced 50 bp above the market's secured overnight interest rate.[15] Also, both facilities require banks to define a credit limit and to preplege the limit determined with collateral of the same value on a yearly basis. The Lombard facility was phased out by the end of 2005. From 2006 on, the only facility to insure against liquidity shortages is the LSFF.

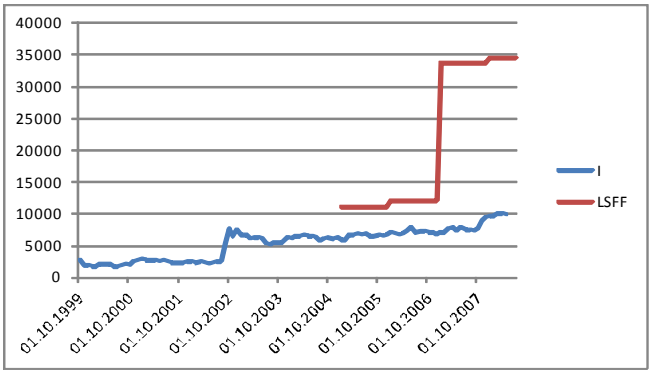
The SNB provides free but collateralised intraday liquidity by means of repos. Thus, intraday repos are conducted against collateral eligible for repo transactions with the SNB. While collateral prepledged for the Lombard facility was not made available to draw intraday credits, collateral prepledged for the LSFF is available to draw intraday credits. Thus, the period before 2005 is associated with a variable opportunity cost of collateral because collateral of intraday credits that were repaid can be reused. In contrast, collateral that is permanently pledged for the LSFF is blocked and results in a fixed opportunity cost of collateral.

To assess potential effects of the change from the Lombard facility to the LSFF, we can draw on proposition 4 and proposition 5. We associate two potential effects with such a policy change. Settlement behaviour and intraday liquidity demand may change. Proposition 5 predicts early settlement for a fixed cost. Proposition 4 predicts early or late equilibrium depending on the chosen two-part tariff. If $\tau < \omega(1 + \varepsilon - p)$ the model predicts (a, a), if $\tau > \omega(1 + \varepsilon)$ the model predicts (m, m). Therefore, to assess whether a change can be expected, we need to evaluate the steepness of the two-part tariff. Let us simply consider whether $\tau < \omega$ by a considerable margin. Given this is the case, we can be confident that late settlement results with a variable opportunity cost of collateral.

We can do so on the basis of an hourly implicit intraday interest rate of repo transactions that mirrors the opportunity cost of collateral. Nellen and Kränzlin (2010) estimate the annualised implicit hourly intraday interest rate to be 0.45bp from the Swiss franc repo market before the financial crisis 2007.

[15] In the course of the financial crisis the penalty rate was reduced from 200bp to 50bp.

Figure 10: Monthly averages of intraday credits drawn (I) and established limits for the liquidity-shortage financing facility (LSFF) in CHF billions



To be indifferent between sending a payment of CHF 4.58 Mio[16] now or to await incoming funds (assuming the bank receives a payment during the coming hour), the two-part tariff has to be increasing with an hourly rate of CHF 0.57. Currently, the effective beginning of day fee is CHF 0 whereas the end of day fee is CHF 2 from 2pm on.[17] However, starting at CHF 0, the end of day fee has to be CHF 13.60 for a 23 hours settlement day to make banks indifferent between sending the payment nor or awaiting incoming funds. Even if we just consider the 9 opening hours of the repo market, the fee has to raise to CHF 4.60 until the end of the day. As both estimates are far above CHF 2, we infer $\tau < \omega(1 + \varepsilon - p)$. Thus, the current two-part tariff does not support early settlement for many large-value payments if the opportunity cost of collateral is variable. This view is validated by the move towards earlier settlement after 2009 when overnight interest rates reached the zero lower bound and reserve balances reached unpreceded levels (see figure 9).

First, in line with the theory and this observation we predict that the equilibrium to change from (a, a) to (m, m) with the move from the Lombard credit facility to the LSFF. However, inspection of figure 9 clearly reveals that no change in settlement behaviour took place around 2006.

Second, the move from (a, a) to (m, m) is expected to go along with a change in the demand for intraday credit. We assign a value of 1\$ for an intraday credit drawn over a period, i.e. we assign a value of 2\$ for an intraday credit drawn during two periods. With a variable cost, bank i draws an intraday credit in period 1 with probability $(1 - \varepsilon)$ (remember that we presume bank i to receive a payment instruction for sure). With probability p, bank j also receives a payment instruction. With probability $(1 - \varepsilon)$, bank i receives the payment and draws an intraday credit while with probability ε, it delays the

[16] This is the average payment value for payments exceeding CHF 100'000 in 2006.
[17] The SIC day starts at 5pm (the day before the value date) and ends at 4.15pm.

payment until period 2. With probability $(1-p)$, only bank i receives a payment instruction. Again, with probability $(1-\varepsilon)$, it draws and intraday credit while with probability ε it delays the payment until period 2 and directly draws an overnight credit. Thus, the expected intraday volume equals $1-\varepsilon$.

With a fixed opportunity cost the probability is p that both banks receive a payment instruction and prefund their payments. Then payments are offset in period 0 and banks do not need to draw further intraday credits. The probability is $(1-p)$ that bank j does not receive a payment instruction. Bank i cannot pay back the intraday credit drawn at the end of period 0 and prolongs it to period 2. Whether settlement risk materialises does not play a role as bank i will have to pay back the intraday credit at the end of period 1 and needs to draw an overnight credit. Thus, the expected demand for intraday credit is $1+(1-p)$. Thus, with a fixed opportunity cost of collateral the demand for intraday credit is larger than under variable opportunity cost of collateral $(2-p > 1-\varepsilon)$.

Intraday credit demand can change in two possible ways. First, the overall demand measured as total intraday credit drawings over the day changes. Second, total drawings of intraday credits can be drawn for a shorter or longer period of time, i.e. outstanding intraday credits can be drawn earlier and be repaid later. None of these effects were observed after the change in collateralisation policy.

Figure 10 shows the maximum value of intraday credits outstanding and the established limit for the LSFF since 2005[18], when the new facility was introduced. The demand of intraday credits has steadily increased since 2003. However, as reported in Kraenzlin and Nellen (2012), this is primarily related to the increasing number of SIC participants. Only after the second half of 2007 a pronounced increased can be seen. However, this increase is related to the financial crisis starting in the second half of 2007. Another astonishing fact is that banks in drawing intraday credits have never exploited their established limits by a considerable margin. If their demand were not satiated, banks could exploit limits without incurring any substantial extra costs.

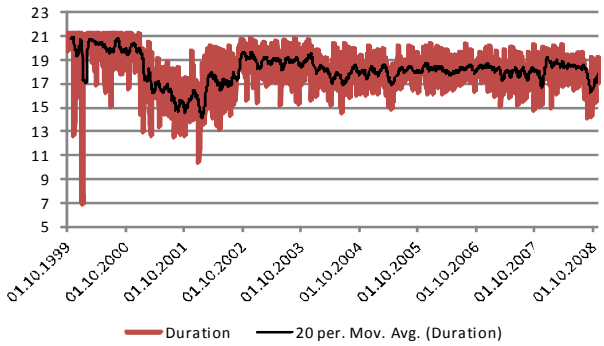
Figure 11 shows a value-weighted daily duration of intraday credit drawings as an avarage number of hours intraday credits are drawn. Again, we cannot observe a change in the demand for intraday credits.

We infer from this that banks perceived the opportunity cost of collateral to be fixed both before and after the introduction of the LSFF and settled early as a consquence. This provides evidence for the presumption stipulated by Ball et al. (2011). If banks can use collateral that belongs to their Basle II liquidity buffers, double duty allows them to draw intraday credits essentially for free. This is indeed the case for Switzerland. Both before and after the switch to the LSFF collateral used to back up intraday credits has been taken into account as Basle II eligible liquidity buffers.[19]. Thus, collateralisation policy crucially

[18] The heavy increase in the sum of LSFF limits from 2006 on is related to a Swiss finish of Basle II liquidity regulations for larger banks in Switzerland.

[19] See http://www.snb.ch/en/emi/liqq for a list of collateral elligible as liquidity buffers. See http://www.snb.ch/en/iabout/stat/statpub/bchpub/stats/bankench for statistical evidence on the liquidity regulation. The list of eligilbe collateral for intraday repos is found

Figure 11: Value-weighted daily duration of intraday credit drawings in hours



determines the opportunity cost of collateral and resulting settlement behaviour.

6 Conclusions

We analyse the intraday liquidity management game assuming settlement risk to be the driving force of strategic interaction. While Mills and Nesmith (2008) analyse a system with priced but uncollateralised overdrafts, we focus on settlement behaviour in RTGS systems with free but collateralised intraday liquidity. Settlement behaviour in such systems is shown to depend on the collateralisation policy. Because the policy influences the cost of intraday liquidity, it shows corresponding effects on settlement behaviour. Moreover, we find the effectiveness of a two-part tariff to depend on the collateralisation policy. In addition to intraday credit facilities with a variable or a fixed cost of intraday liquidity, we analyse the effect on settlement behaviour of the new facility introduced by the Federal Reserve System, namely free but collateralised overdrafts. Findings are validated by contrasting model predictions with stylised facts that result from a comparison between the settlement timing in Fedwire funds and SIC and from a change in the collateralisation policy of the SNB.

A variable opportunity cost of intraday credits results in late settlement. The two-part tariff may be able to induce early settlementbe but is difficult to implement. To induce early settlement the tariff has to consider appropriately the intraday and overnight cost of liquidity, payment uncertainty and settlement risk. One might consider whether a through-put rule is more appropriate for this setup. A fixed cost for intraday credit results in all strategy pairs to be equilibria. Even though early settlement is Pareto-efficient, early settlement is just one equilibrium. However, as all strategy pairs are equilibria, a small but strictly positive two-part tariff can easily establish early settlement as the unique

on http://www.snb.ch/en/ifor/finmkt/operat/snbgc/id/finmkt_repos_baskets.

equilibrium. Thus, the two-part tariff is an effective instrument to coordinate payment strategies and implement early settlement for a fixed opportunity cost of collateral. A collateralised overdraft facility also results in late settlement. Even though a two-part tariff is able to induce early settlement, careful calibration is required too to avoid multiplicity of equilibria.

Model predictions are validated by a comparison between Fedwire funds and SIC. Furthermore, both regulatory practice and stylised facts from a change in the collateralisation policy of the SNB support the view that a permanent prepledging requirement is a sufficient but not a necessary condition to result in a fixed opportunity cost of collateral. As Ball et al. (2011) point out, it may suffice for banks to be able to use assets as collateral for intraday credits that at the same time serve as liquidity buffers required by regulation - a practice often referred to as double duty.

The analysis suggests different policy conclusions. First, the Basle Commitee on Banking Supervision (BCBS) is currently reviewing how to regulate intraday liquidity risk under Basel III.[20] Ball et al. (2011) understand double duty on exisiting liquidity buffers under Basel II to be the reason for the relatively better performance of payment systems with collateralised intraday credit facilities. However, if a new intraday liquidity regulation changes the cost of intraday liquidity from a fixed one to a variable one, it may affect settlement performance of major payment systems. In particular, if the opportunity cost of collateral becomes variable due to new regulations, coordination on early settlement might become more difficult. Therefore, as Ball et al. (2011) suggest, RTGS systems might have to provide additional incentives to preserve early settlement. While their focus is on liquidity-saving mechanisms, we point out that a prepledging requirement for collateralised overdrafts can make the intraday liquidity cost sunk.

Second, Ota (2011) suggests a two-part tariff to be more efficient in comparison to through-put rules given an environment with a delay cost, payment certainty and heterogeneity with regard to participants' liquidity cost. While Ota (2011) highlights that his findings may not survive payment uncertainty, we analyse a liquidity management game without a cost of delay but assume settlement risk and payment uncertainty. We find payment coordination with a two-part tariff to be non-trivial unless the cost of intraday credit is fixed. Fixed or sunk costs are strategically irrelevant, leaving all strategy pairs as equilbria. Thus, a small but strictly positive two-part tariff is sufficient to induce early settlement. We find the calibration of the two-part tariff to be challenging for systems with a variable cost of intraday credit. Next to the cost of both intraday and overnight liquidity, the central bank would have to consider the extent of payment uncertainty and settlement risk to induce early settlement. Thus, we point out that the calibration of the two-part tariff is difficult and that a through-put rule to implement early settlement should be evaluated, in particular for system with intraday credits and a variable cost.

Third, one may think of collateralised overdraft as an instrument to overcome

[20] See BCBS (2010).

late settlement. The model predicts that a complete change from a system with a priced but uncollateralised daylight overdraft facility to a system with a free but collateralised daylight overdraft facility does not eliminate incentives to strategically delay payments. Thus, if the Federal Reserve System's new collateralised overdraft facility - next to the reduction of credit risk - is aimed to reduce settlement delay, additional instruments are necessary to induce early settlement. This puts the focus on a two-part tariff or a through-put rule. While early settlement Pareto-dominates other strategy pairs for any steepness of the two-part tariff, early settlement to be the unique equilibrium requires the two-part tariff to be above some threshold determined by the overnight interest rate, payment uncertainty and settlement risk.

Therefore, in line with Ota (2011) and this paper, the two-part tariff is effective and easy to implement for systems with an intraday credit facility that exhibits a fixed opportunity cost of collateral such as SIC. However, for systems with a variable cost of intraday credits a two-part tariff may not be recommendable as a wrongly calibrated tariff may destroy settlement coordination. To a somewhat lesser degree this holds true for systems that offer a collateralised overdraft facility. However, having reached the zero lower bound in many economies, this could be the perfect moment to introduce a two-part tariff.

While the choice of instrument to coordinate settlement early seems to be appropriate for SIC, Ota (2011) raises doubts on whether the calibration of the two-part tariff is appropriate. As outlined in Heller, Nellen and Sturm (2000), one has to consider that SIC serves both as a retail and a large-value payment system. This may call for further research, particularly if one considers Vital (1990) as well as Rochet and Tirole (1996). Rather than to understand the two-part tariff as an instrument to induce early settlement, they understand it as a device to sequence payments efficiently. This is in line with the observation by Nellen (2010) that SIC participants have released and settled small-value payments earlier and large-value payments later after the two-part tariff was introduced in April 1988. As discussed in this paper, the steepness of the two-part tariff indicates that it was not primarily aimed to provide incentives for the early settlement of large-value payments.

7 References

Angelini, Paolo (1998). An analysis of competitive externalities in gross settlement systems. Journal of Banking and Finance 22, 1-18.

Armantier, Olivier, Jeffrey Arnold and James McAndrews (2008). Changes in the timing distribution of Fedwire funds transfers. Federal Reserve Bank of New York Economic Policy Review, Volume 14, Number 2, 83-112.

Ball, Alan, Edward Danbee, Mark Manning and Anna Wetherilt (2011). Intraday Liquidity: Risk and Regulation. Bank of England Financial Stability Papers No. 11.

Bartolini, Leonardo, Spence Hilton and James McAndrews (2008). Settlement delays in the money market. Federal Reserve Bank of New York Staff

Report no. 319.

Basel Committee on Banking Supervision (2008), 'Principles for sound liquidity risk management and supervision', Bank for International Settlements.

Basel Committee on Banking Supervision (2009), 'International framework for liquidity risk measurement, standards and monitoring', Bank for International Settlements.

Basel Committee on Banking Supervision (2010), 'Basel III: International framework for liquidity risk measurement, standards and monitoring', Bank for International Settlements.

Bech, Morten and Rod Garratt (2003). The intraday liquidity management game. Journal of Economic Theory 109 (2), 198-219.

Bech, Morten, Antoine Martin and James McAndrews (2011). Settlement Liquidity and Monetary Policy Implementation: Lessons from the Financial Crisis. Presentation held at the Bank of Canada Conference on New Developments in Payments and Settlement,17/18 November 2011.

Federal Reserve System (2011). Guide to the Federal Rserve's Payment System Risk Policy on Intraday Credit. Updated to reflect policy revisions effective March 24, 2011.

Furfine, C. (2001): Banks as monitors of other banks: evidence from the overnight federal funds market, Journal of Business, 74, 33-57.

Heller, Daniel, Thomas Nellen and Andy Sturm (2000). The Swiss Interbank Clearing. Finanzmarkt und Portfolio Management, 14. Jahrgang 2000 - Nr. 4.

Koboyakawa, Shuji. (1997). The comparative analysis of settlement systems. Centre for Economic Policy Research Discussion Paper No. 1667.

Kraenzlin, Sébastien and Thomas Nellen (2010). Daytime is money. Swiss National Bank Working Paper Series 2010-6.

Jurgilas, Marius and Antoine Martin (2010). Liquidity-saving mechanisms in collateral-based RTGS payment systems. Bank of England Working Paper No.389.

Mills, David C. Jr. and Travis D. Nesmith (2007). Risk and concentration in payment and securities settlement systems. Journal of Monetary Economics 55, 542-553.

Mills, David C. Jr. and Samia Y. Husain (2009). Interlinkages between payment and securities settlement systems. Federal Reserve Board Working Paper.

Nellen, Thomas (2010). What drives settlement performance? Published in: Nellen, Thomas (2010). Essays in Payment Economics. Dissertation at the University of Berne. http://www.zb.unibe.ch/download/eldiss/10nellen_t.pdf.

World Bank (2008). Payment Systems Worldwide. A snapshot. Outcomes of the global payment system survey 2008. World Bank Financial Infrastructure and Research Series.

8 Appendix

8.1 Cost functions for Propositions 1 and 3

Equation (1/13) evaluates bank i's cost if both banks play morning and bank j sends its payment in the morning. The probability is p that bank j receives a payment instruction. Altough payments are offset, both banks incur the opportunity cost for drawing intraday credits because collateral has to be pledged ahead of sending payments. The morning cost only depends on bank i's action. The probability is $(1-p)$ that bank j does not receive a payment instruction. Therefore, bank i ends up with an intraday credit - it concludes both its morning and afternoon period with an intraday credit - and must borrow in the overnight market to cover it. Therefore, in addition to the intraday credit for the morning it bears the opportunity cost for the afternoon and the interest rate for the overnight loan.

Equation (2/14) pertains to bank i's cost if it sends a payment in the morning and bank j sends its payment in the afternoon. The probability is p that bank j receives a payment instruction. Bank i sends its payment and bears the opportunity cost for the morning. In the afternoon, bank j sends its payment. The probability is $(1-\varepsilon)$ that the payment is received by bank i and it can repay the intraday credit without having to draw an overnight loan. However, the intraday credit has to be prolonged from period 0 to period 1 causing opportunity cost ω. The probability is ε that a settlement shock occurs. In this case, bank i must also prolong the intraday credit and incurs the associated opportunity cost for another period. Furthermore, it ends ends up with an intraday credit at the end of period 1 and, therefore, must borrow in the overnight market to bring the account balance back to zero. Finally, the probability is $(1-p)$ that bank j does not receive a payment instruction. As before, bank i's cost of settlement is the sum of the opportunity cost of collateral and the overnight interest rate.

Equation (3/15) shows bank i's cost if it sends a payment in the afternoon while bank j sends its payment in the morning. The probability is p that bank j receives a payment instruction. Bank i's account balance will increase to 1. Bank i will then send its payment in the afternoon. Regardless of whether there is a settlement shock, bank i does not face a settlement cost as it enters the afternoon with a positive account balance. Bank i does neither have to borrow an intraday credit nor does it have to borrow in the overnight market. The probability is $(1-p)$ that bank j does not receive an instruction. Bank i sends its payment in the afternoon. The probability is $(1-\varepsilon)$ that the payment will go through. In this case, bank i's cost is $\omega + R$ because the payment requires an afternoon intraday credit and a loan from the overnight market to repay the intraday credit at the end of period 1. The probability is ε that a settlement shock occurs. In this case bank i does not draw an intraday credit and delays its payment to period 2. However, in period 2 it will have to draw an overnight loan in order to process the payment. Thus, bank i faces the cost of an overnight loan R in case a settlement shock occurs.

Equation (4/16) evaluates bank i's cost if both banks send payments in the

afternoon. The probability is p that bank j receives a payment instruction. The probability is $(1-\varepsilon)$ that there is no settlement shock. Then both payments will offset each other. However, banks incur the opportunity cost of collateral ω. The probability is ε that a settlement shock occurs. Because information regarding the shock is public, both banks delay their payments until period 2 to avoid the cost of drawing intraday credits. Even though payments would offset each other such that no overnight loans have to be made, banks have to prefund settlement. Therefore, banks incur the cost of an overnight loan. The probability is $(1-p)$ that bank j does not receive a payment instruction and bank i's cost is determined in the same manner as for equation (11).

8.2 Cost functions for Propositions 2 and 4

Equation (5/17) evaluates bank i's cost if both banks play morning. The probability is p that bank j receives a payment instruction. Since there is no possibility of a settlement shock taking place and payments offset each other, an overnight loan is not required. The probability is $(1-p)$ that bank j does not receive a payment instruction. Bank i ends up with an intraday credit drawn at the end of period 1 and must borrow in the overnight market to cover it. Therefore, in addition to the fixed opportunity cost ψ, bank i incurs the cost of an overnight loan.

Equation (6/18) pertains to bank i's cost if it sends a payment in the morning and bank j sends it in the afternoon. The probability is p that bank j receives a payment instruction. Bank i sends its payment in the morning and for that purpose will draw an intraday credit. In the afternoon, bank j sends its payment. The probability is $(1-\varepsilon)$ that the payment is received by bank i and the intraday credit can be repaid. Bank i is able to avoid an overnight loan. The probability is ε that a settlement shock occurs. In this case, bank i ends period 1 with an open intraday credit and must borrow in the overnight market to pay back the intraday credit. Finally, the probability is $(1-p)$ that bank j does not receive a payment instruction and bank i's cost is the opportunity cost plus the overnight interest rate.

Equation (7/19) analyses bank i's cost if it sends a payment in the afternoon while bank j sends its payment in the morning. The probability is p that bank j receives a payment instruction. Bank i's account balance increases to 1. Bank i then sends its payment in the afternoon. Regardless of whether there is a settlement shock, bank i does not incur any costs because it enters the afternoon with a positive account balance of 1. Either the payment goes out in the afternoon or it goes out in period 2. In any case, bank i does neither have to draw an intraday nor an overnight loan. The probability is $(1-p)$ that bank j does not receive a payment instruction. In any case, bank i sends its payment in the afternoon and bank i needs an overnight loan to pay back the intraday credit.

Equation (8/20) evaluates bank i's cost if both banks send payments in the afternoon. The probability is p that bank j receives a payment instruction. The probability is $(1-\varepsilon)$ that the payment is received by bank i. Thus, both

banks settle their payments in the afternoon and pay back their intraday credit without having to draw an overnight loan. The probability is ε that a settlement shock occurs. Thus, both banks send payments in period 2 and, therefore, both banks have to draw an overnight loan. The probability is $(1-p)$ that bank j does not receive a payment instruction, and bank i's cost is determined by the need to draw an overnight loan to pay back the intraday credit.

8.3 Cost functions for Propositions 3 and 6

Equation (9/21) evaluates bank i's cost if both banks play morning. The probability is p that bank j receives a payment instruction. Since there is no possibility of a settlement shock taking place, payments offset each other and there is no overdraft at the end of the morning period. The probability is $(1-p)$ that bank j does not receive a payment instruction. Bank i ends up with an overdraft at the end of period 1 and must borrow in the overnight market to cover it. Therefore, in addition to the fixed opportunity cost ψ bank i incurs the cost of an overnight loan.

Equation (10/22) pertains to bank i's cost if it sends a payment in the morning and bank j sends it in the afternoon. The probability is p that bank j receives a payment instruction. Bank i sends its payment in the morning and, thus, incurs an overdraft. In the afternoon, bank j sends its payment. The probability is $(1-\varepsilon)$ that the payment is received by bank i and the overdraft is eliminated. The probability is ε that a settlement shock occurs. In this case, bank i ends period 1 with an overdraft and must borrow in the overnight market to set the account back to zero. Finally, the probability is $(1-p)$ that bank j does not receive a payment instruction and bank i's cost is the opportunity cost plus the overnight interest rate.

Equation (11/23) analyses bank i's cost if it sends a payment in the afternoon while bank j sends its payment in the morning. The probability is p that bank j receives a payment instruction. Bank i's account balance increases to 1. Bank i then sends its payment in the afternoon. Regardless of whether there is a settlement shock, bank i does not need additional liquidity because it enters the afternoon with a positive account balance. Either the payment goes out in the afternoon or it goes out in period 2. The probability is $(1-p)$ that bank j does not receive a payment instruction. Bank i sends its payment in the afternoon and needs an overnight loan to set the account balance back to zero at the end of period 1or period 2.

Equation (12/24) evaluates bank i's cost if both banks send payments in the afternoon. The probability is p that bank j receives a payment instruction. If there is no settlement shock both banks settle their payments in the afternoon and payments offset so that no bank has to draw an overnight loan. If there is a settlement shock both banks send payments in period 2. Again, payments offset each other. The probability is $(1-p)$ that bank j does not receive a payment instruction. Therefore, bank i needs an overnight loan to set the account balance back to zero.