Essays in payment economics

Inauguraldissertation zur Erlangung der Würde eines
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der Wirtschafts- und Sozialwissenschaftlichen Fakultät der Universität Bern

vorgelegt von

Thomas Nellen

von Baltschieder/VS

2010

Die Fakultät hat diese Arbeit am 16.12.2010 auf Antrag der beiden Gutachter Prof. Dr. Ernst Baltensperger und Dr. Antoine Martin, als Dissertation angenommen, ohne damit zu den darin ausgesprochenen Auffassungen Stellung nehmen zu wollen.

To Dorothea Elvira Nellen-Viotti and Joseph Nellen

Preface

I am grateful above all to my supervisors Ernst Baltensperger and Antoine Martin for their advice, trust and generosity.

I am very much indebted to my co-author Sébastien Kränzlin for infecting me with his enthusiasm. By now, life told us both that the ‘money’ does not always compensate for the ‘daytime’ lost to it, indeed. Be that as it may, we will not perish but publish soon!

I am also grateful for having been able to work with my co-authors Jürg Mägerle, Robert Oleschak and Beatrice Kraus in other related projects.

Special thanks go to my colleagues at the Swiss National Bank for helpful discussions and valuable support: Andy Sturm, David Maurer, Marco Cecchini, Peter Karrer, Philipp Doesegger, Philipp Haene, Reto Nyffeler, Silvio Schumacher, Thomas Nitschka and Urs Birchler.

Finally, I would like to thank my parents who have made all this possible.

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Essays in payment economics

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

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Abstract

This note introduces three essays in payment economics I wrote to obtain the Doctor of Philosophy in Economics from the University of Berne. The first essay, *'Daytime is money'*, is an empirical investigation of the Friedman rule for intraday monetary policy. Taking notice of the fact that the intraday interest rate is close to but not equal to zero, the second essay, *'Determinants of intraday settlement timing'*, analyses settlement performance of payment systems from a theoretical perspective by modelling an intraday liquidity management game. The third essay, *'What drives settlement performance?'*, is dedicated to further empirical methods to investigate settlement performance, relating findings to the theoretical literature.

JEL classifications: C43, E58, G21, G28.

Key words: interbank money market, intraday credit, payment systems, bank behaviour, strategic games, reserve requirements, collateralisation

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1 Introduction

While Kahn and Roberds (2009) provide an extensive overview of the literature on payment economics, Green (2005) focuses on the central bank's role in payment systems, postulating that this role should be confined to

- first, the provision of a system of accounts that all financial intermediaries settling transactions for customers are eligible to hold and to use to settle 'interbank' transactions;
- and, second, the provision of free intraday credit that is sloley used to facilitate interbank transactions and not for investment.

These two essential roles of a central bank are the objects of investigation of the three essays introduced in this note.

2 Payment economics and monetary policy

While Martin and McAndrews (2010b) provide an overview of the literature, Freeman (1996) and Green (1999) were the first to explore the dichotomy between high overnight and low or basically zero interest rates for intraday monetary policy. By now, a large body of theoretical literature backs the idea of the Friedman rule for intraday monetary policy. Indeed, Martin (2004), Millard et al. (2006) and Bhattacharya et al. (2007) support existing intraday monetary policies by showing that a zero nominal risk-free intraday rate can enhance welfare due to the unique frictions that can arise in the intraday settlement of obligations. They show that this holds even in environments where a zero-rate overnight monetary policy might not be desirable.

While these papers relate monetary policy and payment economics on a theoretical level, in *'Daytime is money'*, Sébastien Kränzlin and me look at the issue from the empirical side. Based on trade data from the Swiss franc overnight interbank repo market we gain valuable insights into the intraday value of money. In analogy to Baglioni and Monticini (2008), we provide evidence that an implicit intraday money market exists. We further show that the introduction of the foreign exchange settlement system, Continuous Linked Settlement (CLS), increased the implicit value of intraday liquidity during CLS settlement cycle hours, thus providing further evidence of the cost of immediacy postulated in Kahn and Roberts (2001).

Furthermore, we provide evidence that - during the financial market turmoil from 2007 to 2009 - the implicit intraday interest in the secured money market was much less affected than that in the unsecured money market. While we find that the central bank can effectively set the implicit intraday interest rate equal to zero in a secured overnight market, findings for an unsecured overnight market by Baglioni and Monticini (2010) validate that the implicit intraday interest rate in the presence of credit risk is hardly forced down to zero. These findings are in line with the considerations put forward in the theoretical literature that the intraday interest rate should be set to zero in a risk-free environment.

The almost risk-free environment in the secured Swiss franc overnight market as well as for the Swiss National Bank's intraday credit operations is achieved through collateralisation by means of a repo transaction. Therefore, the implicit intraday interest rate is close to but not equal to zero. This is consistent with the idea that the implicit intraday rate is capped by the opportunity cost of the collateral pledged to obtain intraday liquidity from the central bank.

3 Settlement and monetary credit operations

A branch of the theoretical literature in payment economics analyses the strategic interaction among participants in payment systems that is understood to arise exactly due to the cost of intraday funding analysed in *'Daytime is money'*.

Starting with Koboyakawa (1997) and Angelini (1998), this literature is largely based on the delay cost approach. In the context of liquidity externalities, Angelini (1998) understands the bank's objective to minimise the opportunity costs of liquidity and the cost arising due to settlement delay. Each bank will postpone forwarding outgoing payments until the perceived marginal cost of delaying equals the marginal cost of providing liquidity. However, while a decision to postpone reduces the expected cost of liquidity for the sending bank, it also tends to increase the same cost by an analogous amount for the receiving bank, thereby generating a deadweight loss at the system level relative to a cooperative outcome. Furthermore, delayed payments on a system level are associated with negative effects on the quality of information available for cash management purposes. Since incoming payments are delayed, information on the net position is revealed later and causes cash managers to allocate higher than optimal end-of-day reserve holdings as derived from the literature on precautionary demand for reserves such as Baltensperger (1974).

Bech and Garratt (2003) investigate an intraday liquidity management game assuming a cost of delay. However, the intraday settlement patterns predicted are perceived to be inconsistent with the evidence as expressed in Green (2005). Therefore, the literature has begun to focus on other reasons why banks delay payments. Mills and Nesmith (2008) explain settlement behaviour on the basis of private costs associated with settlement risk. By delaying own payments information on incoming payments from other banks is revealed that reduces the uncertainty over incoming funds. Resolved uncertainty in turn helps to avoid potentially unnecessary and costly borrowings in the overnight market.

As in Mills and Nesmith (2008), I assume settlement risk to be the driving force of intraday settlement timing. They analyse a real-time gross settlement (RTGS) system without centralised queues and an automated overdraft facility. With *'Determinants of intraday settlement timing'* I close two gaps in the literature by investigating, first, a RTGS systems with centralised queues for which the central bank provides collateralised intraday credit, and, as a novelty in the literature, I analyse RTGS systems with centralised queues that settle on the basis of overnight reserve balances only. In payment systems based on central queues - be it with or without collateralised intraday credits - settlement has to be prefunded. The prefunding constraint results from the provision of collateralised credits as a source of funding. In contrast to uncollateralised overdrafts, such collateralised credits have to be actively drawn. The prefunding constraint is also applied in Koboyakawa (1997) and Bech and Garratt (2003).

The model is shown to predict stylised facts related to the Swiss Interbank Clearing (SIC) before and after the introduction of intraday credits. In particular, I show that in the absence of an intraday liquidity facility, minimum reserve requirements can influence settlement behaviour to a large extent by reducing or resolving rivalry in costly liquidity. Furthermore, I find the collateralisation policy applied by a central bank to be of crucial importance in determining settlement behaviour as it influences the opportunity cost of collateralisation. In particular, collateralisation on a credit-by-credit basis implies a variable opportunity cost whereas collateralisation on a pre-pledged basis results in a fixed opportunity cost. Interestingly, stylised facts from before and after the Swiss National Bank's policy change suggest that banks perceive opportunity costs of collateral to be fixed irrespective of the collateralisation policy.

Assuming a variable opportunity cost, Mills and Nesmith (2008) predict a late settlement equilibrium for Fedwire funds. I suggest an early settlement equilibrium for SIC under the assumption of a fixed cost of collateral. Comparing stylised facts of Fedwire funds and SIC, the models' predicitions are in line with settlement taking place substantially later in Fedwire funds than it does in SIC. While the overdraft fee charged by the Federal Reserve System results in banks facing a variable cost of intraday liquidity, the fixed opportunity cost perceived by SIC participants results in the strategic irrelevance of funding costs. Therefore, the central bank's collateralisation policy influences settlement behaviour via the determination of the opportunity cost of collateral.

The overall cost implications of different policies are not easy to capture. However, the empirical evidence provided in *'Daytime is money'* suggests that the opportunity cost of collateral is lower than the overdraft fee charged by the Federal Reserve System in order to be compensated for and to lower the credit risk it encounters by providing uncollateralised overdrafts. A direct policy conlcusion out of this set of combined findings is that the Federal Reserve System should introduce an overdraft system based on prepledged collateralisation. This might, first, reduce overall intraday funding costs and, second, result in earlier settlement. As a consequence, settlement risk is lowered and the Federal Reserve System frees itself from credit risk resulting from uncollateralised overdrafts.

4 Extracting empirical evidence

The literature on RTGS systems suffers from a dichotomy. One branch of literature is theoretical and the other simulation based. The former allows to analyse behavioural settings and is based on anecdotal and descriptive evidence. Econometric verification is rare and what has been generated as valuable analytical insights suffers from this caveat. Even though the simulation based literature yields valuable insights into the mechanics of payment systems, it suffers from a type of Lucas critique. In essence, simulations can not take account of behavioural reactions induced by the investigated policy changes.

Against this background, the third paper, *'What drives settlement performance?'*, furthers empirical methods to analyse RTGS systems. I describe old and develop new indicators to analyse real data in the context of RTGS systems. Part of the evidence on SIC presented in *'Determinants of intraday settlement timing'* is also based on this work.

Settlement performance is defined as the trade-off between liquidity and delay. Bartolini et al. (2008) find evidence that strategic delay of payments is a real phenomenon that takes place in the decentrally managed queues of participants. However, the prevailing definition of delay applied in empirical research is based on centrally managed queues and suffers from two caveats. On the one hand, it can not take into account for strategic delay being hidden in decentralised queues, and, on the other hand, it is not applicable for systems with an intraday overdraft facility as this type of system does not provide a central queuing facility. Therefore, as a major innovation in *'What drives settlement performance?'* I present a new definition of settlement delay such that it is possible to do comparative empirical research on the basis of a comprehensive definition of settlement delay.

Since information on strategic delay is private, we have to rely on a proxy. I suggest a measure that takes all payments to be in delay since the beginning of the settlement day until settlement actually takes place. Admittedly, this extension of the definition of delay overstates delay. However, in constrast to a definition based on central queuing that both overstates and understates delay over time, this new definition does only overstate delay. Therefore, even though the new definition results in a distorted measure, it yields at least a measure that is consistently distorted over time and does not entirely ignore strategic delay.

An econometric analysis of settlement performance reveals that the trade-off between delay and liquidity is to a large degree explained by settlement value and available liquidity. However, other variables such as behavioural and environmental ones are relevant too and help to explain performance. In particular, I find that the earlier release of payments positively influences settlement performance in a RTGS system with central queues. This is in line with the theoretical literature on liquidity-saving mechanisms such as Martin and McAndrews (2010a) and Jurgilas and Martin (2010). In Atalay et al. (2010), the effects of a liquidity-saving mechanism are assessed to be significant if introduced into a pure RTGS system. I find that the effects of a balance reactive liquidity-saving mechanism can be further increased by releasing payments earlier.

As mentioned above, the theoretical literature such as Angelini (1998) postulates free-riding behaviour. An underlying assumption of this idea is that the distribution of liquidity among participants does not influence settlement performance. In order to test this hypothesis, I construct two indicators measuring individual liquidity contribution in relation to individual settlement value.

Whereas a first measure looks at dispersion giving equal weight to each participant, a second indicator weighs participants according to their settlement value. Consistent with the theory, none of these indicators is found to influence settlement performance.

5 Conclusions

The essays introduced in this short note provide evidence that even if a central bank confines itself to the two roles in the payment system postulated by Green (2005), it faces a difficult and demanding task. Altough payment economics has just scratched the surface of the plumbing system of the economy, it provides theoretical backing and some empirical evidence for that central banks can influence the welfare effects of settlement frictions in payment systems. However, how central banks should exactly perform the two roles remains a challenging field of theoretical and applied research.

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

November 21, 2011

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Daytime is money

Sébastien Kraenzlin and Thomas Nellen*

November 14, 2010

Abstract

Based on trade data from the Swiss franc overnight interbank repo market we gain valuable insights into the daytime value of money. In analogy to Baglioni and Monticini (2008), we provide evidence that an implicit intraday money market exists. We further show that the introduction of foreign exchange settlement system, Continuous Linked Settlement, increased the implicit value of intraday liquidity during settlement cycle hours, thus providing further evidence of the cost of immediacy. Finally, we provide evidence that during the financial market turmoil the implicit intraday interest in a secured money market was less affected than that in an unsecured money market.

JEL-Codes: E58, G21, G28

Keywords: interbank money market, intraday credit, term structure, liquidity crisis

*Sébastien Kraenzlin, Senior Economist, Money Market and Foreign Exchange, Swiss National Bank (E-mail: sebastien.kraenzlin@snb.ch). Thomas Nellen, Senior Economist, Oversight, Swiss National Bank (E-mail: thomas.nellen@snb.ch). The authors are indebted to H. Baumer, P. Haene, K. Hug, M. Schlegel and A. Sturm for valuable discussions. The authors also thank two anonymous referees for valuable comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily represent those of the Swiss National Bank.

1 Introduction

The institutional frameworks through which central banks provide the financial system with intraday and overnight liquidity share a number of features. Martin and McAndrews (2008) provide a summary of the literature, which points to one crucial and puzzling difference between intraday and overnight liquidity: There is an interbank market for overnight reserves whereas there appears to be no interbank market for intraday reserves. We provide empirical evidence that the overnight rate in the Swiss franc repo interbank money market shows a downward trend throughout the operating day of SIX Interbank Clearing (SIC), the Swiss real-time gross settlement (RTGS) system. Based on real-time trade data from the Swiss franc repo market, we closely follow the approach by Baglioni and Monticini (2008) and derive an implicit intraday interest rate from the intraday term structure of the overnight market. We conclude that, in Switzerland, like in some other countries as well, an implicit intraday interbank market for funds exists.

The literature on monetary theory (e.g. (Bhattacharya et.al. 2007)) and payments (e.g. (Mills and Nesmith 2008)) suggests that the implicit intraday interest rate should be set to zero. Like other central banks, the Swiss National Bank (SNB) offers free but collateralized intraday credit. The deviation found in the interbank market from this zero interest rate may be attributable to the opportunity cost of collateral or the uncertainty on the availability of funds in the interbank market, as Baglioni and Monticini (2010) suggest. However, the secured interbank market in Switzerland remained active throughout all phases of the financial crisis and, since its opportunity cost of collateral is the same as that of the SNB's intraday credit facility, it is likely that other frictions related to money's role as a medium of exchange are decisive. We interpret the existence of an implicit intraday interest rate as evidence for the cost of immediacy of

RTGS systems postulated by Kahn and Roberds (2001). Using a neoclassical monetary model they show that if intraday credit is available from the central bank on a collateralized basis, RTGS will impose an intraday liquidity cost. This also mirrors the theoretical findings outlined in VanHoose (1991) and Angelini (1998), where a model of a bank's intraday liquidity management in an RTGS system is applied.

The cost of immediacy of RTGS systems is further highlighted by the change that took place after the introduction of the foreign exchange settlement system Continuous Linked Settlement (CLS) in 2002.[1] During CLS opening hours, the level of the implicit intraday interest rate rose. The introduction of CLS thus further increased the cost of immediacy. Incorporating settlement features such as payment-versus-payment (PVP) or delivery-versus-payment (DVP) mechanisms into RTGS systems can increase the number and value of time-critical payments that have to be settled before a certain time of day. As a consequence, banks face higher intraday liquidity needs for meeting their settlement obligations.

The available data covers the period of financial market turmoil which started in August 2007. We find evidence that, compared to the periods before the crisis, banks were willing to pay a premium to obtain overnight funds in order to settle their payments in CLS and SIC in good time. This can be taken as evidence that tensions resulting from uncertainties over payments and refinancing conditions increased during the crisis, mirroring the theory put forward by Angelini (2000). This is further substantiated by the fact that banks drew substantially more intraday credits during the first phase of the financial crisis until the time of the collapse of Lehman Brothers. After this, tension was resolved through massive injections of reserves by the SNB. Consequently, the implicit hourly interest rate moved back to pre-crisis levels.

[1] For more information on CLS and its settlement mechanism see (Kahn and Roberds 2000).

The paper is structured as follows. Section 2 provides a short description of SIC, outlines the data stemming from the Eurex repo trading platform and presents some stylized facts relating to the data. In the subsequent section, the econometric methodology is presented. The last two sections discuss the results and provide concluding remarks.

2 SIC, data and stylized facts

SIC, which began its operations in 1987, is one of the oldest RTGS systems.[2] Ever since the early stages of planning, the idea has been to provide for the settlement of various interbank payment services in SIC. In 2002, the integration of CLS took place. This was done in a quite straightforward way. All CLS members were given a special subaccount in SIC. This account serves the sole purpose of settling CLS-related cover payments. For all other payments, the main accounts are used. SIC operations start at 17.00 p.m. the day before the actual value date. End of day is scheduled for 16.15 p.m. Within the SIC settlement day, CLS settlement cycles take place on an hourly basis from 7 a.m. to 12 p.m. on the actual value date. CLS members have to meet a pay-in schedule set by CLS in good time. This requires large amounts of reserve balances to be transferred during specific time slots.

The data used in this study consists of interest rates charged for Swiss franc overnight repo transactions between commercial banks on the Eurex repo trading platform.[3] In particular, each data point provides information on the two banks involved, the interest rate charged, the collateral category chosen, and the cash amount provided. The sample covers all transactions concluded from 18 June 1999 to 31 December 2009. The Eurex repo trading platform is the representative market for repo transactions in Swiss francs. Cash settlement takes

[2]For a comprehensive description of the system, see (Heller et al. 2000).

[3]For a detailed overview of the characteristics and development of the Swiss franc repo market, see (Jordan 2007) and (Kraenzlin 2007).

place on the main accounts of participants in SIC whereas securities settlement takes place in the books of the Swiss central securities depository. All banks that have access to this trading platform can also obtain free intraday funds from the SNB. This standing facility was introduced in 1999 and has been used intensively by market participants since then. Starting with the introduction of intraday liquidity specifically designated for CLS, the average monthly drawn volume increased by CHF 4 billion to approximately CHF 7 billion. During the crisis, the average monthly volume drawn increased to roughly CHF 10 billion. This increase can be ascribed to banks' precautionary behavior designed to prevent the emergence of rumors that they were in arrears with their payment obligations. After the collapse of Lehman Brothers and the massive injection of reserves by the SNB, coinciding with a level of reserves substantially above the pre-crisis level of CHF 5 billion, the use of intraday gradually fell to a level of CHF 6 billion (see figure 1).

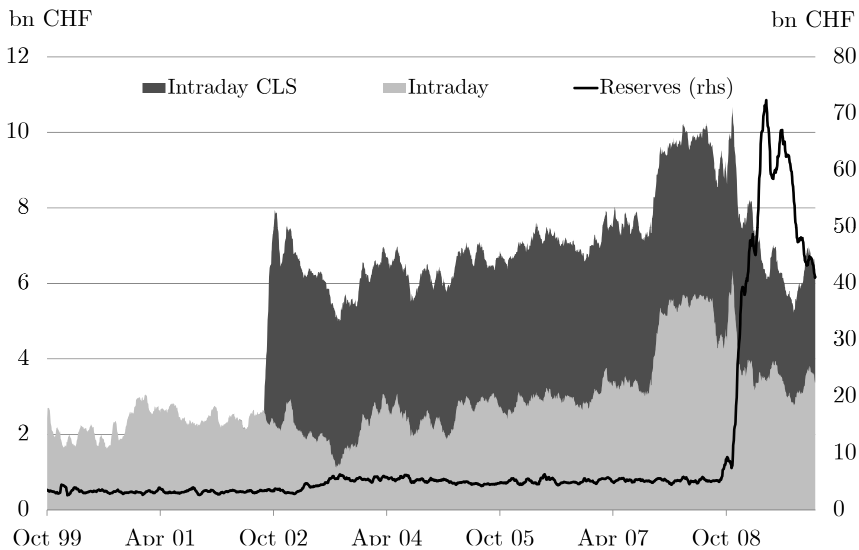

Figure 1: Average intraday volume drawn and level of reserves by month (in billion CHF)

The overnight repo market is the most liquid segment of the Swiss franc repo market. During the period under consideration a total of approximately

130 banks acted either as cash taker or provider. Since the introduction of the platform in 1999, the average number of active banks as well as the average daily volume has increased significantly. In 2000, nine banks traded an average daily volume of CHF 320 million, while in 2009, approximately 30 banks traded CHF 4 billion per day. Overall, the dataset consists of 119,807 overnight transactions conducted on 2,647 business days.[4] Approximately 45% of the overnight liquidity was transacted during the last two hours of the business day (between 2 and 4 p.m.), both in the periods before and after CLS. After the start of the financial crisis and before the collapse of Lehman Brothers, significantly more overnight liquidity was traded in the afternoon, approximately 55%. During this phase, substantially more intraday credits were drawn, showing that banks were willing to substitute overnight credits in the early morning with intraday credits and refinance themselves later in the day. After mid September 2008, we see a shift in trading activity towards the morning hours (see figure 2).

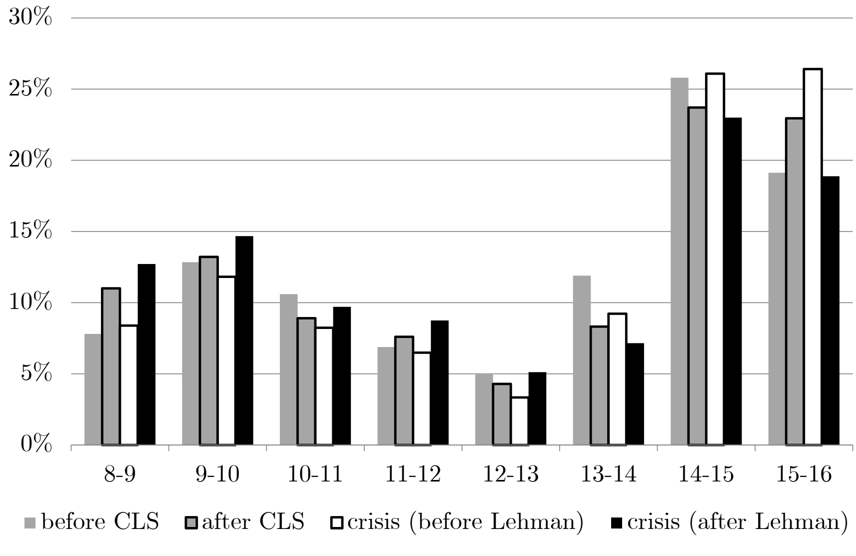

Figure 2: Hourly overnight volume in % of total

[4]These transactions are fully comparable with each other as they are made against SNB eligible collateral and as the collateral is not subject to a haircut (or initial margin). No haircut applies as the net exposure a party holds vis-a-vis each participant is calculated twice daily. If the net exposure exceeds the unilaterally defined threshold, a margin call is triggered. Credit and market risks are therefore offset to a considerable extent and as a result no haircut applies.

3 Methodology

We estimate the implicit intraday term structure of the overnight interest rate applying the same regression analysis as in Baglioni and Monticini (2008). The regression is run for the whole sample, namely from 18 June 1999 to 31 December 2009.[5] The sample not only covers the period after the introduction of CLS on 10 September 2002 but also the period of financial market turmoil which started in August 2007. On the one hand, we can assess whether the introduction of PVP for foreign exchange transactions, namely the introduction of CLS, increased the cost of immediacy.

An increase in the implicit price for intraday credits would validate the hypothesis by Baglioni and Monticini (2008), that CLS has fostered the establishment of an implicit market for intraday credits. On the other hand, we can analyze the impact of the financial market turmoil on the intraday pattern of the overnight rate and compare the results with those obtained by Baglioni and Monticini (2010), who analyze the intraday pattern for the minimum reserve maintenance period directly before and after the outbreak of financial market turmoil in August 2007.

In order to measure the implicit intraday interest rate we closely follow the approach adopted by Baglioni and Monticini (2008). Let $t = 1, ..., 8$ denote the time bands during the day, with $t = 1$ being the first time band from 8 a.m. to 9 a.m. and $t = 8$ the last time band from 15 p.m. to 16 p.m.[6] Trades are settled immediately after they are concluded. Once a trade is concluded, the securities are instantaneously blocked and a payment message with high priority is sent to SIC. Given the availability of securities and funds, settlement usually takes

[5]The last two days of the minimum reserve period as well as the last day of the month are excluded from the regression, as overnight rates tend to be particularly volatile on these days. See (Benito et.al. 2006) for an empirical analysis on the volatility of the euro overnight interest rate (EONIA).

[6]Banks can conclude trades on the Swiss franc repo market starting at 7 a.m. However, since trades are seldom concluded between 7 a.m. and 8 a.m., the first time band is defined to take place between 8 a.m. and 9 a.m.

place within a few seconds.[7] Repayment of all overnight trades concluded on the Swiss franc repo market is automatically triggered by SIS at 7:50 a.m. Hence, compared to an overnight trade concluded at 10 a.m., an overnight trade at 9 a.m. allows the cash taker to dispose of the money for one more hour. The set of hourly interest rates $[r_1, r_2, ..., r_8]$ thus represents the "intraday term structure" of the overnight rates and, therefore, the intraday price of money. In contrast to Baglioni and Monticini (2008), r_t represents the hourly "volume-weighted" interest rate.

To account for day-to-day differences in the level of overnight rates which may, for example, result from interest rate hikes or "day-specific" tensions, an hourly interest rate differential is derived ($\bar{r}_t$). The hourly interest rate differential is calculated by taking the difference between the "volume-weighted" interest rate (r_t) charged on overnight loans for each hourly band ($t = 1, ..., 7$ or 8) and the overnight rate over the entire day (r_T). Finally, this differential is used to obtain the net intraday term structure.

To estimate the intraday term structure of the overnight interest rate, we run a least square dummy variable regression. We use equation (1) to test whether the overnight rate significantly depends on hourly dummies ($d_i = 1$ if $t = i$ and $d_i = 0$ otherwise) for each opening hour of the Swiss franc repo market. The time band $t = 1$ (from 8 to 9 a.m.) is used as the reference variable and is represented by the constant (α). ε_t are the regression residuals. In order to directly evaluate the effect of CLS and the financial market turmoil we add hourly dummies for these subperiods. The hourly dummies ($d_{cls,i}$) cover the period from the introduction of CLS on 10 September 2002 to the date of the outbreak of the crisis, namely August 8, 2007. The hourly dummies ($d_{bl,i}$) cover the phase after the outbreak of the financial crisis until the collapse of Lehman

[7] In 2008 and 2009, the settlement of an overnight repo took place, on average, ten seconds after conclusion of business on the electronic trading platform.

Brothers on September 15, 2008. $d_{al,i}$, finally, comprises the phase after mid September 2008 to the end of the sample. The division in these subperiods avoids specific CLS effects being identified which may, for example, be due to the financial market turmoil. The division into two crisis periods is explained by the fact that, after the collapse of Lehman Brothers, the SNB started to provide the banking system with generous amounts of liquidity and lowered its repo rate to five basis points. The low level of interest rates and the high level of reserves are likely to have affected the intraday term structure of the overnight interest rate. A significant dummy variable in one of these subperiods states that the hourly interest rate differential is significantly different from the hourly value of the reference period, which is the period before the introduction of CLS. In order to evaluate whether the coefficients from the three subperiods are different from each other, we eventually test the null hypotheses that the dummy variables of the respective hours are the same.

$$\bar{r}_t = \alpha + \sum_{i=2}^{8} \beta_i d_i + \sum_{i=1}^{8} \gamma_i d_{cls,i} + \sum_{i=1}^{8} \delta_i d_{bl,i} + \sum_{i=1}^{8} \theta_i d_{al,i} + \varepsilon_t \tag{1}$$

4 Regression results

The regression results are displayed in table 1 in the appendix and plotted in figure 3. For the period before the introduction of CLS, the constant, which represents the time band from 8 to 9 a.m., is positive and significant. This implies that banks pay significantly higher prices at the beginning of the day than the daily "volume-weighted" overnight rate. Thereafter all coefficients are negative and become significantly different from zero, starting from 11 a.m. At noon, for example, banks paid on average $2bp$ less than in the early morning. As the day proceeds, this difference increases up to $3.6bp$. This in turn implies that the price for overnight funds was approximately 2.6bp below the daily "volume-weighted" overnight rate. Regression results for the sample before the introduction of CLS imply a clear downward pattern of the overnight interest rate throughout the opening hours of the Swiss franc repo market. However, economically the difference is negligible compared to an average level for the overnight rate of 2%.

Comparing the coefficients for the period before and after introduction of CLS reveals that the introduction of CLS marks a structural break. Before the introduction, all coefficients – apart from the constant – are negative, and starting from the fourth time band (11 to 12 a.m.) statistically different from zero. This indicates that the banks' willingness to pay for overnight funds decreased at an early stage of the day. After the introduction of CLS, by contrast, the majority of coefficients for the morning time bands ($d_{cls,10}$ to $d_{cls,12}$) remain positive. Until 10 a.m. the mark-up in the morning hours is equivalent to the price paid during the first time band (8 to 9 a.m.) of the period before September 2002. Thereafter the mark-ups amount to roughly 1.5bp and are significantly different from the hourly interest rate differentials of the preceding period. Hence, after the introduction of CLS, overnight rates stay as high as at the beginning of the day and even increase, the closer the end of the CLS settlement cycle gets. This confirms the result that the value of intraday money has increased during the hours of the CLS settlement cycle. The intraday term structure then follows the clear downward pattern seen beforehand. Since the hourly overnight rate decreases later in the day than in the sample before the introduction of CLS, the decline in banks' willingness to pay in the afternoon is higher (2.4bp) than in the period before CLS (1.5bp). The total difference from the beginning to the end of day fell from (3.6bp) to (2.9bp). The increasing use of intraday credits due to CLS and the reduction of settlement risk through CLS led to a flatter intraday term structure. Overall, the introduction of CLS helped to stabilize the implicit intraday interest rate around zero even though it remained high during the CLS settlement cycle.

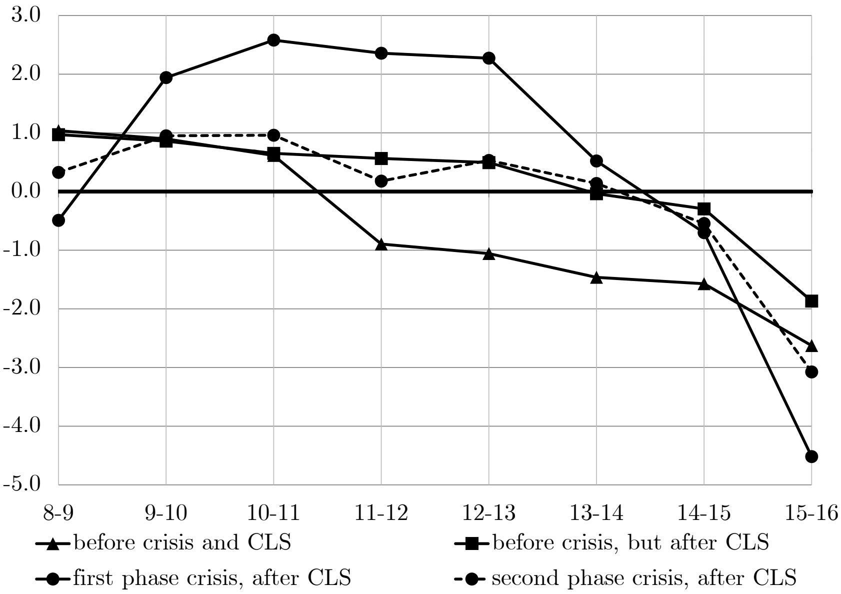

Figure 3: Intraday term structure (in bp)

The coefficients on the dummy variables ($d_{bl,i}$ and $d_{al,i}$) depict the effects of the money market turmoil on the intraday pattern of the overnight rate. For the period before the collapse of Lehman Brothers ($d_{bl,i}$), regression results indicate that banks paid – with the exception of the first two time bands – up to $3.3bp$ more in the morning than before the crisis. From 10 to 11 a.m. the mark-up reached its peak and reduced strongly after 13 a.m. During the CLS settlement hours the implicit intraday interest rate was significantly higher than before. Therefore, banks were willing to pay a premium in order to obtain overnight funds early in the morning, either to settle their payments in CLS and SIC in good time or to reduce uncertainty regarding their refinancing conditions later in the day. However, the arbitrage opportunity provided by free intraday credits from the SNB helped to prevent a higher increase in the implicit intraday interest rate. Banks effectively substituted overnight credits in the early morning with intraday credits (see figure 1) and entered the overnight market later in the afternoon, when the hourly interest rate differential converged to that before the outbreak of the crisis. During the last trading hour (3 to 4 p.m.) banks paid approximately 2.6*bp* less than before the money market turmoil started. This in turn implies that as soon as the majority of payments had been settled in the payment system and liquidity positions had been balanced out, the implicit intraday value of overnight funds substantially dropped. The F-tests confirm that the mark-ups are significantly different from pre-crisis levels.

For the period after the collapse of Lehman Brothers ($d_{al,i}$), regression results indicate that banks did not pay significantly more than after the introduction of CLS (before the crisis). For the majority of the coefficients, the null hypothesis, that $d_{al,i} = d_{cls,i}$, cannot be rejected. Hence, overnight money market tensions did not result in an increase of the implicit intraday interest rate as was the case before the collapse of Lehman Brothers. This result can mainly be ascribed to the fact that the SNB started to provide the market with generous amounts of liquidity and lowered its repo rate from 1.9% to five basis points. Bank reserves amounted to more than CHF 60 billion, compared to a pre-crisis level of CHF 5 billion (see figure 1). As the majority of banks held sufficient funds, liquidity needs stemming from SIC and CLS were less pronounced than during the first part of the financial market turmoil. Repo market activity during the day returned to pre-crisis levels and the amount of intraday credit drawn even dropped to pre-CLS levels.

Overall, regression results provide evidence that the value of intraday money increased during the hours of the CLS settlement cycle. This can be taken as evidence that the introduction of PVP for foreign exchange settlement has increased the cost of immediacy during the hours of the CLS settlement cycle. Before CLS, a bank could delay paying its leg of a transaction until it was convenient and less expensive. With the introduction of CLS and hence PVP, banks have to make their payments at a specific time of the day – which is relatively early in Switzerland – when there is competition from other payment needs. We estimate the mark-up on hourly overnight rates due to CLS to be approximately $0.46bp$ per hour, leading to a total of roughly $1.4bp$ for the CLS settlement cycle.[8] Contrary to our findings, Baglioni and Monticini (2008) find a declining implicit intraday term structure throughout the day in a sample that covers a period after the introduction of CLS. A possible explanation may be the difference in relative importance of CLS banks in the different markets. In markets where CLS banks are the dominant players, such as in Switzerland, the implicit cost of intraday funding during CLS hours is more likely to increase.

Finally, we find evidence that during the first phase of the crisis, banks became more risk averse and developed a preference for settling their payments early in the morning to avoid the emergence of rumors that they were in arrears with their payment obligations. This higher risk awareness in turn led to a higher willingness to pay for overnight funds early in the morning. However, the arbitrage opportunity of free intraday credits from the SNB helped to tame a higher increase in the implicit intraday interest rate. In other words, some banks were willing to pay a premium of up to $2bp$ to obtain overnight funds in order to settle payments early in the morning, whereas other banks were willing to substitute overnight credits in the early morning with intraday credits and profit from cheaper overnight funds later in the afternoon. Contrary to Baglioni and Monticini (2010) – who analyze the intraday pattern for the maintenance period directly before and after the outbreak of the financial market turmoil in August 2007 – the effects of the crisis on the implicit hourly overnight rates are much less pronounced in our analysis. This may be due to the fact that the analysis by Baglioni and Monticini (2010) is based on data stemming from

[8] To quantify the average hourly mark-up we sum up the differences between the $\bar{r}_{\text{ after CLS}} - \bar{r}_{\text{ before CLS}}$ at 8 a.m. and 12 p.m. respectively and divide this sum by the number of time bands.

an unsecured money market, where counterparty risk affects the interest rate paid. Banks with limited creditworthiness have become more risk averse during the crisis and as a consequence tried to obtain overnight funds early in the morning. The higher implicit intraday interest rate in the morning may thus be due to a sample selection bias, resulting from higher trading activity of worse rated cash takers in the morning and the well rated cash takers in the afternoon. The difference may also result from the fact that we consider a longer time span, namely from August 2007 to September 2008, where month-specific effects may be averaged out. We find no evidence that banks' willingness to pay changed after the collapse of Lehman Brothers compared to the period after the introduction of CLS but before the outbreak of the financial market turmoil. This evidence can be explained by the fact that the overall interest rate level was near the zero lower bound – limiting the scope of variation in overnight rates – and the banks' reserves were at historically high levels, leaving banks without tensions from either the payment or the refinancing side. Economically the intraday interest rate remained basically insignificant throughout the entire period of financial market turmoil.

5 Comparisons and conclusions

The theoretical literature represented by VanHoose (1991) and Angelini (1998) postulates the emergence of an intraday interest rate in the interbank market. Baglioni and Monticini (2008) perceive the empirical evidence on the price of intraday liquidity to be rare and inconclusive. Indeed, (Angelini 2000) finds no relevant intraday pattern in the level of interest rates for the overnight market in the Italian screen-based e-MID interbank market for the period from mid-1993 to end-1996. Looking at the same market, Barucci et.al. (2003) find a downward pattern for the period January 1999 to August 2001, and Baglioni and Monticini (2008) find a clear downward pattern for the period 2003 to 2004. For the unsecured US overnight federal funds market, Bartolini et.al. (2005) find a similar downward pattern for the deviation of an average half-hourly rate from the target rate in the period from February 2002 to September 2004. This paper provides further empirical evidence on the implicit price of intraday liquidity. Based on data from the secured overnight market in Switzerland, we show that a downward sloping intraday term structure has existed at least since the introduction of the Swiss franc repo market in 1999. This is additional evidence for the theoretical results by VanHoose (1991) and Angelini (1998).

Baglioni and Monticini (2008) explain the switch from no discernable pattern to a clear downward pattern of the overnight rate that took place between Angelini (2000) and their own analysis by the introduction of real-time settlement gross settlement and the PVP mechanism for foreign exchange transactions (TARGET in 1999 and CLS in 2002). Baglioni and Monticini (2008) suggest that the move towards gross settlement and PVP made intraday liquidity more valuable and created incentives for banks to charge a price for it. We find evidence supporting these suggestions. We interpret this as evidence for the "cost of immediacy" of RTGS systems as postulated by Kahn and Roberds (2001). Additionally, we provide empirical evidence that the introduction of CLS has increased the price of intraday liquidity during the CLS settlement hours. This is due to the strict pay-in schedule of the CLS settlement cycle. Since the introduction of CLS, the level of overnight rates has remained more or less constant from the beginning of the day until the end of the CLS settlement cycle at noon. In the afternoon the implicit price of intraday liquidity follows a clear downward pattern. Overall, reduced settlement risk through CLS and high amounts of intraday liquidity drawn from the SNB has slightly reduced the difference between overnight interest rates in the morning and in the afternoon compared to the period before the introduction of CLS.

As the dataset covers the financial market turmoil which started in August 2007, we also analyze the impacts of the financial market turmoil on the intraday pattern of the overnight rate. We find evidence that, compared to the period before the crisis, banks were willing to pay a premium of up to 2.5bp to obtain overnight funds in order to settle their payments in CLS and SIC in good time. This can be taken as evidence that tensions resulting from payment systems increased during the crisis. The higher implicit hourly overnight rates in the morning may also have been complemented by uncertainties of banks as to their own refinancing conditions in the afternoon. Contrary to Baglioni and Monticini (2010) – who analyze the intraday pattern for the maintenance period directly before and after the outbreak of the financial market turmoil in August 2007 – the effects of the crisis on the implicit hourly overnight rates in Switzerland are less pronounced and insignificant in economic terms.

Overall, the intraday term structure derived from secured interbank transactions in Switzerland can be regarded as economically insignificant. The SNB sets intraday interest rates equal to zero by providing free but collateralized intraday credits. This policy appears to be successful in containing tensions in a secured interbank market stemming from payment needs as well as money market stress. This may be taken as evidence that, in a secured interbank market, a higher cost of collateral and the uncertainty about the availability of funds as suggested by Baglioni and Monticini (2010) play much less of a role than in an unsecured market. Furthermore, the evidence found suggests that a central bank's policy of maintaining intraday interest rates at zero can be effective in secured interbank markets whereas it may not be effective in unsecured interbank markets.

It is also interesting to compare the hourly implicit intraday interest rate of the euro with that of the Swiss franc money market. The difference between the beginning and end-of-day overnight interest rates are virtually the same, namely roughly 3.5*bp*. This corresponds to an hourly fee of 0.45*bp*. Baglioni and Monticini (2008) point out that the market intraday interest rate in the US is pegged by the overdraft fee applied by the Fed. The annualized hourly fee for overdrafts is 1.5*bp*.[9] Furfine (2001) derives the hourly implicit intraday interest rate for the unsecured US money market and obtains a rate of 0.9*bp*. Compared to the empirical evidence for the US, the hourly implicit intraday interest rate for the Swiss franc and euro money market are half. Baglioni and Monticini (2008) argue that their estimate of the intraday interest rate provides an indirect evidence that the cost of collateralizing intraday loans from the Eurosystem is lower than the fee charged by the Fed. This might explain why the Fed is investigating the introduction of an additional collateralized intraday overdraft facility for Fedwire.[10] The drawback is that in times of financial crisis the implicit hourly intraday interest rate in an unsecured market can raise substantially above the level of the Federal Reserve Systems hourly overdraft fee. Baglioni and Monticini (2010) report an hourly fee of 2.19*bp* for the maintenance period directly after the outbreak of the financial turmoil.

In normal times, the similarity of the hourly implicit intraday interest for the Swiss franc and euro money markets can, in turn, be explained by the negligible counterparty risk premium in unsecured interbank transactions and by the large overlap of the collateral policies applied by the two central banks. Although the SNB allows for a much wider variety of currencies than the European Central Bank (ECB), more than 80% of the SNB-eligible collateral is also eligible for the ECB. The majority of the collateral delivered in repo transactions with the SNB and between banks (interbank repo market) is denominated in euros.[11]

[9] See (Baglioni and Monticini 2008) for the derivation of the annualized hourly fee.

[10] See the Federal Reserve Board's request for public comment on its proposed changes to its daylight overdraft policy:
www.federalreserve.gov/newsevents/press/other/20080228b.htm

[11] See (Bank for International Settlement 2006) for more information on the collateralization policies of the different G10 central banks.

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6 Appendix

	Coeff.	Std. err.	F-test with $d_{cls,i}$	F-test with $d_{bl,i}$
constant	0.01016*	-0.00504		
d_9	-0.00118	-0.00666		
d_{10}	-0.00400	-0.00636		
d_{11}	-0.01911*	-0.00756		
d_{12}	-0.02073**	-0.00687		
d_{13}	-0.02478***	-0.00592		
d_{14}	-0.02587***	-0.00596		
d_{15}	-0.03642***	-0.00690		
$d_{cls,8}$	-0.00046	-0.00541		
$d_{cls,9}$	-0.00038	-0.00459		
$d_{cls,10}$	0.00035	-0.00411		
$d_{cls,11}$	0.01459*	-0.00581		
$d_{cls,12}$	0.01551**	-0.00498		
$d_{cls,13}$	0.01425***	-0.00329		
$d_{cls,14}$	0.01276***	-0.00331		
$d_{cls,15}$	0.00759	-0.00498		
$d_{bl,8}$	-0.01507*	-0.00720	7.05 (0.00)	
$d_{bl,9}$	0.01044	-0.00612	5.66 (0.01)	
$d_{bl,10}$	0.01965***	-0.00543	22.7 (0.00)	
$d_{bl,11}$	0.03253***	-0.00648	25.9 (0.00)	
$d_{bl,12}$	0.03331***	-0.00582	20.7 (0.00)	
$d_{bl,13}$	0.01983***	-0.00421	3.35 (0.06)	
$d_{bl,14}$	0.00870*	-0.00425	1.87 (0.17)	
$d_{bl,15}$	-0.01892**	-0.00715	22.3 (0.00)	

table 1 continued

$d_{al,8}$	-0.00689	-0.00607	2.72 (0.09)	1.76 (0.18)
$d_{al,9}$	0.00052	-0.00520	0.07 (0.78)	3.70 (0.05)
$d_{al,10}$	0.00344	-0.00464	1.11 (0.29)	12.4 (0.00)
$d_{al,11}$	0.01073	-0.00655	1.11 (0.29)	21.9 (0.00)
$d_{al,12}$	0.01588**	-0.00610	0.00 (0.93)	10.9 (0.00)
$d_{al,13}$	0.01600***	-0.00433	0.3 (0.58)	0.85 (0.35)
$d_{al,14}$	0.01026*	-0.00433	0.66 (0.41)	0.14 (0.70)
$d_{al,15}$	-0.00449	-0.00825	3.00 (0.08)	2.78 (0.09)
No. Obs.	15,394			
R-squared	0.041			
Adj. R-squared	0.04321			

Notes: ***: significance on the 1% level; **: 5% level; *: 10% level;

robust standard errors were calculated; for F-tests, p-values are reported in parentheses.

Table 1: Regression results

Determinants of intraday settlement timing

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

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Abstract

This paper explores intraday timing of settlement in real-time gross settlement systems (RTGS). In the context of settlement risk, systems with and without collateralised intraday liquidity facilities have not been investigated. The models applied for this purpose are shown to predict stylised facts relating to Swiss Interbank Clearing (SIC) from before and after the introduction of intraday credits, from a regime switch in the collateralisation of the standing liquidity facilities of the Swiss National Bank (SNB) and a comparison between settlement data of SIC and Fedwire funds. It is shown that in the absence of an intraday liquidity facility, minimum reserve requirements influence settlement behaviour. Another determinant of settlement behaviour is found to be the collateralisation policy applied. Relating stylised facts to the models' predictions suggests that banks perceive opportunity costs of collateralisation to be fixed rather than dependent on the period of time of intraday credit usage. The analysis is relevant for policy. A prepledged overdraft facility and collateralised intraday credits are shown to be equivalent, since both are found to result in early settlement.

JEL classification: E58; G21; G28

Key words: Interbank payments; Reserve requirements; Intraday credit, Collateralization, Strategic games; Bank behaviour

1 Introduction

The goal of this paper is to investigate the strategic interaction between participants in real-time gross settlement (RTGS) payment systems in order to better

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

understand how participants' incentives affect intraday patterns of settlement. Thus, the paper is closely related to those by Bech and Garratt (2003) and by Mills and Nesmith (2008) (hereinafter BG and MN).

BG analyse an intraday liquidity management game for RTGS systems with free and priced intraday overdrafts and with collateralised intraday credits. BG use the concept of delay cost in order to analyse intraday settlement behaviour in the strategic context of a liquidity management game. Settlement delay of payments is associated with private and social costs.[1] Starting with Koboyakawa (1997) and Angelini (1998), a large branch of the payment literature is based on the delay cost approach. Green (2005) questions this approach based on the lack of supportive evidence.[2]

In a model based on BG, MN incorporate settlement risk. While BG also motivate delay cost as originating from settlement risk, MN rely on endogenously modelled settlement risk whereas BG base their model on exogenously introduced delay costs. MN analyse RTGS systems with uncollateralised overdrafts and securities settlement systems applying a delivery-versus-payment (DvP) mechanism.[3] In contrast to BG, MN's model is able to predict behavioural changes in Fedwire funds and Fedwire securities that originated from a change from free to priced intraday overdrafts.

This paper furthers MN's analysis insofar as settlement risk is applied in the context of RTGS systems without an intraday liquidity facility and to systems with collateralised intraday liquidity facilities. Using data from Swiss Interbank Clearing (SIC), the analysis examines whether or not the model's predictions fit stylised facts from before and after the introduction of intraday credits in 1999. Valuable insights can also be gained from a regime switch in the Swiss National Bank's (SNB) collateralisation policy. Further evidence is gained from a comparison of settlement between SIC and Fedwire funds. While the delay cost approach yields inconsistent predictions, the settlement risk approach results in predictions that are consistent with stylised facts.

Two reasons suggest an analysis of systems without an intraday liquidity facility and with a collateralised intraday liquidity facility. First, worldwide systems predominately offer collateralised intraday liquidity instead of uncollateralised overdrafts. RTGS systems such as BOJNET in Japan, Target2 for the Eurosystem, CHAPS in the United Kingdom and SIC in Switzerland are just a few examples. Furthermore, there are still a few systems without any intraday liquidity facility.[4] Second, it is relevant to extend the analysis since central

[1] See Bech (2008) for a more detailed explanation of delay cost.

[2] For a recent survey of the academic literature on payments economics see Kahn and Roberds (2009). For a more general discussion of RTGS systems see CPSS (2005) and Bech et al. (2008).

[3] DVP insures that the securities leg is settled if and only if the money leg of a securities transaction is settled at the same time. This eliminates principal risk. See CPSS (1992).

[4] See World Bank (2008). Out of 98 surveyed RTGS systems 85 provide intraday credits on a collaterlised basis, 3 provide either limited or unlimited overdrafts on an intraday basis. Furthermore, there are 10 systems that do not provide any form of intraday liquidity facility. For these countries the use of reserve requirements alone results in turnover ratios near one. However, World Bank (2008) reports that substantial economic growth also in the financial

banks are naturally interested in a framework to think about the implications of a regime switch. For example, the Federal Reserve Board recently implemented a major policy change. On the one hand, the priced overdraft framework was made more expensive, and, on the other hand, the Federal Reserve Board introduced an additional and unpriced collateralised intraday overdraft facility.[5]

Systems with no intraday credit facility and systems with collateralised intraday credits have a different design than Fedwire funds. Since there is no automated overdraft facility to fund settlement when payments are released to the system, such systems normally exhibit a centralised queueing facility. When no funds are available at the time of sending the instructions, payments remain pending in a centralised queue until funds arrive. The common feature of these systems is that settlement has to be prefunded, either by overnight credits or by intraday credits. Analysing an RTGS system without an intraday liquidity facility, Bech (2008) abstracts from reserve requirements. In contrast to this, we understand minimum reserve requirements in systems with no intraday liquidity facility as an indispensable real world feature. In essence, minimum reserve requirements relax the prefunding constraint by causing liquidity costs to be sunk. Therefore, rivalry on liquidity is substantially relaxed, which leads to corresponding changes in settlement behaviour. The prefunding constraint is also an issue if queuing systems provide free but collateralised intraday liquidity as a source of settlement. Intraday credit has to be actively drawn since it has to be backed with collateral. In other words, participants are required to actively draw intraday liquidity, to rely on incoming funds or to accept settlement delay. Prefunding is a feature that is also applied by BG in the context of systems with collateralised intraday credits.

In systems with a collateralised intraday liquidity facility, the opportunity cost of collateral is a major determinant of liquidity costs. Opportunity cost of collateral is either taken to be dependent on the time of usage - e.g. in BG - or as a sunk cost - e.g. in Koboyakawa (1997) and Jurgilas and Martin (2010). To our knowledge nobody has shed light on the way collateralisation takes place. There are two prevalent ways to post collateral. One is the immediate posting of collateral at the time of demand. Collateral backs the credit as long as it is not paid back. When the credit is paid back and the collateral is reimbursed, collateral is at the bank's free disposal again. Given that the market provides valuable opportunities to reuse collateral intraday and overnight, the cost of collateralisation is variable, as it depends on the time period of usage. The other form of collateralisation allows banks to draw intraday credits up to a limit that has been prepledged at the central bank. This up-front posting of collateral takes place on a permanent basis and, hence, does not allow for any other reuse by the pledgor, neither intraday nor overnight. Whereas the former method of collateralisation suggests a variable cost, the latter method gives raise to a fixed opportunity cost of collateral. Since these different forms of collateralisation imply different liquidity costs, they affect settlement behaviour

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sector increases payment volumes and values steadily.

[5] For more details see the Federal Reserve Board's policy decision on the new framework: http://www.federalreserve.gov/newsevents/press/other/20081219a.htm

accordingly. The model's predictions are late settlement for a variable opportunity cost of collateral and early settlement for a fixed opportunity cost. We find a fixed opportunity cost to result in an equilibrium that is consistent with stylised facts. After the introduction of intraday credits in SIC, a remarkable move towards early settlement was noticed.

In 2005, the SNB initiated a regime shift in the collateralisation policy and reformed its 'liquidity-shortage financing facility' (LSFF). Before the regime shift took place, intraday credits were collateralised ad hoc by means of repos. Since then, collateral has to be prepledged permanently in order to draw an intraday repo. Collateralisation policy before the regime shift suggests variable opportunity costs. By contrast, the regime based on prepledged collateral is associated with fixed opportunity costs. However, the regime shift has not brought with it the kinds of effects that the model would suggest. Rather, the evidence found supports the view that banks perceived opportunity cost of collateral fixed or sunk, both before and after the policy change took place.

We further the analysis of MN and BG insofar as we analyse a collateralised overdraft facility. Such a facility works on the basis of prepledged collateral, namely an overdraft facility that is not priced but permanently backed with collateral. Such a framework also exhibits a fixed opportunity cost of collateral. The conjecture of the model is that such a facility results in an early settlement equilibrium. With regard to the policy changes by the Federal Reserve Board, the conjecture for a complete change to a collateralised overdraft facility instead of a priced one is that settlement in Fedwire funds would take place earlier. However, the model setup is limited to analysing each liquidity facility separately. Since the Federal Reserve Board opted for a coexistence of both types of liquidity facilities, the analysis of the effectively implemented changes remains a task for future research.

The settlement risk approach also yields consistent prediction across systems. Comparing SIC and Fedwire funds settlement data, we find evidence that settlement takes place substantially earlier in SIC than in Fedwire funds. Indeed, MN predict a late settlement equilibrium in a setup with priced overdrafts. In this paper we present a model with collateralised intraday credits that yields an early settlement equilibrium.

The paper is organised as follows. Section 2 illustrates how SIC works and accounts for the liquidity provision by the SNB. Three stylised facts are documented in order to contrast them with the models' predictions. Section 3 presents the basic features of the model. The absence of intraday liquidity is analysed in section 4. A system without an intraday liquidity facility is analysed with both the delay costs and the settlement risk approach. Section 5 examines a RTGS system with intraday liquidity facilities. First, a system with intraday credits that cause a variable opportunity cost of collateral is analysed. Then a system with a fixed opportunity cost of collateral is explored. In the last subsection, a prepledged overdraft facility is discussed. The final section concludes and sets out future lines of research.

2 SIC and stylized facts

2.1 A description of SIC

As one of the oldest RTGS systems, SIC operations started in 1987.[6] Initially, design and architecture of the system were simple. The main building blocks consisted of the non-allowance of intraday overdrafts (in contrast to Fedwire), a central queuing mechanism and the strict 'first in - first out' (FIFO) rule for payments processing and settlement. The settlement algorithm stayed the same until 1994 when priorities were introduced. From an individual participant's perspective, the settlement sequence of payments is determined, in the first place, by the priority chosen from then on. Within a specific order of priority, the FIFO rule applies. In relation to the topic at hand, the most important change of the basic setup took place in September 1999. From then on, banks were allowed to rely on free but collateralized intraday credits. In December 2001, the settlement algorithm was enriched with a gridlock resultion mechanism.[7]

The beginning of SIC's settlement cycle is scheduled at 4:40 p.m. the day before the value date. Then the initial transfer of reserve balances from the participants' master accounts at the SNB to their SIC accounts takes place. From this moment on, payments can be settled until 4:15 p.m. on the following bank working day, which is the settlement date. At 3 p.m. 'clearing stop 1' occurs. Until then an unlimited number of transfer orders for same-day settlement may be entered. After 3 p.m. payment orders entered for same-day settlement are automatically marked for settlement on the following day. Exceptions to this rule are money market transactions, which may be entered for same-day settlement until 'clearing stop 2' that takes place at 4 p.m. The last time window between 'clearing stop 2' and 'end-of-day processing' at 4:15 p.m. is exclusively reserved for payments entered by the SNB. The SNB uses this last time window to answer additional calls for overnight credits from the LSFF. Other payments still pending in the queues are settled until 4:15 p.m.

2.2 Settlement performance and liquidity facilities

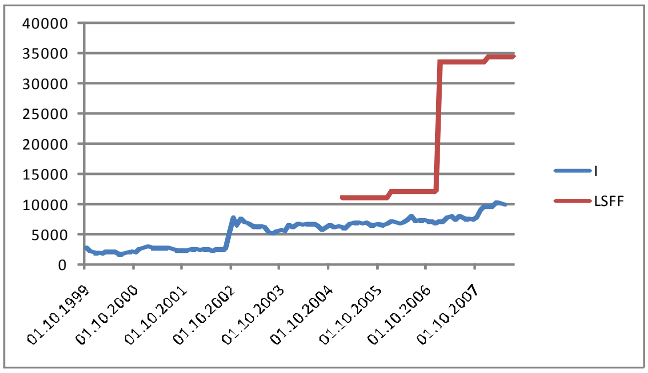
In September 1999, SNB introduced intraday credits. With its intraday facility, the SNB provides its counterparties with interest-free intraday liquidity through repo transactions to facilitate the settlement of payments in general and time critical transactions in particular. Every afternoon the SNB invites its counterparties to submit requests for intraday credits for the next bank business day.

[6] Bech and Hobijn (2007) take account of the introduction of RTGS systems around the world. Heller et al. (2000) provide an in-depth description of SIC. Nellen (2010) contains an up-to-date history of the development of SIC's design as well as an in-depth analysis of SIC's settlement performance.

[7] As soon as the system is not able to settle payments for a certain period of time, the algorithm searches for bilateral off-setting possibilities and initiates an off-setting transaction. After this off-setting transaction is executed to replace both other transactions, the system starts to settle in the usual manner again. Due to ample means of liquidity, the bilateral off-setting mechanism remains practically inactive.

Counterparties may submit any desired number of offers. The SNB normally meets requests in full, as long as its counterparties provide sufficient collateral to cover intraday credits. The amount is credited to their accounts shortly after SIC resumes the processing of payment orders, i.e. at 6 p.m. Furthermore, counterparties have access to additional intraday liquidity from 7:30 a.m. (7 a.m. for CLS members) to 2:45 p.m. of each working day. Banks must repay these cash amounts by the end of the same day at the latest. Liquidity received via the intraday facility can be repaid at any time during the day. However, reverse settlement of intraday drawings which a counterparty has not yet initiated itself is triggered automatically at 3 p.m. by means of a direct debit with a high priority in SIC. This results in relatively fast settlement of repurchase transactions and the corresponding debiting of accounts until shortly after 3 p.m.

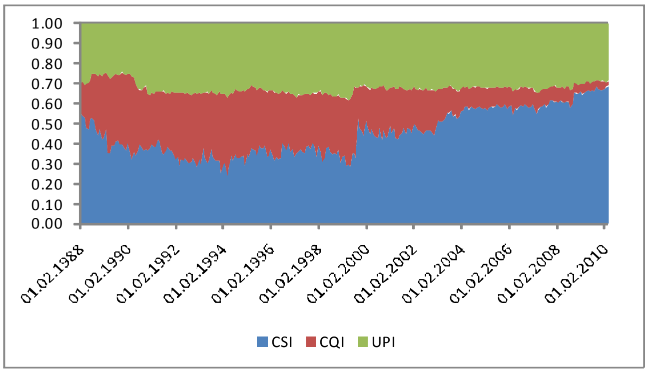
Figure 1: Monthly averages of intraday credits drawn (I) and established limits for the liquidity-shortage financing facility (LSFF) in CHF billions



As a consequence of the introduction of intraday credits, available liquidity in SIC rose substantially. Figure 1 displays intraday credit drawings as monthly averages and figure 3 shows available liquidity (AL) as the sum of reserve balances (RB) and intraday credits (I). Initially, banks on average draw a daily value of CHF 2.5 Bio of intraday credits until the introduction of CLS in September 2009. CLS settlement banks demanded additional CHF 4 to 5 Bio of intraday credits. The steadily increasing participation in the repo interbank market also led to an increasing participation in the intraday liquidity facility of the SNB, which is why after 2003 the total intraday credits drawn steadily increased again after CLS banks adjusted their demand to actual needs. The increase in the third quarter of 2007 is an effect of the financial crisis. Intraday credits drawn reached peak values of over CHF 11 Bio.

The introduction of intraday credits resulted in a substantially improved settlement speed. Two factors are responsible for this. First, after September 1999 payments were released earlier. Second, additional liquidity made it pos-

Figure 2: Monthly averages of accumulated comprehensive settlement indicator (CSI), central queuing indicators (CQI) and unreleased payment indicator (UPI). The release time indicator (RTI) is displayed indirectly through the sum of settled and queued payments: RTI=CSI+CQI



sible to reduce central queueing activity. Two indicators are shown in figure 2 that illustrate these effects. First, the comprehensive settlement indicator (CSI) is a measure of settlement time over the course of the day (the closer to one the earlier settlement takes place). Second, the release time indicator (RTI=CSI+CQI=1-UPI) as the sum of the comprehensive settlement indicator (CSI) and the central queuing indicator (CQI) is a measure of release behaviour in the course of the day (the closer to one the earlier banks release payments).[8] The indicators are displayed for the period 1988 to 2008 as monthly averages. In relation to the use of intraday credits, two substantial changes can be seen. In September 1999, intraday credits were introduced and in September 2002, CLS commenced operations. For the first date, both indicators exhibit a substantial change. Both release and settlement have taken place much earlier since then. The introduction of CLS has resulted in a further increase of liquidity in SIC. CLS banks draw more intraday credits in order to settle time-critical CLS payments in special CLS subaccounts. The CLS funding cycle starts at 7 a.m. with a first pay-in deadline at 8 a.m. The last CLS pay-in deadline in SIC is at noon. After the CLS funding cycle, intraday liquidity drawn for the subaccounts is to a great extent transferred to the main accounts. This further speeds up settlement of payments settled on the main accounts. That is why CSI increases substantially after the introduction of CLS in September 2002.[9]

Looking at the inital phase of SIC, two other influential policy changes took place. First, reserve requirements changed in 1988 what allowed banks to reduce

[8] For further explanation see section 8.5 or consult Nellen (2010).

[9] Data restrictions do not allow to exhibit CSI, CQI and UPI for the intial phase from July 1987 to January 1988. However, CSI was even higher and CQI lower before Feburary 1988. Overall, RTI=CSI+CQI was lower before February 1988, saying that the unreleased payment indicators - UPI=1-RTI - was larger.

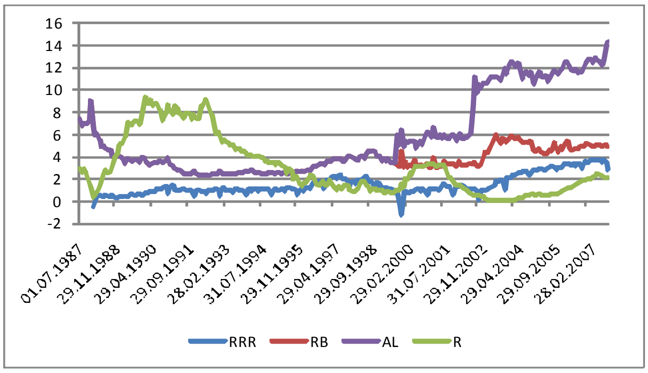
there reserve balances substantially. This went along with a period of substantial inflation pressure that induced SNB to increase interest rates substantially (see figure 3 for the tomorrow/next Swiss franc Euromarket interest rate (R)). These facts account for the steady decrease of reserve balances to CHF 2 Bio until 1991. Figure 3 depicts available liquidity (AL) as the the sum of reserve balances (RB) and total intraday credits drawn (I). As can be seen in figure 3, reserve balances increased again only after 1993. The residual reserve requirement (RRR) is defined as the remaining level of requirements to be fulfilled after other eligible reserves are deducted from the reserve requirement.[10] The reserve requirement before 1988 was completely different. It was not based on a mid-month to mid-month average but was defined as an end-of-month requirement. Relevant for our analysis is that residual reserve requirements before 1988 exceeded monthly average reserve holdings as depicted in figure 3 and, especially, that the average reserve holdings in general were much higher than the residual reserve requirement after 1988.

Second, as described in Heller et al. (2000), in April 1988 SIC introduced a two-part tariff aimed at incentivising early release and settlement of payments. As a further reaction to higher interest rates and lower reserve balances, the two-part tariff was made more progressive in 1989. Indeed, these changes led to ealier release of payments (as can be seen in figure 2; RTI=CSI+CQI). This effect was revoked again when interest rates peaked and reserve balance reached there lowest levels in 1991.

To summarise, in the very early stage of SIC reserve levels were so high that early settlement went along with a rather late release of payment. After April 1988 erlier release was induced by the two-part tariff, however, settlement continuously took place later until 1993 when both interest rates and reserve levels were at their most extreme levels. After 1990 also the release of payments started to take place substantially later again and remained fairly constant until the introduction of intraday credits in 1999. Settlement of payments took place slightly earlier after 1993, being in line with increasing reserve balances due to lowering interest rates and slowly increasing residual reserve requirements. The introduction of intraday credits resulted in a move to much earlier settlement and substantially reduced central queuing activity as depicted by CQI. Also the release of payments took place earlier again and reached levels of before 1991. Also, the levels of reserve balances available to settle decoupled from the levels of the interest rate and the residual reserve requirement. The subsequent increase in the provision of intraday credits due to CLS has again moved settlement of payments to earlier hours. We refer to this as stylised fact 1.

[10] Other eligible reserves at this time were cash, sight deposits on accounts at clearing houses and in the postal account system.

Figure 3: As monthly averages in CHF Bio: Residual reserve requirements (RRR), reserve balances (RB) and available liqudity as the sum of reserve balances and intraday credits (AL) and the monthly average of the tomorrow/next Swiss franc Euromarket interest rate (R).



2.3 Collateralisation policy and intraday liquidity demand

In the given context, one other monetary policy instrument is of special interest: the 'liquidity-shortage financing facility' (LSFF).[11] LSFF serves to bridge unexpected liquidity bottlenecks in order to support the smooth operation of the payment system. The interest rate for liquidity provided through this facility is at least 50 basis points above the call money rate. The interest premium is intended to prevent banks from using the facility as a permanent source of refinancing.[12] In the case of usual monetary repo transactions, the initiative for concluding a transaction generally lies with the SNB. Only where intraday and LSFF facilities are concerned does the SNB merely lay down the terms under which the commercial banks can obtain liquidity at their own discretion.

The only way of accessing the LSFF is via a special-rate repo transaction. The precondition for concluding a special-rate repo transactions is that a limit is granted by the SNB and this limit is covered by collateral (the limit is depicted in figure 1 as LSFF).[13] The limit determines the maximum amount of liquidity that a counterparty may obtain. The securities are held by the counterparty in a 'Custody Cover Account SNB' at SIX SIS Ltd, the Swiss international central securities depository. This special account requires that the collateral is pledged to the SNB. During the settlement day, the limit is also available

[11]See SNB's homepage for further information on its monetary policy instruments and liquidity facilities: www.snb.ch/en/iabout/monpol/id/monpol_instr

[12]The SNB fines any rollover of intraday to overnight credit at a level which will make this an unattractive option. The penalty rate is twice as high as for the LSFF overnight credit at the end of the day.

[13]The sharp increase of limits established in 2006 is related to changed liquidity regulations. Some banks used the LSFF limit to fulfil these new regulations.

for drawing intraday credits. This facility has been available since 2005. As of 2006, the LSFF completely replaced the former Lombard facility. Since then, SIC participants that are responsible for more than 80% of the turnover of SIC make use of this facility. This does not differ from the previous situation, although the limit established for the Lombard facility was not available for intraday credits and eligible collateral was different to some extent from the SNB eligible repo baskets.

Figure 4: Value-weighted daily duration of intraday credit drawings in hours

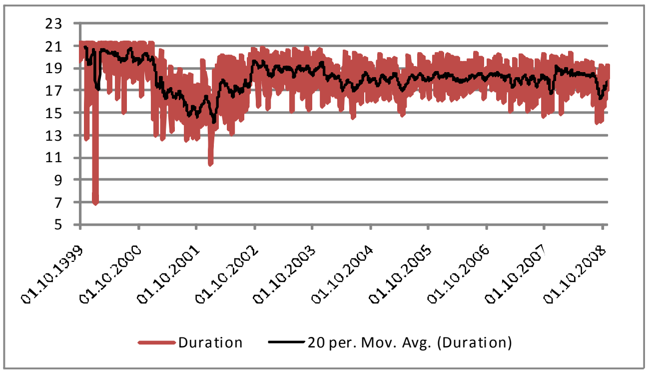
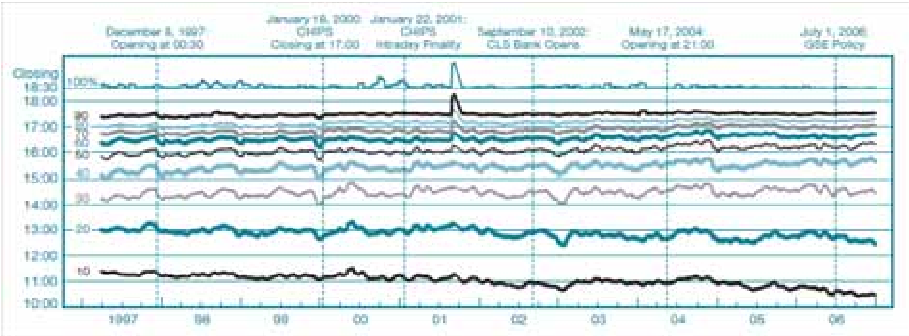


Figure 1 also shows the limit for the LSFF since 2005, when the new facility was introduced. The limit is established on an annual basis. At the beginning of 2006, the former Lombard facility[14] was completely replaced by LSFF. In the given context, the introduction of LSFF is supposed to mark a regime switch in the opportunity cost of collateral. The change from a flexible repo framework for intraday credits to such a prepledged framework marks a change to a fixed opportunity cost, since this framework does not allow for an alternative usage of collateral. However, the introduction of LSFF has neither resulted in an additional demand for intraday liquidity nor has it changed the average time period of intraday credit usage (see figure 4).[15] Another astonishing fact is that banks in drawing intraday credits have never exploited their established limits by a considerable margin (see figure 1). If their demand is not satiated, banks could exploit limits without incurring any substantial extra costs. To summarise, the introduction of the LSFF in 2005 and the corresponding changes in collateralization policy have not changed the demand for intraday credits. We refer to this as stylised fact 2.

Figure 5: Settlement times of settled percentiles of Fedwire funds' settlement value. Taken from Armantier et al. (2008)



2.4 Comparing SIC and Fedwire funds

Having available stylised facts about Fedwire funds and SIC, it is interesting to compare settlement patterns of both systems. A comparison between SIC and Fedwire funds shows that settlement in SIC takes place earlier than in Fedwire funds. Armantier et al. (2008) provide an empricial analysis of the timing of payments in Fedwire funds (see figure 5).[16] As it is done for Fedwire, all payments to and from settlement institutions such as CLS are removed from SIC data (see figure 6). This allows to focus on the non-settlement institutions' fund transfers that are subject to strategic decisions of the sending party.[17]

By looking at figures 5 and 6, 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.[18] Armantier, Arnold and McAndrews (2008) 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 6 shows that before 2 1/4 hourse before SIC closes more than 95% of turnover is settled. Furthermore, 5 1/4 hours before end of day 50% of turnover is settled in SIC. This is the case for the period from September 2002 on, which is the period after the introduction of CLS.

Even though institutionalised payments with fixed settlement times are removed from the data analysed, many further issues may affect release and set-

[14] This facility had more than CHF 8 billion of collateral value prepledged at the SNB.

[15] The average time period is an aggregated value for different contracts. However, the picture remains the same if analysed for each separate contract individually.

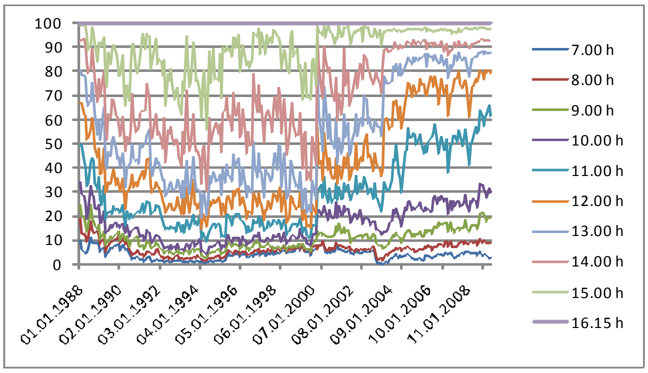
[16] Reprint of Figure 4 was kindly permitted by the authors of Armantier et al. (2008).

[17] In the case of SIC, institutionalised payments stem from CLS, payments that originate from securities 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.

[18] Data restrictions do not allow to have the same setup for figure 5 as given in figure 4. See also section 8.5 for the data available on SIC.

tlement behaviour. Effects stemming from different market structures in the different systems' market places (e.g. 8000 participants in Fedwire versus less than 400 in SIC) and issues such as four different time zones in the USA versus only one time zone in Switzerland may all influence settlement patterns due to late arriving payments. MN 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. 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. Armentier et al. (2008) also find late settlement activity for this secured money market. As pointed out in Kraenzlin and Nellen (2010) the secured money market in Switzerland settles the repurchase transaction early in the morning.

Figure 6: Percentage of settlement value settled on an hourly basis from 7 a.m. to end of day at 4.15 p.m.



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 could be related to customer payments and interbank money market transactions, for example. In a recent paper by Bartolini et al. (2008), it is found that for same day transactions originating in the money market, substantial strategic delay occurs. 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 payments in April 1988 and its more progressive application from 1989 on is that many more payments were released earlier than as early release and settlement incurs lower fees. However, in terms of the overall value of transaction released, a remarkable move towards later release can be noticed from 1990 on (see figure 1). Relating both 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 to be an issue. While the exact extent of the issue is hard to quantify, the phenomenon of strategic delay in payment systems is real. That is the case for both type of systems. 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 also stems from differences related to strategic delay. In summary, settlement in SIC takes place substantially earlier than in Fedwire funds. We refer to this as stylised fact 3.

3 Model

Two basic setups are considered in the following chapters. First, a regime is analysed without an intraday liquidity facility. We analyse two models in order to compare their predictions - the first assumes a delay cost such as in BG and the second assumes a settlement risk such as in MN. Second, two models with an intraday liquidity facility on a collateralised basis are considered, one with a per period opportunity cost of collateral and one with a fixed opportunity cost of collateral. In contrast to models with an overdraft facility, the overall theme of the models in this paper is that settlement requires prefunding. In the setting with fixed opportunity costs of collateral an overdraft facility with prepledged collateral is discussed. This section describes the basic setup of the model.

There are three periods denoted by $t = 0, 1, 2$, for morning, afternoon and end-of-day. In relation to the settlement schedule of SIC, morning is envisaged as the time period until 11 a.m.[19], afternoon is envisaged as the period to 3 p.m., whereas the time from 3 p.m. to 4:15 p.m. is considered as the end-of-day period. During the latter period, banks can only release instructions that are related to money market operations and receive LSFF credits from the SNB. During the last quarter of an hour only LSFF credits are accepted as new payments for same day settlement. In the model setup this can be envisaged as the last period where banks can draw overnight credits from the central bank in order to settle remaining payments. 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).[20] 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,

[19] The two-part tariff for releasing and settling payments in SIC imposes much higher release and settlement fees for transactions after 11 a.m. This is why 11 a.m. might serve as a natural candidate for a time definition.

[20] Interpreting this third institution as a central bank and the settlement medium as central bank money justifies ignoring settlement bank risk.

such as overnight credits or intraday credits.

In the setup with no intraday liquidity facility, banks are required to hold a minimum reserve requirement $\alpha = 1$. This is in contrast to BG and Bech (2008) who implement a zero reserve requirement. In the setup with an intraday liquidity facility, 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. These assumptions allow us to describe the timing of events such that banks start period 0 either with prefunded accounts for settlement purposes (in the models without an intraday liquidity facility) or with a zero account balance (in the models with intraday credits). Then, with probability p, bank $i \in \{1, 2\}$ receives an instruction to make a payment of value 1 to bank $j \neq i$.[21] 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. MN 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, Target2 and Fedwire, where hundreds or thousands of banks participate.

It is assumed that the cost of holding overnight reserves on central bank accounts is greater than the opportunity cost banks incur if they draw a collateralized intraday credit. We further assume that banks are granted intraday credits by the central bank which are posted on their central bank accounts. As is the case in SIC, intraday credits are interest free but have to be collateralised. Posting collateral comes at an opportunity cost of either $o > 0$ per period $t \in \{0, 1\}$ or at a fixed cost $f > 0$. The time-dependent opportunity cost of collateral is charged whenever an intraday credit is not paid back by the end of a period. If a bank has not paid back by the end of period 1, it must borrow funds from the central bank at interest rate $R > o$ or $R > f$ in order to pay back the intraday credit. During period 2 any outstanding payment is made and funded by borrowing overnight at interest rate R if necessary. We understand this setup to be broadly consistent with the procedures in SIC as set out in section 2.

If bank i receives a payment instruction it can decide to make the payment either in the morning (period 0) or in the afternoon (period 1). As in MN 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 $e > 0$, 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 among the banks. However, whether or not a bank is to receive a

[21] As in MN this is a difference to the model in BG where banks receive a second payment instruction shock in the afternoon. In a model setup as in MN a second shock would complicate the analysis without fundamentally changing the results.

payment from the affected bank 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. This settlement shock represents a certain type of settlement risk to the receiving bank - defined as the risk that a payment is not sent 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 costs of sending payments. MN think of the settlement shock as a proxy for uncertainty regarding incoming funds. Even though the shock e can be relatively small in scope, it does have a cost in the model's setup as it raises the probability that a bank needs to borrow in the overnight market, or from the central bank.

The bank's objective function is taken to minimise the expected cost of making a payment. This objective becomes relevant only when a bank receives a payment shock at the beginning of period 0. That is why it is possible to focus on a bank's payment strategy in the state of the world in which it receives a payment instruction; otherwise its expected cost of making payments is either zero or equal to the sunk cost of the prepledged collateral. 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 (at period 0) and a denotes an afternoon payment (at 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 credits (either a variable cost - o - or a fixed cost - f), the cost of reserve requirements of 1 in the absence of an intraday credit facility (which is the overnight interest rate R) and the probability of settlement risk e. $c(s_i, s_j)$ 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. The setup generates four possible realisations of expected costs.

4 Absence of an intraday liquidity facility

In a context of delay costs D, Bech (2008) applies a simplified framework such as in BG. This setup is also applied to a RTGS system without an intraday liquidity facility.[22] The absence of intraday liquidity requires banks to fund settlement by drawing overnight credits or to wait for incoming payments from other banks. Given that the overnight interest rate is higher than the cost of delay, the liquidity management game in Bech (2008) results in an anti-coordination game where the opposite strategy of the other player is the optimal answer for each player - if the equilibrium strategy of player 1 is morning, player 2's equilibrium strategy is afternoon and vice versa. Thus, the underlying conflict in the game

[22] See box on page 15 in Bech (2008).

is that both banks want to free ride on the other bank's liquidity. Liquidity is rivalrous since both banks cannot benefit from it at the same time. Should an exogenous shock raise the cost of overnight liquidity to such an extent that it becomes higher than the delay cost, the result can be that the equilibrium strategies change from (m, m) into (a, m) and (m, a) or vice versa. Bech (2008) argues that the change of equilibrium strategies explains the steady reduction in congestion in SIC from 1993 to 1999, a period of continuously lowered interest rates in Switzerland and steadily increasing liquidity holdings. This is argued to have caused a reduced level of congestion and earlier settlement. Indeed, figure 2 validates that congestion or central queuing depicted as CQI was reduced during this time period.

The changes reported in Bech (2008) can be explained by the fact that banks steadily increased reserve holdings after 1993. However, the evidence at hand may not support an equilibrium shift as indicated by Bech (2008). Looking at the settlement indicator in figure 2, we argue that an indicative shift to an earlier settlement equilibrium did only take place after the introduction of intraday credits in 1999. This is further supported by the fact that, in contrast to 1999, there was no shift in release behaviour during the period 1993 to 1999. In this light, referring to a steady change towards a morning equilibrium in a context without intraday liquidity, such as for the period from 1993 to 1999 in SIC, may not be an accurate description. Rather, increased liquidity holdings due to lower interest rates and steadily increasing reserve requirements resulted in a lower central queuing activity.

Two further shifts in release and settlement behaviour took place. The first one is related to the the introduction of the two-part tariff in April 1988 and the second one realised after 1990 when reserve balances reached the lowest and the interest rate reached the highest level. Rather than delay costs and interest rates alone, stylised facts suggest that available reserve balances and other cost factors, such as a two-part tariff, play a crucial role in determining settlement behaviour. Especially, the interest rate level alone might not affect settlement behaviour if reserve requirements are high enough. Furthermore, after April 1988 the two-part tariff induced earlier release and could shortly compensate for lower levels of available reserve balances until 1990 (see figures 2 and 3).

The important role of reserve requirements is confirmed in Heller and Lengwiler (2003). They provide a model in which a bank's demand for reserves depends on the joint distribution of transactions, reserve requirements, the interest rate and the cost of liquidity management. In Switzerland, reserve requirements are a binding factor for larger banks, for most smaller banks reserve balances exceed minimum reserve requirements.[23] This is astonishing insofar as neither minimum reserve requirements nor excess balances earn any interest if deposited on the SNB's accounts. Baltensperger (1974) and literature on precautionary demand for reserves cited therein explain excess reserves by making reference to the uncertainty about cash flows. Arguing in the vein of the literature on

[23] This is true for the period before and after 1999. The experience during the recent financial turmoil is different due to extensive liquidity provision by the SNB after the bankruptcy of Lehman Brothers.

precautionary demand for reserves, Heller and Lengwiler (2003) understand the bank's problem to be the joint minimisation of the opportunity costs of liquidity, the management cost of liquidity, uncertain payment obligations and reserve requirements. Using econometric methods, they confirm that the turnover ratio depends largely on the joint distribution of transactions, reserve requirements and the interest rate.

In this paper we incorporate the considerations put forward in Heller and Lengwiler (2003) in order to analyse settlement timing. Thereby, we keep the framework as simple as possible. First, we impose a reserve requirement of $\alpha = 1$ on the banks. Reserves requirements are understood to relax the prefunding constraint. In particular, by assuming $\alpha = 1$ we leave banks with a completely satiated intraday liquidity demand, i.e. they do not have an incentive to wait for incoming funds. Since we restrict the analysis to a static game with a payment obligation equal to 1 and a reserve requirement of $\alpha = 1$, excess reserve holdings are not an issue in a model with delay costs.[24] Excess reserves naturally arise in a model with settlement risk as reserve requirements have to be fulfilled until the end of period 1 and delayed payments due to settlement risk may only arrive in period 2. Second, uncertainty about payment obligations is part of the model given the payment shock that realises with probability $1-p$. Third, the interest rate uncertainty is also absent in a static framework - R is taken to be certain or can be considered as an expected interest rate. For the sake of simplicity and comparability with BG, Bech (2008) and MN, we restrict the analysis to this simple one shot game. Since a model setup without an intraday liquidity facility has neither been analysed in the context of delay cost nor in the context of settlement risk, we proceed by analysing one after the other. We consider above setup as an interesting benchmark case to evaluate the predictions of two approaches, leaving a more open framework with lower reserve requirements ($0 < \alpha < 1$) and a two-part tariff for future research.

4.1 Delay cost and reserve requirements

If banks receive a payment instruction in the morning, they face the choice to either settle immediately or to delay. If banks end the day with zero balances, they have to draw an overnight credit to fulfil reserve requirements. Funding of accounts takes place at the end of period 1 after payments are processed. In the model, banks are not allowed to end period 1 with zero balances on the account. Banks are assumed not to strategically delay until period 2 since no settlement risk occurs. Banks minimise their exptected costs by choosing when to settle.

For each game a thorough derivation of the cost functions is described in the appendix. For this setup the following cost functions result:

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

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

[24] Due to uncertainty over payment obligations excess reserves would result if $\alpha < 1$ is allowed for.

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

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

Generally, for all pairs of strategies, with probability $(1 - p)$ bank j does not receive a payment instruction and bank i incurs the cost of the overnight credit since it has to fulfil reserve requirements at the end of period 1. If bank i sends its payment in the afternoon it entails a delay cost D. Figure 7 represents the game in normal form with equations (1) to (4) simplified where appropriate.

Figure 7: RTGS with minimum reserve requirements, without intraday liquidity and with a delay cost

	m	a
m	0 0	0 D
a	D 0	D D

Proposition 1 *Under a regime without an intraday liquidity facility, a delay cost D and a reserve requirement of* 1*, the following pure strategy set* (m, m) *is the unique Bayesian Nash equilibrium.* (m, m) *is a strictly dominant equilibrium.*

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* $c(a, m) < c(a, a)$. ■

In the context of a delay cost and a reserve requirement of 1 early settlement is the efficient and predicted equilibrium. Under high reserve requirements that satiate intraday liquidity demands of banks early settlement is the equilibrium. Looking at figure 2 and 3 this was largely the case before 1988 and remained so until reserve balances were strongly reduced.

The model by Bech (2008) implies that liquidity is rivalrous. Introducing high reserve requirements resolves rivalry since liquidity is held to fulfil reserve requirements. In essence, reserve requirements make the cost of liquidity sunk. Therefore, liquidity becomes strategically irrelevant and banks coordinate their payments in the morning to avoid the costs of delay. Uncertainty over payment instructions does not alter the conclusion if liquidity is strategically irrelvant. However, if we allow reserve requirements to be $\alpha < 1$, liquidity becomes rivalrous again and the strategy chosen depends on the compound effect of the interest rate, the delay cost and uncertainty over payment flows. The steady reduction of reserves due to changed reserve requirements in 1988 and the increased interest rates led banks to release and settle payments later in line with reduced holdings of reserve balances and a rising interest rate. In essence, liquidity became rivalrous again after 1988.

However, allowing for high enough reserve requirements results in early settlement to be the unique Nash equilibrium whatever the relation of interest rate and delay cost is. With regard to the initial phase of SIC, this does not account for the changes before the introduction of the two-part tariff in April 1988. After the introduction of the two-part tariff banks started to release and settle earlier than before. The late level of release before the introduction of the two-part tariff can be regarded as a hint that even though high reserve requirements were in place there seems to be a force at work that induces banks to rather release and settle late. In particular, the low interest rate levels during this initial phase may not account for this. Therefore, a framework without intraday credit as in Bech (2008), enriched with a reserve requirement of 1, fails to predict late release and settlement acitivity and does not seem to be fully consistent with the initial phase. Ultimately, this is connected to the exogeneity of the delay cost. The result of the game resembles the free intraday credit game in Bech (2008) and BG. In such a game too, liquidity is non-rivalrous, which explains the outcome of a morning equilibrium.

A second caveat applies. Even though interest rates fall substantially again after 1993, the early levels of release and settlement before 1990 were reached again only after the introduction of intraday credits in 1999. However, lowered interest rates after 1993 would rather call for an earlier release and settlement behaviour before 1999. This is especially true so if the effect of a two-part tariff is considered. If we allow $\alpha < 1$, the equilibrium would depend on the relation between settlement uncertainty, delay costs and interest rate since rivlary on liquidity is reintroduced and may well explain occuring changes. Therefore, after 1993 either lower delay costs and a decrease in payment flow uncertainty must have compensated for lower interest rates such that late release and settlement remained until 1999. However, neither a particular event nor any other effect is known that would have caused such changes.

The basic insight of this model is that the size of reserve requirements allows to resolve rivalry to the extent defined by the before mentioned variables. Even though the reduced framework in Bech (2008) replicates the results by BG for systems with intraday liquidity, it seems not to be entirely consistent in a context without intraday liquidity and reserve requirements. Since in a context of free overdrafts the delay cost approach also fails to predict stylised facts on Fedwire funds, the delay cost approach may lack a fundamental force that drives late settlement.

4.2 Settlement risk and reserve requirements

This section is concerned with a payment system where banks do not incur a delay cost. Rather, at the beginning of period 1, a bank may receive a settlement shock. Specifically, with a small probability $e > 0$, bank i cannot receive a payment from bank j during period 1, but will receive it in period 2. Again, banks are assumed to fulfil a reserve requirement of 1 at the end of period 1. If still payments are to be processed in period 2, banks are assumed to fulfil reserve requirements at the end of period 2.

The following expected cost functions result:

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

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

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

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

Again, for each pair of strategies with probability $(1-p)$, bank j does not receive a payment instruction and bank i incurs the cost of the overnight credit since it has to fulfil its reserve requirement at the end of period 1. The second cost function is different since with probability p bank j receives a payment instruction and delays it until the afternoon. Then, with probability e, a settlement shock might take place and bank j sends the instruction in period 2. Therefore, bank i has to draw an additional overnight credit at the end of period 1 in order to fulfil reserve requirements. Figure 8 represents the game in normal form with equation (5) to (8) simplified where appropriate.

Figure 8: RTGS with minimum reserve requirements, without intraday liquidity and with settlement risk

	m	a
m	0 0	peR 0
a	0 peR	0 0

Proposition 2 *Under a regime without an intraday liquidity facility, a settlement shock $e > 0$ and reserve requirements of 1, the following pure strategy sets (m, m) and (a, a) are Bayesian Nash equilibria. The strategy set (a, a) survives the elimination of weakly dominated equilibria.*

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 $c(a, m) = c(a, a)$.* ■

In the payment game without intraday credit both equilibria minimise the joint expected cost of the two banks and are efficient. In contrast to the delay cost approach, rather than choosing the morning equilibrium, banks go for the afternoon equilibrium. Delaying payments can save costs due to unsettled incoming payments. Having sent payments in the morning but having received no off-setting transaction itself, a bank may be forced to draw additional overnight credits in order to fulfil reserve requirements at the end of period 1 - even though there is a fair chance of receiving a payment in period 2. To insure against this possibility, banks delay payments until the afternoon. Therefore, also in the context of a payment system without an intraday liquidity facility the settlement risk approach delivers the fundamental force that incentivises late release and settlement of payments.

However, late settlement is not entirely in line with stylised fact 1. In the initial period with large holdings of reserve balances due to very high reserve requirements, settlement took place early (see CSI and RTI in figure 2). After 1990 settlement took place rather late due to much lower reserve balances resulting from the reform of reserve requirements. This situation remained until autumn 1999, when intraday credits were introduced. Since settlement risk makes delaying payments worthwhile as, by delaying, information can be revealed that may help banks to minimize costs. In essence, if a shock is revealed, a bank can delay payments until period 2 in order to reduce the likelihood of having to borrow in the overnight market. Even if intraday liquidity demand is completely satiated settlement risk can give raise for late settlement acitivity. Allowing for $\alpha < 1$ further enforces late settlement since liquidity becomes rivalrous again.

Therefore, either the settlement risk approach may not be able to account for incentives to settle early or the model is too restricted. We argue that the model does not take account of two issues. First, even though late settlement is enforced further if we allow for $\alpha < 1$, this also reintroduces the dependence on interest rates which had changed drastically during the period in question and favours early settlement equilibrium for the period before April 1988 for example. Second, the two-part tariff obviously had quite profound effects on release and settlement behaviour during this period which is not taking into account in our model but favours an early settlement equilibrium.

Above suggestions may be reinforced by evaluating possible corner solutions. If there is no settlement shock, $e = 0$, every strategy pair would be an equilibrium outcome. As in MN, settlement risk is an important factor explaining late settlement. Banks focus on a late payment strategy in order to avoid costs resulting from settlement risk. An early equibilibrium as seen before 1989 could be explained by a dependence of e on the available liquidity. If liquidity levels are high enough, the consequences of operational shocks in combination with early release of payments might be negligible. This was the case before 1989 and after 1999 again. If liquidity is low as it was the case between 1990 and 1999 settlement risk might be higher and late settlement results. If payments are certain, $p = 1$, every strategy pair would be an equilibrium outcome since any uncertainty over liquidity costs is resolved.

To summarise, settlement risk is an important factor in explaining late settlement behaviour of banks in a regime without intraday liquidity facility and reserve requirements. To take full account of the changing environment before 1999, the model would have to be enlarged to allow for lower reserve requirements in order to let the model react on the interest rate level and payment uncertainty. Also, the model needs to be extended to evaluate the effects of a two-part tariff.

5 Collateralised intraday liquidity facilities

The following subsections are concerned with RTGS systems for which the central bank offers an intraday liquidity facility. The first two subsections look at a collateralised intraday credit facility such as is prevalent in Europe. In the first subsection we investigate the case of a variable opportunity cost of collateral whereas the second subsection analyses the case of a fixed opportunity cost of collateral. The last subsection is concerned with an automated overdraft facility that is prepledged with collateral and, thus, exhibits a fixed opportunity cost of collateral. In contrast to before, reserve holdings are assumed to be zero at the beginning of the day. As in BG and MN, this makes it possible to focus on the intraday liquidity management game and to abstain from minimum reserve requirements.

5.1 Variable opportunity cost of collateral

First, we assume a per-period opportunity cost $o \geq 0$ 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 cover the 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 o if the bank processes the request and zero if the bank decides to delay. If a bank's 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. This accurately reflects the procedures in SIC: intraday credits are automatically repaid by means of a direct debit instruction. If no funds are available to pay back the intraday credit, it is turned over into an overnight credit. Alternatively, the bank borrows in the overnight market.

Again, the settlement shock takes place at the beginning of period 1. Banks then 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 credit in order to process outstanding payments.

The game leads to the following four realisations of expected costs:

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

$$c(m,a) = o + p(1-e)o + pe(o+R) + (1-p)(o+R) \tag{10}$$

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

$$c(a,a) = p(1-e)o + peR + (1-p)(1-e)(o+R) + (1-p)eR \tag{12}$$

The first term in equations (9) and (10) mirrors the necessity for bank i to draw an intraday credit in order to settle early. The second term in equation

(9) 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 credit to bring the account balance back to zero. In equation (10) 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 to additionally draw an overnight credit. In equation (11) and (12) 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 (11) and (12) can be explained by the fact that in equation (11) 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 any settlement cost since its payment is prefunded. Otherwise, bank i has to draw an intraday credit and, finally, an overnight credit to bring its account balance back to zero. If settlement risk realises, it can delay to period 2 and circumvent to draw an intraday credit. The same holds true for cost function (12) for the last two terms. 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 (10), the realisation of settlement risk forces bank i to draw an additional overnight credit. Figure 9 represents the game in normal form with equations (9) to (12) simplified where appropriate.

Figure 9: RTGS with a variable opportunity cost of collateralisation and with settlement risk

	m	a
m	o(1+(1-p)e) o(1+(1-p)e)	o(1+p+(1-p)e)+peR 0
a	0 o(1+p+(1-p)e)+peR	p(1-e)o+peR p(1-e)o+peR

Proposition 3 *Under a collateralised intraday credit regime with a per period opportunity cost of collateral $o > 0$ and a settlement shock $e > 0$, the strategy profile (a, a) is the unique Bayesian Nash equilibrium. Furthermore, a is a strongly dominating 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 the following cost relations hold $c(m, a) + c(a, m) > 2c(m, m)$ and $c(m, a) + c(a, m) > 2c(a, a)$ are valid. Comparing (a, a) with (m, m), the unique equilibrium (a, a) is efficient if

$$o\frac{1 - p + e}{pe} > R$$

We argue that for reasonable values of p, e and o the interest rate R would have to be tremendously high for (m, m) to be the efficient equilibrium.[25] However, the expected cost of a bank is not smaller for every bank and for every strategy profile - i.e. (a, a) is not a pareto-dominant equilibrium - only the aggregated expected cost is smaller. Nevertheless, banks have no incentive to deviate. As under a regime of priced overdrafts, delaying payments can insure a bank against the possibility that incoming payments are not settled. This strategic behaviour helps to economise on the bank's cost of sending payments.

In comparison to a regime without any intraday credit a collateralised regime with a per period opportunity cost leads to a stronger case for delaying payments. However, empirically settlement takes place much earlier after the introduction of intraday credits. Therefore, the model's prediction is inconsistent with stylized fact 1.

Even though central banks under a collateralized regime are not concerned about credit risk per se, for comparative reasons it is interesting to analyse the demand for intraday credits. Given the chosen equilibrium (a, a), the expected value of intraday credits drawn is $2p + (1-p)(1-e)$ (it is presumed that bank i received a payment instruction). With probability p, the other bank also receives a payment instruction and prefunds the payment. With probability $(1-p)$, only bank i receives a payment instruction and draws an intraday credit. However, it does so with probability $(1-e)$ only. With probability e, a settlement shock occurs and the bank funds payments with an overnight credit and settles in period 2.

It is interesting to note that if $o = 0$, all strategy pairs are Bayesian Nash and the morning equilibrium is the Pareto-dominant equilibrium. If there are no costs to intraday liquidity at all, the first-best outcome would result. Banks are keen to avoid to settle late, since the late settlement equilibrium exposes them to settlement risk. A realising settlement risk could require banks to pay back intraday credits ahead of receiving the other banks payments. This would expose them to a potentially unnecessary refinancing in the overnight market. Therefore, banks choose to settle early. This is in contrast to MN. Free overdrafts result in (a, a) as the equilibrium outcome. Banks make sure that they pay around the same time in order to avoid that they run into refinancing an overdraft that results either due to a mismatch of timing or due to a realising settlement risk. Both can end in a costly and potentially unnecessary refinancing in the overnight market. Therefore, it is a weakly dominating strategy for banks to delay payments. The difference in results is driven by the prefunding constraint in our model that does not allow for an offsetting of transactions without incurring the opportunity cost of collateral. If $e = 0$, (a, a) results as the unique equilibrium with a being the dominant strategy for all players. Banks seek to avoid the cost of intraday liquidity by waiting for incoming payments from the other participants. If both $o = 0$ and $e = 0$, all strategy pairs are Bayesian Nash and no particular equilibrium is chosen.

[25] Let us look at some concrete values: $p = 0.1$, $e = 0.01$ and $o = 0.02\%$. Then, in order for the strategy pair (m, m) to be the efficient equilibrium, R would be required to exceed a level of 18%.

5.2 Fixed opportunity cost of collateral

In their model of collateralised intraday credits, BG assume that the opportunity cost of collateral accumulates per period. Implicitly they assume that the market offers valuable opportunities to reuse collateral intraday. Another hypothesis is that the decision to draw intraday credits requires banks to hold collateral, which implies the restructuring of a bank's assets such that the asset structure for the bank becomes suboptimal. Koboyakawa (1997) and Mills and Husain (2009) apply a fixed opportunity cost of collateral, saying that it is questionable whether the market provides opportunities to reuse collateral on an intraday basis such that the opportunity cost of holding collateral can be eliminated or substantially reduced.

The change in the SNB's collateralisation policy offers a way to shed light on this unsolved issue, as outlined in section two. Given that the market offers reuse opportunities intraday, the preceeding game was played before 2005. From 2006 on, at the latest, the change in SNB's collateralisation policy gave rise to a fixed opportunity cost since collateral has to be pledged permanently. Therefore, for the period after 2005/2006, instead of modelling opportunity costs as per-period costs, collateral holdings are assumed to cause a daily fixed cost, $f > 0$.

Related to the model setup, both banks are assumed to have prepledged collateral at the central bank of value 1. The opportunity cost of collateral f is considered to be lower than the overnight rate $R > f$. Banks use the possibility of drawing 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 at a cost R.

The following cost functions result from this setup:

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

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

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

$$c(a, a) = f + peR + (1 - p)R \tag{16}$$

Whatever the payment strategy is and whether or not a bank actually receives a payment instruction, it incurs opportunity cost f since it has to prepledge collateral to the amount that covers its intraday liquidity needs. Therefore, its cost funtions are determined by the fixed cost of collateral provision and the payment uncertainty imposed by the other bank. If bank j's strategy is to pay late, bank i's cost is additionally affected by settlement risk. If settlement risk occurs, bank i is urged it to draw additional overnight credit. Without 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. Figure 10 represents the game in normal form with equations (13-16) simplified where appropriate.

Figure 10: RTGS with a fixed opportunity cost of collateralisation and with settlement risk

	m	a
m	0 0	peR 0
a	0 peR	peR peR

Proposition 4 *Under a collateralised intraday credit regime with a daily fixed opportunity cost of collateral $f > 0$ and a settlement shock $e > 0$, all strategy profiles are Bayesian Nash equilibria. The strategy profile (m, m) is a strictly Pareto-dominant equilibrium.*

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 $c(a, m) = c(a, a)$. It also easy to see from figure 10 that $c_i(m, m) + c_j(m, m) < c_i(x, y) + c_j(x, y)$ where $(x, y) \neq (m, m)$ for all strategy pairs (x, y) and all banks i and j. Therefore, the strategy set (m, m) is strictly Pareto-dominant.* ■

The fixed opportunity cost of collateral leaves all possibilities open and does not make it possible to choose one or a small selection of strategy profiles as Nash equilibria, since all profiles have to fall under this heading. Moreover, the strategy profile (m, m) is a strictly Pareto-dominant equilibrium. Since all strategy profiles are Bayesian Nash equilibria, it is compelling to assume that (m, m) will be the effectively chosen equilibrium. It is interesting to note that in a framework with a delay cost (m, m) results as the chosen equilibrium, if we assume a fixed opportunity cost of collateral. Koboyakawa (1997) applies such a framework and also obtains an early settlement equilibrium. In essence, in a delay cost framework, sunk opportunity cost of collateral results in the equivalent outcome to that obtained in a framework with free overdrafts.

Given that the market offers valuable reuse opportunities for collateral intraday, we would expect to see a change in behaviour after the introduction of the new collateralization policy in 2005/2006. However, as stylised fact 1 suggests, a change from late to early settlement equilibrium already took place after the introduction of intraday credits, when release and settlement of payments started to take place much earlier than before (see figure 2). No corresponding changes can be seen around 2006. Therefore, a per-period opportunity cost of collateral is not consistent with stylised fact 1. In essence, the opportunity cost of collateral does not appear to be perceived as dependent on the time of usage but as fixed.

Stylised fact 2 also supports this view. Given that banks perceived the opportunity cost of collateral as variable before 2005, one would expect a rise in the demand for intraday credits after the introduction of the LSFF. Under a framework with permanently prepledged collateral, opportunity costs are considered as sunk up to the given limit. However, figure 1 shows that no change in the demand for intraday credits occured in the years 2005 and 2006 when the new collateralisation policy was introduced. Neither did banks change their demand for intraday credits in terms of value nor did they keep intraday credits for a longer period of time. Furthermore, banks have never exploited the limit established for the LSFF.

Indeed, in terms of the model, a clear difference to a case with a variable opportunity cost emerges. The expected value of intraday credits drawn with fixed opportunity costs is larger, namely $2p + (1 - p)$. With probability p both banks receive a payment instruction and prefund their payments. The probability is $(1 - p)$ that bank j does not receive a payment instruction and will not draw an intraday credit. Bank i draws an intraday credit and pays it back either at the end of period 0, 1 or 2. However, the point of time when the bank pays back its intraday credit will not affect its intraday cost. So, the amount drawn is at least $2p + (1 - p)$, which is indeed larger than $2p + (1 - p)(1 - e)$, the expected value of intraday credits drawn under a variable opportunity cost. To summarise, stylised facts 1 and 2 suggest that a regime shift from a variable opportunity cost to a fixed opportunity cost did not take place. We conclude that banks perceived opportunity costs of collateral to be fixed before and after the introduction of the new facility and the new collateralisation policy.

The payment model with a fixed cost of collateral predicts earlier settlement than does the payment model by MN that predicts late settlement for a regime with priced overdrafts. This mirrors stylised fact 3. Indeed, compared to Fedwire funds, settlement in SIC has taken place earlier since the introduction of intraday credits and moved to even earlier hours after the introduction of CLS. The fixed opportunity cost of collateral is responsible for these differing results. A sunk cost of intraday liquidity allows banks to reduce settlement risk by making use of intraday credits without incurring additional costs. Strategically, this mirrors results of free intraday credits in BG and MN.

The above conclusions do not change if $f = 0$. Also, if $e = 0$, all strategy pairs remain equilibria. In contrast to the analysed case above, however, no particular equilibrium is Pareto-dominant.

It is easy to see that the introduction of a two-part tariff would make the early settlement equilibirum also the efficient and dominant equilibrium.

5.3 A prepledged overdraft facility

A fixed opportunity cost of collateral invites to reflect on the Federal Reserve Board policy change to allow for an additional prepledged overdraft facility. To analyse the coexistence of a collateralised and an uncollateralised overdraft facility remains a task for future research. However, what the given model setup allows for is to analyse the case when banks prepledge the full amount of collateral needed for overdrafts. The full amount of prepledged overdraft is 1 in the given setup. Again prepledging entails the opportunity cost f. Applying the same rules of the game as set out in MN, the same cost functions as in the above game result. This is a mere consequence of the fact that in terms of cost implications, it does not matter when overdrafts are incurred or whether they are incurred at all.

Proposition 5 *Under a collateralised overdraft regime with a daily fixed opportunity cost of collateral $f > 0$ and a settlement shock $e > 0$, all strategy profiles are Bayesian Nash equilibria. The strategy profile (m, m) is a strictly Pareto-dominant equilibrium.*

In the light of the above proposition and the Federal Reserve System's policy plans, we propose the following conjecture.

Conjecture 6 *A change from a priced overdraft system to a fully collateralised overdraft system would result in earlier settlement.*

The Federal Reserve Board actually implemented a mixture of both facilities, uncollateralised but priced and free but collateralised overdrafts. Abstracting from any specificities and assuming free choice of usage, we expect banks to opt for the less expensive solution. However, it is not obvious what would result unless one or the other option is clearly less expensive. Kraenzlin and Nellen (2010) find collateralisation to be less expensive than the Federal Reserve System's fee based overdraft facility. However, a full cost-benefit analysis would have to consider total cost and not merely the price of intraday liquidity.

6 Conclusions

This paper models the strategic interaction of participants in payment systems in order to better understand the intraday pattern of settlement. Whereas MN analyse a system that works on the basis of intraday overdrafts this paper investigates systems with no intraday liquidity facility and systems with intraday liquidity facilities that are based on collateralisation. Both MN's paper and this paper question the delay cost approach that results in predictions that do not mirror stylised facts and does not account for a fundamental force that favours late settlement. In contrast, a framework applying settlement risk results in predictions that are consistent with stylized facts. Also, BG consider settlement risk to be a key element of delay costs. However, the effects of settlement risk on behaviour do not appear to be captured if modelled as an exogenous cost such as applied in the literature based on the delay cost approach.

In an environment without any intraday liquidity facility, reserve requirements are found to be a crucial factor influencing settlement timing. In a delay cost approach rivalry in costly liquidity is dissolved through reserve requirements that make the cost of liquidity sunk and result in an early settlement equilibirium. Whereas this is understood to be only partially in line with stylised facts, the settlement risk approach too results in a late settlement equilibrium that is only partially in line with stylised facts. It is argued that extending the models with flexible reserve requirements and a two-part tariff can not result in consistent predictions under the delay cost approach but may result in consistent predictions under a settlement risk approach. However, extending the model is left for future research.

Apart from the factors analysed in MN, this paper shows that the design of the intraday liquidity facility plays a crucial role in determining the cost function of banks and, therefore, their settlement behaviour. Essentially, the active drawing of liquidity in combination with collateralisation leads to a prefunding requirement that drives results. Furthermore, market opportunities and central banks' collateralisation policy can crucially influence the opportunity cost of collateral and, therefore, the strategic interaction of banks. Results can be summarised as a policy relevant equivalence postulate. Payment systems with up front collateralisation exhibit an early settlement equilibrium under both a regime with intraday credits and a collateralized overdraft facility. Essentially, upfront collateralization comes with a fixed opportunity cost of collateral. Strategically, a fixed opportunity cost of collateral makes it mutually beneficial for banks to avoid settlement risk by early settlement.[26]

Using observations from SIC and Fedwire funds, models are tested for their consistency with stylised facts. First, the models predict late settlement under a regime without any intraday liquidity facility, and early settlement under a regime with a fixed opportunity cost of collateral. Indeed, since the introduction of intraday credits, release and settlement of payments in SIC has taken place substantially earlier. Second, empirical evidence suggests that banks perceive the opportunity cost of collateral as being fixed. A change in the collateralisation regime for intraday credits at the SNB did not cause a corresponding change in the demand for intraday credits. The given repo framework in Switzerland would suggest a variable opportunity cost, since banks can basically draw and pay back intraday credits throughout the day and, therefore, make alternative use of their collateral. Along with the introduction of the LSFF and the possibility to draw intraday credits on the prepledged collateral of this facility, banks' opportunity cost of collateral was modified in two ways. First, banks can pledge the same collateral for both facilities. Second, the prepledging of collateral implies fixed opportunity costs of intraday credits. Given that opportunity costs were variable before, the regime switch should have caused banks to perceive these costs to be sunk. From then on, banks could draw intraday credits up to the prepledged limit without any further costs involved. However, the policy change did not affect banks' demand for intraday credits as the model suggests. Banks neither started drawing more intraday credits nor did they hold intraday credits for longer time periods. This is understood as evidence that banks face a fixed opportunity cost of collateral. Third, MN predict late settlement under the current arrangement applied in Fedwire funds. The payment model with a fixed opportunity cost of collateral predicts early settlement under the given setup in SIC. Data on Fedwire funds and on SIC support these predictions. Indeed, settlement in SIC takes place substantially earlier in comparison

[26]Securities settlement systems are not discussed in this paper. However, it is easy to adapt the same set of games analysed here to the analysis of securities settlement systems. For them a stronger equivalence results. DvP is such a powerful mechanism that the morning equilibrium emerges whatever the surrounding factors look like.

to Fedwire funds.

The insights gained in MN and this paper are relevant for future policy-oriented work. The new overdraft policy by the Federal Reserve Board is directly related to the analysis. The Federal Reserve Board implemented a new strategy for providing intraday credit to depository institutions and encourages institutions to collateralise their daylight overdrafts. Applying a fixed opportunity cost of collateral to an overdraft framework as modelled in MN results in the conjecture that settlement in Fedwire funds would take place earlier than it does a regime with priced overdrafts only. Future research may analyse the effectively proposed mixture of both types of overdraft regimes, priced and pre-collateralized overdrafts.

Even though the evidence provided reveals that banks perceive opportunity costs of collateral to be fixed, the reasons why they do so remain unclear. While it is true that the collateralisation policy of the SNB after 2006 implies a fixed opportunity cost of collateral, it is very questionable that markets do not offer reuse opportunities for collateral intraday. The latter view contrasts with the literature that analyses the intraday term structure of overnight money markets, such as Kraenzlin and Nellen (2010). Future research may address this question in more detail.

Yet another field of research may be to further models that analyse RTGS system with central queuing facilities. Obviously, a basic difference between RTGS systems with automatic overdrafts and intraday credits on a collateralised basis is that the release and the settlement of payments coincide for the first and differ for the latter type of systems. The time difference between release and settlement of payments results in central queuing. A further implication of central queuing facilities is that releasing payments does not imply immediate settlement of payments. Therefore, concentrating payments, as found by Armantier et al. (2008) for Fedwire funds, is less important for speeding up settlement if queues are already fuelled with pending payments. Rather than concentrating payments what matters most is the level of liquidity available that drives settlement. As set out in Nellen (2010), this is especially true in the case of SIC, both before and after the introduction of intraday credits on a collateralised basis. Jurgilas and Martin (2010) point out that in collateralised RTGS systems the application of liquidity-saving mechanisms may result in incentives to release payments earlier to the central queuing facility since this allows to save on costly liquidity and assists earlier settlement. However, their insights are based on a delay cost approach. Furthermore, there is not literature that takes into account the enlarged strategy set of participants in such systems. Essentially, banks face a wider choice of actions than simply to settle or delay. They can either release and immediately settle by prefunding, just release (either the payment settles due to incoming funds from other banks or it is queued) or delay (banks do not release payment instructions and leave them in their internal queues). Whether such a model would alter derived conclusions in this paper remains an unanswered question.

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8 Appendix

8.1 Cost functions for proposition 1

Equation (1) pertains to bank i's cost if it sends its payment in the morning. If it receives a payment, bank j sends it in the morning too. The probability is p that bank j receives a payment. Both end up with an account balance of 1. Therefore, no additional overnight credits are required to fulfil reserve requirements. The probability is $(1-p)$ that bank j does not receive a payment instruction. Therefore, bank i incurs the cost of the overnight credit since it has to fulfil reserve requirements at the end of period 1.

Equation (2) analyses the case where bank i sends its payment in the morning and bank j sends its payment in the afternoon. The probability is p that bank j receives a payment instruction. Both banks end period 1 with a positive account balance. The probability is $(1-p)$ that bank j does not receive a payment instruction. Therefore, bank i will ask for an overnight credit to fulfil reserve requirements at the end of period 1.

Equation (3) evaluates bank i's cost if bank i sends its payment in the afternoon whereas 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 by 1. Bank i sends its payment in the afternoon, implying a delay cost D. The probability is $(1-p)$ that bank j does not receive a payment instruction in the morning. Therefore, bank i needs an overnight credit to fulfil reserve requirements at the end of period 1.

Equation (4) represents the case where both banks choose to send their payments in the afternoon. The probability is p that bank j receives an instruction. Therefore, both banks do not have to provide additional funds to fulfil reserve requirements at the end of period 1 since they end period one with a positive account balance. However, the delay cost D has to be taken into account. The probability is $(1-p)$ that bank j does not receive a payment. Again, at the end of period 1 bank i will require an overnight credit to fulfil reserve requirements.

8.2 Cost functions for proposition 2

Equation (5) pertains to bank i's cost if it sends its payment in the morning. The probability is p that bank j receives a payment instruction too. Both end up with an account balance of 1. Therefore, no additional funds are required to fulfil reserve requirements. The probability is $(1-p)$ that bank j does not receive a payment instruction and bank i incurs the cost of the overnight credit since it has to fulfil its reserve requirement at the end of period 1.

Equation (6) analyses the case when bank i sends its payment in the morning and bank j sends it in the afternoon. The probability is p that bank j receives a payment instruction and delays it until the afternoon. The probability is $(1-e)$ that no settlement shock takes place and both banks end period 1 with a positive account balance of 1. Thus, they do not have to draw overnight credits to fulfil reserve requirements. The probability is e that a settlement shock takes place. Therefore, bank j sends the instruction in period 2. Bank i has to draw an additional overnight credit at the end of period 1 in order to fulfil reserve requirements. The probability is $(1-p)$ that bank j does not receive a payment instruction. Bank i, therefore, draws an overnight credit in order to fulfil reserve requirements at the end of period 1.

Equation (7) evaluates bank i's cost if bank i sends its instruction in the afternoon whereas bank j sends it in the morning. The probability is p that bank j receives a payment. Bank i's account balance increases by 1 and it can easily send the payment in the afternoon. Whether or not there is a settlement shock will not affect its costs. The probability is $(1-p)$ that bank j does not receive a payment instruction. Therefore, bank i draws an overnight credit to fulifil its reserve requirements at the end of period 1.

Equation (8) shows the case where both banks choose to send their payments in the afternoon. The probability is p that bank j receives an instruction. If a settlement shock materialises, both banks delay payments until period 2. Therefore, they do not have to draw additional funds to fulfil reserve requirements. In period 2 payments are offset and banks end period 2 with a positive account balance, avoiding the cost of prefunding. If there is no settlement shock, they conclude the day with a positive account balance of 1 and do not need any additional funds. The probability is $(1-p)$ that bank j does not receive a payment. If there is a settlement shock, bank i delays its instruction until period 2. If there is no settlement shock, it settles in period 1. In any case, bank i draws an overnight credit either in period 1 or in period 2 in order to fulfil reserve requirements.

8.3 Cost functions for proposition 3

Equation (9) evaluates bank i's cost if both banks play morning an 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 of intraday credits. In order to send payments, 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 credit.

Equation (10) 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 $(1-e)$ that the payment is received by bank i and it can repay the intraday credit without having to draw an overnight credit. However, the intraday credit has to be prolonged from period 0 to period 1 and causes opportunity cost o. The probability is e 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 the day 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 plus the overnight interest rate.

Equation (11) 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. Either the payment goes out in the afternoon or it is settled in the last period. In any case, 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. There is a probability of $(1-e)$ that the payment will go through. In this case, bank i's cost is $o + R$ because the payment requires an afternoon intraday credit and a loan from the overnight market. The probability is e that a settlement shock occurs. In this case bank i would not have to ask for an intraday credit. However, in period 2 it will have to draw an overnight credit in order to process the payment. Thus, bank i faces the cost of an overnight credit R in case a settlement shock occurs.

Equation (12) 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, then both payments will offset each other but banks incur the opportunity cost of collateral o since they had to prepledge before the settlement shock reveals. If there is a settlement shock, both banks will send payments at time 2. Since information regarding the shock is public, both banks actually delay their payments until period 2 in order not to avoid the cost of 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 credit. 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).

8.4 Cost functions for proposition 4

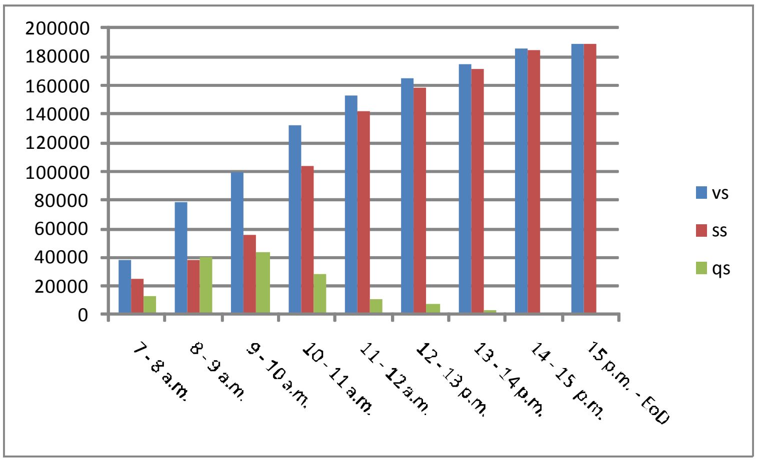
Equation (13) evaluates bank i's cost if both banks play morning. The probability is p that bank j receives a payment instruction. Since there is no possibility of a settlement shock taking place and payments offset each other, overnight credit is not required.The probability is $(1 - p)$ that bank j 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 f bank i incurs the cost of an overnight credit.

Equation (14) 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 $(1-e)$ 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 e 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 (15) 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 a settlement cost since it enters the afternoon with a positive account balance. 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 credit. The probability is $(1 - p)$ that bank j does not receive a payment instruction. Bank i sends its payment in the afternoon and the probability is $(1 - e)$ that it goes through. In this case, bank i needs an overnight loan to pay back the intraday credit at the end of period 1. The probability is e that a settlement shock occurs. Even though bank i can delay until period 2, its cost stays the same.

Equation (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. If there is no settlement shock both banks settle their payments in the afternoon and pay back their intraday credit without having to draw an overnight credit. If there is a settlement shock both banks send payments in period 2 and, therefore, both banks have to draw an overnight credit. 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 credit to pay back the intraday credit.

Figure 11: Monthly averages for March 2007 of daily values of the hourly stock of released (vs), settled (ss) and queued (qs) payments in CHF Mio



8.5 Release, settlement and queuing indicators

This subsection serves to briefly explain indicators applied in section two. The SNB's database on SIC contains ten mostly hourly aggregated data points on settlement and queuing. The first data point spans the settlement day from 5 p.m. (beginning of the SIC day) to 7 a.m., the remaining data points span each hour until 3 p.m. and the last one spans the period from 3 p.m. to the end of day at 4.15 p.m (EoD). The data set provides different variables within each category. We refer to the stock of queued and settled payments in CHF Mio. as qs and ss. The sum of queued and settled payments yields the variable released payments vs. The system's aggregated stock values are depicted in figure 11 as monthly averages. Connecting the points, we receive release, settlement and queuing curves.On the basis of the data available, indicators are easily derived as normalised values of the areas below the respective curves. The comprehensive settlement indicator (CSI) is readily computed as

$$CSI = \sum_{i=1}^{T} \frac{1}{T} \frac{ss^i}{V}$$

where V indicates the considered day's turnover. Therefore, $CSI = 1$ indicates that all settlement takes place at the beginning of the day whereas a value approaching zero indicates that all settlement takes place at the end of the day, respectively during the last time period.

Traditional delay indicators from the simulation literature such as Koponen and Soramäki (1988) measure congestion in central queues. With the principle applied it is easy to construct a similar delay indicator. The centralized queuing indicator (CQI) measures the normalised area below the queuing curve. A value approaching zero indicates that no queuing takes place whereas a value approaching one means that all payments were queued from the beginning of the day until the end of the day.

$$CQI = \sum_{i=1}^{T} \frac{1}{T} \frac{qs^i}{V}$$

A release time indicator (RTI) is readily constructed as the area under the release curve which is nothing but the sum of settled (ss) and queued (qs) payment value ($vs = ss + qs$). RTI is the normalised area below the release curve where early release of all payments to be settled yields a value near 1. In contrast, if all payments to be settled are released in the last period, RTI approaches zero.

$$RTI = \sum_{i=1}^{T} \frac{1}{T} \frac{vs^i}{V}$$

It is easy to see that $RTI = CSI + CQI$. The backside of RTI are unreleased payments which can be measured as the unreleased payment indicator (UPI) in exactly the same way. We take the normalised area above the curve that indicates the stock of released payments as an indictor. A value approaching one means that payments are all released at the end of the day whereas a value of zero says that all payments are release at the beginning of the day.

$$UPI = 1 - \sum_{i=1}^{T} \frac{1}{T} \frac{vs^i}{V}$$

By construction it is true that $CSI + CQI + UPI = 1 = RTI + UPI$.

What drives settlement performance?

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

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Abstract

Settlement performance of real-time gross settlement (RTGS) payment systems is defined as the trade-off between liquidity usage and resulting settlement delay. We propose a new measure of delay that can be applied consistently for the main types of RTGS systems and permits to analyse settlement performance more comprehensively. We explore old and develop new indicators that measure different aspects of release behaviour and the system's topology. An econometric investigation of settlement performance in the Swiss Interbank Clearing (SIC) reveals that the main drivers of settlement performance are turnover, liquidity and release time. The dispersion of liquidity holdings does not have a significant effect on settlement performance, indicating that the provision of privately costly liquidity resembles the private provision of a public good.

JEL classifications: C43, E58, G21, G28.

Key words: RTGS payment system, settlement performance, settlement delay, bank behaviour, liquidity-saving mechanism, indicators

1 Introduction

The literature on real-time gross settlement (RTGS) payment systems suffers from a dichotomy. One branch of literature is theoretical and the other simulation based. The former literature allows to analyse behavioural settings and is based on anecdotal and descriptive evidence. Econometric verification is rare and what has been generated as valuable analytical insights suffers from this caveat. Even though the simulation based literature yields valuable insights into the mechanics of payment systems, it suffers from a type of Lucas critique. In

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

essence, simulations can not take account of behavioural reactions induced by the investigated policy changes.[1]

This article serves to further empirical methods. We describe old and some new indicators to analyse real data on RTGS payment systems. The empirical history of one of the oldest RTGS system, the Swiss Interbank Clearing (SIC), is presented and analysed. In an econometric study we apply indicators to investigate by what settlement performance is driven in SIC. Settlement value and available liquidity are the most relevant ones. However, the case of SIC reveals that many other forces exert substantial influence on settlement performance. The most influential is found to be release time. Others such as the system's topology and large-value payments also affect settlement performance. However, the dispersion of individual liquidity contributions in relation to turnover does not influence aggregate settlement performance.

One can differentiate between two basic forms of RTGS systems: the ones with (e.g. Target2 and SIC) and the ones without central queuing facilities (e.g. Fedwire). These two types of systems can also be differentiated according to the way participants can access intraday liquidity: queuing systems provide collateralised intraday credits whereas systems without central queuing facilities generally provide automated overdrafts.[2] Settlement performance in RTGS payment systems with queuing is described as the trade-off between liquidity available and the resulting settlement delay that is measured as payments pending in central payment system queues. In essence, the following question is asked: with how much central queuing is the system capable to settle a certain turnover given a certain level of liquidity.[3] Given this prevailing definition of settlement performance, empirically we can not compare settlement performance for the two types of systems. For the latter type the definition of settlement delay is a meaningless concept since release and settlement of payments go hand in hand.

In an economic sense settlement performance is associated with the trade-off between the cost of liquidity and the cost of delay. Delay of settlement goes along with later finality than could have been obtained with more liquidity. Later finality is associated with higher costs related to delay and settlement risks. The cost trade-off and its beavioural implications is analysed theoretically e.g. by Angelini (1998) and Jurgilas and Martin (2010) for queuing systems and by Bech and Garratt (2003) and Mills and Nesmith (2008) for overdraft systems. As set out in Mills and Nesmith (2008) for systems with an overdraft facility, releasing payments early or late is one major way to influence the economic trade-off. Liquidity usage in such systems is basically defined by the choice of release time that is identical to the settlement time. This is different in queuing

[1] Notable exceptions to this are Galbiati and Soramäki (2008) who run simulations on the basis of an agent-based model and Atalay et al. (2010) who calibrate a theoretical model with Fedwire Funds data.

[2] See World Bank (2008) for a general overview and Committee for Payment and Settlement Systems (CPSS; 1997 and 2005) for further information on RTGS systems and new developments such as hybrid systems.

[3] Even though technological capacity can be a limiting factor for settlement performance, it is not addressed in this paper. We persue a day to day analysis of settlement performance, assuming that the capacity problem is not an issue.

systems, for which the level of liquidity becomes a trade-off endogenous variable as discussed in Nellen (2010) and Heller and Lengwiler (2003). In RTGS systems with central queuing the chosen liquidity level influences settlement time to a large extent.

In order to investigate settlement performance empirically, we have to be able to describe the underlying trade-off between liquidity and delay. However, the given definition of delay is misleading, since delay costs stemming from later finality are also caused by decentrally queued payments. As the theoretical literature points out, strategic delay is an issue for RTGS system. Bartolini et al. (2008) were the first to provide evidence on strategic delay. In matching payment with trade data related to the US money market, they find that strategic delay is a real issue. Given strategic delay is real, settlement performance does not only depend on the structural capacity of the system, but it is crucially influenced by the economic trade-off. Therefore, in order to perform theory based econometric investigations, we need to know the substitution rate between delay and liquidity in a more comprehensive sense. If the limit of processing capacity is not touched, we could purely measure the structural settlement performance of the system. However, in a structural sense too, queued payments are a misleading indicator for delay. In the case of SIC many changes of the level of centrally queued payments are known that are a mere reflection of changing tariffs or banks' IT reorganisations.[4] Therefore, taking central queuing as a measure of delay can be misleading and, as a consequence, an analysis of settlement performance based on such a measure may yield wrong conclusions in both a structural and an economic sense.

Therefore, the objective of this paper is to pin down a definition of settlement delay such that it is possible, first, to compare the two types of RTGS systems and, second, to gain a more comprehensive picture of settlement performance . We suggest the most simple measure for such a new delay indicator. Since strategic delay taking place on decentralised queues is private information, we have to rely on the best proxy available. We simply take all payments to be in delay since the beginning of the settlement day until settlement actually takes place. Thus, delay is extended from queued or pending payments to payments that are not settled but will still be during the settlement day - in other words, delay includes queued and unreleased payments. This new definition of settlement delay can be applied in two ways, either directly, or, as its inverse, an indicator of settlement in the course of the day.

Real data is exposed to 'noise' generated by developments from outside the payment system. In order to reduce such noise, we need to build indicators that serve to better disentangle other influences from the measurement of settlement performance. For example, the topology of the payment flows may influence settlement performance for it shapes the settlement speed of transactions among

[4] In April 1988 SIC replaced a flat tariff with a two-part tariff meant to induce earlier release and settlement. As a response, banks indeed started to release payments earlier. Looking at the individual bank level, the extent of central queuing often changes dramatically due to out- or insourcing decisions of payment queueing related to these changes in fees or other reasons such as internal IT reorganisations.

the participants of the payment system. These variables may well change over time. Also the size of the payment network may play a role. For instance, SIC experienced several sharp and slow changes of the number of participants. Therefore, without incorporating indictors for environmental variables we would eventually gain a misleading measure of settlement performance.

The paper is structured as follows. First, we briefly describe SIC. Major characteristics and policy changes of the systems are explained. The third section characterises data, variables and basic statistics. In section four we look at different liquidity usage indicators. Then we discuss delay and settlement indicators. Section six introduces indicators that capture behavioural and environmental influences such as indicators of release behaviour by participants, two simple topological indicators and two indicators of liquidity dispersion in relation to turnover. In section seven econometric analysis is applied in order to answer the initial question: what drives settlement performance? Section eight concludes.

2 Description of SIC

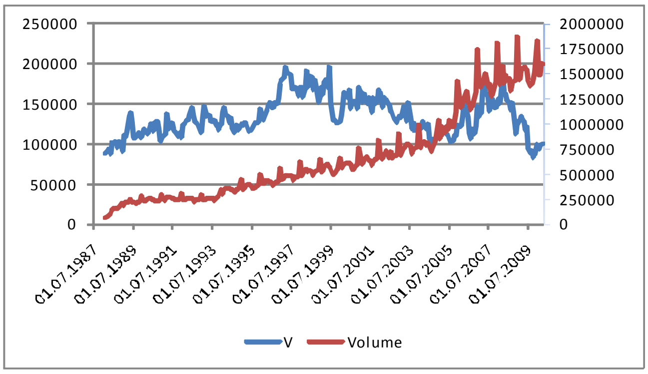
SIC was put into operation in June 1987 as a simple RTGS system driven by a first-in-first-out algorithm (FIFO).[5] Banks release payments to central queues. Payments will be settled given enough cash lies on the settlement accounts. Should not enough reserve balances be available, payments keep pending in the central queues until enough funds arrive. During the introductory phase, which lasted until January 1989, participants were linked step-by-step and the settlement volume and value gradually increased (see figure 1). The former paper systems were phased out in June 1988, the magnetic tape system in January 1989. The settlement algorithm stayed the same until 1994 when priorities were introduced. From an individual participant's perspective, the settlement sequence of payments in the first place is determined by the chosen priority. Within a specific order of priority, the FIFO-rule applies. Priorities should allow to settle time-critical and thus delay-sensitive payments more accurately. In December 2001, the settlement algorithm was enriched with circles processing, a gridlock resolution mechanism. If the system is not able to settle payments for a certain period of time, the algorithm is searching for bilateral off-setting possibilities and initiates one single payment to off-set two other payments.[6] After the off-setting took place, the algorithm starts to settle in the standard way again. With regard to the settlement algorithm there have been no other changes.

In April 1988, SIC adopted a two-part tariff. The later payments are released and settled, the more expensive is the fee. Furthermore, payments below

[5] See Heller, Nellen and Sturm (2000) or Vital (1990, 1997) for other comprehensive descriptions of SIC.

[6] The influence of the bilateral off-setting mechanism is limited. On average it is applied once a day. The given liquidity levels are sufficient to ensure a smooth settlement process without the help of the bilateral off-setting mechanism.

Figure 1: Monthly averages of settlement value (V) in Mio CHF on the primary axis and settlement volume of payments on the secondary axis



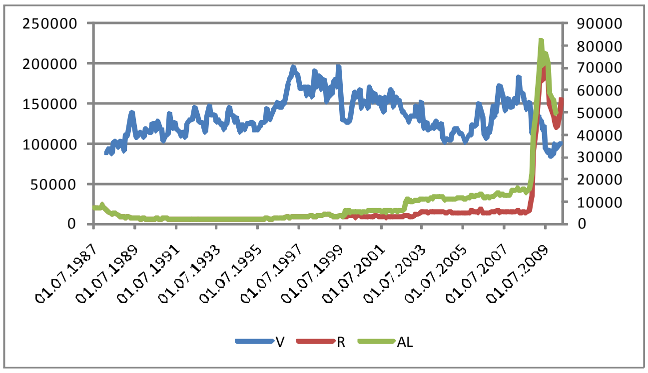
100'000 CHF are less expensive than large-value payments. This fee structure was made more progressive in 1989 and its nature has been preserved since then.[7] As pointed out in Vital (1990) the new fee structure was mainly meant to encourage early initiation of payments. Additionally, it was aimed at increasing the transaction cost for participants holding low reserve balances in relation to their turnover. Furthermore, it encourages releasing small-value payments before large-value payments to prevent capacity bottlenecks on peak days. Influencing the release sequence of payments is indeed an issue for SIC considering that it is processing both large-value and small-value payments as is well illustrated in figure 1. While the monthly averages of daily values settled in SIC are within a range between CHF 100 and 200 billion, the volume of payments steadily increased to an average daily number of over 1.5 Mio in 2010 of which 95% are bellow CHF 100'000.[8]

Banks can use their reserve balances deposited at the Swiss National Bank (SNB) to fulifil their minimum reserve requirements but also for settlement purposes either on the books of the central bank or in SIC. In January 1988 new regulations calling for lower levels of liquid balances (reserve account balances, postal giro account balances and cash) took effect. In comparison to before 1988, most banks draw their reserve account balances down to lower levels until 1993 without violating the regulations. Vital (1990) stated that, "as a rule, SIC operates now without binding reserve requirements". This conclusion is further highlighted in Heller and Lengwiler (2003). Whereas it is true that a lot of small and medium sized banks do fulfil requirements to a higher degree than necessary, larger banks, in contrast, often hold cash and reserves only slightly

[7] See Heller, Nellen and Sturm (2000) for a more detailed description of the fee structure and Ota (2010) for a theoretical analysis of the application of two-part tariffs in large-value payment systems.

[8] Payments made by the SNB are excluded.

Figure 2: Monthly averages of daily settlement value (V) on the primary axis, daily reserves balances at end of day (R) and available liquidity (AL) on the secondary axis (all in Mio CHF)



above the level of their minimum requirements.[9]

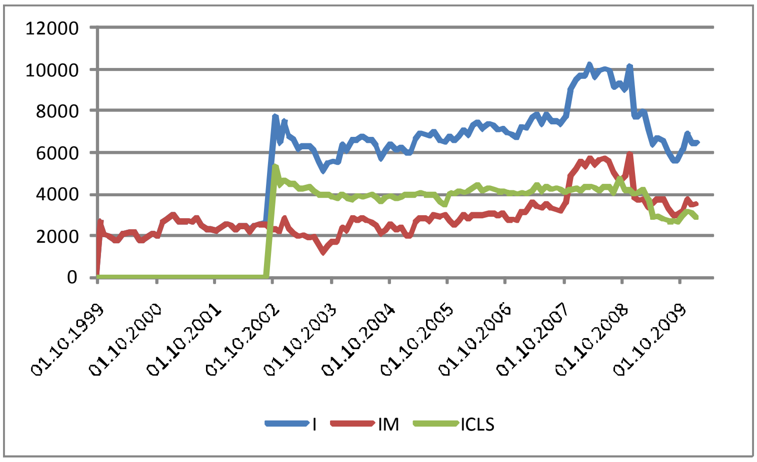
Until 1st of October 1999 when intraday credits were introduced, SIC was one of the very few RTGS systems that did not allow for any overdrafts nor did it provide collateralised intraday credits. Despite the well-known argument that an RTGS system without any form of intraday liquidity would imply substantial liquidity costs for participating institutions, SNB has not allowed for this form of inexpensive liquidity before 1999. Even though queuing or settlement delay was on a high level (see figures 8,9 and 10), SIC operations generally ran fairly smoothly without much liquidity. Heller, Nellen and Sturm (2000) claim that due to a liquid money market and sophisticated liquidity management by some market participants, banks were able to gradually reduce their reserve balances without jeopardising smooth settlement.[10] Along with substantial queues, the system was able to turn over available reserve balances more than 70 times (see figure 6). As from October 1999 on, the SNB has been placing interest-free intraday liquidity at the banks' disposal. This change in policy was motivated mostly by an increase in time-critical payments. In particular, the expected introduction of the CLS system for settling foreign exchange transaction was perceived to trigger an additional need to settle potentially very large payments without delay.[11] Figure 2 displays available liquiditiy consisting of reserve balances and intraday credits drawn and contrasts available liquidity with the value

[9] In 2005, a new regulation on the minimum reserve requirement came into effect without changing the overall picture of how banks fulfil requirements. Since then postal giro account balances are not eligible anymore. Due to the financial crises the picture changed dramatically in the last quarter of 2008 when the SNB started to provide the financial system with ample reserve balances (see figure 2).

[10] See also Heller and Lengwiler (2003) for a theoretical and empirical account of the period before 1999.

[11] For a description of CLS and its relation to the foreign exchange market see CPSS (2008).

Figure 3: Monthly averages of daily total intraday credits (I), intraday credits drawn for main accounts (IM) and intraday credits drawn for CLS subaccounts (ICLS)



settled.

The introduction of CLS on 10 September 2002 came along with the creation of special CLS sub-accounts for CLS members. While banks drew on average about CHF 2 billion of intraday credits in total for their main accounts before September 2002, the amount increased by about CHF 5 billion to fuel CLS sub-accounts with intraday liquidity (see figure 3 where total intraday credits (I), intraday credits drawn for the main accounts (IM) and intraday credits drawn for CLS subaccounts ($ICLS$) are displayed: $I = IM + ICLS$). These additional intraday credits were drawn in order to settle time-critial CLS payments. CLS related intraday credits are transferred directly to specific CLS subaccounts. After CLS payments are finalised at noon, most CLS banks transfer this liquidity to the main accounts in order to speed up settlement of other payments before intraday credits are paid back. Therefore, these CLS intraday credits are used exclusively to settle CLS payments until noon. From noon until the end of the day a substantial fraction of this intraday liquidity is transferred to the main accounts to speed up settlement of other payments.

The SIC settlement day starts the day before the value date at around 5 p.m. Before the settlement day starts, a first intraday credit window is available at around 4 p.m. Intraday credits drawn at this window are paid out at 6 p.m. shortly after the beginning of the SIC day at 5 p.m. During the night no intraday credits can be drawn until 7.30 a.m., when CLS banks can draw intraday credits for their CLS subaccounts, and at 8.00 a.m., when all participants can draw intraday credits for their main accounts. From then on, participants can draw and repay as they wish until 2.45 p.m., when the intraday window closes. If not executed earlier, repurchase transactions are automatically initiated by the Swiss central securities depository, SIX SIS, at 3 p.m. Intraday credits have to be repaid latest until 4.15 p.m. when the SIC settlement day finishes.

From 1995 on, many links were built in order to settle interbank services in SIC. Before such links were established, these interbank services were directly settled on the reserve accounts of the SNB. One major example is the organisation of securities settlement. Since 27 March 1995, payments related to SIX Swiss Exchange transactions initiated by SIX SIS as direct debits are settled in SIC directly on a "delivery-versus-payment" (DvP) basis. Due to this change SIC gained many new participants (see figure 16). In terms of the number of participants two other links are of importance. Margins and money settlements stemming from the derivatives exchange Eurex (merger of the former German and Swiss derivatives exchanges) are settled in SIC since June 27 1997. Connected to the establishment of Eurex was a change in the SNB's access policy to its reserve and SIC accounts. As substantial trading of derivatives in CHF underlyings takes place on the derivative platform Eurex, SNB opened reserve and SIC accounts to so called 'remote members' (SIC participants that are not located in Switzerland). This was meant to allow for a secure and efficient payment settlement in central bank money. In addition, payments originating from the Eurex Repo platform are settled in SIC since 8 April 1998. The introduction of the Eurex Repo platform was accompanied by the switch to repo transaction as the monetary policy instrument of the SNB. Also, the establishement of a secured interbank money market on the basis of repo transactions as well as the introduction of intraday credits by the SNB in 1999 explain the increasing number of participants after September 1998. The slow but steady increase thereafter are a result of these changes but also originates in a revitalised interest of having a physical presence in the Swiss financial centre.

The growing settlement volume in figure 1 is a result of banks settling more and more retail payments in SIC since mid 1993. The faster growing volume after 2004 is related to the phase out of two clearinghouses by end of 2006. Therefore, faster increasing volumes since 2004 can be explained by banks substituting clearinghouse settlement services with individual payment orders to SIC.[12]

The settlement value depicted in figure 1 and figure 2 refers to payments of participants excluding the SNB. Settlement value steadily increased until mid 1995 which can be explained by the general tendency of the growing interbank business. From then on, the settlement value grew faster until mid 1997 due to the integration of settlement services that beforehand were conducted on the reserve accounts banks hold at the SNB. After mid 1997, the value settled became more volatile but generally stayed on high level until mid 1999 when it dropped to a level of about CHF 150 Bio. Two mergers of the four largest Swiss banks are responsible for this reduction since these mergers caused a substantial internalisation of settlement value between 1997 and mid 1999. In 1996, Credit

[12] The migration of the clearinghouse for direct credits started in 2004 and was finished at the end of 2005. In October 2005, clearinghouse services for direct debits started to be phased out and the clearinghouse was closed by the end of September 2006.

Suisse Group (formerly Schweizerische Kreditanstalt) took over Schweizerische Volksbank. Beginning of 1997, their SIC-accounts were merged and the value settled in SIC dropped remarkably. In 1998, Schweizerischer Bankgesellschaft and Schweizerischer Bankverein merged into UBS AG. On the 19th of July 1999, their SIC-accounts were merged and the value settled dropped again.[13] After then, settlement value stayed constant until the introduction of CLS in September 2002. Since then, settlement value steadily reduced to a level of almost CHF 100 Bio in 2005. CLS itself led to a profound slowdown of settlement value in SIC, since a substantial fraction of foreign exchange transactions - that were settled as gross payments before - are settled as net amounts since then. Furthermore, interbank activities in general lowered after the burst of the dotcom bubble. The increasing settlement value after 2005 can be attributed to greater interbank activities that took off again. The sharp drop at the end of 2008 is the result of the collapse of the interbank market as a result of the financial crisis after the Lehman collapse in the last quarter of 2008.

3 Data and variables

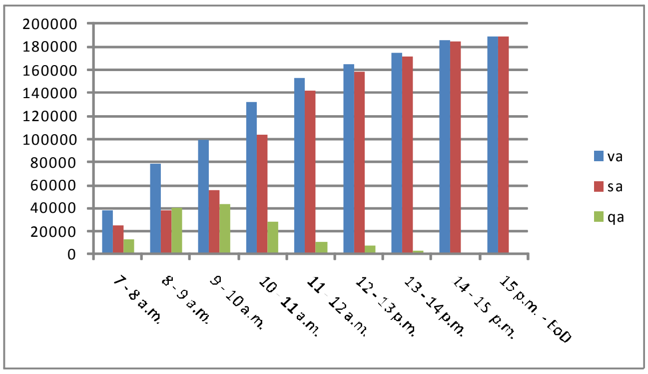
Data on reserve balances (R) and total intraday credits drawn (I) is available on a daily basis. The sum of both of these variables yields available liquidity: $AL = R + I$ (see figure 2). Next to the data on turnover and liquidity, the SNB's database provides ten mostly hourly data points for each settlement day on released and settled values and volumes of payments. The data is available for individual settlement accounts. Since we are interested in commercial banks' payment behaviour only, we exlude all payments made by the SNB to construct the system's settlement value V (see figure 1). However, banks' payments to the SNB are taken into account. We apply this principle wherever possible in the construction of indicators explained in the following sections.

Since the SIC settlement day starts the day before the value date, the first data point spans the settlement day from 5 p.m. to 7 a.m. on the value date, the remaining data points span each hour until 3 p.m. and the last one spans the period from 3 p.m. to the end of day at 4.15 p.m (EoD). The data set provides different variables within each category, namely the stock of value and volume of queued q and settled s payments. Additionally, the sum of queued and settled payments yields the variable released payments v. These variables can be used to compute flow variables. The second letter - a or b - indicates whether we refer to stock or flow variables, such as qa for the stock or qb for the flow of queued payments. The same data is available on a participant level.

In a payment system $j, k = 1, ..., N$ participants exchange payments of value va_{jk}, where va_{jk} is the stock of payments from bank $j = 1, ..., N$ to bank $k = 1, ..., N$. The system's settlement value is the added sum of payments

[13] The transaction value droped by more than 15% due to last merger (see figure 1).

Figure 4: Monthly averages of daily values of the hourly stock in March 2007 of released (va), settled (sa) and queued (qa) payments in CHF Mio



released or settled[14]

$$\sum_{j=1}^{N}\sum_{k=1}^{N} va_{jk} = V = S = \sum_{j=1}^{N}\sum_{k=1}^{N} sa_{jk} \tag{1}$$

The system is open from $i = 0, ..., T$. The stock of payments released to the system at time i is va_i and can be described as follows

$$va_t = \sum_{i=1}^{t}\sum_{j=1}^{N}\sum_{k=1}^{N} vb^i_{jk} = \sum_{i=1}^{t} vb^i \tag{2}$$

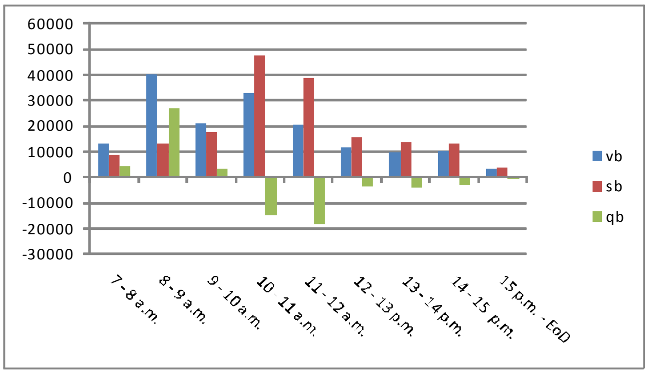
The flow of released payments between time $i-1$ and i is $vb^i = va^i - va^{i-1}$ for $i = 2, ..., T$. For the first period we define stock and flow variables to be identical: $vb^1 = va^1$ for $i = 1$. We take the end of the day stock variable to be denoted in capital letters: $va^T = V$. The stock of settled payments which are settled until time $i = t$ is denoted as

$$sa^t = \sum_{i=1}^{t}\sum_{j=1}^{N}\sum_{k=1}^{N} sb^i_{jk} = \sum_{i=1}^{t} sb^i \tag{3}$$

For the initial period the same definition is applied as before: $sb^1 = sa^1$ for $i = 1$. Since we neglect payments that are still pending at the end of the day, the following identity holds: $sa^T = V = S$. The stock of queued payments is

[14] In reality, there may be pending payments left in the queues at the end of the day. Due to this, released and settled payment values may not be equal at the end of day. Since their volume and value is negligible, we ignore such payments. The system deletes them and participants have to release such payments again for the next day.

Figure 5: Monthly averages of daily values of the hourly flow in March 2007 of released (vb), settled (sb) and queued (qb) payments in CHF Mio



denoted as

$$qa^t = \sum_{i=1}^{t} \sum_{j=1}^{N} \sum_{k=1}^{N} qb^i_{jk} = \sum_{i=1}^{t} qb^i \tag{4}$$

This can also be expressed in terms of the other two variables

$$qa^t = \sum_{i=1}^{t} \sum_{j=1}^{N} \sum_{k=1}^{N} (vb^i_{jk} - sb^i_{jk}) = \sum_{i=1}^{t} vb^i - sb^i$$

The flow of these two variables is computed in the same way as for released payments. In contrast to vb^t and sb^t, it can now be the case that $qb^t < 0$, whereas the other variables are always non-negative. For end of day values, read as V, S and Q, it is assumed that $Q = 0 = V - S$. Furthermore, flows and stock of variables for time $i = 0$ are defined to be zero.[15] We mostly use aggregate variables on a system level and for some indicators explained in the subsequent section also apply bank specific data.

The data set contains two further variables. The variable v^x yields the average value of the first x per cent of payments on a given day. This variable is available in steps of 5% of the volume of payments. The variable is constructed with data that contains payments made by the SNB. Therefore, applying the variable to construct indicators, we have to keep in mind that the indicators are distorted to the extend that payments made by the SNB and CLS related payments are included.

The other variable measures the volume and value of payments in different categories of payment sizes, for which categories range from CHF 0 to 50, 50 to 100, 100 to 200, ..., 700 to 800 Mio and a last category for payments larger than

[15] In reality payments can be released ahead of the settlement start. However, for the analysis at hand, this is irrelvant. All payments are assumed to be released from 5 p.m. on.

CHF 800 Mio. These variables are denoted as cn_l for the aggregated volume and cv_l for the aggregated value of payments in each category (where $l = 1, ..., 10$ denotes the payment category referred to). Also for these variables the same caveat as before applies, these variables are constructed with data that entails payments that are both CLS related and released by the SNB.

4 Liquidity usage indicators

Having introduced the main elements of SIC and the data available, we can proceed with the analysis of settlement performance. For this purpose, the two elements of settlement performance, namely liquidity usage and delay have to be pinned down empirically. In this section we look at possible indicators for liquidity usage. Generally, there are two components that determine aggregate liquidity in a RTGS system, namely reserve balances held overnight and intraday liquidity provided by the central bank.

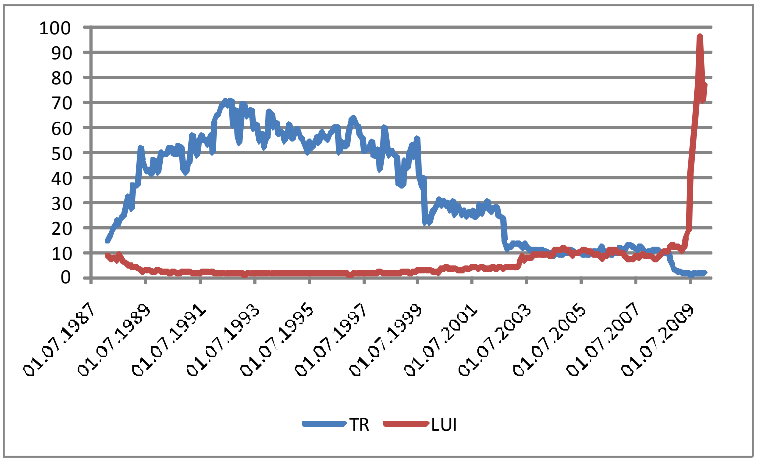
The level of reserve balances in the banking system is mostly determined by the SNB's open market operations by means of repo transactions with a maturity of one day or longer. Banks hold overnight balances mainly to meet their minimum reserve requirements, for cash holdings and settlement purposes in SIC. Most of the reserve holdings on the reserve accounts at the SNB are used to fund settlement accounts in SIC at the beginning of the settlement day. At the end of the settlement day reserves are transferred back to the accounts at the SNB. The variable available is reserve holdings (R) on the accounts at the SNB measured as end of day holdings. We focus on settlement performance in terms of settlement value. Most relevant changes in reserve balances take place shortly before 8 and after 9 a.m. This corresponds well with the settlement period during which most of the settlement value is settled, namely from 7 a.m. on. Therefore, we consider end of day reserve balances as an accurate proxy of the available liquidity in the case of SIC.

Since October 1999, participants have intraday credits at their disposal. Even though in the case of SIC intraday credits can flexibly be drawn and repaid during the day, participants make use of this possibility rather seldomly. Different intraday credit windows exist. As pointed out, one window delivers intraday credit at 6 p.m. and another two at 7.30 a.m. (for CLS banks and their CLS subaccounts) and 8.00 a.m. (for all banks' main accounts). So the maximum value of intraday credits outstanding is reached shortly after 8.00 a.m. From this time on until the end of day, the substantial part of payments in terms of value is settled. The available data set focuses on the time after 7 a.m. Again, since the focus of the analysis lies on the settlement value, we consider the maximum value of intraday credits outstanding, denoted with I, as an accurate proxy. To summarise, available liqudity in the system can be defined as the sum of reserve balances and intraday credits

$$AL = R + I$$

The literature defines liquidity usage as a measure of the value of liquidity

Figure 6: Monthly averages of the turnover ratio (TR) and the liquidity usage indicator (LUI)



used in relation to the turnover settled. For example, Heller and Lengwiler (2003) use the turnover ratio (TR) as a measure of liquidity usage.

$$TR = V/AL$$

It expresses the total value of payments in relation to the total value of reserve balances. After the introduction of intraday credits the turnover ratio has to be adjusted by taking into account a measure of the value of intraday credits outstanding. The turnover ratio can serve as a measure of liquidity efficiency since it states how many times per day one franc of reserve balances or settlement balances available is turned over. However, it can not serve as a proxy for settlement performance since it does not relate liqudity usage to settlement delay.

Another liquidity usage indicator is often applied in the simulation literature starting with Koponen and Soramäki (2008). They define the liquidity usage indicator (LUI) as follows

$$LUI = \frac{100 * AL}{V} = \frac{100}{TR} = \frac{NR}{100}$$

The higher the ratio of the liquidity usage indicator, the higher the liquidity usage of the system. Galbiati and Soramäki (2008) apply the netting ratio (NR) which is basically the same as LUI - they define the netting ratio as the exact reciprocal of the turnover ratio, thus ranging between 0 and 1.

Figure 6 presents monthly averages of the turnover ratio and the liquidity usage indicator. Both indicators well reflect changes that took place with regard to settlement value and liquidity provision since 1987.

5 Settlement delay indicators

Payment economics understands a banks' settlement behaviour as a strategic problem. In Angelini (1998) the bank's objective is to minimize the opportunity costs of liquidity and settlement delay costs in the context of liquidity externalities. Since liquidity is costly banks have an incentive to free ride on the liquidity of others. In order to reuse other banks' liquidity a bank waits for incoming from other banks and delays its own payments relative to a cooperative outcome. Each bank will postpone forwarding outgoing payments until the perceived marginal cost of delaying equals the marginal cost of providing reserves. However, while a decision to postpone does reduce the expected cost of liquidity for the sending bank, it also tends to increase the same cost by an analogous amount for the receiving bank, thereby generating a deadweight loss at the system level. Furthermore, delayed payments on a system level are associated with negative effects on the quality of information available for cash management purposes. Since incoming payments are delayed, information on the net position is revealed later and causes cash managers to allocate higher than optimal end-of-day reserve holdings as is also suggested in the literature on precautionary demand for reserves such as Baltensperger (1974). Delayed settlement of payments is often associated with further costs. Furfine and Stehm (1998) assume delaying payments to be costly because it damages the bank's reputation as an efficient payment processor. This results in a loss of goodwill and future business. Also, they presume delaying payments to require more computing resources and additional staff. Bech and Garratt (2003) investigate these issues with the help of an intraday liquidity management game assuming a cost of delay as in Angelini (1998).

The approach followed in papers such as Bech and Garratt (2002) is perceived to be inconsistent with the evidence. Starting with the doubts on the delay cost approach as expressed in Green (2005), the literature on payment systems has begun to focus on other reasons why banks delay payments. Instead of modelling unspecified and unverifiable costs of delay the literature has focused on the primary effect of settlement delay, namley later finality. Later finality is associated with costs related to settlement risk such as liquidity and operational risk. Mills and Nesmith (2008) try to explain banks' behaviour on the basis of the private costs associated with settlement risks. Those certainly depend on the interdependencies between participants within the payment system. Therefore, Mills and Nesmith (2008) follow the approach by Bech and Garratt (2003) and model an intraday liquidity management game. However, instead of delay costs, settlement risk is incorporated as a novel and important factor insofar as settlement risk gives raise to different liquidity costs as a consequence of different settlement behaviours. Delaying payments is understood to be liquidity-saving since by delaying payment information from other banks is revealed. In particular, it is understood as a way to reduce the undercertainty over incoming funds if settlemend risk is present. Resolved uncertainty by delaying payments and awaiting for incoming funds can help to avoid costly borrowings in the overnight market. Whereas Mills and Nesmith (2008) analyse an RTGS system without queues and an automated overdraft facility, Nellen (2010) investigates RTGS systems with collateralised intraday credits and centralised queues.

If we take the settlement technology of a payment system and the behaviour of participants as given, we can analyse settlement performance in terms of the trade-off between liquidity and resulting delay. In order to empirically investigate the economic trade-off analysed in the theoretical literature, essentially, one has to first understand how the system or its settlement mechanism influences the economic trade-off. Essentially, one can ask the question how much liquidity is needed in the system to result in a certain level of central queuing.

Looking at the theoretical literature as well as the rare empirical literature on delay, it is evident that delay can not only be measured as centrally queued payments. Essentially, strategic delay of payments is private information of payment system participants since banks do not release their payments immediately after these payments have been generated either by their customers or their own banking business. Rather, banks delay payments strategically in order to minimise their settlement costs over the whole day taking into account the expected settlement value. Therefore, banks hold payments back by storing them in internal queues to be released later in order to minimise expected settlement cost. This is true both for systems, the one with and the ones without central queues.

In essence, for system with central queues one can measure settlement performance as the trade-off between central queuing and liquidity. For neither type of system one can measure settlement performance taking into account strategic delay. The trade-off between delay and liquidity is not touched upon since there is essentially no data at hand to do so. To our knowledge only Bartolini et al. (2008) managed to look behind the curtain. By combining trade data and settlement data for money market transactions they are able to capture real settlement delay in an important but particular payment segment. However, this is an exception and we can not hope for such data on a wide scale. Therefore, the question we deal with in this section is how delay or its inverse, settlement speed can best be captured empirically if such data remains private.

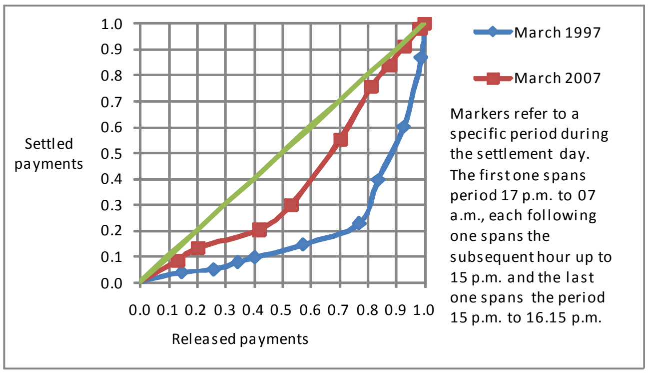
For the sake of completeness, we start with the traditional delay indicators and proceed with two new ways to measure delay.

5.1 The Lorenz curve and the Gini delay indicator

In the context of payment systems, the Gini coefficient was introduced by Vital (1990) as a measure of congestion.[16] With respect to payment systems, the Lorenz curve indicates how many percentage of the daily transaction value is settled if a certain percentage of the total transaction value is released to the system. For the available ten hourly data points the relation between released and settled payments is indicated in Figure 7. Each point on the curve indicates the share of value released and settled at a specific time. For instance, in the

[16] Gini coefficients are usually applied in measuring income and wealth inequalities. Gini coefficients can be calculated based on the knowlegde of how many percentages of the population owe how many percentages of total wealth.

Figure 7: Monthly averages of Lorenz curves in March 1997 and March 2007



examined period, by 7 a.m. 14 percent of the daily settlement value was released to SIC while about 3.8 percent was settled by then. 7 a.m. refers to the first marker in figure 7 - each subsequent marker indicates one further hour until the end of the day when 100 percent of payments are released as well as settled. Connecting each hourly point results in the Lorenz curve.

The Gini queuing indicator (GDI) is defined as the ratio of the surface below the Lorenz curve to the surface below the diagonal that indicates a situation of immediate settlement, i.e. release and settlement of payments take place simultaneously. Within the given setup a simple mathematical approximation of the Gini coefficient is given by

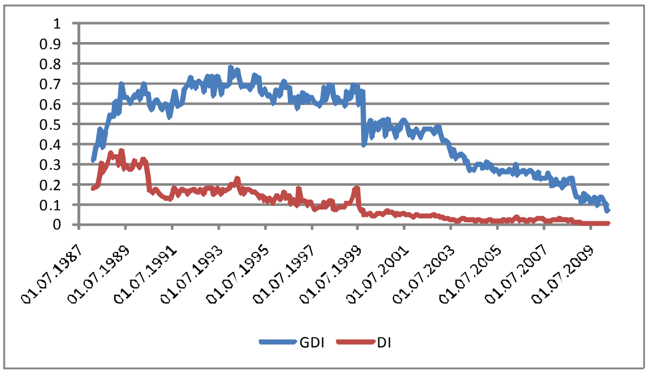
$$GDI = 1 - 2\sum_{i=1}^{T} \frac{1}{V^2}\left(\frac{vf_t sf_t}{2} + vf_t ss_{t-1}\right) \tag{5}$$

If all payment orders are settled immediately when released (as for instance in a system with unlimited overdrafts), the curve would move along the diagonal and $GDI = 1$. In general, the shorter the queues, the closer the coefficient to 1. At the other extreme, if $GDI = 0$, then all orders are released before the first one is settled (as for instance in a net settlement system for which settlement takes place at the end of the day).Figure 8 depicts the Gini delay indicators (GDI) for the value of payments and the delay indicator (DI) for the number of payments - the delay indicator is explained in the next subchapter - as monthly averages from 1987 on.

5.2 The delay indicator

Another measure of congestion for a RTGS system with queues is the delay indicator (DI). This measure is proposed by Koponen and Soramäki (1998) in the context of payment system simulations. DI is calculated as the ratio of

Figure 8: Monthly averages of the Gini delay indicator (GDI for the value of payments) and the delay indicator (DI for the number of payments)



the cumulative value of queued payments to the cumulative value of released payments over the whole settlement day:

$$DI = \frac{\sum_{i=1}^{T}(vs^i - ss^i)}{\sum_{t=1}^{T}\sum_{i=1}^{t} vf^i} = \frac{\sum_{i=1}^{T} qs^i}{\sum_{t=1}^{T}\sum_{i=1}^{t} vf^i}$$

If all payments are settled immediately upon entry into the system, then $DI = 0$, whereas if all payments are delayed until the end of the day, then $DI = 1$.

Even though GDI and DI exhibit slight differences, the development of both indicators is almost identical for both value and volume (correlation for the value indicators is 0.99 and for volume indicators is 0.98). This is not suprising since both indicators are based on the same prinicple, looking at queued or settled payments in relation to released payments. Therefore, in figure 8, we simply display GDI for the value and DI for the volume of payments. As we can see in figures 8, the delay indicator for the number of payments is lower than the one for the value of payments. This fact is in line with the observation that the bulk of small payments is entered and settled during the night while a small number of high value payment orders is kept fairly long in the queue or is released later in the settlement day.

Congestion, as Vital (1990) labelled it, or central queuing developed more or less in line with the liquidity available in the system and the settlement value to be processed. The initial increase for both indicators mirrors increased congestion during the first two years of operation. This is due to the fact that banks substantially reduced their reserve balances while simultaneously more and more payments were transferred through SIC. A striking point is the remarkable decreases of the delay indicator for the volume of payments before mid

1989 and in 1990 which is either not followed or not followed as pronounced by the Gini delay indicator for the value of payments which stays rather constant during this phase. These shifts conincide with the introduction of the two-part tariff that was aimed at encouraging earlier release and settlement of payments, and in particular retail payments. Obviously, this helped to reduce congestion of both small-value and large-value payments. While small-value payments were released and settled earlier, large-value payments were released later and, as a consequence, reduced the extend of value related central queuing. The following increase in both indicators after the second half of 1991 reflects tough monetary conditions which led to very low reserve balances as reflected in the very high turnover ratios culminating in 1992 (see figure 6). The slight decrease in both delay indicators after 1993 can be explained mainly by a less restrictive stance in monetary policy and increasing reserve requirements over time. Both caused reserve balances to increase and, in return, reduced congestion in SIC. Furthermore, the soaring indicators in the last quarter of the year 1999 are the result of the introduction of intraday liquidity. The further decrease in both indicators after 2002 is the effect of the positive injection of additional intraday credits due to the introduction of CLS. Also, the introduction of CLS led to a general shift to earlier settlement. Two effects are responsible for this. First, instead of gross settlement CLS introduced a net settlement of foreign exchange transactions which substantially reduced the value of foreign exchange settlement that normally settles later in the day. Second, the CLS settlement cycle takes place between 7 a.m. and noon what moved settlement of the surviving net settlement value to earlier hours of the settlement day. In addition, monetary policy has not been very restrictive from 2002 onwards. The substantial decrease in the last quarter of 2008 is due to the massive injection of reserve balances by the SNB as a reaction to the financial crisis and the collapse of interbank money markets after the insolvency of Lehman Brothers. Central queuing or delay are basically eliminated since then.[17]

5.3 Comprehensive delay and settlement indicator

A major shortcoming of above indicators is that they do not take account of decentrally, respectively internally queued payments of banks. As a matter of fact, such payments are private information of payment system participants and, besides of Bartolini et al. (2008) no other study has so far shed light on the extent of internally queued payments.

The best proxy at hand to account for internally queued payments is to take the total settlement value over the whole settlement day as known by payment system participants. This is in contrast to the methodology of traditional delay indicators as represented by GDI and DI. They are both based on released payments and neglect unreleased payments. Unreleased payments are either

[17] This is line with simulation studies conducted by Glaser and Haene (2009) that report Upper Bound liquidity levels necessary to eliminate central queues of about CHF 40 to 60 Bio for SIC. As can be seen in figure 2, liquidity levels in SIC reached values even far above CHF 60 Bio after the forth quarter 2008.

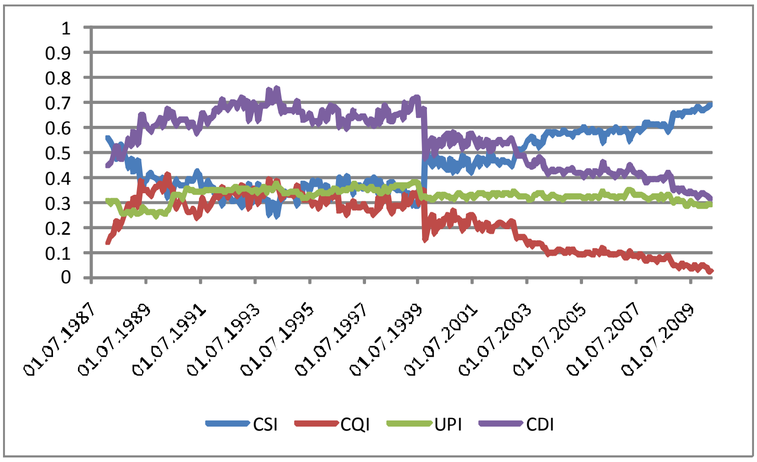
pending in the internal queues of banks (private information) or are unknown to the banks themselves at a given point in time. The latter can be the case because either banks themselves or their customers will still generate these payments in the course of the day. As a consequence of taking the whole settlement value as known from the beginning of the day, we create the opposite distortion by taking into account unknown payments as internally queued payments.

Naturally, the question arises why we should replace one misleading variable (centralised queues) by an other misleading variable (overall settlement) in order to evaluate settlement performance? We argue that the former proxy is worse than the latter to analyse settlement performance. In essence, due to unreleased payments or hidden payments any kind of policy change may either affect centralised queuing without affecting settlement performance or vice versa. Changes in the system's tariff can lead to changes in release behaviour that affect central queuing without affecting overall settlement performance. The introduction of a two-part tariff for SIC payments in April 1988 may serve as an example of such a change. As a consequence of it, banks started to release smaller payments earlier while releasing larger payments later. Due to the later release of larger payments central queuing reduced while at the same time reserve balances still decreased. If delay is measured by central queuing, settlement performance improves crucially (see figure 8 for the delay indicators and figure 10 depicting the release time indicator). However, value related queuing is just moved from central queues to internal queues of participants, settlement does not acutally take place earlier. Therefore, settlement does not take place earlier and it is hardly justifiable to talk about improved settlement performance.[18]

Theoretical arguments too justify to take into account the whole settlement day rather than central queueing to analyse settlement performance. To a certain degree banks do know in advance what payments are going out over the course of the day. This is particularly true with to the settlement value since a large proportion of interbank settlement results from trades that were concluded up to three days ahead of settlement. In terms of data available these payments are considered to be unkown if we apply traditional delay indicators. As pointed out in the literature on intraday liquidity management games such as Bech and Garratt (2003) or Mills and Nesmith (2008) these payments are released later in the day due to risk or liquidity considerations. Therefore, these payments reveal information about the economic trade-off and should be incorporated in empirical work about liquidity management. Bartolini et al. (2008) provide evidence that strategic delay of payments is a real phenomenon in Fedwire funds. However, also in relation to unkown payments banks' cash

[18]This may further be highlighted by a simple thought experiment. If liquidity is so low such that every payment released is queued, essentially delay should not be assessed as being worse since settlement speed is the same whether payments are queued decentrally or centrally. Given liquidity is available to an extent that does not result in queued payments at all, earlier release of payments would lead to a lower level of delay since settlement takes place ealier. However, this is not indicated by central queues since they are empty. Therefore, if delay is measured as central queueing, settlement performance will be distorted. Worse, it may be distorted in any direction depending on the level of liquidity and changes in queuing activity.

Figure 9: Monthly averages of comprehensive settlement indicator (CSI), central queuing indictor (CQI), unreleased payment indicator (UPI) and comprehensive delay indicator (CDI)



and payment managers build expectations. In turn, such expectations influence the liquidity and release management of payments chosen and, therefore, determine resulting delay. For instance, liquidity managers must take account of late incoming payments. In order to be able to settle these payments on short notice, the bank may have to engage in costly activities such as to have liquidity at its disposal either in the form of precautionary reserves or as collateral to be able to draw intraday or overnight liquidity. Therefore, this information is missing if traditional indicators are applied. Relating this to payment systems with central queuing, strategic delay can be achieved in two ways. Either a bank releases payments later or it counts on the fact that the system is provided with a low level of liquidity such that congestion prevents payments from being settled early. Therefore, both unreleased and centrally queued payments should be taken into account when analysing settlement performance in order to gain a more comprehenisve measure of delay and its inverse, settlement speed.[19]

Such an indicator of delay yields an appealing further advantage. Analysing settlement performance by taking into account all unreleased payments allows to apply the same indicator for both kind of systems, the ones that do offer centralised queues (such as SIC) and the ones that do not provide centralised queues (such as Fedwire funds in the US). This allows us to directly compare settlement performance of both types of systems.

Looking at figure 4, a comprehensive settlement indicator (CSI) can be

[19] Taking up the thought experiment put forward in the preceeding footnote, overestimating delay by including unreleased payments also distorts our measure of delay. However, delay is at least distorted in one direction only.

readily constructed with the available data. We simply take the normalised area below the settlement curve that indicates the stock of settled payments in the course of the day. A value of one would indicate that all settlement takes place at the beginning of the day whereas a value of zero indicates that all settlement takes place at the end of the day. The indicator can be computed as follows:

$$CSI = \sum_{i=1}^{T} \frac{1}{T} \frac{ss^i}{V}$$

Coming back to the traditional delay indicators, constructing another one of the this kind is straightforward. A centralised queuing indicator (CQI) is constructed as the normalised area below the queuing curve that indicates the stock of queued payments over the course of the day. A value of zero indicates that no queuing takes place whereas a value of one means that all payments were queued from the beginning of the day until the end of the day. A simple approximation can be computed as follows:

$$CQI = \sum_{i=1}^{T} \frac{1}{T} \frac{qs^i}{V}$$

Again, we can look at the correlation between this new central queuing indicator and the two traditional delay indicators: the correlation between GDI and CQI is 0.97 whereas the correlation between DI and CQI is 0.99.

What we denoted as unreleased payments can be measured as the unreleased payment indicator (UPI) in exactly the same way. We take the normalised area above the curve that indicates the stock of released payments as an indicator. A value of one means that payments are all released at the end of the day whereas a value of zero says that all payments are released at the beginning of the day:

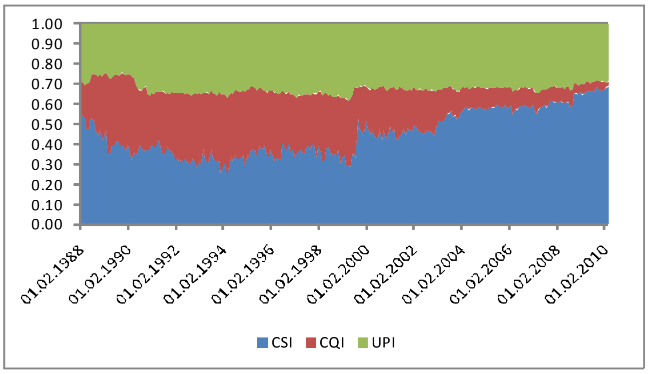
$$UPI = 1 - \sum_{i=1}^{T} \frac{1}{T} \frac{vs^i}{V} = 1 - \sum_{i=1}^{T} \left(\frac{1}{T} \frac{ss^i}{V} + \frac{1}{T} \frac{qs^i}{V} \right)$$

By construction, all three indicators sum up to one. Since CSI mirrors centrally queued and unreleased payments, we can easily gain a comprehensive delay indicator (CDI) that takes into account centrally queued and unreleased payments:

$$CDI = 1 - CSI = CQI + UPI$$

Due to the changes in unreleased payments - as indicated by UPI - the comprehenisve delay indicator (CDI) does not mirror traditional delay indicators such as GDI and DI. Correspondingly, the correlations between the traditional delay indicators are lower even though they are close to one: the correlation is 0.96 between GDI and CDI, 0.98 between DI and CDI and 0.96 between CQI and CDI. Even though the fundamental forces behind the changes are often the same, UPI and CQI are influenced to a different extent, so that CQI and

Figure 10: Monthly averages of accumulated comprehensive settlement indicator (CSI), central queuing indicators (CQI) and unreleased payment indicator (UPI)



CDI do not mirror each other. For example, while CQI decreases after 1990 until mid 1991, CDI stays constant (see figure 9). This is related to the later release behaviour after 1990 - as is mirrored in the decreasing value of UPI. This is a rather astonishing fact, as in April 1988 a two-part tariff was introduced in order to incentivise earlier release and settlement of payments. This two-part tariff was made more progressive in 1989. Nevertheless, in 1990 banks started to release payments later again which might be explained by decreasing reserve balances. While looking at CQI and available liquidity (AL), one would conclude that settlement performance increased strongly, looking at CDI and AL, settlement performance only improved slightly. To summarise, strategic delay is better mirrored in CDI than in CQI.

As is indicated in figure 9 and 10, settlement speed expressed through CSI closely follows the liquidity available in the system. CSI soars together with the falling liquidity levels due to relaxed reserve requirements in 1988 and a restrictive monetary policy in the early 90ies. A remarkable jump is recongised in 1999 which is connected to the introduction of intraday credits that led to a profound increase in available liquidity. A further jump is related to the introduction of CLS. CLS banks draw substantial amounts of intraday credits. Most of these banks transfer this money to the main accounts after noon when the CLS settlement cycle ends. This liquidity further boosts settlement speed since the fourth quarter of 2002. The steady increase in the following years can be attributed to a higher participation in the intraday liquidity facility. The jump at the end of 2008 can be explained by the SNB injecting massive amounts of reserve balances into the banking system.

UPI was affected by the introduction of the new pricing scheme in April 1988 and 1989. As a consequence, banks shifted smaller payments to earlier hours and larger payments to later hours. Overall, the effect was that the release in terms of value took place later. Since then, UPI has been very stable until the introduction of intraday credits in 1999 when banks started to release payments earlier again. Also, banks started to release payments earlier versus the end of 2008 when the system was flooded with reserve balances. The SNB's massive injections of funds into the banking system basically eliminated settlement risk. Furthermore, the opportunity costs of liquidity was close to zero after the collapse of Lehman. As a consequence, banks became less reluctant to release payments earlier.

6 Behavioural and environmental indicators

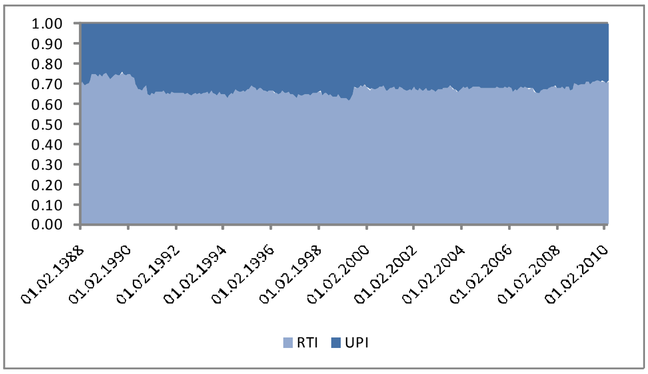
There are different important factors that shape settlement performance. Of course, the two crucial elements are the value of payments to be settled and the liquidity available. However, further factors may crucially influence settlement performance. This section is concerned with three such factors, namely release behaviour, the participation structure and the liquidity choice by individual participants. In terms of release behaviour we investigate particular factors such as the release time, the choice of payment size and the sequencing of payments. A rather environmental variable is the participation structure that determines the topology of payment flows. We consider two very basic topology indicators. In addition, we investigate an aggregated measure of the individual choices of liquidity contribution by participants in relation to their turnovers.

6.1 Release time indicator

The earlier payments are released the earlier they can be settled. Two effects are responsible for this in a queuing system such as SIC. Payments that are released early can be settled on the basis of the liquidity regularly available in a payment system, namely reserve balances that also serve to fulfil minimum reserve requirements. Furthermore, this first effect will be reinforced by a second round effect, that is, pending payments in central queues are going to be settled due to the effected turnover of liquidity of the first round effect. In essence, settled payments enable settlement of other payments. This is often referred to as the off-setting effect. Both effects result in a reduction of settlement delay. Given there is no or not enough liquidity in the system, however, the opposite may result if delay is measured as central queueing. Queues would be filled up earlier and remain for longer. As a consequence, traditional delay indicators increase and settlement performance gets worse.

SIC applies a queuing system that is fairly simple, in terms of the literature on liquidity-saving mechanisms it is a balance-reactive system. Other systems exist that apply more sophisticated liquidity-saving mechanisms as pointed out in Martin and McAndrews (2008) and Jurgilas and Martin (2010). A model-based comparison of different designs of liquidity-saving mechanisms is found in Martin and McAndrews (2010). As is shown in Atalay et al. (2010), the effect of liquidity-saving mechanism on settlement performance can be substantial. All mechanisms in common is that release time crucially influences the off-setting

Figure 11: Monthly averages of accumulated release time indicator (RTI)and unreleased payment indicator (UPI)

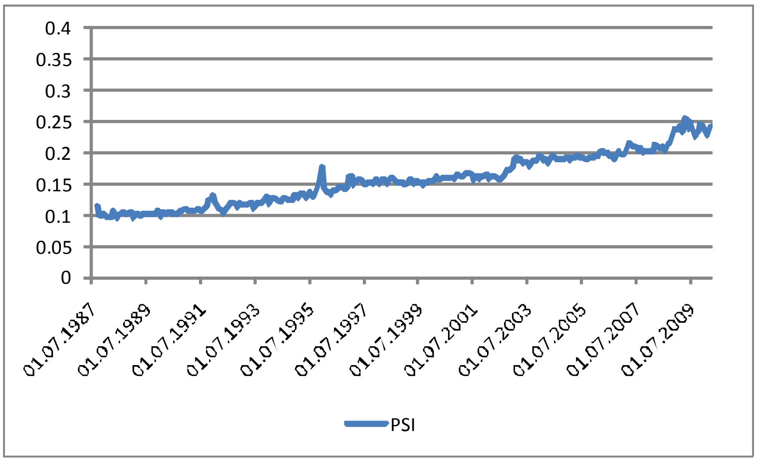


effect or the efficiency of liquidity-saving mechanisms. The earlier payments are released, the earlier can such mechanisms be applied. If payments are released earlier to central queues, the greater is the volume and value of payments that can be processed with such mechanisms. As a consequence, liquidity-savings can be more pronounced. Therefore, release time is an indispensable variable for the analysis of settlement performance of queuing system such as SIC or Target2. It is not so, however, for pure RTGS systems as Fedwire Funds, since such systems do not have queuing facilities, and consquently do no apply any liquidity-saving mechanisms.In terms of the data available, released payments are the sum of settled and centrally queued payments. This is saying that $RTI = CSI + CQI$. Furthermore, unreleased payments are the opposite side of the coin: $RTI + UPI = 1$ (see figure 12). RTI computes the area below the release curve where early input of all payments at the beginning of the day is normalised to one.

$$RTI = \sum_{i=1}^{T} \frac{1}{T} \frac{vs^i}{V}$$

RTI is depicted in figure 11. The increas of RTI in April 1988 can be attributed to the introduction of a new pricing scheme in April 1988. Banks started to release smaller payments during the night whereas larger payments were released later. The drop after 1990 is indicates that banks started to release payments later again with the falling levels of available liquidity. After 1991, behaviour remained fairly constant until 1999. The increase in the last quarter of 1999 was due to the introduction of the repo platform in 1998 and the corresponding switch in monetary policy implementation by the SNB. The repo platform made it possible to address a wider community of banks by monetary policy auctions through repos in the morning, whereas before monetary credit operations were conducted through a much smaller set of banks. Also, the repurchase of mon-

Figure 12: Monthly averages of payment size indicator (PSI)



etary policy repos as well as interbank repos takes place in the early morning hours at 7.50 a.m. This and the additional intraday liquidity reduced interbank activity in the later settlement hours and led to earlier settlement activity in the morning hours. Overall, banks became less reluctant to release payments earlier due to increasing levels of available liquidity stemming from intraday credits. The increase of RTI after 2008 goes along with the massive injections of reserve balances by the SNB after the collapse of Lehman and the corresponding collapse of the interbank market. The massive aggregate level of reserve balances may have resulted in lower levels of strategic delay due to decreased settlement risks. Furthermore, monetary credit operations that replaced the interbank money market take place in the early morning hours.

6.2 Payment size indicator

Payments of a value much higher than the average size of payments may considerably delay other payments from being settled. As a consequence of the FIFO rule, these large payments block liquidity on the accounts of payors until enough liquidity is accumulated to settle again. This does not only hinder payors to settle other payments released later to their queues but also blocks liquidity on the payors' accounts such that other participants of the system can not use the blocked liquidity to settle their payments. In a simulation study, Koponen and Soramäki (1998) find that settlement delay is significantly reduced if large payments are splitted into smaller ones. The purpose of a payment size indicator is to measure the effect of liquidity blockings. Having a payment size indicator available, we can assess the influence of large payments on settlement performance.

We have data available on ten different ranges of payments $l = \{1, ..., 10\}$ for which the total number cn_l and the total value cv_l of payments are available. Taking into consideration the overall distribution of the payment categories, a simple way to assess the effect of liquidity blocking is to measure the normalized area below the distribution curve of payment values. A simple approximation of the indicator can be computed as follows:

$$PSI = 1 - \frac{1}{10} \sum_{l=1}^{L} \sum_{i=1}^{l} \frac{cv_i}{V}$$

If all payments are bellow CHF 50 Mio, the indicator would be equal to zero, if all payments are larger than CHF 800 Mio the indicator would be equal to 1. Essentially, PSI is based on a nomalised average of the shares of each category's value to total value. This latter measure is substracted from one to receive the PSI.

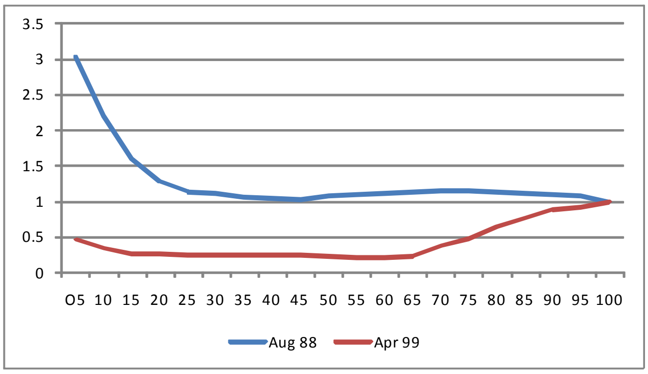
The data base of this indicator does not allow to exclude payments made by the SNB. Since the introduction of repos these payments make up a large proportion of SIC turnover and consist of many payments up to and equal to CHF 100 Mio (all monetary policy operations and intraday credits are granted in tranches equal to or lower than CHF 100 Mio). This explains the slow increase after 1998 to 2002. The sharper increase of the indicator after 2002 can be explained with CLS payments. Most CLS payments are above CHF 100 Mio. In addition, banks participating in CLS started to draw intraday credits to fund settlement in CLS subaccounts, mostly in tranches equal to a CHF 100 Mio. The sharp increase at the end of 2008 can be explained by the financial crisis. Banks started to fund themselves almost exclusively through repos with the SNB - again such payments mostly have a value of CHF 100 Mio.

The indicator is problematic due to two reasons. CLS related payments and SNB payments are are mostly of a considerable size and are all included in the categorised statistics. These payments should not be taken into account to measure settlement performance due to their special nature as central bank payments or as payments that are settled in a separated circuit. However, the database does not allow to exlcude CLS and SNB payments.

6.3 Two payment sequencing indicators

A blocking of liquidity can not only be related to the size and number of large payments and their relative importance but also to the sequence in which payments are released. How payments are sequenced over the day may improve or worsen settlement performance. This is a result of the FIFO rule which is applied by almost all RTGS systems in one or the other variation. Due to the FIFO rule the sequence - in which payments of different sizes are released - matters. The order in which large-value payments and small-value payments are released can delay the settlement of payments which are released subsequently. Also, if banks release similarly sized payments around the same time, the off-setting effect can be increased and speeds up settlement. In order to test the influence

Figure 13: Monthly averages of the input sequence curve for August 1988 and April 1999



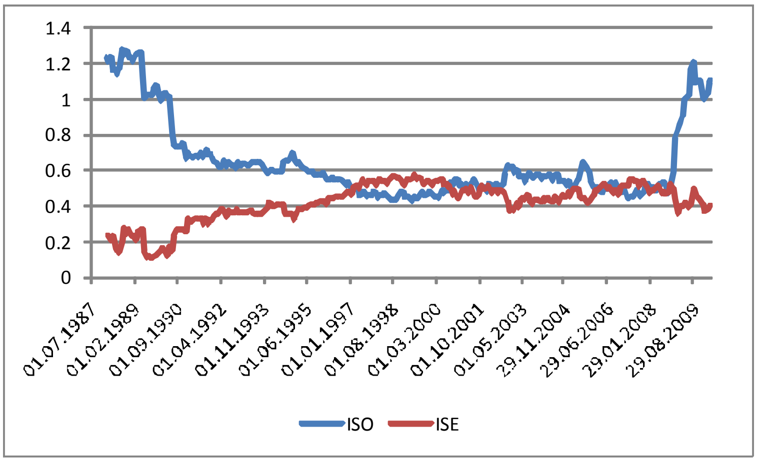
of sequencing, we investigate two input sequence indicators. The first indicator was introduced by Vital (1990) and captures the ordering of payments over the course of the day, i.e. whether or not smaller payments are released before or after larger payments on average. The second indicator attemps to capture the extent of sequencing.

We can build these indicators on the basis of the following data: value and number of payments in categories of the first $x = 5\%, 10\%..., 95\%, 100\%$ of payments. What was named the *input sequence by payment size index* in Vital (1990) is meant to capture the sequence of release order. The index is calculated by the ratio of the average payment size u^x of the first x percent of payment messages entered (where $x \in [0, X/a]$ and $X = 100$ in steps of $a = 5$) to the average size of all payment messages entered on a given day u^X (u^x/u^X for all $x \in [0, X/a]$). The ratio can be plotted against the percentage of payment messages which yields the input sequence curve (see figure 13).The area under this curve is defined as the *input sequence by payment size index*, which we simply refer to as indicator of sequence order (ISO).

$$ISO = (1/\frac{X}{a})\sum_{x=1}^{X/a}\frac{u^x}{u^X}$$

u^x represents the average payment size of the first x percent of payments whereas u^X represents the average payment size of all payments. ISO has the value of one if payments of different sizes are uniformly distributed over all classes of percentage levels (meaning that the average size of payments entered stays the same over all percentage levels). The indicator exhibits a value larger (smaller) than one, if, on average, large-value payments are entered before (after) small-value payments. This is related to the feature of convergence to one at the end of the sample, where $u^x = u^X$ and the ratio equals one. In essence, the

Figure 14: Monthly averages of the input sequence by payment size indicator (ISO) and the input sequence extent indicator (ISE)



sequencing indicator represents a measure of ordering where ordering refers to whether smaller (larger) payments are released before larger (smaller) payments on average.

Settlement performance may not only depend on the order of released payments but may also depend on the extent of sequencing. If similarly sized payments are released around the same time they may increase off-setting effects unrelated to the ordering. Therefore, we look for a new measure that indicates the extent of sequencing rather than the ordering of sequencing. A simple proxy for such an indicator might be to take the distance of ISO from one. We label it the input sequence extend indicator (ISE):

$$ISE = (1/\frac{X}{a})\sum_{x=1}^{X/a} abs(\frac{u^x}{u^X} - 1)$$

Again, major policy changes are reflected by the indicators (see figure 14). For both indicators, we find the effects of the new fee scheme to have resulted in a major drop due to the changed release behaviour by banks. The decrease of ISO and increase of ISE after 1990 can be attributed to more and more banks adjusting to the new fee structure. The general decrease of ISO and the increase of ISE from then on is mostly related to more and more retail payments being processed. Since settlement of smaller payments takes place mostly during the night when fees are low, the indicators exhibit corresponding changes. The increase of ISO (decrease of ISE) in the last quarter of 1999 reflects the introduction of the repo platform and intraday credits; from then on a growing number of larger payments were settled in the early morning hours.

The same is true for the drop of ISO (increase of ISE) in the last quarter of 2002. This reflects the introduction of CLS. From then on, much less large-value payments related to foreign exchange transactions are settled late in the afternoon since these are settled during the CLS settlement cycle from 8 a.m. to 12 a.m. Therefore, foreign exchange settlement moved to a large degree to earlier hours. The decrease of ISO after 2002 can be attributed to CLS and the steadily growing participation in the repo platform. The increase of ISE after 2002 can be attributed to the growing number of retail payments that are released early during the night, especially also after 2004 when two clearinghouses started to be phased out and retail payments were instead settled one by one in SIC directly. The reported changes may also be attributed to the increasing liquidity levels more generally that caused release and settlement to take place earlier after 1999 as well as after 2002. In last quarter of 2008, both indicator react to financial crisis that resulted in the replacement of the interbank market with monetary credit operations by the SNB. Many large-value payments related to the interbank money market for instance were replace by monetary policy transactions being settled earlier in the morning.

Both indicators suffer from the same caveat as expressed for the payment size indicator. CLS and SNB payments are included.

6.4 Two simple topology indicators

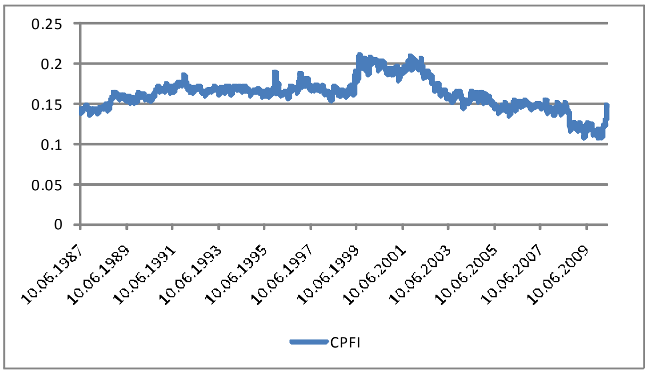
In their agent-based payment system simulation Galbiati and Soramäki (2008) find that leaving the turnover constant while reducing the number of banks results in a significant reduction of the netting ratio (NR), respectively of the liquidity usage indicator (LUI). The same holds true, if they allow for a constant turnover per participant and decrease the number of participants. These findings suggest that the liquidity efficiency increases with increasing concentration of payment flows. In order to pin this down empirically, we consider the concentration of payment flows as being high if payments are shuffled to a large extent hence and forth between a few dominating participants. We propose the Herfindahl-Hirschman-Index for the settlement value over indidividual accounts as a simple measure of payment flow concentration.[20] Furthermore, we take the number of participants (N) as another simple indicator of the complexity of the payment system.

6.4.1 Concentration of payment flow indicator

While liquidity efficiency is increased by having a higher concentration of payment flows it remains open whether settlement performance too is positively affected by a higher concentration of payment flows. A high concentration within

[20] Note, we do not intend to measure the concentration flow between banks but the concentration of payment flows between accounts in SIC. That is why we do not aggregate main and CLS subaccounts or any other account of the same bank. Thus, the CPFI does not reflect the banking concentration in payments but the concentration of payment flows between SIC accounts.

Figure 15: 20-day moving average of daily concentration of payment flow indicators (CPFI)



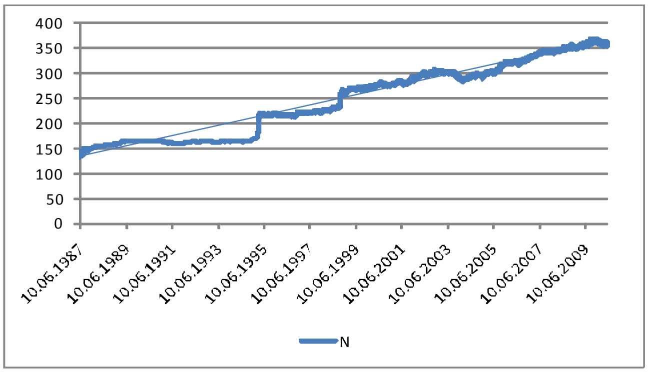
a circuit of participants may establish a payment flow that turns over liquidity with a higher velocity and, therefore, speeds up settlement and avoids building up queues. The more concentrated payment flows are among participants the easier might be the coordination of a continuous exchange of payments such that liquidity may not end up blocked over too many accounts but keeps on flowing among a few accounts. This may result in a higher off-setting effect that allows to settle with less liquidity while reducing or keeping delay constant.

In order to test this hypothesis we consider the normalized Herfindahl-Hirschman-Index as a simple proxy for a real measure of the concentration of payment flows:

$$CPFI = \left(\sum_{i=1}^{N} \left(\frac{V_i}{\sum_{j=1}^{N} V_j} \right)^2 - 1/N \right) / \left(1 - 1/N\right)$$

Figure 15 shows a 20-day moving average of the $CPFI$ from 1987 to 2009. Interestingly, in the first years increasing participation in SIC also goes along with increasing concentration. This may be attributed to the inclusion of more and more interbank business settled by larger participants. After a pretty constant phase in the early nineties, the $CPFI$ shows a somehow more volatile pattern after 1996. Particular events of change can be identified. In January 1996, the accounts of two larger participants were merged. The same took place for two other major banks on 19 July 1999. The introduction of the repo platform as well as the introduction of intraday credits in October 1999 increased concentration substantially. The decrease thereafter is caused by other banks slowly entering the repo platform and by the introduction of CLS in late 2002. The main accounts of larger banks active in the foreign exchange market were supplemented with special CLS subaccounts. In addition to the separation of accounts, a large percentage of foreign exchange settlement transactions were netted out through CLS and reduced the turnover of larger banks substantially.

Figure 16: Daily number of participants with a positive turnover (N)



Both effects resulted in a strongly reduced concentration. The decrease of concentration at the end of 2008 reflects the financial crisis which was going along with substantial reductions of interbank payments. The increase at the end of 2009 can be attributed to massive foreign exchange interventions of the SNB. After the Lehman collapse the money market was to a large extent replaced by monetary policy transaction via repos with the SNB but also interbank repos. In late 2009, the foreign exchange interventions by the SNB replaced monetary policy transctions via repos and also led to a collapse of the interbank repo market as noted in Kränzlin and von Scarpatetti (2010). Whereas the repo transactions are based on a broader base of participants, foreign exchange transactions are based on only a few larger participants which regained their role as market makers in the money market.

6.4.2 The number of participants

The number of participants may serve as a rough indicator of the complexity of the transaction flow. As Galbiati and Soramäki (2008) point out, the number of participants in the system might affect settlement performance. In order to test this hypothesis, we extract the number of active participants defined as participants with a positive turnover of more than CHF half a million.[21] After the steady increase of participants during the introductory phase until 1989, the number of participants remained fairly constant until 1995 when the electronic straight-through processing between the Swiss stock exchange, the Swiss CSD and SIC was established. Due to this change the number of participants in SIC increased by about 50. In 1998, SNB enforced a new access policy to the SNB's reserve accounts and the SIC accounts. Eurex - the merger of the Swiss and German derivatives exchanges - established a single trading book

[21] The chosen turnover is a mere result of the SNB database that only reveals turnover in CHF millions. A turnover of below CHF 500'000 is thus revealed as CHF 0 Mio.

for derivatives trading in CHF and EUR underlyings for members of of both former exchanges. However, many German participants of Eurex wanted to trade derivatives in CHF underlying but did not have access to SIC. In order to allow such Eurex participants to settle in central bank money, remote access was allowed for. As a consequence, the number of participants increased again by about 50. The number of participants kept growing steadily up to a number of over 350 participants in 2010. This may be due to serveral factors. For instance, monetary credit operations are conducted on a repo basis since 1999. At the same time, a repo interbank money market was established. This seems to have made the CHF money market more attractive. Additionally, the introduction of intraday credits in the last quarter of 1999 further lowered funding costs of settlement in CHF. Also, the general interest of foreign particpants in a remote presence grew to a number of 103 by the end of 2009 (of which many do not trade on Eurex). The slight decreases in 2003 as well as at the end of the sample can be explained by the respective financial crisis that took place during these periods.[22]

6.5 Liquidity dispersion indicators

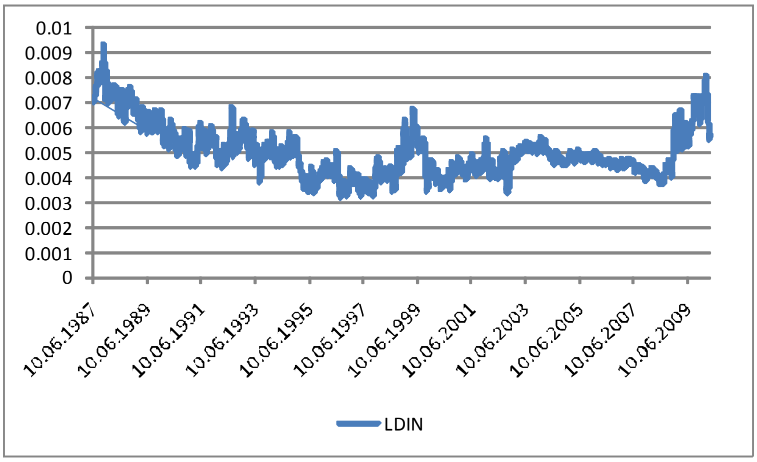
Angelini (1998) and other theoretical literature on settlement behaviour postulate that participants of payments systems try to free ride on the liquidity of other participants. By delaying their own payments participants fund their settlement by incoming payments from other participants. To our knowledge nobody has ever tried to capture existence and extent of free riding empirically. We propose an indicator of aggregate dispersion of liquidity holdings as a crude indicator for free riding behaviour. The more diverse liquidity holdings are distributed in relation to turnover or, in other words, the higher liquidity dispersion is, the more pronounced might be free riding behaviour. If participants' contribution to the available liquidity is equal to their share in total value settled, we may assume that free riding is not present. The more pronounced liquidity dispersion is, the more pronounced might be free-riding behaviour.

Naturally, the question arises how liquidity dispersion affects settlement performance. In an agent-based model of payment systems Galbiati and Soramäki (2008) find that the liquidity distribution does not influence delay to a great degree. Rather it looks like settlement performance is independent of the liquidity distribution over participants. This may be attributed to the fact that a payment system represents a complete symmetric network and that the high number of payments result in a continuous redistribution of liquidity over all participants.

We can capture the dispersion of liquidity holdings in relation to the turnover by measuring the sum of distances between the individual bank's ratio of individually available liquidity to the available liquidity of the system and the

[22] With available real-time data more sophistated measures of payment flow topology could be gained such as applied in Soramäki et.al. (2007). However, we restrict ourselves to the Herfindahl-Hirschman-Index and the number of participants in order to take advantage of the available data that covers the more than 20 years old history of SIC.

Figure 17: 20-day moving average of daily individual weighted liquidity dispersion indicators (LDIN)



bank's individual settlement value to the system's settlement value. Inequality among banks can either be measured on an individually weighted basis or on a turnover weighted basis. For the former we suggest the following measure:

$$LDIN = \sum_{i=1}^{N} abs\left(\frac{AL_i}{AL} - \frac{V_i}{V}\right)$$

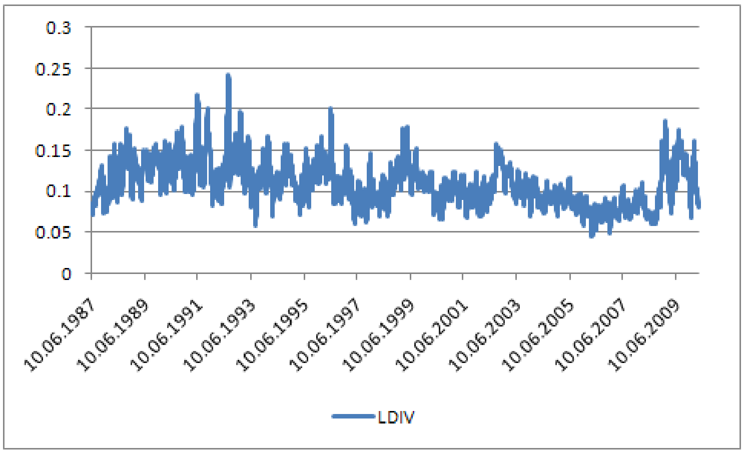
For a measure of turnover weighted liquidity dispersion we simply multiply the individual distance of inequality by the ratio of individual turnover to total turnover:

$$LDIV = \sum_{i=1}^{N} abs\left(\frac{AL_i}{AL} - \frac{V_i}{V}\right)\frac{V_i}{V}$$

The individually weighted liquidity dispersion indicator ($LDIN$) is depicted in Figure 16 whereas the turnover weighted liqudity dispersion indicator ($LDIV$) is depicted in Figure 17. Both are displayed as a 20-day moving average.

During the first years of SIC, the more liquidity is available in the system, the more dispersed seems to be $LDIN$ (see figure 2 and figure 6 for inidicators of liquidity holdings). Liquidity dispersion steadily decreased until 1995. In 1995 it decreased sharply due to many new participants entering the system. After then, liquidity dispersion remained low until mid 1997. The increasing participation in SIC in the year 1998 might explain the increase in dispersion during this time. However, the introduction of repos and intraday credits in 1998 and 1999 made liquidity dispersion fell remarkably again until 2000. This may be due to many larger banks holding much more liquidity in the form of intraday credits. Liquidity dispersion increased again after the year 2000 when more and more banks joined the repo platform. The increase after 2002 until

Figure 18: 20-day moving average of daily turnover weighted liquidity dispersion indicators (LDIV)



2003 might be explained by the introduction of CLS. In September 2002, six larger participants started to settle foreign exchange transaction in their CLS subaccounts which are exclusively funded by intraday credits. The funding level for these CLS subaccounts is large compared to their settlement value. At the same time, the funding level increased for main accounts since the settlement value decreased while the available liqudity remained constant. After mid 2003, steadily increasing participation on the Repo platform allowed more and more banks to draw intraday credits what decreased liquidity dispersion. After the collapse of Lehman the dispersion grew again due to SNB's massive injections of liquidity into the banking system.

In the early years of SIC the turnover weighted liquidity dispersion indicator ($LDIV$) shows a different behaviour than the individual weighted indicator. It increases while banks are reducing reserve holdings due to relaxed miminimum reserve requirements after 1988. Obviously, larger banks succeeded to reduce reserves to a much higher extent and experienced much higher turnover growth than smaller banks. From 1993 on, a volatile but steady decrease in dispersion can be observed until the Lehman bankruptcy in October 2008. The sharp decrease for $LDIV$ and the increase for $LDIN$ around 1995 and 1999 can for both indicactors be explained by the increasing participation experienced during these years. After 1999 indicators basically show the same patterns. For instance, the introduction of CLS increased dispersion for both indicators. Due to the increasing participation in the SNB's intraday credit facility dispersion decreased again after 2003. Both indicators exhibit increasing dispersion after the collapse of Lehman that was followed by massive liquidity injections of the SNB.

The indicators are too rough to make a thourough assessment of banks' free-riding behaviour. On the one hand, this is certainly related to the fact that we derive an indicator per SIC account in order to investigate the effect on settlement performance. Probably the indicators were more indicative if applied per bank. However, after the introduction of CLS this approach might also be problematic. On the other hand, we believe that without a disaggregated and much more in depth analysis it is very difficult to make any qualified statement. Nevertheless, it looks like larger banks were providing relatively less liquidity than smaller banks until 1999 when intraday credits were introduced. Since then both indicators show a similar downward pattern. The increase of both indicators in 2002 when CLS was introduced could be a sign that after 1999 smaller banks seem to profit more from the liquidity provision by larger banks due to their more intense use of intraday credit before and after the introduction of CLS. However, increasing participation on the repo platform resulted in the reduction of liquidity dispersion for both indicators from mid 2003 onwards. This indicates that more and more banks contribute liquidity proportionally in line with their share in aggegate settlement value. Overall, the introduction of intraday credits seems to have lowered free riding behaviour due a relative inexpensive source of intraday liquidity.

As for the liquidity dispersion indicator's influence on settlement performance, we run a regression analysis for all indicators' influence on settlement performance in the following section.

7 What drives settlement performance?

Both in the theoretical and in the simulation based literature the trade-off between delay and liqudity usage is emphasised. While the theoretical literature focuses on the trade-off between costs of delay and funding, the simulation based literature focuses on the system's settlement trade-off, i.e. how much delay results from a given level of liquidity and turnover. We follow this approach analysing real data from the more than twenty year old history of SIC.

On the one hand, the system's settlement performance is analysed in terms of the traditional delay indicators that focus on central queues. Since results of the Gini delay indicator (GDI), the delay indicator (DI) and the central queuing indicator (CQI) mirror each other, we just display the ones for CQI. On the other hand, we go beyond the traditional analysis of settlement performance based on central queuing by investigating settlement performance based on the comprehensive delay indicator (CDI). As suggested in preceeding sections, this measure is supposed to be a more accurate measure of delay as it does not only focus on central queues but allows to assess delay in a more comprehenisve sense. In particular, we suppose CDI to be a more realistic measure as it is not prone to distortions that result from strategic delay being channelled through either decentrally or centrally queued payments.

We do not restrict the econometric analysis by only incorporating settlement value and available liquidity as explanotory variables but try to incorporate new and old indicators that allow to take account of insights from the empirical and simulation based literature on payment systems. Insofar we take account of the changing behaviour of participants by incorporating behavioural indicators analysed in the preceeding section. Furthermore, we incorporate additional environmental indicators to assess topological influences on settlement performance. Thereby, we hope to gain a more thorough understanding of what settlement performance is driven by.

Even though data is available from 1987 to 2009 on a daily basis, we restrict the sample to the period from 25 January 1988 to 31 December 2007. For the period from 6 June 1987 to 24 January 1988 not all data was collected so that many indicators can not be computed for the period ahead of 24 January 1988. Furthermore, the data available from before 24 January 1988 does not allow to exclude SNB's settlement activity. The end of the sample is associated with the financial crisis that broke out in the second half of 2007. Latest after the collapse of Lehman Brothers in 2008, reserve holdings by participants in SIC exploded to levels around half of SIC's settlement value. Since then, settlement takes place almost immediately after release of payments and central queuing is basically inexistent. Due to the substantial change in available liquidity after the introduction of intraday credits on 1 October 1999 and CLS on 10 September 2002, we also estimate the following subsamples of 25 January 1988 to 30 September 1999, 1 October 1999 to 9 September 2002 and 10 September 2002 to 31 December 2009.

For all specifications and samples considered regressions exhibit heteroscedasticity and serial correlation. That is valid also for the regression results in differences. Payment system data is generally known to exhibit substantial serial correlation, e.g. turnover is known to have day of the week and other seasonal effects as shown in Oord and Lin (2005) for example. Therefore, we rely on the Newey-West serial correlation adjusted standard errors and covariance estimation for all regressions. We estimate the regression equation both in logarithmic values and differenced logarithmic values in order to control for the consistency of results.

Looking at the simulation based literature, the trade-off is often analysed based on the delay indicator and the liquidity usage indicator such as in the following specification:

$$CQI \text{ and } CDI = \alpha LUI^{\beta} RTI^{\beta_3} = \alpha AL^{\beta_1} V^{\beta_2} RTI^{\beta_3}$$

The appealing idea of the liquidity usage indicator is to assess liquidity efficiency in a combined variable. However, this can also be a disadvantage since it is unnecessarily restrictive to rely on the liquidity usage indicator in an econometric study. The liquidity available (AL) and the settlement value (V) can be incorporated as individual explanatory variables into the econometric equation (see figure 19).Since the null hypothesis that $\beta_1 + \beta_2 = 0$ is decisively rejected for both regressions in both specifications (i.e. for logarithms and differences), we consider settlement value and available liquidity separately.

As a basic insight of the discussion on delay indicators, the release time indicator (RTI) is identified as another crucial strategic variable to influence

Figure 19: Regression results for dependent varialbes CQI and CDI on explanatory variables V, AL and RTI

Sample: 1/25/1988 to 12/31/2007				
Observations	**5029**	**4902**	**5030**	**4904**
Specification	log	dlog	log	dlog
Dependent Var	**CQI**	**CQI**	**CDI**	**CDI**
C	-0.931*** (0.192)	-0.005*** (0.001)	-0.569 ***(0.041)	-0.002***(0.001)
V	0.459*** (0.014)	0.457*** (0.015)	0.149***(0.003)	0.148***(0.003)
AL	-0.679*** (0.012)	-0.783*** (0.038)	-0.248***(0.002)	-0.321***(0.011)
RTI	0.809***(0.103)	0.670***(0.137)	-0.793***(0.024)	-0.785***(0.027)
R-squared	0.81	0.56	0.81	0.44
Adj R-squared	0.81	0.56	0.81	0.44
Significance on the: * 1% level, ** 5% level, * 10% level**				
Standard errors in parentheses				

delay and, therefore, settlement performance. While around more than 90% of the explained variation in delay originate from the two explanatory variables settlement value and available liquidity, release time matters, yielding highly significant coefficients.

Whereas RTI exhibits a positive sign for both specification with CQI as dependent variable, RTI shows a negative sign in both specifications with CDI as dependent variable. Earlier release of payments does increase delay if measured as centrally queued payments (CQI) and, therefore, has a negative influence on settlement performance. Given delay is measured by means of the comprehensive delay indicator (CDI), earlier release does reduce delay. We interprete this difference in results as a clear indication that CDI is a more comprehensive measure of delay than CQI. As long as liquidity is not available to an extent such as to completely eliminate central queues, earlier release does build up central queues and makes settlement performance measured as the trade-off between liquidity usage and delay worse. However, earlier release of payments can be associated with better use of liquidity since central queues allow to use liquidity more efficiently.

Obviously, the marginal rate of substitution between delay and liquidity to settle a certain settlement value V is different depending on whether settlement performance is measured in terms of CQI or CDI. It is obvious that a higher level of liquidity reduces central queues to a higher degree than it does reduce delay measured in terms of CDI.

In order to analyse whether other influences affect the performance of the system we add the above presented indicators to the regression analysis. We rely on the given Cobb-Douglas function by simply extending the regression equation:

$$CQI \text{ and } CDI = \alpha V^{\beta_1} AL^{\beta_2} RTI^{\beta_3} PSI^{\beta_4} ISO^{\beta_5} ISE^{\beta_6} CPFI^{\beta_7} N^{\beta_8} LDIV^{\beta_9}$$

7.1 Central queing indicator as dependent variable

Coefficients for the explanatory variables settlement value (V) and available liquidity (AL) are consistently the same over all regressions as displayed in figure 20. All other variables are unstable either because their sign changes or their significance level varies considerably. To summarise, the more turnover and the less liquidity the larger queues become.

The release time indicator (RTI) in the overall sample reduces central queing for the specification in logarithms. For the specification in differences a postive but insignificant coefficient results. The first subsample in logarithms yields inconsistent results with the overall sample and the last two subsamples for which the coefficients' signs are negative and significant, both in logarithms and differences. This confirms initial results. Central queing is a poor indicator to assess settlement performance. If available liquidity is lower than a certain level, queing is increased by earlier release whereas queing is lowered if a certain amount of liquidity is overstepped. Therefore, the effect of earlier release is dependent on the level of available liquidity. The Chow break point test applied on the full sample reveals that the null hypothesis of no structural break for the coefficent in RTI can not be rejected, neither for the break point in 1999 nor in 2002. This is further indicating that earlier release may have different effects on central queuing depending on the liquidity levels available.

In the overall sample, the payment size indicator (PSI) is negative but highly insignificant whereas for the specification in differences it is positive and significant. For the logarithmic specification the coefficients change sign and significance throughout the subsamples. They are consistently positive for the specification in differences and insignificant only for the last subsample. The payment size indicator entails payments made by the SNB and settled on the CLS subaccounts. Therefore, for the subsample after the introduction of intraday credits, the indicator is highly correlated with liquidity operations by the SNB and CLS related payments after the last quarter in 2002. This may account for the negative values and the insignificant coefficients. For the overall sample, the Chow breakpoint test rejects the null hypothesis of no structural break for both break points in 1999 and 2002. Since the first subsample as the most reliable one, we assess the effect of an increasing number of high-value payments on queuing as being positive. However, in this natural experiment, we do not find a similarly strong effect as does the simulation literature as for example Koponen and Soramäki (1998). Next to the data problems, we might find another reason for this to be that parts of the effect of large payments is also captured by other indicators of release behaviour such as the following ones.

The input sequence indicator for payment size ording (ISO) is significant and positive for the logarithmic and the specification in differences. The more large-value payments are released early the higher are central queues. This is intuitive, since the less large payments are released early, the lower is the chance that they are queued for a long time and block liquidity that would help to settle lower valued payments and other participants' payments. The results are consistent throughout the first two samples. However, results change for the last subsample where in the case of logarithms the coefficent is significant and negative. The result in differences is negative, however, the coefficient is not significant. Again, the indicator suffers from the same problems as does the payment size indicator, SNB and CLS related payments are included. For the last sample, both CLS and SNB related payments that are executed from early morning until noon affect settlement positively and reduce queuing substantially. This is mirrored in the negative coefficient for the last subsample. Also, the Chow breakpoint test does reject the null hypothesis that no structural break took place in 1999. To summarise, the order of payments is influential and affects queing positively if larger payments are released earlier.

Figure 20: Regression results for the central queuing indicator (CQI) as dependent variable

Samples:
1988: 01/25/1988 to 12/31/2007
1999: 01/25/1988 to 09/30/1999
2002: 10/09/1999 to 09/09/2002
2007: 09/10/2002 to 12/31/2007

Sample	**1988**	**1988**	**1999**	**1999**	**2002**	**2002**	**2007**	**2007**
No obs	5024	4892	2946	2867	737	716	1340	1308
Spec	log	dlog	log	dlog	log	dlog	log	dlog
Dependent Variable :	**Central Queing Indicator (CQI)**							
C	-2.788***	-0.004***	-3.494***	-0.004**	6.187***	-0.004	6.506***	-0.005*
	(0.691)	(0.001)	(0.648)	(0.002)	(2.346)	(0.004)	(1.271)	(0.003)
V	0.442***	0.484***	0.468***	0.478***	0.488***	0.453***	0.428***	0.392***
	(0.020)	(0.023)	(0.025)	(0.030)	(0.064)	(0.045)	(0.044)	(0.045)
AL	-0.784***	-0.754***	-0.721***	-0.727***	-0.997***	-0.942***	-1.041***	-0.569***
	(0.020)	(0.035)	(0.026)	(0.046)	(0.056)	(0.055)	(0.081)	(0.082)
RTI	-0.342**	0.022	0.414***	0.462**	-1.432***	-1.548***	-3.713***	-2.127***
	(0.161)	(0.189)	(0.120)	(0.191)	(0.357)	(0.344)	(0.445)	(0.372)
PSI	-0.075	0.230**	0.026	0.237**	0.534***	0.258	-0.480***	0.279**
	(0.085)	(0.096)	(0.092)	(0.119)	(0.178)	(0.160)	(0.136)	(0.123)
ISO	0.477***	0.425***	0.335***	0.476***	0.306	0.403**	-0.290***	-0.187
	(0.048)	(0.058)	(0.045)	(0.068)	(0.347)	(0.210)	(0.105)	(0.132)
ISE	-0.014	0.041	0.001	0.084***	-0.164	-0.139	-0.770***	-0.556***
	(0.024)	(0.033)	(0.022)	(0.032)	(0.289)	(0.160)	(0.093)	(0.111)
CPFI	0.391***	-0.146	-0.058	-0.301	-0.271	-0.013	0.267**	-0.017
	(0.071)	(0.092)	(0.142)	(0.186)	(0.229)	(0.118)	(0.122)	(0.097)
N	0.613***	1.299*	0.520***	-0.691	-0.870**	5.602***	-1.123***	2.266*
	(0.067)	(0.680)	(0.078)	(0.883)	(0.367)	(1.792)	(0.226)	(1.318)
LDIV	0.017***	0.001	-0.003	0.005	-0.004	-0.024**	0.035***	0.024**
	(0.006)	(0.005)	(0.006)	(0.006)	(0.011)	(0.010)	(0.013)	(0.011)
R^2	0.83	0.58	0.64	0.70	0.51	0.56	0.57	0.24
Adj. R^2	0.83	0.58	0.64	0.70	0.51	0.55	0.57	0.23

Significance on the: * 1% level, ** 5% level, * 10% level**
Standard errors in paratheses

The coefficients of the input sequence extent indicator (ISE) are mostly insignificant but for the last subsample where they show a negative sign. Again, the indicator suffers from the above mentioned data problems. The Chow test shows a structural break for the specification in differences, however, does not indicate one in logarithms. That is true for both breakpoints, 1999 and 2002. Overall, the results are very ambiguous for this indicator. The least affected first subsample suggest a postive sign whereas the most affected last subsample delivers the expected negative sign.

The results on the concentration of the payment flow indicator ($CPFI$) are ambiguous too. For the logarithmic specification the coefficients are positive in the overall sample and the last subsample, both being significant. All the other coefficients are negative and insignificant. We would expect concentration to reduce central queuing insofar as it helps to increase off-setting effects between some larger banks. However, significant coefficients tell another story that is difficult to disentangle from the insignificant values with a negative sign for the other coefficients. It may well be that larger concentration goes along with larger queues related to larger banks. The Herfindahl index may be too crude as a measure of the concentration of payment flows.

For the number of participants (N) almost all coefficients are significant for both specifications and show a positive sign as expected. However, in each subsample one of the specifications shows a negative sign. For both specifications the Chow break point test rejects the hypothesis of no structural break for the year 1999. It does so too if the break point is taken to be 1995. Results are rather inconclusive.

The value weighted liquidity dispersion indicator ($LDIV$) carries significant positive coefficients in the overall sample as well as in the last subsample. For the two first subsamples the coefficients are mostly negative and insignificant. The Chow breakpoint test indicates for both specifications a clear structural break in 1999. It looks like the comovement of the indicator with available liquidity affects results accordingly and yields some significant and positive coefficients. Looking at the most reliable first subsample, coefficients are insignificant. To summarise, liquidity dispersion does not affect central queuing to a large degree.

7.2 Comprehensive delay indicator as dependent variable

The regression results for the comprehensive delay indicator are generally more stable (see figure 21). For the first three explanatory variables all coefficients are significant and keep their signs over all specifications and samples. Signs of coefficients are in line with expectations. The lower levels of settlement value (V), the more available liquidity (AL) and the earlier payments are released (RTI), the less delay results or the earlier settlement takes place.

The coefficients of the payment size indicator (PSI) are generally positive, but just one of them is significant. Again, data problems may be responsible for this. However, the first and most reliable subsample exhibits opposite signs for the two specifications and both coefficients are insignificant. The Chow break point test accepts the null hypothesis of no structrual break in 1999 and 2002 for both specifications and all samples. The effects may also be captured by other indicators of release behaviour such as the following one.

The coefficients for the input sequence ordering indicator (ISO) are all positive and all but one are highly significant. The results are in line with the expecations of a rather postive effect on settlement performance if smaller payments are released before larger payments on average. Both specifications and all samples do not show a structural break, neither in 1999 nor in 2002.

For both specifications and all samples the coefficients of the input sequence extent indicator (ISE) are negative. The coefficients show mixed significance in the logarithmic specification but generally lack significance for the specification in differences. No structural break is indicated for ISE. Again, data problems are present and may overstate the influence of sequencing in the last subsample. To summarise, the extent of sequencing may positively affect settlement performance but to a very low degree.

Figure 21: Regression results for the comprehensive delay indicator as dependent variable

Samples:
1988: 01/25/1988 to 12/31/2007
1999: 01/25/1988 to 09/30/1999
2002: 10/09/1999 to 09/09/2002
2007: 09/10/2002 to 12/31/2007

Sample	1988	1988	1999	1999	2002	2002	2007	2007
No obs	5024	4892	2947	2868	738	717	1341	1309
Spec	log	dlog	log	dlog	log	dlog	log	dlog
Dependent Variable : Comprehensive Delay Indicator (CDI)								
C	-1.501***	-0.002***	-1.645***	-0.002***	2.324***	-0.002	-1.500***	-0.002***
	(0.247)	(0.001)	(0.256)	(0.001)	(0.857)	(0.002)	(0.247)	(0.001)
V	0.154***	0.161***	0.157***	0.153***	0.168***	0.158***	0.154***	0.160***
	(0.006)	(0.008)	(0.009)	(0.011)	(0.019)	(0.013)	(0.006)	(0.008)
AL	-0.306***	-0.308***	-0.333***	-0.334***	-0.370***	-0.356***	-0.306***	-0.308***
	(0.008)	(0.016)	(0.013)	(0.023)	(0.021)	(0.021)	(0.008)	(0.016)
RTI	-1.196***	-1.073***	-0.949***	-0.871***	-1.820***	-1.840***	-1.197***	-1.074***
	(0.088)	(0.141)	(0.091)	(0.156)	(0.139)	(0.132)	(0.088)	(0.141)
PSI	0.007	0.041	-0.013	0.014	0.202***	0.080	0.007	0.041
	(0.029)	(0.029)	(0.033)	(0.034)	(0.064)	(0.059)	(0.029)	(0.029)
ISO	0.148***	0.149***	0.130***	0.189***	0.138	0.187**	0.148***	0.148***
	(0.022)	(0.027)	(0.026)	(0.034)	(0.126)	(0.076)	(0.022)	(0.026)
ISE	-0.038***	-0.018	-0.025**	-0.007	-0.050	-0.039	-0.038***	-0.018*
	(0.011)	(0.011)	(0.010)	(0.011)	(0.105)	(0.058)	(0.011)	(0.011)
CPFI	0.041*	-0.037	-0.033	-0.057	-0.084	0.015	0.041*	-0.037
	(0.024)	(0.030)	(0.055)	(0.066)	(0.081)	(0.038)	(0.024)	(0.030)
N	0.246***	0.540**	0.292***	0.055	-0.384***	2.366***	0.246***	0.540**
	(0.027)	(0.235)	(0.034)	(0.339)	(0.141)	(0.671)	(0.027)	(0.235)
LDIV	-0.003	-0.001	-0.002	0.002	-0.0003	-0.009**	0.033	-0.001
	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)	(0.00)	(0.002)	(0.002)
R^2	0.83	0.48	0.60	0.48	0.56	0.64	0.83	0.48
Adj. R^2	0.83	0.48	0.60	0.48	0.55	0.63	0.83	0.48

Significance on the: * 1% level, ** 5% level, * 10% level**
Standard errors in paratheses

All coefficients of the concentration of payment flow indicator ($CPFI$) but two are insignificant. Coefficients exhibit mixed signs. The Chow break point tests indicates a structural break for the logarithmic specification in 1999 and for the specification in differences in 2002. Overall, it looks fair to say that concentration does not crucially influence settlement performance.

The coefficients for the number of participants (N) are all but one found to be positive and strongly significant. In differences the introduction of CLS marks a structural break whereas for the logarithmic specification a structural break is indicated for the introduction of intraday credits. In 1994 and 1998, the number of participants grew substantially. No structural break is indicated in the logarithmic specification whereas the specification for differences marks a structural break for 1994. Overall, settlement delay seems to increase and negatively influence settlement performance with an increasing participation.

The coefficients of the liquidity dispersion indicator ($LDIV$) are generally insignificant but for one coefficient and show negative as well as some positive signs. For the specification in differences, the introduction of CLS marks a clear structural break. Overall, it looks fair to say that liquidity dispersion does not influence settlement performance[23]

7.3 Discussion of results

To summarise, it is very difficult to empirically capture a complex payment system with its manyfold influences. The most indicative variables are turnover, available liquidity and release time which explain most of the variation of both dependent variables. Some of the other indicators are indicative but do not explain much more of the variation.

Indicators in regressions with CDI as dependent variable are generally more indicative and show a more stable behaviour over both specifications and all samples. The sequencing order indicator (ISO), the number of participants (N) and the liquidity dispersion indicator ($LDIV$) are among the most indicative explanatory variables. The payment size indicator (PSI), the sequencing extent indicator (ISE) and the concentration of payment flow indicator ($CPFI$) exhibit rather inconclusive results.

Several reasons may account for this. First, a fundamental problem might be that many variables are not really independent. For instance, available liquidity (AL) and the number of participants (N) may structurally affect release time in so far as they influence strategic behaviour by affecting incentives to delay. Second, settlement value (V), available liquidity (AL) and release time (RTI) explain most of the variation and might be influential to a degree that leaves no room for other variables. In particular, indicators of release behaviour such as PSI, ISO and ISE are shown to have effects in the simulation literature but are not indicative in our regression analysis. This might suggest that another

[23] We focuse on the settlement value weighted liquidity dispersion indicator since this one may influence settlement performance more profoundly than the individual weighted indicator. However, overall results of the individual weighted indicator mirror the ones of the settlement value weighted indicator. For both reasons we omit regression results with $LDIN$ as explanatory variable.

specification is asked for to disentangle the effects. Third, the special feature of a seperated CLS settlement cycle that takes place in specific subaccounts can not be captured with such indicators and may affect overall results. Forth, the inclusion of SNB and CLS specific data in some of the indicators too may distort overall results. Therefore, from a data accuracy point of view the first subsample may generally be regarded as the most reliable one.

Considering these caveats and focusing on the first subsample, it may be stated that regression results meet expectations. Furthermore, results for the comprehensive delay indicator (CDI) are more stable in showing less structural breaks as well as more consistent results over all subsamples and both specifications. We argue that this is at least partially related to the arbitrary nature of the central queuing indicator as a measure of delay. The overall results derived in the initial regression are reflected in the subsequent two regressions. In particular, looking at the first subsample, the release time indicator (RTI) shows opposite signs for the different dependent variables. Equal signs of RTI's coefficients in subsequent samples for both dependent variables suggest that the level of available liquidity (AL) is a crucial factor that influences the explanatory variables' effects in relation to central queuing. Furthermore, over all samples the impression that the influence of settlement value (V) and available liquidity (AL) is overstated if delay is measured as central queuing is reinforced by the consistent coefficients. Thus, the regression analysis supports comprehensive delay as a more reliable measure of delay.

8 Conclusions

This paper serves to stimulate the empirical investigation of payment systems with real data. Some new indicators are shown to be useful in the empirical description of a payment system. In particular, we propose a new indicator to describe settlement delay. We argue that the comprehensive settlement delay (CDI) indicator is more directly related to its inverse, namely settlement speed. Therefore, CDI is conceptually different to traditional delay indicators (as for instance CQI) and arguably more comprehensive. In constrast to existing indicators, this new measure of delay is also applicable for both types of systems, those with and the ones without central queuing. Furthermore, we suggest new indicators to analyse release behaviour and confront these measures with the more than twenty year old history of SIC. We find indicators to reflect policy and to appropriately take into account environmental changes. Described indicators can easily be applied in the context of real-time data as applied in the simulation literature.

The prevailing use of centralized queues as a definition for delay has a major shortcoming. By applying a definition of delay on grounds of centralised queues we only take into account payments already released to the system and neglect payments which will still be released in the course of the day. In line with the theoretical literature, we argue that a measure of settlement performance has to be based on the total settlement value known ahead or to be expected. We suggest such a more comprehensive delay indicator (CDI) that is constructed by simply extending the traditional delay indicators by unreleased payments. In doing so, we refer to all unsettled payments as being delayed. In constrast to traditional delay indicators, CDI also allows to compare both types of systems, the ones with and the ones without central queues. Furthermore, such a measure of delay is conceptually in line with settlement speed being the opposite side of the coin. The comprehensive settlement indicator (CSI) as a measure of settlement speed is the inverse of settlement delay: $CSI = 1 - CDI$. Essentially, central queuing (CQI) is shown to be only one aspect of delay as $CSI = 1 - UPI - CQI$. Therefore, it can be distorted in any direction whereas CDI only overstates delay. Furthermore, in contrast to CDI, CQI can neither account for strategic delay such as known to take place in decentrally queued payments nor can it account for yet unknown payments - both being indicated by the unreleased payment indicator (UPI).

The problem with measuring settlement performance is that the trade-off between delay and liquidity is empirically intertwined by environmental factors such as behavioural aspects that would have to be kept constant in order to gain an accurate measure of performance. Working with real data, this is hardly the case. Therefore, we investigate some ideas on how to capture a changing environment such as to avoid distortions in measuring the trade-off. For that purpose, existing and newly developed indicators of release behaviour are analysed. The release time indicator (RTI) allows to evaluate the effect of earlier release of payments on settlement performance. A payment size indicator (PSI) captures the idea of liquidity blockings as a result of large payments. Sequencing indicators are build to assess how the order (ISO) and the extent (ISE) of sequencing of payments influcence settlement performance. Next to behavioural indicators, we also expect the topology of payment flows to have an influence on settlement performance. Especially, the concentration of payment flows ($CPFI$) between participants is supposed to have such an influence. Additionally, we take the number of participants (N) as a simple indicator of the complexity of the payment system network. Furthermore, two indicator for the dispersion of liquidity distributions ($LDIN/LDIV$) in relation to turnover allow to discuss participants free riding behaviour.

These indicators are applied in the context of real data stemming from the 20 year old history of SIC in order to econometrically analyse the trade-off between delay and liquidity. As suggested in existing literature, settlement performance is to a large degree explained by settlement value (V) and available liquidity (AL). However, other variables such as behavioural and environmental ones are relevant too and help to explain performance. In particular, earlier release of payments (RTI) is found to positively influence settlement performance in a RTGS system with central queues. This is line with the theoretical literature on liquidity-saving mechanism such as Martin and McAndrews (2008) and Jurgilas and Martin (2010). In Atalay et al. (2010), the effects of a liquidity-saving mechanisms are assessed to be significant if introduced into a pure RTGS system. We further qualify this result by showing that the effects of liquidity-saving mechanisms can be further increased by earlier release of payments.

Less consistent results that may be connected to data problems are found for other indicators. The effect of larger payments, however, seems to be negative. The order of sequencing can also affect settlement. In particular, earlier release of smaller payments and later release of larger payments seems to have a positive effect. Indicative results are found for the number of participants. Settlement performance seems to be rather negatively influenced by an increasing number of participants. The dispersion of liquidity in relation to settlement value is also indicative. It does not seem to affect settlement performance at all. To summarise, the results for the central queuing indicator are largely consistent with those of the simulation literature starting with Koponen and Soramäki (1998). However, CQI yields results that are less consistent than those for CDI. We take this as evidence of an inherent problem to the measurement of delay by central queues. Since central queues are prone to many effects that are not related to settlement performance per se, they yield a rather arbitrary measure of delay. Regression results confirm that a measure of delay based on central queuing results in wrong conclusions by overstating the effect of available liquidity and settlement value on delay. Worse, earlier relase of payments is assessed wrongly as to decrease settlement performance. Therefore, settlement performance should be evaluated on grounds of the comprehensive settlement indicator (CDI) rather than on a traditional delay indicator based on central queing.

Aggregate liquidity in the system is the major relevant factor for settlement performance. The liquidity dispersion indicators ($LDIV/LDIN$) as aggregate measures of individual liquidity contribution in relation to individual turnover do not affect settlement performance. This indicates that costly and private liquidity provision to a RTGS system can be understood as the private provision of a public good. By making payments, participants share their privately provided pot of liquidity with other participants. In essence, no participant of the payment network can be excluded from receiving a payment whereas enabling a payment by providing liquidity gives raise to private costs. This is strong evidence for competitive externalities mentioned in the theoretical literature such as Angelini (1998).

The liquidity disperison indicators ($LDIV/LDIN$) are tempting to be used as a measure of free-riding behaviour. However, both theoretically and empirically they have to be used with caution. For instance, Ota (2010) argues that liquidity dispersion is not necessarily something bad in a payment system with a two-part tariff where banks with high-funding costs provide less liquidity than those with low-funding costs and, as a consequence, delay their payments to await incoming funds from low-funding cost participants. The two-part tariff is understood as a compensation mechansim since high-funding cost participants with comparatively lower levels of liquidity contribute more to the operational cost of the system as they incur higher fees. Since SIC knows such a two-part tariff since April 1988, inferring the extent of free-riding from liquidity dispersion indicators is, indeed, to be enjoyed with caution.

However, used in combination, dispersion indicators allow to infer whether smaller or larger banks may be responsible for increases or decreases of the indicators. Overall, the introduction of the intraday credit facility and, as a result, the substantial decrease of liquidity costs seem to have resulted in less liquidity dispersion as larger participants have contributed relatively more to aggregate liquidity in relation to settlement value. I understand this to be in line with Ota (2010) as smaller banks are generally considered to be long in cash and, thus, dispose over ample and relatively inexpensive funds, whereas larger banks are generally thought of as being short in cash and, thus, rely on relatively expensive borrowings in the interbank money market. Therefore, considering liquidity dispersion as valid indicators of the extent of free-riding, on a crude aggregate level emprical evidence seems to back theoretical insights on competitive externalities. However, more work would be needed to make these insights operational. In particular, indicators on an individual level in combination with a measure of a bank's funding cost could allow to gain further insights into the extent of free-riding and the appropriate design of tariffs for RTGS systems.

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