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An analysis of competitive externalities in gross settlement systems

Paolo Angelini [1]

Banca d'Italia, Research Department, Via Nazionale 91, 00184 Rome, Italy

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Abstract

Following the ongoing debate on risks in interbank payment networks, gross settlement systems are being adopted in several industrialized countries. These systems, which effect real-time transfers of monetary base among bank accounts, add management of intraday liquidity to the duties traditionally performed by central banks, and require new, ad hoc policy instruments. The paper presents a simple model of a real-time gross settlement (RTGS) system, which is used to analyze the reaction of banks and monetary policy variables to this new environment. It is shown that if daylight liquidity is costly, a network externality may induce banks to postpone payment activity, thereby affecting the quality of the information available to counterparts for cash management purposes. The increased noise may in turn induce higher than optimal levels of banks' end-of-day reserve holdings, relative to a social optimum, with adverse effects on expected profits. The rise of a daylight market for funds, predicted by the model, does not solve the mentioned externality problem. Some corrective policy measures are discussed. © 1998 Elsevier Science B.V. All rights reserved.

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[1] Tel.: 39-6-4792 3308; fax: 39-6-4792 3723; e-mail: i8353139@interbusiness.it.

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1. Introduction

Over the last few years, rapid financial innovation and technological progress have triggered an exceptional growth in the volume of funds transferred over interbank payment systems, which have become the subject of extensive debate within the banking community and among policy makers. In particular, the intraday debit positions characterizing traditional interbank systems have been increasingly criticized as a source of credit risk, systemic risk and moral hazard. [2] At the same time, the so-called real-time gross settlement (RTGS) systems, made feasible by the recent advances in computer technology, have been proposed among the possible solutions to these problems. With this new class of systems each transaction is settled individually, irrevocably and in real time during the day via a transfer of base money from the sending to the receiving bank's settlement account at the central bank; thus, intraday debits are eliminated altogether, and so are payment system-related systemic risk and moral hazard. This is the main reason why in Europe central banks are among the main supporters of the RTGS approach. On the other hand, the operation of these systems requires relatively large amounts of liquidity. Thus, commercial banks worry that their adoption could result in a substantial increase in operating costs (see European Banking Federation, 1993). Presently the EU countries as well as several Eastern Europe and Asian ones are heading for the gross settlement option.

Not surprisingly, these developments have spawned a large body of theoretical and empirical research. Until recently, the main focus has been on policy-oriented analysis or description of current arrangements. [3] Early attempts at developing a formal analysis are by Gelfand and Lindsey (1989), who present a welfare analysis of the various policies for the management of daylight credit, and VanHoose (1991), who builds a model of the Federal funds market, focusing on the relationship between overdraft reduction mechanisms and the be-

[2] Concern about the potential risks of interbank networks was first raised by Humphrey (1986). In the mid 1980s the Federal Reserve started a major risk reduction program that led to substantial changes in the operation mechanisms of the main US interbank payment systems. See Board of Governors of the Federal Reserve System (1988, 1990); Bank for International Settlements (1993). Towards the end of the decade the debate extended at the G-10 and the EEC level. See Bank for International Settlements (1990); Committee of Governors of the Central Banks of the Member States of the European Economic Community (1992, 1993).

[3] See Frankel and Marquardt (1983, 1987); Padoa-Schioppa (1988, 1989, 1992); Humphrey (1989, 1990); Garber and Weisbrod (1990); Passacantando (1991); Folkerts-Landau et al. (1993); Angelini and Giannini (1993). On the issue of risk and risk reduction policies see the references in Footnote 2; see also Belton et al. (1987); Mengle et al. (1987); Evanoff (1988); VanHoose and Sellon (1989); Mengle (1990); Borio et al. (1991); Borio and Van den Bergh (1993). Detailed descriptions of the interbank networks in the main industrialized countries are in Bank for International Settlements (1993); European Monetary Institute (1996).

havior of interbank interest rates, as well as on its monetary policy implications. More recently, a growing body of analysis is being developed. Berger et al. (1996) present a graphical analysis of the trade-off between risks and costs arising in payment systems, as well as their external effects. Schoenmaker (1995), Kahn and Roberds (1996) address the problem of the relative merits of gross vs. net settlement systems. Rochet and Tirole (1996a) suggest that current configurations can be improved upon by combining the respective benefits of net and gross systems. In the model presented by Flannery (1996), most of the risk reduction-related costs are borne by the private market participants, but during financial crises it may be optimal for the central bank to provide discount window liquidity. Humphrey (1986) and Angelini et al. (1996) provide empirical evidence on systemic risk in interbank clearing systems, whereas an analytical framework is developed by Rochet and Tirole (1996b). Chakravorti (1995), McAndrews and Roberds (1995) investigate payment system issues within a Diamond–Dybvig type of model; Lacker (1996) adopts the island paradigm. Furfine and Stehm (1996) develop a model of a RTGS system, focusing on the relative desirability of the various intraday credit policies available to central banks (quantity limits, collateralized credit, priced credit), whereas Hancock and Wilcox (1996) present an empirical analysis of the effects of these options. Rossi (1995), Dale and Rossi (1996) focus on intraday markets for liquidity in RTGS systems.

The present paper narrows the analysis to RTGS systems, focusing on the incentive mechanisms operating in this context and their impact on the behavior of key monetary policy variables such as short-term interest rates and bank reserves. The model builds on the setup devised by the literature on precautionary demand for reserves. [4] I compare Cournot–Nash market equilibria resulting from individual profit maximization by each bank, and "cooperative" outcomes, in which the choice variables are determined so as to maximize the sum of each participant's profits. It turns out that in this context the cooperative outcome coincides with a social optimum, in which bank profits and consumer surplus are maximized.

The main results are the following. First, it is shown that if daylight liquidity is costly (either because the central bank charges a price for it or because it entails an opportunity cost), then banks will tend to postpone outgoing payments, relative to the cooperative outcome. For the processing of payments in real time banks need liquidity, but since intraday reserves entail an opportunity cost, each participant has an incentive to reduce its own holdings, expecting to be able to use some other participant's reserves. As a consequence, each bank will postpone forwarding outgoing payments until the perceived marginal

[4] See Orr and Mellon (1961); Grossman (1965); Miller and Orr (1966); Poole (1968); Baltensperger (1974).

cost of delaying equals the marginal cost of reserves. However, while a decision to postpone does reduce the expected cost of daylight overdraft for the sending bank, it also tends to increase that same cost by an analogous amount for the receiving bank, thereby generating a deadweight loss at the system level. Payment delays will tend to worsen the quality of the screen-based information available to banks for cash management optimization. This may induce banks to demand a higher than optimal level of end-of-day precautionary reserves, a surprising result, considering that positive external effects are often associated with liquidity holdings. [5] This effect tends to reduce expected profits. In this context, it is shown that the creation of an intraday market for funds, predicted by the model, does not by itself eliminate the mentioned externality. [6] The paper discusses some alternative policy options which should restore optimality.

Section 2 develops a simple model of an RTGS system and derives the main results. Section 3 discusses some policy options to deal with the problems analyzed in the previous section and the monetary policy implications of RTGS systems. Section 4 summarizes the main results.

2. The analytical framework

Normally, banks begin the day with a good idea of what the payment-related inflows and outflows for that day are going to be. For instance, since foreign exchange contracts are typically settled with a two-day lag, at the beginning of any given day banks know with certainty that the payments related to contracts signed two days before are coming due. However, for the share of the daily operations which cannot be foreseen at the beginning of the day, banks must depend on real time, screen-based information supplied by the electronic interbank payment system. In what follows I assume that these payments are one main source of uncertainty affecting banks' daily decision making in this area.

2.1. Basic notation and definitions

Assume that the market for electronic payment services is composed of n banks, interacting with a central agent offering settlement services. Banks may differ as to volume of payments processed, cost structures etc. The busi-

[5] In a different context, Cothren and Waud (1994) show that a free-market Nash equilibrium will yield lower-than-optimal reserve levels. See also Laidler (1977) within the context of money demand analysis.

[6] Several authors have argued that pricing or restriction of daylight credit by the Federal Reserve may generate payment delays (Humphrey, 1989) or give rise to an intraday market (Simmons, 1987; Evanoff, 1988; Humphrey, 1989; Stevens, 1989).

ness day, which begins at time t_0 and ends at time t_1 is subdivided into m intervals of length $(t_1 - t_0)/m$. Banks face a demand for payment services by their clients, who wish to send money to their business counterparts, holding accounts at other banks. Let $\mu_t^i \in [0, \infty)$ be the monetary value of clients' demands collected by bank i over the interval ending at time t. For reasons that will be made clear in what follows, the bank may decide to withhold some payments requested by clients, and send them at some later period. This may create a backlog of payments that clients requested to be sent in period t but the bank chooses to send only in later periods. Let z_t^i be the amount of payments waiting to be sent at time t. This amount is composed of the sum of new payment orders μ_t^i and the backlog from previous periods, which I denote by $a_{t-1}^i \in [0, z_{t-1}^i]$:

$$z_t^i = \mu_t^i + a_{t-1}^i, \qquad a_{t_0}^i = a_{t_0-1}^i = \mu_{t_0}^i = 0. \tag{1}$$

Banks also send and receive payments on their own account. Specifically, banks that expect to end the day with an excess (shortage) of funds will turn to the interbank market to invest (borrow) them, and to do so they will send (receive) payments. Let v_t^i be the amount borrowed ($v_t^i > 0$) or lent at time t and flowing through the settlement account. Lending and borrowing takes place at the same interbank rate $r_{b,t}$, which can be thought of as the overnight rate, or any other short-term money market rate. The total volume of funds flowing out of bank i's account at time t is then

$$(z_t^i - a_t^i) + \max(0, -v_t^i), \tag{2}$$

where $a_t^i > 0$ indicates that some outgoing payments are being withheld. Similarly, I define the total amount of funds received by bank i in the same period as

$$y_t^i + \max(0, v_t^i), \tag{3}$$

where

$$y_t^i = \sum_{j \neq i} b^{ji} (z_t^j - a_t^j) \tag{4}$$

and b^{ji} are nonnegative weights, $\sum_{i \neq j} b^{ji} \equiv 1$. Specifically, b^{ji} is the share of bank j's total outflow of payments at time t going to bank i, assumed to be constant over time for simplicity. In both (2) and (3) the first term summarizes the payment activity performed on behalf of clients, while v_t^i denotes activity in the interbank market. All the payments requested by customers must be sent by the end of the business day, so that the following constraint must hold:

$$a_{t_1}^i = 0. \tag{5}$$

Denote by $R_{t_0}^i$ the initial liquidity that the bank holds "idle" on its account for the purpose of making payments, which will in general be equal to the previous end-of-day position. Thus, the liquidity position of the bank's settlement account at any time t will be given by the algebraic sum of outgoing minus incoming payments, both on clients' and own account, plus the beginning-of-day level of reserves $R^i_{t_0}$. Subtracting Eq. (3) from Eq. (2) and summing over t, I get an expression for the monetary value of this liquidity position

$$D^i_t \equiv \sum_{s=t_0}^{t}[z^i_s - a^i_s - y^i_s - v^i_s] - R^i_{t_0}. \tag{6}$$

$D_t < 0$ means that the bank has excess liquidity on its settlement account, whereas $D_t > 0$ implies that the bank is incurring an overdraft. In the latter case the bank may face costs due to reserve deficiency. I define $r_{d,t}$ to be the rate charged by the central bank for the use of overdrafts in period t. For $t = t_1$ $r_{d,t}$ is the discount rate, whereas for $t < t_1$ it is the rate charged for the use of daylight overdrafts, which may be positive or zero, depending on the specific type of payment system considered.

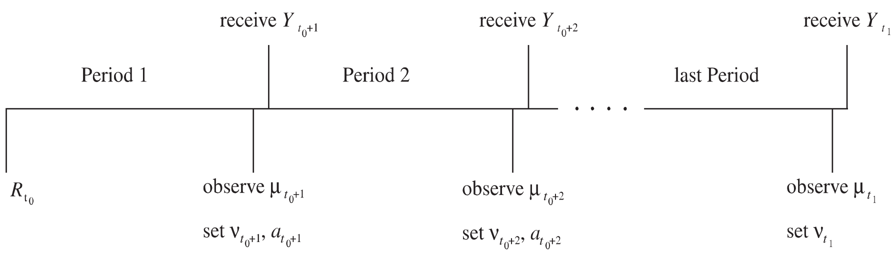
Concerning revenue from payment processing, I assume that bank customers are charged a fee proportional to the amount transferred, which for simplicity is imposed only on outgoing payments. I describe bank i's revenue by a function g^i_t and assume that delaying the settlement of payment messages ordered by clients (setting $a^i_t > 0$ for some t) entails a monetary loss. This may be the case if customers demand a compensation when payments are delayed. Alternatively, one may think that the day's revenue is fixed and that g^i_t represents expected future revenue from payment services. In this case, clients' dissatisfaction caused by delayed transfers will generate a revenue loss through reduction of future demand. In both cases, a direct relationship between revenue and speed of settlement stems from the intrinsic usefulness of gross settlement, which is taken for granted in this stage of the analysis. Thus, let the period t money value of the revenue from payments activity be $g^i_t = g(a^i_t, z^i_t, \delta^i)$ and assume $\partial g/\partial a^i_t \leqslant 0$, $\partial g(0, z^i_t, \delta^i)/\partial a^i_t = 0$, $\partial^2 g/\partial(a^i_t)^2 < 0$. Concavity in the first argument captures the idea that small delays will have little impact on revenue, but as they become large customers' dissatisfaction will grow substantially, and heavier consequences on revenue will accrue. The parameter $\delta^i \in [0, 1]$ measures bank i's sensitivity to payment delays; values close to zero mean that the bank's clients are insensitive to payment delays, and so is the bank's revenue, whereas values of δ^i close to one characterize banks at the opposite side of the spectrum. In what follows I assume that although each bank knows its own δ^i, this parameter is unknown to the other banks, who view it as a random variable with a known density, independent of the payment flows.

The specification of the revenue function is clearly ad hoc. However, the main results of this section would follow even if g were linear in a^i_t, as would be the case if banks' clients minimized a quadratic cost function. Thus, none of the above assumptions is strictly indispensable; the assumption

$\partial g(0, z_t^i, \delta^i)/\partial a_t^i = 0$, which plays the role of an Inada condition, will be relaxed in Section 2.4.

2.2. Timing of the operations and information structure

As already mentioned, during the business day banks collect payment orders μ_t^i from clients, who come in until closing time t_1. I assume that from the banks' viewpoint the $\mu_t^i (i = 1, 2, \ldots, n,\ s = t_0, \ldots, t_1)$ are exogenously given nonnegative stochastic variables, independent across time and banks, distributed according to a known density. [7] Omitting superscripts, the timing of the system operation for bank i is the following figure:



Reception of incoming funds y_s^i as well as decision making regarding v_s^i (the amount to be borrowed/lent in the interbank market) and a_s^i (the amount of payments to withhold) are simultaneous. However, the figure displays a lag between the two instants to emphasize that when the decision is made, uncertainty remains over incoming payments. At the end of period t bank i observes the demand for payment services by its own clients (μ_s^i for $s \leqslant t$), as well the past history of payments sent by other banks on behalf of their clients up to time $t - 1$. The information set available to bank i at time t is denoted by I_t^i. The functions g are assumed to be common knowledge. Finally, the following assumptions are made: there are no reserve requirements; the interest rate earned on free reserves is zero; there are no transaction costs related to borrowing or lending operations; banks are risk neutral; and there are no caps on daylight exposures.

[7] The assumption of exogeneity of the demand for payment services is warranted by the short time horizon of the analysis. Customers cannot react within the day to bank's decisions having an impact on demand, such as fee variations or excessive delays. The latter are allowed to have an impact on demand over a longer time horizon via reduction of (future) bank revenue.

2.3. The model

In this section I consider the problem faced by a bank operating in an RTGS system in which daylight credit from the central bank is available at a charge. For the sake of simplicity I consider the case of two banks, A and B, operating for two periods (morning and afternoon). Thus, set $t_0 = 0$ for ease of notation. Suppressing superscripts relative to bank A, the problem for the latter can be written as follows:

$$\max_{[v_1, v_2, a_1]} g(a_1, \mu_1, \delta) - r_{d,1} \int_0^{k_1} D_1 \, \mathrm{d}F_1(\mu_1^B | I_1) - r_{d,2} \int_0^{k_2} D_2 \, \mathrm{d}F_2(\mu_2^B | I_2) - \sum_{s=1}^{2} v_s r_{b,s}, \tag{7}$$

where

$$k_1 \equiv \mu_1 - a_1^{\mathrm{A}} + a_1^{\mathrm{B}} - v_1 - R_0 \qquad k_2 \equiv \mu_1 + \mu_2 - \mu_1^{\mathrm{B}} - v_1 - v_2 - R_0 \tag{8}$$

and the expressions for D_t^{A} are given by Eq. (6). The first term of Eq. (7) is the gross revenue function described above, the second is the expected cost of daylight overdrafts in period 1, and the third captures the expected cost of resorting to the discount window at the end of the day. [8] The latter is the equivalent of the term appearing in the well-known static model for the analysis of the demand for reserves under uncertainty. [9] The k_t^{A} are defined so as to integrate over the subspace where realizations of the random variables yield positive overdrafts ($D_t^{\mathrm{A}} > 0$). The cost of borrowing (or, depending on the sign of v_t^{A}, the gain from lending) in the interbank market is given by the terms in the summation operator.

The formulation of problem (7) is relatively standard. The main novelties are represented by g^i, expressing revenue as a decreasing function of the settlement delay, and by the second term, which gives the expected cost of daylight overdrafts. These two terms capture the trade-off faced by the sending bank: delaying payments will generate a loss of revenue due to customer dissatisfaction, but will reduce the expected cost of daylight overdrafts.

Adopting the standard backward solution technique, it is convenient to optimize in the second period with respect to $(v_1^{\mathrm{A}} + v_2^{\mathrm{A}})$. To this end, the interbank rate in period 1 can be expressed in terms of its end-of-day level and an additive component: $r_{b,1} \equiv r_{b,2} + r_o$, where the term r_o can be thought of as the market

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[8] Gross revenue for the second period is not included in Eq. (8) since due to constraint (5) a_2^{A} must be equal to zero (all payments must be sent by the end of the day). Substituting Eqs. (1) and (4) into Eq. (6), and noting that in the two banks, two periods case $b_t^{ji} = 1$ for every i, j, t, I get $D_1 = \mu_1 - a_1 - \mu_1^{\mathrm{B}} + a_1^{\mathrm{B}} - v_1 - R_0$, and $D_2 = \mu_1 + \mu_2 - \mu_1^{\mathrm{B}} - \mu_2^{\mathrm{B}} - v_1 - v_2 - R_0$, where superscripts for bank A have been omitted.

[9] See e.g. Eq. (3) in Baltensperger (1974).

interest rate on daylight overdrafts. Replacing this expression for $r_{b,1}$ in Eq. (8), first order conditions can be derived for the second period optimization, with respect to $(v_1^{\mathrm{A}} + v_2^{\mathrm{A}})$, and for the first period, with respect to v_1^{A} and a_1^{A} [10], in the order:

$$r_{d,2} \int_0^{k_2} \mathrm{d}F_2(\mu_2^{\mathrm{B}} | I_2) = r_{b,2}, \tag{9}$$

$$r_{d,1} \int_0^{k_1} \mathrm{d}F_1(\mu_1^{\mathrm{B}} | I_1) = r_o, \tag{10}$$

$$r_{d,1} \int_0^{k_1} \mathrm{d}F_1(\mu_1^{\mathrm{B}} | I_1) = -\partial g / \partial a_1, \tag{11}$$

where bank A's superscripts have been omitted. Although a closed form expression cannot be computed unless an explicit functional form is adopted for the densities, the market clearing interbank interest rate $r_{b,2}$ along with the optimal amount of end-of-day borrowing can in principle be determined by solving the three equation system formed by Eq. (9) for A and B plus the market clearing condition $v_t^{\mathrm{A}} + v_t^{\mathrm{B}} = 0$ for $t = 2$. Using the latter condition for $t = 1$ along with Eqs. (10) and (11) for A and B will determine the intraday rate r_o as well as optimal values for v_1^i and a_1^i as a function of policy rates, initial level of reserves and parameters.

2.4. Results

I now assume $\sum_{i=\mathrm{A,B}} (\mu_1^i - R_{t_0}^i) > 0$. That is, in the aggregate the amount of funds processed by the interbank system in period 1 is larger than the reserve level. For most existing systems this assumption is quite reasonable, as the former is usually a large multiple of the latter. I can now state the following proposition. [11]

Proposition 1. *In the competitive equilibrium: (i)* $r_o > 0$ *(ii)* $a_1^i > 0$ *for* $i = \mathrm{A, B}$.

[10] In principle, one can derive an optimal value for the sum $(v_1^{\mathrm{A}} + v_2^{\mathrm{A}})$ and replace it in the value function; it then turns out that the integral multiplied by $r_{d,2}$ does not depend on v_1^{A}.

[11] The proofs of the propositions are available from the author.

Proposition 1 says that when the sending bank is charged for daylight overdrafts an intraday market for reserves will materialize. In practice, r_o would most likely take the form of a premium on overnight loans delivered earlier during the business day, given that the cost of setting up a formal intraday market may be high. At the same time, input of payments will be delayed ($a_1^i > 0$) to avoid the cost of overdrafts, so a backlog will tend to accumulate. [12] ents, pricing daylight overdrafts may in practice trigger several other responses from banks, not analyzed in the model of this section, which may weaken the impact of pricing on payment delays; see Humphrey (1989). [12] These results are fairly intuitive. In an RTGS system reserves have a role to play during the day (and not just at the end of it, as in clearing systems) in that they allow banks to avoid the loss of revenue related to payments delay. As long as $r_o = 0$, banks will expect to use reserves at no cost, since they may borrow in the morning and lend back at the same rate in the afternoon. This will create an excess demand for reserves in the morning, which will drive a wedge between interbank rates in the two periods.

I now derive the necessary optimality conditions for the cooperative problem, resulting from the determination of bank A's choice variables to maximize the joint profits of banks A and B. Following a solution procedure analogous to the previous one, it can be checked that Eqs. (9) and (10) hold unchanged, whereas the equivalent of Eq. (11) becomes

$$r_{d,1}\left[\int_0^{k_1^{\mathrm{A}}} \mathrm{d}F(\mu_1^{\mathrm{B}}|I_1^{\mathrm{A}}) - \int_0^{k_1^{\mathrm{B}}} \mathrm{d}F(\mu_1^{\mathrm{A}}|I_1^{\mathrm{B}})\right] = -\partial g^{\mathrm{A}}/\partial a_1^{\mathrm{A}}. \tag{12}$$

The system of first order and market clearing conditions for the cooperative problem will yield optimal values for the control variables for A and B.

Proposition 2. *In the cooperative outcome* $a_1^i = 0$ *for* $i = \mathrm{A}$, B.

In the cooperative outcome, delaying yields zero benefits because it reduces bank A's expected overdraft cost, but increases by the same amount that of bank B. It is worth mentioning that within this framework the cooperative outcome coincides with a social optimum. Indeed, joint profits are maximized by definition. Interpreting the functions g^i as the product of a fee for payment processing services times a demand schedule decreasing in the delay, for $a_1^i = 0$ consumer surplus is maximized as well. Further, the creation of an intraday market for funds does not eliminate the externality related to payment delays.

[12] In addition to delaying the input of payments, pricing daylight overdrafts may in practice trigger several other responses from banks, not analyzed in the model of this section, which may weaken the impact of pricing on payment delays; see Humphrey (1989).

This depends on the fact that in the Nash equilibrium banks equate at the margin the revenue loss from customer dissatisfaction and the reduction in the expected cost of daylight overdrafts, as imposed by condition (11).

Proposition 3. *Due to the information structure, the sum of banks' expected profits in the second period is lower in the market equilibrium than in the cooperative outcome.*

Since the solution to the cooperative problem yields the monopolistic outcome, joint profits are trivially going to be higher in this case than when banks compete. However, the focus here is on a different source of profit loss: the practice of delaying payments characterizing the competitive equilibrium will reduce the quality of the information available to the receiving bank. In the presence of payment delays, bank A may have problems distinguishing a situation in which the inflow of payments is low because the realization of bank B's demand for payment services is low from one in which the latter is large but bank B chooses to withhold a relevant portion of it. This represents a potentially negative aspect of the practice of delayed sends, which so far have been mainly viewed as an efficient way of reducing the level of daylight overdrafts at the system level (see Humphrey, 1989, 1990).

It is worth noting that payment delays do not affect the quality of the information available to bank A in the second period if the parameter δ^{B}, which measures the sensitivity of bank B's revenue function to payment delays, is known to bank A. In this case direct observation of the first period market clearing interest rate, along with knowledge of the revenue functions, allows each bank to infer the exact amount of payments delayed by the other via Eqs. (4), (10) and (11). Thus, in the second period the information sets for the market equilibrium and the cooperative outcome coincide.

Let m and c superscripts denote market equilibrium and cooperative outcome values, respectively.

Proposition 4. *Assume that interest rates in the market equilibrium and cooperative outcome are the same. Then* $\sum_{i=\mathrm{A,B}}(R_0^{i\mathrm{m}} - R_0^{ic}) > 0$.

The proposition says that for given interest rates, the market equilibrium will be characterized by a higher beginning-of-day reserve level, relative to the cooperative optimum; this will entail a lower use of daylight credit at the system level. The intuition behind this result is that banks' demand for precautionary reserves is increased by the higher uncertainty concerning payment flows characterizing the competitive equilibrium.

The suboptimality of the free market equilibrium stems from the fact that daylight liquidity is costly. In order to quickly process payments, banks must either face a chance of overdrawing at a rate $r_{d,1}$ or borrow in the interbank market at a rate r_0. Banks' behavior will depend on the level of the policy rate, but also on the revenue loss caused by payment delays: if even minor delays trigger heavy retaliation by highly risk-conscious clients, banks will clearly be reluctant to put off payments. Thus, it is important to relax the assumption $\partial g(0, z_t^i, \delta^i)/\partial a_t^i = 0$ made in Section 2.1. This assumption means that when delays are very small an increase in the delay will have a negligible impact on revenue. Assume instead that this is not the case.

Proposition 5. *In the free market equilibrium, if* $|\partial g(0, \mu_1^{\mathrm{A}}, \delta^{\mathrm{A}})/\partial a_1^{\mathrm{A}}| > r_{d,1} \int_0^{k_1^{\mathrm{A}}} \mathrm{d}F(\mu_1^{\mathrm{B}}|I_1^{\mathrm{A}})$ *then* $a_1^{\mathrm{A}} = 0$.

If the revenue loss entailed by delaying payments is heavy enough, banks will choose not to delay, and the market equilibrium will be efficient. Proposition 1(i) will still hold true, whereas Proposition 1(ii) as well as Propositions 2–4 will not. This is hardly surprising: if the marginal cost of delaying payments were very high, banks would always prefer to borrow immediately rather than delay. For a given marginal cost of delaying, the lower $r_{d,1}$ is set, the more likely inequality in Proposition 5 will hold, and optimality restored.

3. Assessment and policy implications of the results

Proposition 5 highlights that the level of the intraday policy rate, relative to the marginal revenue loss from delaying payments, is crucial in this context. If the system is to work properly under pricing of daylight credit, the sending bank's marginal revenue loss from delaying must rise sufficiently rapidly as the share of delayed payments is increased. One reason why this may fail to happen is that delaying payments generates external costs that are borne by the receiving bank. Thus, the marginal cost of payment delays perceived by the sending bank may be very low.

These considerations suggest that for the proper functioning of an RTGS system the central bank, while safeguarding itself against moral hazard and credit risk, should supply intraday liquidity so cheap as to allow the inequality of Proposition 5 to hold. [13] For economies characterized by relatively small payment flows, this can be done in several ways. For instance, zero interest rate, collateralized daylight repurchase agreements may be used to inject liquidity at the beginning of the day and drain it at the end, when it is no longer needed (this policy is currently adopted in the UK system CHAPS).

[13] This policy would likely hamper the creation of a private market for intraday funds, which is the main reason why some authors (e.g. Evanoff, 1988) claim that the central bank should charge a relatively high price for daylight credit.

Alternatively, banks can be allowed to mobilize required reserves during the day at zero cost. For economies with highly developed financial markets, in which reserve requirements and available collateral are more likely to be scarce relative to payment flows, each participant could be required to send a certain percentage of its daily payments by a given time each day, subjecting late payments to increasing fees (a policy of this class is currently adopted in the Swiss system SIC). Regardless of the policy adopted, the prescription of a low-cost supply of daylight liquidity would apply, to prevent banks from colluding or seeking cheaper and riskier alternatives to gross settlement.

Concerning the monetary policy implications of the above results, it is worth stressing that the prescription of keeping the cost of liquidity low applies to the price of intraday liquidity, and not to that of end-of-day liquidity. The central bank may control the former quite independently of the latter by resorting to specific instruments, e.g. daylight repurchase agreements, independently of the traditional monetary policy tools. Such new instruments can be easily introduced in the model of Section 2. The declining trend in the interbank interest rate within the business day, predicted by Proposition 1, amounts to the creation of a daylight market for funds and a related intraday yield curve. It can be checked from Eqs. (9)–(11) that during the day the interbank rate will be affected by several factors, including changes in the policy rates and in banks' cost of payment delays. However, regardless of its intraday behavior, the short-term rate is pegged by its end-of-day level, which is determined by the central bank through control of the end-of-day supply of liquidity, in the same way as under netting arrangements.

One final word about the empirical evidence on these issues, which thus far is rather sparse. Until recently, daylight overdrafts on Fedwire had been granted free of charge. In April 1994 the Federal Reserve imposed a 10 basis points fee on average overdrafts and raised it to 15 basis points in April 1995. In the months following the first increase, Summers (1994) finds evidence on overnight loans delivered in the morning at a higher interest rate than equivalent loans delivered in the afternoon, coherent with the prediction of Proposition 1. Richards (1995) finds that the portion of the total daily value of Fedwire fund transfers originated by noon decreased by approximately 5% relative to the period six months before the fee was implemented. Under this aspect the experience of the Swiss gross settlement system SIC is similar. The elimination of reserve requirements for settlement accounts in January 1988 was followed by a surge of payment delays (see Vital, 1990). Concerning the excess demand for end-of-day reserves induced by payment delays (Proposition 4), this effect is likely to be modest if delays remain within reasonable limits. In most existing systems "exogenous" transactions are allowed only up to a certain cutoff time, beyond which banks have a limited time to offset possible excesses or deficiencies in reserves. This implies that at the end of the day uncertainty concerning payments is very low, and so should be the excess reserves held for precautionary reasons. The noise introduced by payment delays is more likely to show up in a lower quality of the information available to bank treasurers for the daily management of liquidity.

4. Conclusions

In recent years, the view that the stability of national and cross-border financial markets may be jeopardized by the malfunctioning of interbank payment systems has become increasingly popular. These concerns have prompted two main responses from commercial banks and regulators: on the one hand, risk reduction measures have been adopted in large value clearing systems; on the other, a move towards RTGS is currently underway in several countries. The present paper has developed a formal analysis of an RTGS system, focusing on its impact on the interbank market and on short-term interest rates. The main conclusions can be summarized as follows.

In RTGS systems where intraday liquidity is provided at a cost by the central bank, banks will tend to excessively postpone the input of payments and/or delay their settlement, relative to a situation of social optimum. Since for real-time payment processing costly reserves must be held, each bank will tend to wait until some payments come in before sending out its own, so as to use other participants' reserves. While at the individual level each bank has an incentive to delay outgoing payments to reduce its expected cost of overdrawing, at the aggregate level this practice leaves overdrafts unaffected and generates a deadweight loss, to the extent that timeliness of payments is valuable to bank customers. In addition, the sending bank's decision to delay outgoing payments also generates an externality by reducing the quality of the screen-based information about intraday balances available to the receiving bank. This added noise will tend, other things equal, to increase banks' precautionary demand for reserves. In the absence of corrective measures, these effects tend to curtail expected profits and to reduce the effectiveness of RTGS systems for risk reduction in financial markets, which constitutes their main attraction. The practical relevance of these effects depends on the costs faced by the banks: if delaying outgoing payments entails a heavy loss of revenue, banks will always prefer to borrow immediately rather than delay, and the mentioned undesired effects will tend to be negligible.

The adoption of RTGS system introduces the new concept of daylight liquidity, as opposed to the traditional notion of liquidity – usually measured in terms of reserves held on settlement accounts at the end of the day – and adds new duties to the daily operation of monetary policy. The adoption of appropriate new instruments, such as daylight repurchase agreements or daylight overdraft facilities, can make the management of intraday liquidity completely independent of the mechanisms traditionally employed for the control of short-term interest rates. However, the price charged by the central bank for intraday liquidity is bound to impact on the level of short-term interbank interest rates, giving rise to an intraday market, most likely in the form of a premium on loans delivered earlier in the morning. It is shown that the creation of this market per se is not sufficient to eliminate the externality mentioned above. In principle, a low-cost supply of intraday liquidity (or of daylight credit) can help solve the problem of excessive delays. In addition, specific policies may be adopted, such as requiring each participant to send a given percentage of its daily payments by a certain time, subjecting late payments to increasing fees. In this case, care must be taken to prevent banks from seeking cheaper and riskier alternatives to gross settlement.

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