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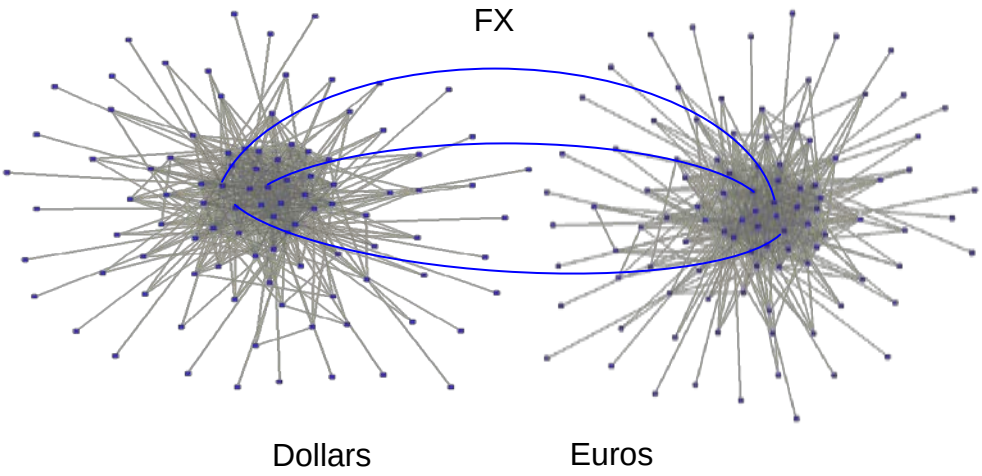
Congestion and Cascades in Interdependent Payment Systems



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Congestion and Cascades in Interdependent Payment Systems

Abstract:

This paper analyses liquidity and credit risks in the context of interdependent interbank payment systems. We develop a simple model to investigate the operation of two real time gross settlement systems interlinked through foreign exchange transactions conducted by a set of global banks. Further interdependence is created by a Payment versus Payment (PvP) constraint that links the two legs of the foreign exchange transactions. The model illustrates under which conditions settlement of payments in the two systems becomes correlated and how large credit exposures can be generated as the result of liquidity pressures in one of the two systems. PvP can eliminate this credit risk but will create a new interdependence by making settlement of payments in both systems dependent on the level of liquidity available in the other system.

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List of Acronyms and Abbreviations

Acronym	Definition
CLS	Continuous Linked Settlement
CPSS	Committee on Payment and Settlement Systems
DvP	Delivery versus Payment
FIFO	First In/First Out
FX	Foreign Exchange
PvP	Payment versus Payment
RTGS	Real-Time Gross Settlement

List of Symbols

Variables related to the local payments are described for RTGS$^{\$}$. Equivalent variables are defined for RTGS$^{€}$. Functions of time are indicated as (t).

Variable	Dimension	Description
$B_i^{\$}(t)$	money ($)	Payments account balance of Bank *i* within RTGS $
$d_0^{\$}$	money ($)	System deposit size parameter in RTGS$^{\$}$, taken equal to $1
$D_i^{\$}(t)$	money ($)	Total amount of $ deposits held by Bank *i* on behalf of

		its customers at time *t*
$I_i^{\$}(0)$	1/time	Rate of arrival of payment instructions to Bank *i* in RTGS$^{\$}$
$I_{ij}^{\$€}(t)$	1/time	Rate of arrival of FX trades instructions consisting of Global Bank *i* selling $1 to Global Bank *j* for €1
$K_i^{\$}$	_	Number of counterparties of Bank *i* in RTGS$^{\$}$
$l^{\$}$	money ($)	Liquidity factor parameter in RTGS$^{\$}$
$N^{\$}$	_	Total number of banks in RTGS$^{\$}$
$N_i^{\$}$	_	Number of counterparties of Bank *i* within RTGS$^{\$}$
$p^{\$}$	1/(money ($).time)	Probability that a payment instruction will be issued in RTGS$^{\$}$ per unit of time and of deposit
p^{FX}	1/(money ($).money (€).time)	Probability that a payment instruction will be issued in RTGS$^{\$}$ per unit of time and of deposit
$w_{ij}^{\$}$	_	Share of Bank *i*'s outgoing payments that are directed towards Bank *j* in RTGS$^{\$}$
γ	_	Power-law exponent of the distribution of counterparties per bank. Its value was fitted so as to produce an average of 12 counterparties per bank
$\lambda_i^{\$}(t)$		Payment instruction arrival rate
$Q_i^{\$}(t)$		Queue of payments awaiting settlement
$t_k^{\$}$		Settlement time of the dollar leg of the kth transaction
D(0)		Vector of initial deposits
T		Duration of the calculation period,
Ω		Matrix composed of the w_{ij}
I		Identity matrix
0		Zero vector
$\rho^{\$}$		Parameter that characterizes the total level of liquidity in RTGS $
ρ_{ED}		Correlation coefficient for settlement rates in the euro and dollar systems

Executive Summary

Technological innovations and structural changes in banking are creating greater interdependence among the world's large value payment and settlement systems. Developments in technology have facilitated the emergence of systems that settle across national borders, at off-shore locations, and via remote access. Given the importance of payment and settlement systems for the smooth operation of the financial system as well as its resiliency, stakeholders need to understand and assess the potential consequences of this evolution and to understand how interdependencies influence liquidity, credit, and even operational risks. In particular, the increasing scope for liquidity interdependence across systems serves to further accentuate the potential role of payment and settlement systems in the transmission of contagion effects. These risks have recently become more pronounced with the credit and solvency problems of major financial institutions.

This paper presents an analysis based on a simple model of the operation of two real-time gross settlement (RTGS) payment systems, operating in two distinct currencies, and interacting with each other through Foreign Exchange (FX) transactions performed by a set of global banks that participate in both systems. This dual participation and the resulting common inflow of FX trades creates an institutional interdependence between the two RTGS systems. A second, system-based, interdependence can be created by imposing policy requirements to settle FX transactions in a payment versus payment (PvP) mode.

The model was able to capture how, due to those two interdependencies, the two systems can become correlated, in the sense that a period of high settlement rate in one system will statistically correspond to a period of high settlement rate in the other system.

In the PvP case, the results show that the average level of queuing within one payment does not depend only on its own level of liquidity, as in the non-PvP case, but also on the level of liquidity in the other system. More specifically, the level of queuing in one system increases when the liquidity level is decreased in the other system. This increase in the queue level is especially strong in the "more liquid" system when the liquidity is decreased in the "less liquid" system.

When the FX trades are settled without the PvP constraint, credit exposures are created among the participating global banks. Those exposures are shown to depend on the level of liquidity present in each system. A structural liquidity imbalance between the two systems leads to very high credit exposures, affecting operations in much the same way as time zone differences.

The approach could be of interest to Central Banks, as growing attention is now being given to system interdependencies. In this context, the presented model can provide a qualitative description of the consequences of the interdependency created by FX transactions on the activity of two systems.

1 Introduction

Technological innovations and structural changes in banking are creating greater interdependence among the world's large value payment and settlement systems. Developments in technology have facilitated the emergence of systems that settle across national borders, at off-shore locations, and via remote access. Given the importance of payment and settlement systems for the smooth operation of the financial system as well as its resiliency, stakeholders need to understand and assess the potential consequences of this evolution and to understand how interdependencies influence liquidity, credit, and even operational risks. In particular, the increasing scope for liquidity interdependence across systems serves to further accentuate the potential role of payment and settlement systems in the transmission of contagion effects. These risks have recently become more pronounced with the credit and solvency problems of major financial institutions.

The study of large value payment and settlement systems is at the intersection of several disciplines including economics, operations research and statistical mechanics of complex systems. It is a fast growing field, with a burgeoning theoretical and empirical literature on payment economics. Recent examples include Martin and McAndrews (2008) who present a theoretical model of liquidity savings mechanisms and Mills and Nesmith (2008) who analyze banks' strategic decisions on when to submit transactions.

In addition, the recent development of simulation methodologies and tools able to replicate the operation of payment and settlement systems using real data has facilitated detailed stress-testing and systemic risk studies (see Bech and Soramäki (2002), Mazars and Woelfel (2005), Bedford et al (2005), McVanel (2005) and Schmitz et al (2006) and among others). Moreover, interesting insights are being gained from a growing literature viewing payment and settlements systems as (complex) networks in which participants are represented as nodes and where weighted and directed links represent either flows or bilateral risk controls.[1]

Despite this scrutiny, the study of payment and settlement systems still has several unexplored areas. A key challenge for the simulations approach is to incorporate behavior. As noted by Bech and Garratt (2006) the actions of participants have both the potential to mitigate impacts and the potential to augment the adverse effects of (wide-scale) disruptions. In fact, most simulations studies produced so far are subject to their own version of the Lucas critique.[2] Encouraging preliminary progress in terms of modeling behavior has been made by Galbiati and Soramäki (2008) in the context of an interbank payment system by using an agent-based modeling approach. An overview of recent literature is available in Ledrut (2006).

[1] The topology of payment flows between participants varies substantially across different large value payment systems. Generally, payment systems with fewer participants tend to form complete networks (see e.g. Lublóy (2006) and Becher et al (2008) whereas larger systems are often characterized by a limited core of large participants that exchange payments with many counterparties, and a large set of smaller participants that exchange a payments with only a few counterparties (see Inaoka et al. (2004), Boss et al (2004), Soramäki et al. (2007). In many instances the (degree) distribution of counterparties follows a power law. In modeling payment systems, the topology of interactions between banks can be important in determining the response dynamics to a perturbation (Bech and Garratt (2006)).

[2] It is naive to try to predict the effect of policy changes in a payment and securities settlement system based purely on relationships between participants and timing of instructions obtained from historical data as both the timing and the relationship would necessarily change whenever policy – the rules of the game – is changed. In order to overcome the critique one must identify the "deep parameters" such as preferences, technology, and resource constraints that govern individual participant's behavior.

A deficiency in the current literature stems from the tendency to look at systems in isolation. Most studies have been dedicated to the study of single systems, an approach that precludes any rigorous treatment of system interdependencies.[3] System interdependencies are, however, high on the agenda of policy makers. In 2001, the Group of Ten “Report on Consolidation in the Financial Sector” (the Ferguson report) reported that “the emergence of multinational institutions and specialized service providers with involvement in several payment and securities settlement systems in different countries, as well as the increasing liquidity interdependence of different systems, further serve to accentuate the potential role of payment and settlement systems in the transmission of contagion effects” (BIS 2001).

As a first step in understanding system interdependencies, the Committee on Payment and Settlement Systems’ recent report "*The interdependencies of payment and settlement systems"* (BIS 2008), published by the Bank of International Settlements, provides a qualitative framework for such analysis. The report identifies three different types of interdependencies. *System-based* interdependency, which includes payment versus payment (PvP) or delivery versus payment arrangements (DvP)[4] as well as liquidity bridges between systems. *Institution-based* interdependence which arises when, for example, a single institution participates in, or provides settlement services to, several systems. The third type is *environmental-based* interdependency which can emerge if multiple systems depend on a common service provider, for example the messaging service provider SWIFT.

In this context, we developed a stylized numerical model of interdependent interbank payment systems[5] with the objective of adding to the understanding of system interdependencies. The model for system interdependencies is obtained by extending the "Congestion and Cascades" model of Beyeler et al. (2007) from single payment system to multiple systems operating in distinct currencies.

In this paper we will consider the case of two separate payment systems operating in two countries with their own currencies. We let a subset of participants - termed ‘global banks’ in this analysis - participate in both systems, along with the local banks that only participate in their home country's payment system. In addition to regular, domestic payments, the global banks can also make foreign exchange (FX) transactions with each other, exchanging one currency for the other. We consider two alternatives for the settlement of these FX transactions in this paper: either PvP or non-PvP. The model includes therefore both an institution-based interdependency, the dual participation of the global banks, and an optional system-based interdependency, the PvP mechanism. In this paper we investigate how the functioning of one system, in terms of settlement performance or risk profile, can become dependent on the other system. By investigating the consequences of various market situations, using several different settlement rules, we are able make some policy recommendations.

The paper is structured as follows. Section 2 presents the model and the assumptions used in its construction. In Section 3 we provide a measure of the correlation between the activity of the two systems, and we investigate under which circumstances and to what extent the two systems

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[3] An exception to this rule is Hellqvist and Snellman (2007) who study the interaction between the interbank payment and securities settlement systems in Finland.

[4] These technologies ensure that each leg of a transaction is settled simultaneously and hence have the ability to eliminate counterparty credit risk.

[5] In the remainder of the paper we use payment system and real-time settlement system (RTGS) interchangeably.

can become correlated. Section 4 presents our analysis of how the FX settlement performance of one system, as measured by its level of queued payments, can be affected by the other system depending on whether or not the PvP constraint is used. In Section 5, we focus on the credit risk created by the FX transactions when the PvP constraint is not used, and look at how the incurred risk depends on the liquidity level in both systems. In Section 6 we conclude and summarize the paper.

2 Model Description

2.1 *Overview*

We consider a simple economy with two countries and two currencies. For the ease of exposition, the currencies are referred to as dollar and euro, respectively. The two countries are both populated with *economic agents*, *banks*, and a *central bank*. Both central banks are benevolent providers of an interbank payment system. The agents hold deposits at banks to settle obligations arising from trades with each other. In turn, banks maintain reserve balances at the central bank to settle payment instructions received from their customers and destined for agents banking at other banks. A graphical representation of the model is provided in **Figure 1**.

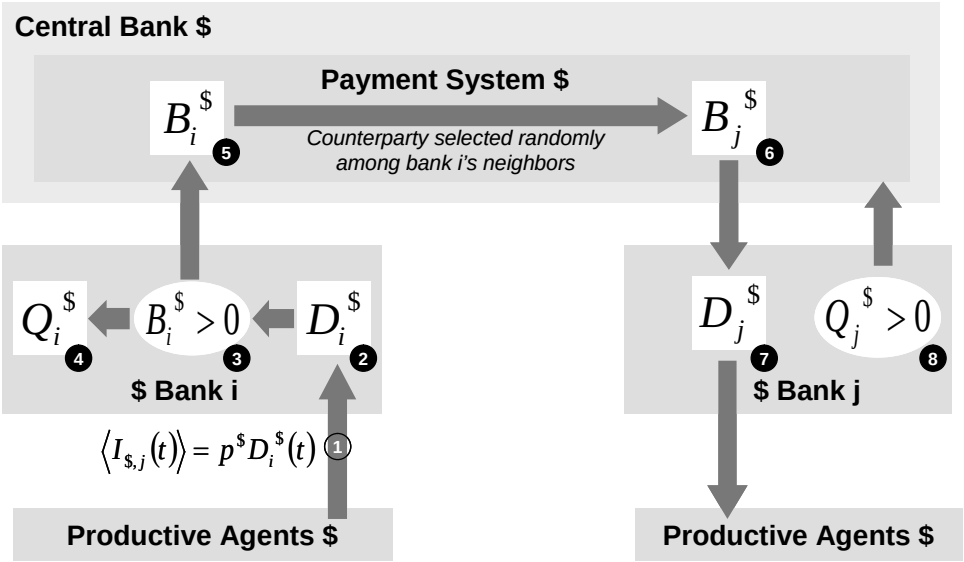

Figure 1: Processing of local payments

❶ Bank i receives a continuous stream of payment instructions from its depositors. The average volume of payment instructions received by a bank is taken as proportional to the current level of deposits at this bank.

❷ Depositor account of bank i, $D_i^{\$}$ is debited.

❸ The account balance of bank i in its real time gross settlement (RTGS) system, $B_i^{\$}$, is checked.

❹ If Bank i does not have sufficient liquidity at the Central Bank to settle the payment, (since we consider only payments of unit size, we just check if $B_i^{\$}$ is greater than zero), the payment is queued.

❺ Otherwise, the payment is settled and $B_i^{\$}$ is decremented.

❻ The receiving bank is taken randomly among Bank i's counterparties. The RTGS account of the receiving bank, bank j, is incremented.

❼ The depositor account of bank j is incremented. The probability of bank j to receive a payment instruction from one of its depositors is thus mechanically increased.

❽ If bank j has some outgoing queued payments waiting, the payment with the earliest submission time is released (FIFO order). This will start the process from (2) again.

The model has two types of banks: local banks and global banks. Local banks only participate to their domestic payment system whereas the global banks are direct participants of both systems and engage in foreign exchange trading with other global banks. Consequently, each system

processes both non FX related payment instructions on behalf of local and global banks and FX related payment instructions on behalf of the global banks.

Payments are settled individually and irrevocably in continuous time. This mode of settlement is commonly referred to as real time gross settlement (RTGS). To simplify matters, the systems are assumed to operate 24 hours a day and seven days a week. Consequently, any issues related to end-of-day management of settlement positions or issues related to overnight lending are ignored.

The two payment systems are linked through two sources of interdependency. A first interdependency is due to the presence of the "global banks," which are direct participants in both systems and make foreign exchange trades with one another. The two legs of these trades are settled as payments in the respective payment systems. This form of interdependency can be described as an institution-based interdependency, following the taxonomy developed by the Committee on Payment and Settlement Systems (CPSS) Working Group on System Interdependencies. Second, the two systems can be linked through a payment versus payment (PvP) mechanism that ensures the simultaneous settlement of both legs of FX transactions. In the model, the PvP mechanism can be turned on (PvP) or off (non-PvP), in which case the two legs of the FX trades are settled independently. The PvP settlement represents a system-based interdependency between the two payment systems. **Figure 2** provides a graphical illustration of the model and highlights the two sources of interdependencies between the two payment systems.

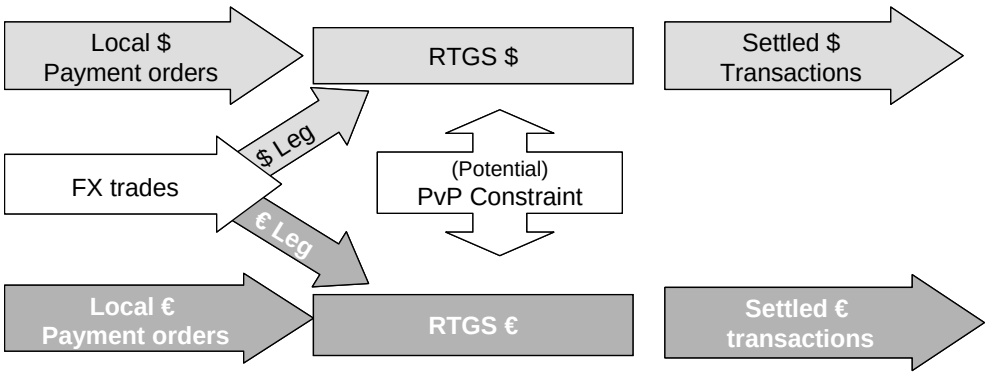

Figure 2: Diagram of model component relationships and system interdependencies (FX trading and PvP constraint)

2.2 *Banks, payments and topology*

A bank's ability to settle payment instructions depends on the availability of funds in its account at the central bank. We assume that banks choose to issue a payment instruction as soon as they receive such an instruction from one of their customers. If a bank does not have the necessary liquidity to settle a payment, then the payment instruction is placed in a queue. When new funds are received, they are immediately used to settle queued instructions.

It follows that a bank, bank $i = \{1, 2, \ldots, n\}$, that participates in, for example, the dollar system can be characterized by its level of customer deposits in dollars, $D_i^{\$}(t)$, its payment instruction arrival rate, $\lambda_i^{\$}(t)$, its queue of payments awaiting settlement, $Q_i^{\$}(t)$, and its balance at the central bank, $B_i^{\$}(t)$. In order to fully characterize a global bank, we also need to specify

deposits, payment arrival process, queue and central bank balance in euros, and the FX trading process among the global banks. The FX trading process is explained in Section 2.3.

Payments come in many sizes but to minimize the number of model features incidental to the purpose of the analysis we assume that all payments are of equal size and normalized to one. The arrival of payment instructions at a bank is modeled as a (non homogenous) Poisson process with time varying intensity, $\lambda_i^{\$}(t)$. We assume that the arrival of payment instructions at a bank is driven by the level of deposits $D_i^{\$}(t)$ held by its customers, so that a higher level of deposits makes it more likely that the bank will receive requests for outgoing payments. Specifically, we assume that the level of deposits is converted into a payment instruction with a constant probability per unit time, $p^{\$}$. Consequently, the expected rate of instruction arrival to bank *i* per unit of time (the intensity), is given by:

$$\lambda_i^{\$}(t) = p^{\$} D_i^{\$}(t) \tag{1}$$

Accordingly, the instruction arrival rate increases as incoming payments add to deposits and decreases as outgoing payments deplete deposits. To be clear, the equation above only describes the expected arrival rate. The actual number of payment instructions arriving at bank *i* will be determined by the random outcome of the Poisson process with the above mentioned expected average value.

We assign a recipient bank *j* to any incoming payment instruction from bank *i* by drawing from a discrete probability distribution defined over the set of banks. Let $\omega_{ij} \in [0,1]$ denote the probability that bank *i* will send a payment to bank *j*, conditional on bank *i* receiving a payment instruction. We impose no constraints on the matrix of conditional probabilities $\mathbf{\Omega} \equiv \{\omega_{ij}\}_{n \times n}$ except obviously that for every bank *i*, $\Sigma_j \omega_{ij} = 1$. In fact, we allow for "on us" or book transfers ($\omega_{ii} > 0$) and we do not impose any symmetry in bilateral relationships between banks ($\omega_{ij} \neq \omega_{ji}$). As a result, we can, in principle, generate any topology of payment flows desired for the system as a whole. For example, for the payment flows to form a complete network over time a strictly positive probability mass has to be assigned to all elements of $\mathbf{\Omega}$.

2.3 *Global banks and FX trades*

In addition to receiving payment instructions to be settled in the respective payment systems, global banks also settle FX trades with each other. In our model, the arrival rate for FX trades is driven by the global banks' levels of deposits in the two currencies. The average number of euro for dollar trades that global bank *j* receives from its clients in a given unit of time is proportional to $D_j^{€}$. Similarly the average number of dollar for euro trades that global bank i receives from its clients in a given unit of time is proportional to $D_i^{\$}$. The probability of one of bank *i*'s clients engaging in a dollar for euro trade with one of bank *j*'s clients is proportional to the product $D_i^{\$} D_j^{€}$.[6]

For every pair (*i*,*j*) of global banks, the average rate at which a bank *i* has a dollar for euro transaction with bank *j* is given by:

[6] Customers do not have any preference regarding their FX trade counterparty and the exchange rate is constant at 1.

$$\lambda_{ij}^{\$€}(t) = p^{FX}\sqrt{\frac{D_i^{€}(0)}{D_i^{\$}(0)}}\sqrt{\frac{D_j^{\$}(0)}{D_j^{€}(0)}}D_i^{\$}(t)D_j^{€}(t) \tag{2}$$

where p^{FX} is a constant parameter describing the level of FX trading activity. The use of the $\sqrt{\frac{D_i^{€}(0)}{D_i^{\$}(0)}}\sqrt{\frac{D_j^{\$}(0)}{D_j^{€}(0)}}$ proportionality coefficient guarantees that $\lambda_{ij}^{\$€}(0) = \lambda_{ji}^{\$€}(0)$ as well as a finite return time towards the initial steady state. The retained proportionality coefficient simply expresses the fact that we expect certain stability regarding the currency holdings of the banks during a simulation. As in reality, we do not expect the largest participant in the euro system to be selling off all its euro holdings in order to become the largest participant in the dollar system: thus the model constrains FX trading activities of the global banks to oscillate around their starting position in both currencies.

2.4 *Simulation Output*

When simulations are run, the following time series information is extracted. The settlement rate in dollars and euros are respectively defined as the total number of settlements occurring in a unit time period in the dollar and the euro systems. The settlement rate in dollars thus includes both the contribution of the domestic payments settled within the dollar system and the contribution of the dollar leg of the FX trades. Similarly, the settlement rate in euros includes both the contribution of the domestic payments settled within the euro system and of the euro leg of the FX trades.

Another informative statistic is the total number (or value since all payments are of unit size) of queued dollar and euro payments. The total number of queued dollar (euro) payments includes the queued domestic dollar (euro) payments as well as the queued dollar (euro) leg of the FX trades.

Finally, the FX exposures are of special interest in the non-PvP case. Section 2.5 describes how these exposures are calculated.

Depending on the case simulated, a steady state characterized by nearly constant settlement rates, queue sizes and FX exposures may arise. In other cases, the system is characterized by periods of congestion with low settlement rates and increasing queues followed by short periods of cascades with very high settlement rates and rapidly decreasing queues. In those cases the simulation output will take the form of several time series.

2.5 *Calculation of the FX exposures*

When FX trades are settled non-PvP, the bank that pays the first leg of the transaction bears a FX credit risk until the other leg of the transaction is settled in the other payment system. We define the time-averaged accumulated exposure of the $ selling banks towards the € selling banks (i.e., the amount of € owed) and the time-averaged accumulated exposure of the € selling banks towards the $ selling banks (i.e., the amount of $ owed) as respectively:

$$Exposure_{€owed} = \sum_k \text{Value}_k \cdot \max\left(0; t_k^{€} - t_k^{\$}\right) \cdot \frac{1}{T} \tag{3}$$

and

$$Exposure_{\$owed} = \sum_k \text{Value}_k \cdot \max\left(0; t_k^{\$} - t_k^{€}\right) \cdot \frac{1}{T} \tag{4}$$

Here k indexes the FX transactions settled during the chosen calculation period, T is the time duration of the calculation period, $t_k^{€}$ is the settlement time of the euro leg of the kth transaction, and $t_k^{\$}$ is the settlement time of the dollar leg of the kth transaction. Value_k refers to the value of the kth transaction which is included for dimensional consistency although the value is 1 for every transaction.

Figure 3 illustrates the concept of time-averaged exposures. Exposures correspond to the area of the patterned rectangles. The equations above simply reflect the fact that, in a FX transaction, the dollar selling bank will be facing an exposure towards the euro selling bank, if the euro leg of the transaction settles after the dollar leg of the transaction (i.e., if $t_k^{€} > t_k^{\$}$).

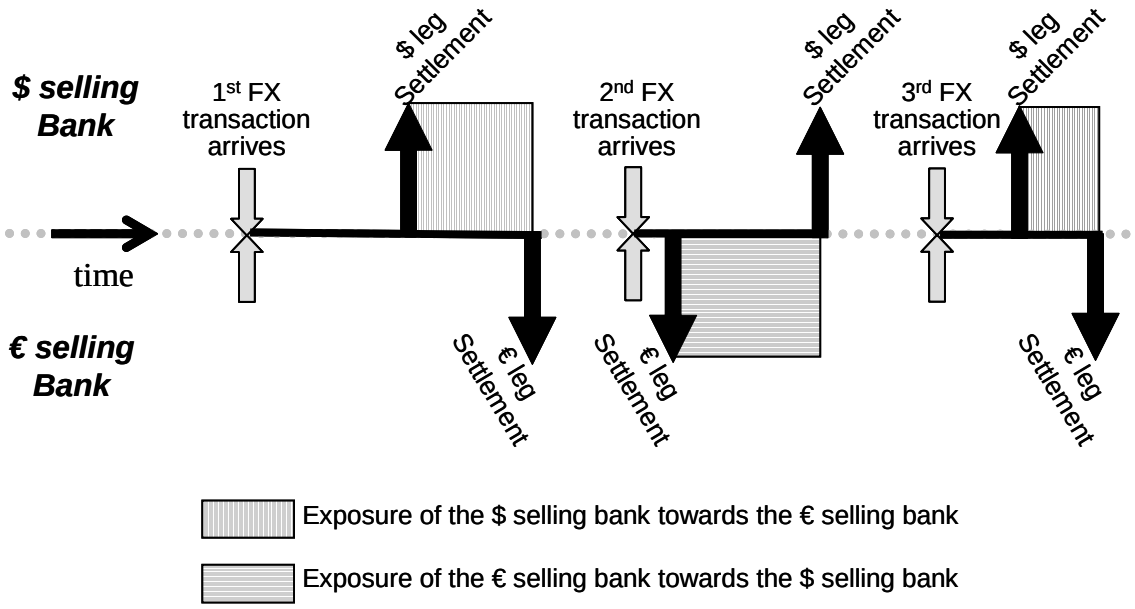

Figure 3: Exposures created by the non-PvP settlement of FX transactions

2.6 *Simulation Configuration*

For the purposes of this analysis, we configure the model in the following manner. We assume that there are 100 participants in each payment system. The "global banks," which participate in both systems, are taken to be the three largest participants in the euro system together with the three largest participants in the dollar system. Consequently, the number of local banks is 94 in each system.[7]

[7] This is likely a conservative estimate for the US. Foreign banking organizations by themselves account for almost 10% of the value transferred over Fedwire. In addition, the value transferred by internationally active US banks is sizeable.

Furthermore, we assume that the number of counterparts to which each bank *i* will send payments, $k_i^{\$} = \sum_j 1(\omega_{ij} > 0)$, follows a power law distribution. That is, bank *i* sends payments to $k_i^{\$}$ counterparties with probability:

$$P\left(k_i^{\$} = x\right) \sim \frac{1}{x^{\gamma}} \tag{5}$$

where γ is the power law coefficient that was fitted to produce an average network degree of twelve, which approximates the average degree of an empirical subnetwork consisting of the 100 largest banks in Fedwire. Given the set of counterparts for a particular bank *i*, the conditional probabilities ω_{ij} of a payment instruction being directed to a specific counterpart bank *j* were drawn randomly using an exponential distribution. In contrast, we choose to describe the FX market as a complete network, i.e. a system where each participant trades with every other participant.

Both payment systems are assumed to be initially in equilibrium in the sense that for each bank the intensity of outgoing payments is equal to the intensity of incoming payments. We have:

$$\lambda_i^{\$}(0) = \sum_j \omega_{ji} \lambda_j^{\$}(0) \tag{6}$$

By equation (1) it follows that the initial equilibrium condition can be written as the following system of equations:

$$p^{\$}(\mathbf{I} - \mathbf{\Omega}')\mathbf{D}(0) = \mathbf{0} \tag{7}$$

where **I** is the identity matrix, **D**(0) is the vector of initial deposits, **Ω** is the matrix composed of the $\omega_{ij,}$ **Ω'** is its transposed matrix, and **0** is a vector of zeros. The system of equations can be solved for the equilibrating vector of initial deposits, **D**(0), given the aggregate amount of initial deposit available. In other words, by allocating the initial deposits appropriately across banks, we can ensure the initial equilibrium condition of equation (6).

We follow Beyeler et al. (2007) on the initial allocation of the banks' reserve balances. Each participant sets its initial central bank balance $B_i^{\$}(0)$ (respectively $B_i^{€}(0)$) in order to control its liquidity risk (the risk of being unable to process the instructions of its customers due to an insufficient balance) at the lowest possible cost (as maintaining large balances at the Central Bank entails an opportunity cost for the banks). The initial reserve balances of the banks are set proportional to the square root of their initial level of deposits:

$$B_i^{\$}(0) = l^{\$}\sqrt{D_i^{\$}(0)} \qquad \text{and} \qquad B_i^{€}(0) = l^{€}\sqrt{D_i^{€}(0)} \tag{8}$$

where $l^{\$}$ and $l^{€}$ are parameters that characterize the total level of liquidity respectively in RTGS $ and in RTGS €.[8]

Graphical representations of the modeled system are provided in **Figures 4 and 5**.

[8] The importance of the initial allocation of bank balances was assessed in a sensitivity study, in which different models of initial allocation were tried. It appeared that the initial allocation of liquidity between the banks does not change qualitatively the results obtained. It was also shown that for a total amount of liquidity within a RTGS, the "square root allocation" used in this paper, led to a significantly lower level of queuing than a "proportional allocation", for high levels of liquidity. This result can be intuitively related to the random walk nature of the evolution of a bank's balance (Beyeler et al 2007).

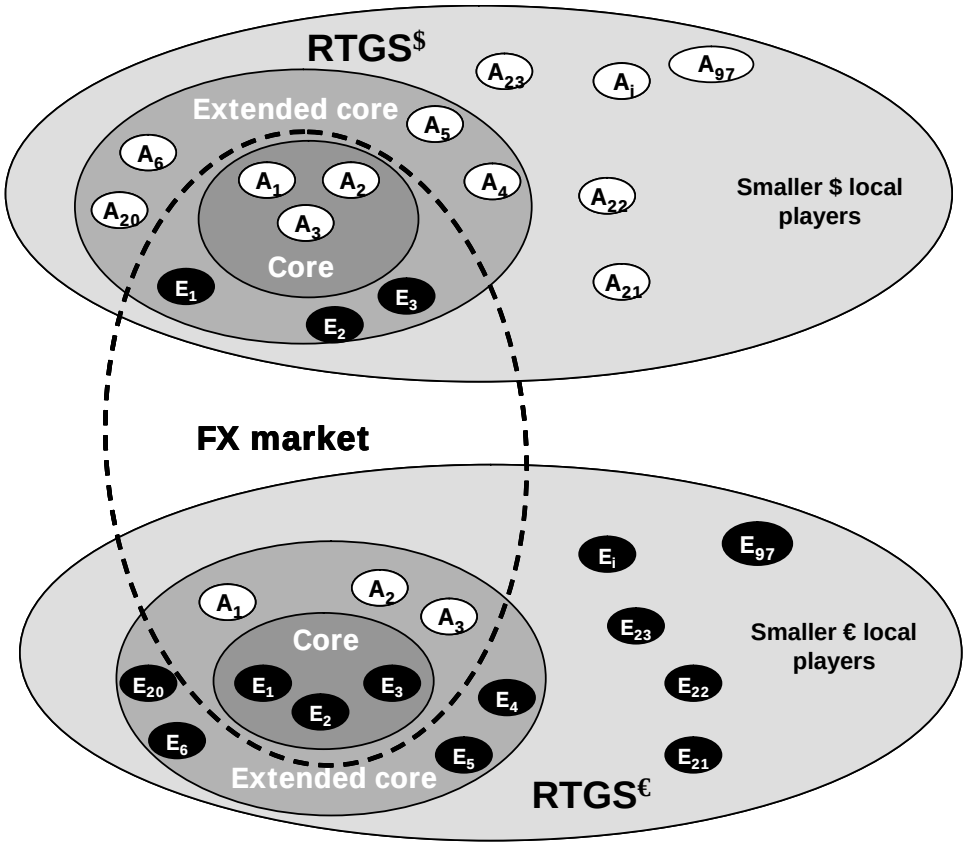

Figure 4: Structure of participation in the model

RTGS$^{\$}$ has 100 direct participants (and no indirect participant):

- 94 "$ local banks (labeled as A_4 to A_{97}), which only participate in RTGS$^{\$}$
- 6 "global banks" which participate to both RTGS$^{\$}$ and RTGS$^{€}$
- the 3 top banks in RTGS$^{\$}$: A_1, A_2 and A_3 which are also in the top 20 of RTGS$^{€}$
- the 3 top banks in RTGS$^{€}$: E_1, E_2 and E_3 which are also in the top 20 of RTGS$^{\$}$

RTGS$^{€}$ has 100 direct participants (and no indirect participant):

- 94 "€ local banks" (labeled as E_4 to E_{97}), which only participate in RTGS$^{€}$
- 6 "global banks" which participate to both RTGS$^{\$}$ and RTGS$^{€}$
- the 3 top banks in RTGS €: E_1, E_2 and E_3 which are also in the top 20 of RTGS$^{\$}$
- the 3 top banks in RTGS$^{\$}$: A_1, A_2 and A_3 which are also in the top 20 of RTGS$^{€}$

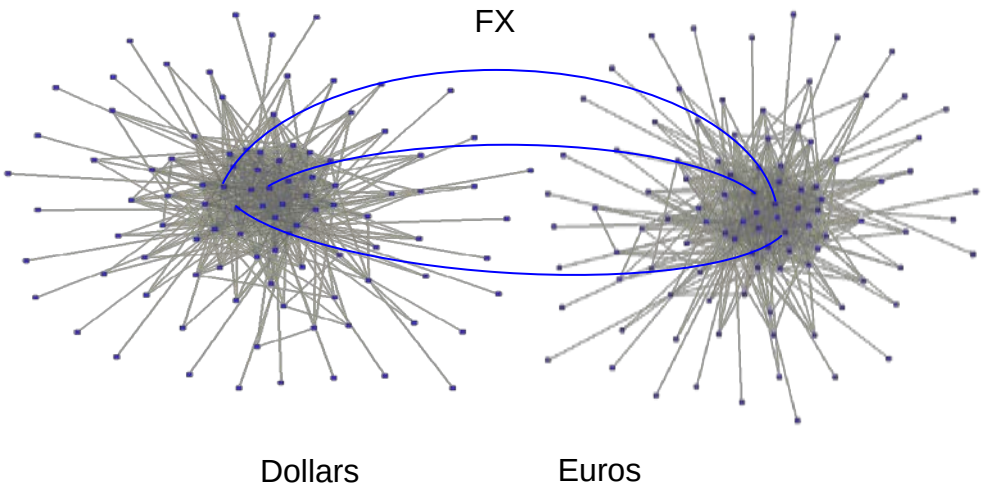

Figure 5: Network representation in the model

3 Correlations between the two systems

In this section, we investigate whether or not the settlement activity in the two payment systems becomes correlated as a result of the two interdependencies introduced in the model (the PvP mechanism and the dual participation of the global banks). We consider that the settlement activity of the two payment systems is (positively) correlated when statistically a period of high settlement activity (respectively a period of low settlement activity) within one system corresponds to a period of high settlement activity in the other system (respectively a period of low settlement activity). **Equation 9** provides a more formal definition of the correlation ρ_{ED} of the activity in the two systems as the ratio between the covariance of the settlement rates in the euro system (E) and in the dollar system (D) and the product of their standard deviations, σ_E and σ_D.

$$\rho_{ED} = \frac{Cov(E,D)}{\sigma_E \sigma_D} = \frac{E\left\{\left(E-\bar{E}\right)\left(D-\bar{D}\right)\right\}}{\sigma_E \sigma_D} \tag{9}$$

We can observe the degree of correlation between the two systems by using settlement rate scatter plots such as those presented in **Figure 6** and **Figure 7**. For each figure, two simulations were performed; one with a low level of liquidity (blue diamond), the other with a high level of liquidity (red squares). Each point corresponds to a certain time window of the simulation (the duration of the simulation was divided into one thousand time windows of equal duration). The abscissa of each point corresponds to the settlement rate observed in one system during the considered time window (i.e., the number of local payments and FX legs settled in the system divided by the duration of the time window). The ordinate of the point corresponds to the settlement rate observed in the other system during the same time window.

In both **Figure 6** (non-PvP settlement of FX trades) and **Figure 7** (PvP settlement), we can observe that the amplitude in the variation of the settlement rates is much higher at low liquidity. Indeed, at high liquidity payments are settled nearly immediately. As a consequence, the queues are almost empty and the settlement rate remains very close to the arrival rate of the payment instructions. At low liquidity however, the size of the queues vary greatly over time. Periods of congestion (characterized by a low settlement rate and the building up of the queues) alternate with periods of cascades (characterized by a high settlement rate and a massive release of queued payments).

With regard to the observed degree of correlation of the two systems, **Table 1** summarizes the main findings of **Figure 6** and **Figure 7**.

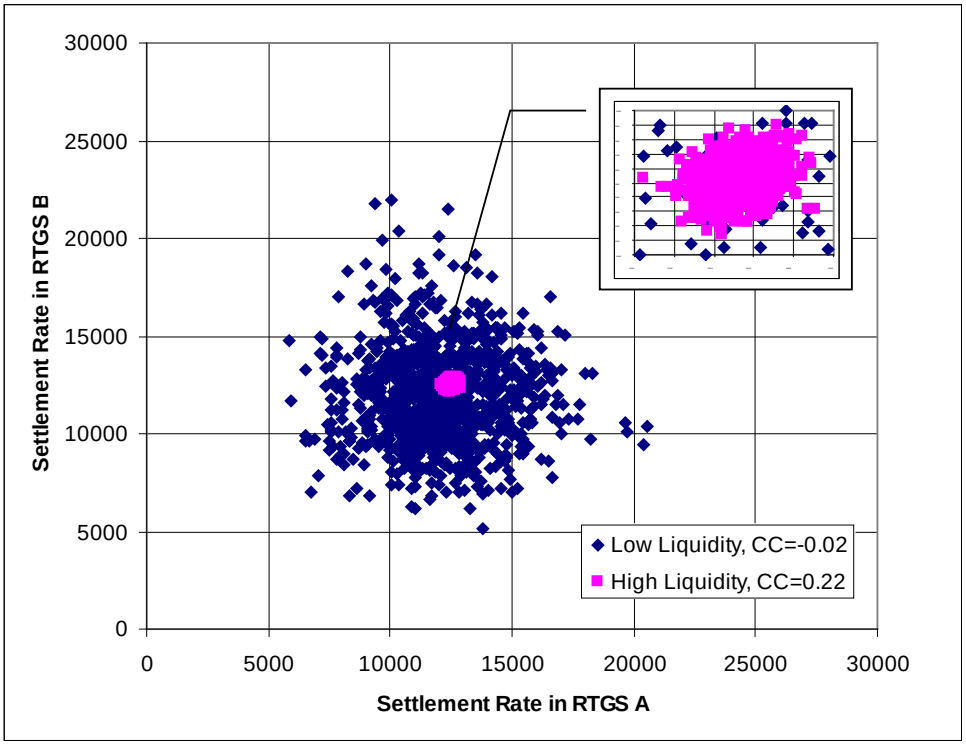

Figure 6: Correlation of the settlement rates in the two systems, non-PvP case

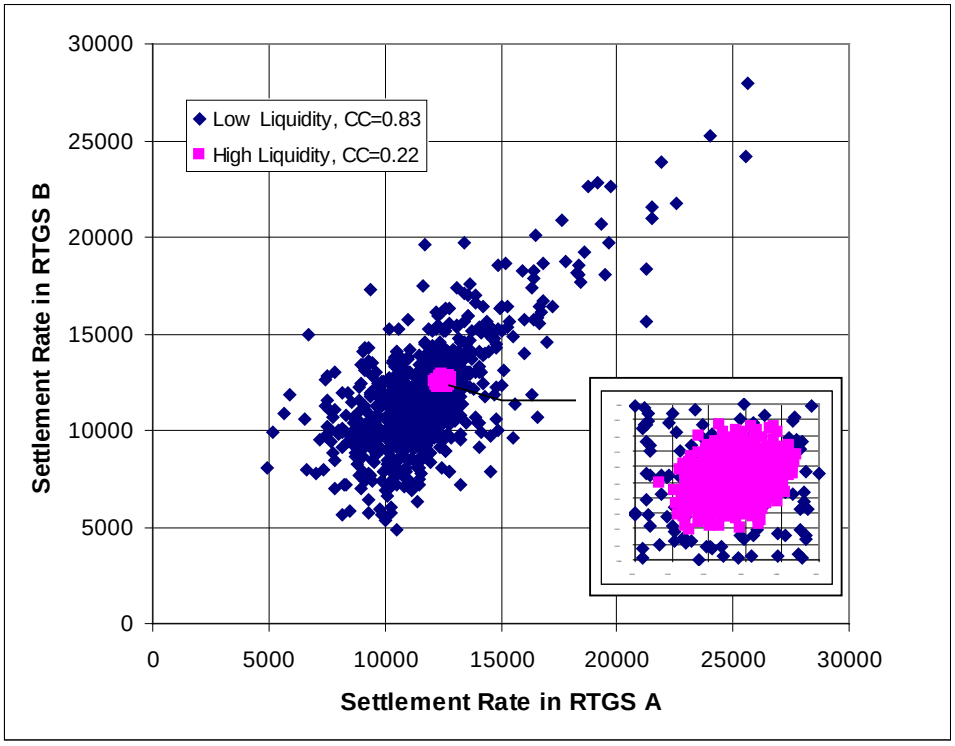

Figure 7: Correlation of the settlement rates in the two systems, PvP case

Table 1: Degree of correlation between the settlement rates of the two systems

Degree of correlation between the settlement rates of the two systems		Settlement mechanism for FX transactions	
		non-PvP	**PvP**
Level of liquidity (the same in both systems)	Low	-0.02	0.83
	High	0.22	0.22

Note: a value of 0 corresponds to a perfectly uncorrelated case, a value of 1 to a perfectly correlated case

At high liquidity, there is a slight degree of correlation between the two systems, corresponding to the level of FX trading. This observation was expected since a period of high FX trading will tend to increase the throughput in both systems simultaneously. At high liquidity (PvP or non-PvP), transactions settle nearly instantly after their submission. The two legs of the FX transactions that are submitted simultaneously to both RTGSs, will settle nearly simultaneously at high liquidity. Therefore the output of the two RTGSs will be correlated, and the amount of correlation between the outputs will increase with the relative importance of FX trading compared to local payments. The settlement mechanism (PvP or non-PvP) does not have any impact on the results. **Figure 8** illustrates the coupling induced by the FX trading activity at high liquidity.

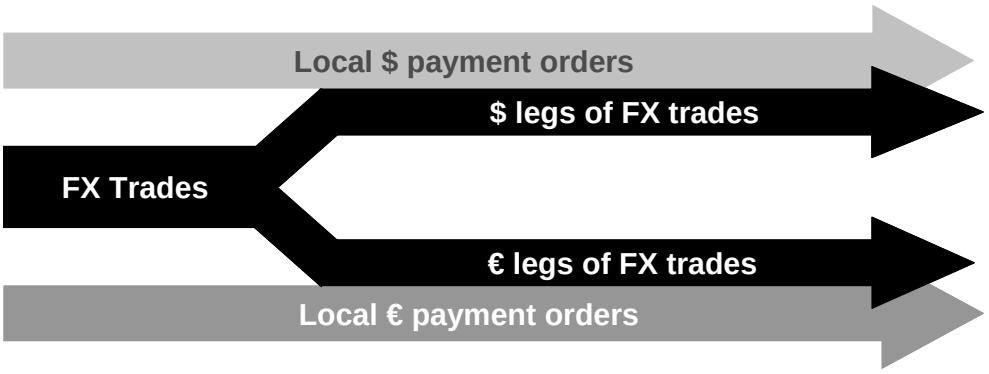

Figure 8: Structure of participation in the model at high liquidity

At low liquidity, the systems are no longer governed by the arrival of payment instructions, but rather by their internal physics of congestion (the payment instructions are queued due to a lack of liquidity) and cascades (as the settlement of a newly arrived payment instruction can trigger the release of several queued payments). The two systems then appear completely uncorrelated in the non-PvP case, as the correlation caused by the common FX input has disappeared in the internal process of congestion and cascades. The scatter plot shown in **Figure 6** has thus a nearly perfect circular shape. **Figure 9** illustrates the decoupling of the two systems.

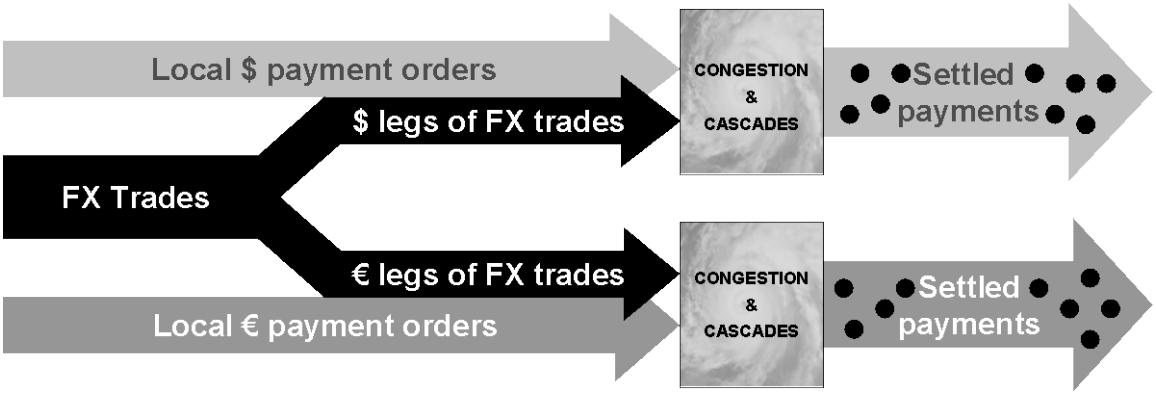

Figure 9 : Structure of the participation in the model at low liquidity

At low liquidity in the PvP case, the settlement rates of the two systems appear highly correlated, as shown by the "comet shape" of the scatter plot presented in **Figure 7**. The correlation caused by the common FX input in the high liquidity case has been replaced by a mechanical PvP release correlation between the two systems. The degree of correlation of the settlement rates of the two systems is then 0.83. **Figure 10** illustrates how the PvP mechanism creates a coupling between the two systems at low liquidity.

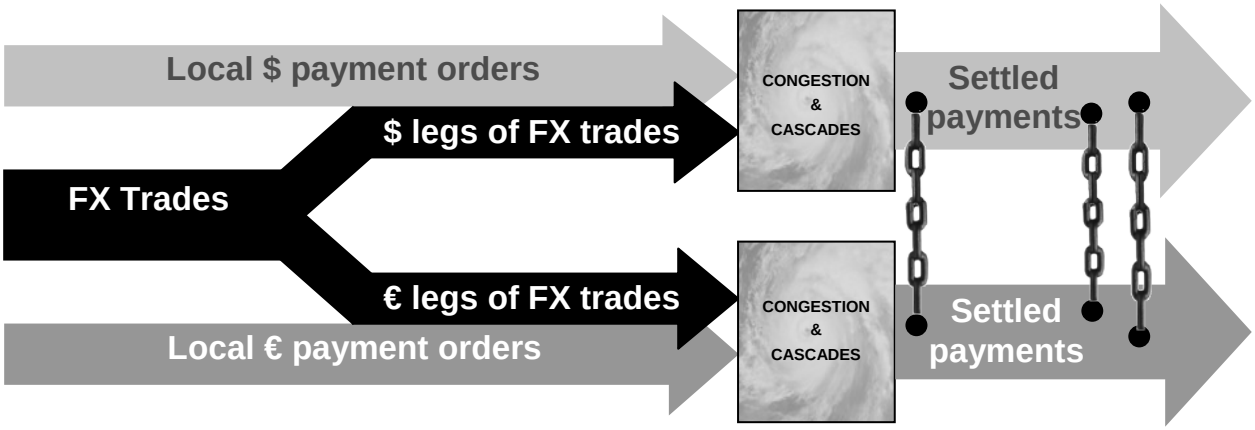

Figure 10: Structure of the participation in the model at low liquidity with PvP mechanism

At low liquidity and under the PvP constraint, the inlet coupling is lost in the internal process of congestions and cascades. However the PvP constraint ensures both legs of the FX transactions will settle simultaneously or never. The queue building and release processes of the two systems will therefore be correlated, as congestion in one system (preventing some FX legs to settle) will prevent the FX trades in the other system from settling as well. Conversely, a release of FX legs in a system will trigger a similar release in the other system, potentially leading to a massive cascade of settlements, including local payments as well as FX legs. The degree of coupling between the two systems can therefore be much larger than in the high liquidity case.

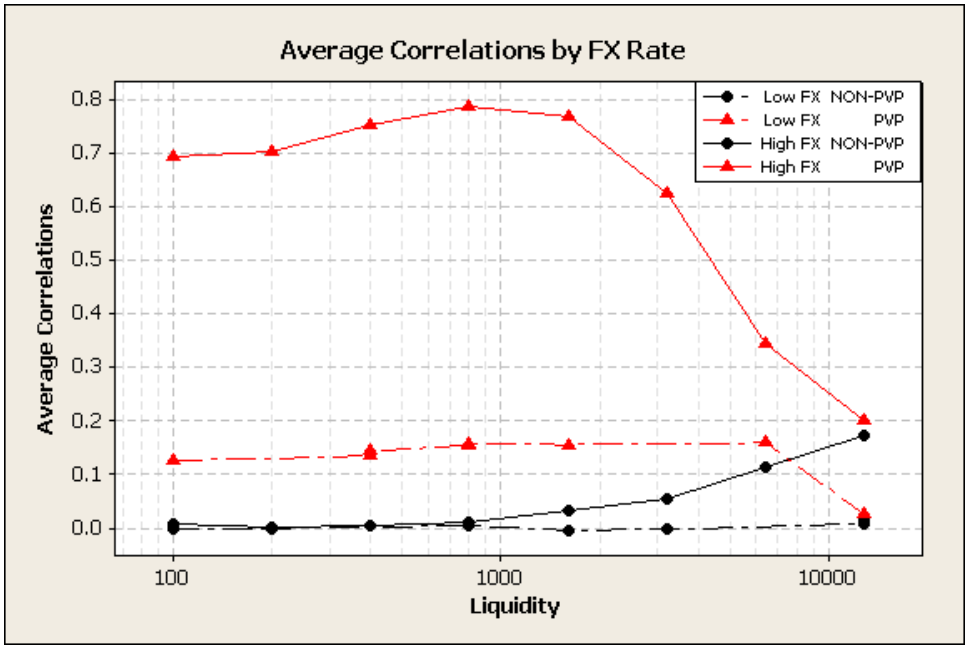

Figure 11: Correlation of the settlement rates in the two systems, non-PvP case

Figure 11 shows how the level of correlation between the two systems varies with the amount of liquidity available (the level of liquidity is the same in both system) and the level of FX activity. At very high levels of liquidity, the settlement mechanism (PvP or non-PvP) in place does not play any role and the average correlation converges towards the level of FX activity. As the liquidity decreases, the level of correlation between the two systems decreases towards zero in the non-PvP case. On the other hand, for low levels of liquidity in the PvP case we observe a high degree of correlation that is dependent on the level of FX activity and that is highest for intermediate liquidity values. It could be seen as surprising that when the liquidity level is low enough, a further reduction of the liquidity leads to a decrease in the level of correlation in the PvP case. The explanation for this result has to be found in **Equation (9)** itself. In the PvP case, when the liquidity is reduced, both the numerator and the denominator of the fraction increase. In a sense the PvP mechanism is still driving the system towards a greater correlation (as the covariance between the two settlement rates still increases) but the "inner variability" of the two systems (represented by the standard deviation of the settlement rate) increases more rapidly. As a smaller share of the observed settlement rate variations within one system can be explained by the variations in the other system, the correlation between the two systems decreases.

4 Queuing under non-PvP and PvP

In this section, we investigate the impact of liquidity on the level of queuing. We consider the case of two payment systems interacting with each other through FX transactions. We will show that the PvP mechanism introduces a strong interdependency between the two systems. We first consider the case where both systems have the same level of liquidity (Section 4.1). Next we show that the level of queuing becomes dependent on the liquidity in the other system when PvP is employed (Section 4.2). As discussed above, in the non-PvP case the level of queuing within one system only depends on the liquidity available within this system. We will also show that this effect sharply decreases when the FX trades are given a higher priority than the local payments (Section 4.3).

4.1 *Queuing with the same level of liquidity in both systems*

We first investigate the case in which both systems have the same level of liquidity. **Figure 12** shows the average number of queued payments in the dollar system as a function of the level of liquidity in the two systems. Clearly, the level of queuing increases as the liquidity decreases, whether PvP is used or not. The shape of the curve obtained is consistent with previous research (see for example Koponen and Soramäki, 1998) which has quantified the level of queuing as a function of liquidity available for single isolated payment systems.

It also appears that the use of PvP settlement increases the level of queuing (and therefore increases settlement delays) in both systems when both systems operate on low levels of liquidity.

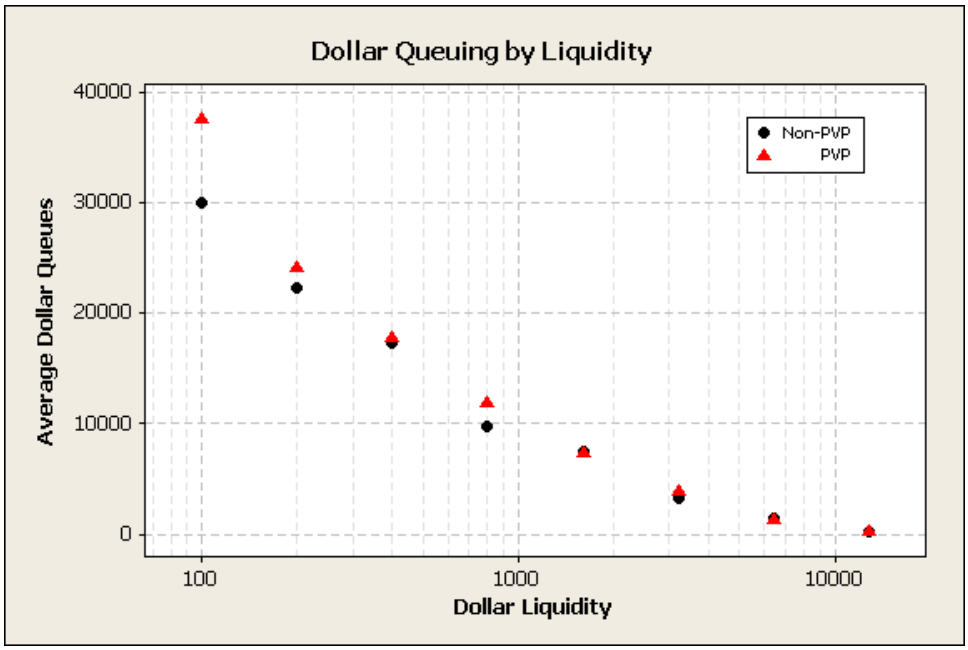

Figure 12: Average queue size in the dollar system when both systems have the same liquidity with normal priority for FX transactions

We can complement this analysis by looking at **Figure 13** which shows the standard deviation of the queue size of the dollar system as a function of the level of liquidity in the two systems. As expected, the use of PvP mechanism increases the variability of the queue size. We can also note

that the tendency of PvP to increase the queue variability is strongest at intermediate liquidity levels.

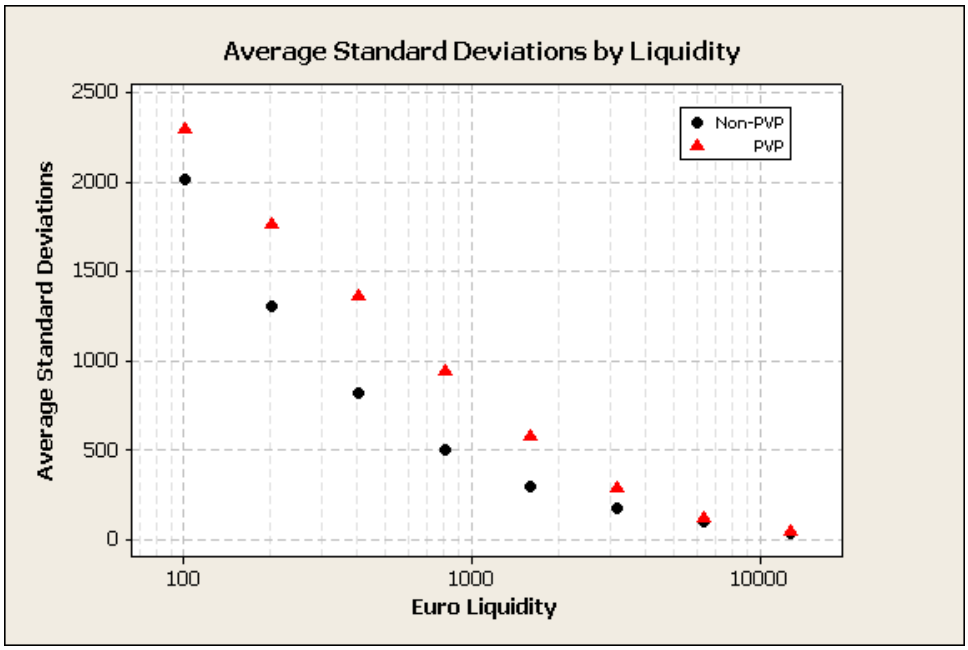

Figure 13: Standard deviation of the queue size in the dollar system when both systems have the same liquidity with normal priority for FX transactions

4.2 *Queuing with different levels of liquidity in the two systems*

4.2.1 Without a PvP mechanism

In this set of simulations, we investigate the consequences of a structural liquidity imbalance between the two systems. As a convention, we set the liquidity of the dollar system to a lower level than the liquidity of the euro system, and we observe how the level of queuing in the dollar system evolves as we let the liquidity level within the two systems vary. It appears that the liquidity contrast between the two systems creates systematic differences in queuing between the richer (higher liquidity) and poorer (lower liquidity) system.

Figure 13 shows the average level of queuing in the dollar system against the level of liquidity in the euro system for various levels of dollar liquidity. As expected, the average size of the queue in the dollar system increases sharply when liquidity within this system is decreased. However, it appears that the average size of the queue in the dollar system does not depend on the level of liquidity available in the euro system. The same conclusion also applies to the variation of the queue in the dollar systems: while the variation of the dollar queue appears to increase sharply when liquidity is decreased in the dollar system, it remains independent of the liquidity level within the euro system.

We can therefore conclude that in the non-PvP case, the average level of queuing in a system and the variability of the size of its queue are determined only by the liquidity present in that system.

4.2.2 With the PvP mechanism

Figure 14 shows the average level of queuing in the dollar system against the level of liquidity in the euro system for various levels of dollar liquidity. **Figure 14** and **Figure 15** thus differ only by the chosen settlement mechanism (non-PvP for **Figure 14**, and PvP for **Figure 15**). A comparison between these two figures clearly reveals the influence of the PvP mechanism.

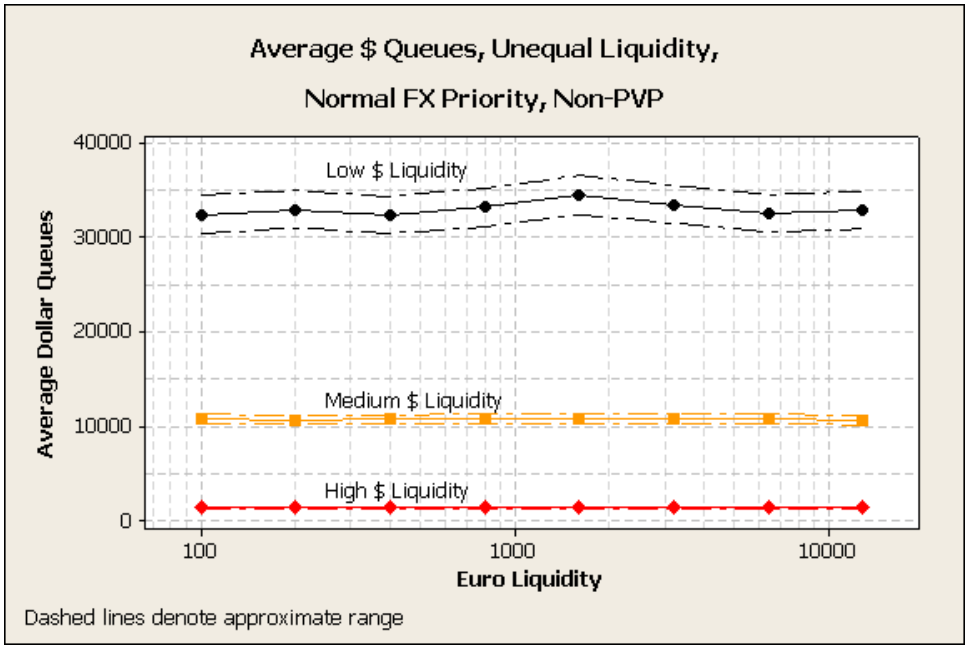

Figure 14: Non-PvP settlement of FX transactions with normal priority for FX transactions

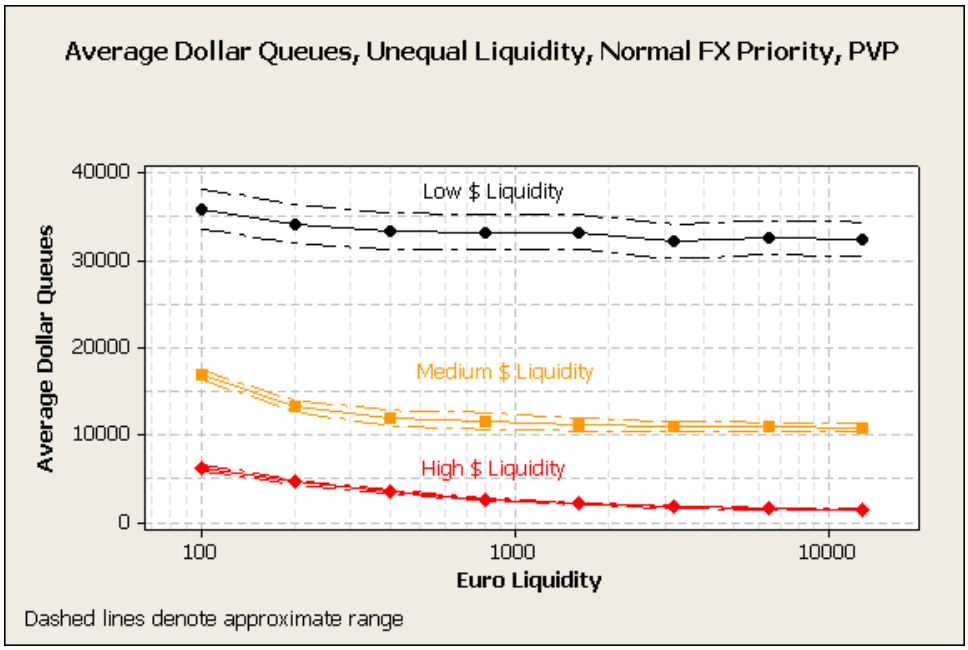

Figure 15: PvP settlement of FX transactions with normal priority for FX transactions

When the liquidity level is sufficiently low in the euro system, a further reduction of the liquidity level in the euro system significantly increases the level of queuing in the dollar system in the

PvP case (**Figure 14**), while it remains without effect on the dollar system in the non-PvP case (**Figure 13**). In relative terms, the effect appears to be most important when the liquidity level is high in the dollar system. In absolute terms however, the effect is largest at the medium level of liquidity in the dollar system, with the dollar queue size increasing from approximately 11 thousand to 18 thousand units as euro liquidity decreases. In addition, we can observe that the PvP mechanism has an impact on the variability of the queue in the dollar system (the dotted lines in **Figure 14** and **Figure 15** give the range of variation of the dollar queue). The difference in the *variability* in queue size between the two settlement mechanisms appears to be strong for intermediate levels of liquidity in both systems and rather mild in other cases.

We can therefore conclude that in the PvP case, the average level of queuing in one payment system and the variations of the size of its queue do not depend only on the level of liquidity available in that given system, but also on the level of liquidity present in the other system. The two systems therefore appear interlinked: an increase in the level of liquidity in one system either through a change in its participants' behavior or through a change in the Central Bank policy will create a positive externality for the other system.

4.3 *Influence of FX transaction priority*

In the model, the two legs of the FX transactions can either be given a higher priority than the local payments (in which case, when a global bank lacking liquidity receives a payment, the received liquidity will only be used to settle a local payment if there is no pending outgoing FX leg to settle), or a normal priority (in which case, the transactions are settled according to their order of arrival, irrespectively of their nature). **Figure 16** (non-PvP case) and **Figure 17** (PvP case) correspond respectively to **Figures 14** and **15** with the difference that this time, a high priority is given to the FX transactions.

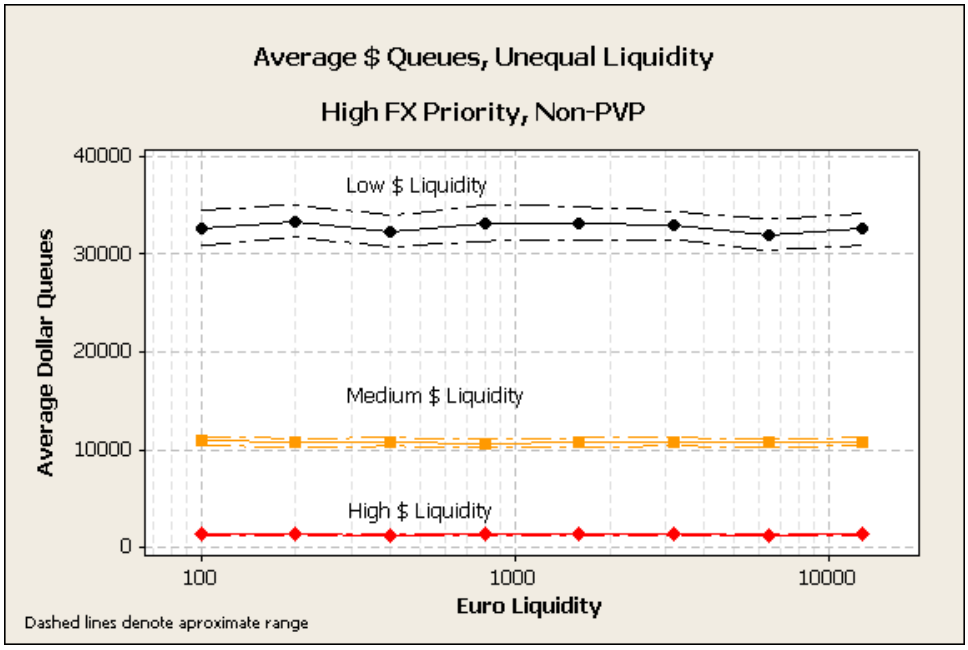

Figure 16: Non-PvP settlement of FX transactions with high priority for FX transactions

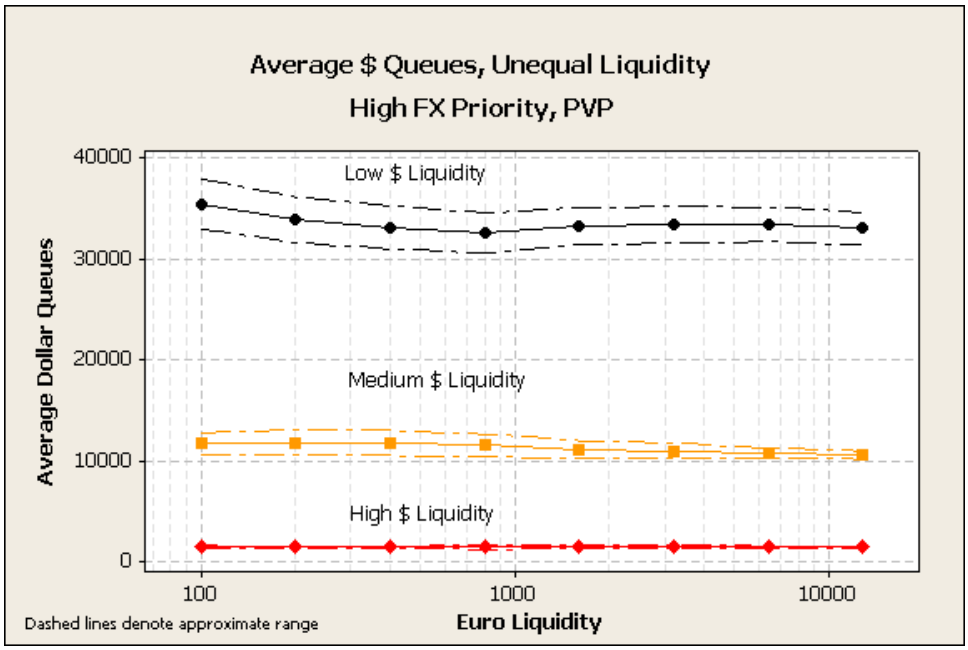

Figure 17: PvP settlement of FX transactions with high priority for FX transactions

In the non-PvP case, granting a high priority to the settlement of FX transactions does not have any effect on the two systems: the average level of queuing in a system is determined only by the liquidity present in that system. In the PvP case however, granting a high priority to the settlement of FX transactions reduces significantly the effects of the interdependency introduced by the PvP mechanism. The effect of euro liquidity on dollar queuing in the high FX priority, PvP case (**Figure 17**) appears intermediate between the indiscernible effect in the non-PvP cases (**Figure 14** and **Figure 16)** and the marked effect in the PvP, normal priority case (**Figure 15**).

When a high priority is used for the settlement of FX trades, the increase in queuing observed in the dollar system due to the PvP mechanism is much smaller and only occurs when the liquidity level in the dollar system is low and medium. We also observe that giving a higher priority for FX transactions in the PvP case has a tendency to increase the variability in queue size in the dollar system, especially for intermediate levels of liquidity in the dollar system and low levels of liquidity in the euro system (compare ranges in **Figure 16** with **Figure 14**, and **Figure 17** with **Figure 15**). This effect is complex to analyze and might depend on the topology used for the simulations.

5 FX settlement risk under non-PvP

In this section, we show that in the non-PvP case credit exposures that arise between the global banks create a strong interdependency between the two systems. The level of exposures is shown to depend on the liquidity available in each of the two systems and to increase as the liquidity is decreased (Section 5.1). Moreover, we demonstrate that a structural imbalance of liquidity between the two systems can have the same effects as a time zone difference between the two systems, and thus result in significantly high levels of exposure (Section 5.2). Finally, we observe that credit exposures can be drastically reduced by granting the FX transactions a higher level of priority than local payments (Section 5.3).

5.1 *Credit exposures with the same level of liquidity in both systems*

The model was run to quantify the gross credit exposures resulting from the FX transactions in the non-PvP case for various levels of liquidity (the method used to calculate FX exposures is presented in Section 2.5). We first investigate the case where both systems have the same level of liquidity. The results are presented in **Figure 18** which shows the total exposure of the banks in the two systems for various liquidity levels, when both systems have the same level of liquidity. From the definitions in Equations 3 and 4, exposure is measured as the average value owed over the simulation period, which is equal to the average number of unit payments owed because the two currencies are assumed to have equal value.

It is not surprising to observe that the credit exposures increase sharply when the liquidity is decreased. At high levels of liquidity in both systems, both legs of FX transactions settle nearly instantly and thus the related credit exposures remain very limited. At low liquidity levels, many FX legs can not settle directly and remain queued, hence creating large exposures. The slight difference observed between the average euro and dollar exposures is simply due to the slightly different network realizations in the two payment systems.

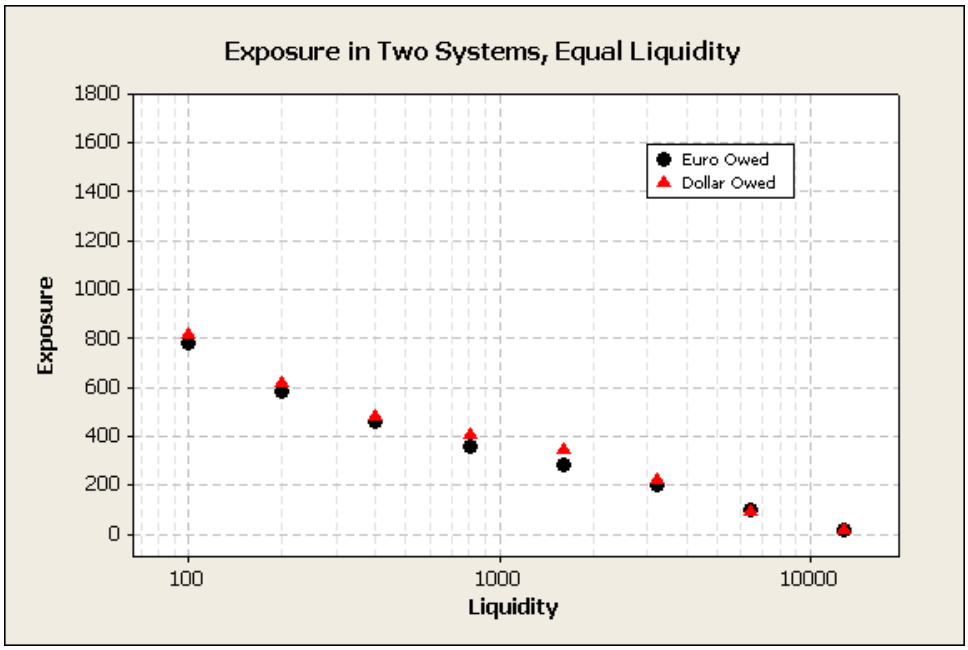

Figure 18: Number of euros and dollars owed as a result of the settlement of only one leg of an FX transaction, when both systems have the same level of liquidity

5.2 *Exposures with different levels of liquidity in the two systems*

It is well known that time zone differences between payment systems result in systematic exposures for non-PvP FX trades. The FX leg settled in an eastern country is usually settled before the corresponding leg in a western country. Similarly, when the euro system has a significantly higher level of liquidity than the other system, the euro leg of the FX transactions will settle significantly faster than the dollar leg. As a consequence, in this case the banks that are selling euro for dollar can expect to face credit risk for the duration of the lag in settling the dollar leg.

This phenomenon is illustrated in **Figure 19** which presents the total FX exposures (dollars owed and euros owed) arising in the non-PvP case, for various levels of liquidity in the dollar and in the euro system. As expected, the exposures are lowest when liquidity is high in both systems. In this situation, both legs of FX transactions are settled nearly immediately, and there is virtually no FX exposure.

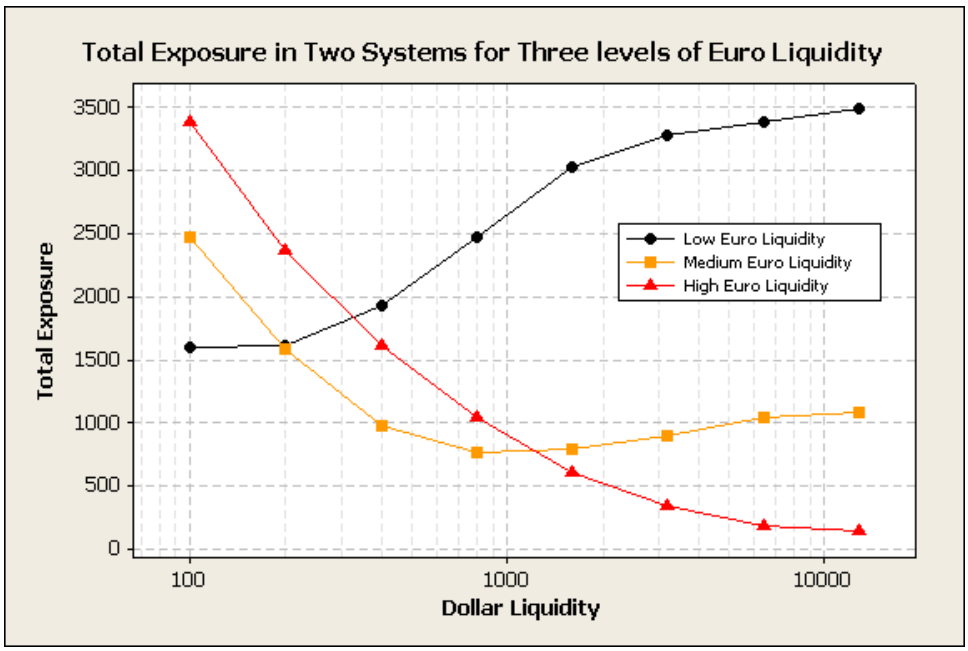

Figure 19: Total exposures (euros and dollars owed) resulting from the settlement of only one leg of an FX transaction, as a function of the liquidity level in the dollar system, for low, medium and high liquidity in the euro system

When liquidity is high in the euro system (red curve on **Figure 19**), the total FX exposure decreases as liquidity is increased in the dollar system. Indeed, the additional dollar liquidity reduces the settlement delay of the dollar legs, thus decreasing the amount of dollars owed and increasing the amount of euros owed. Since the liquidity level is high in the euro system, most exposures are due to pending dollar legs, as shown in **Figure 20** where the exposures due to pending dollar legs and to pending euro legs are plotted separately. Additional dollar liquidity helps settle the pending dollar legs and thus reduce the total exposures.

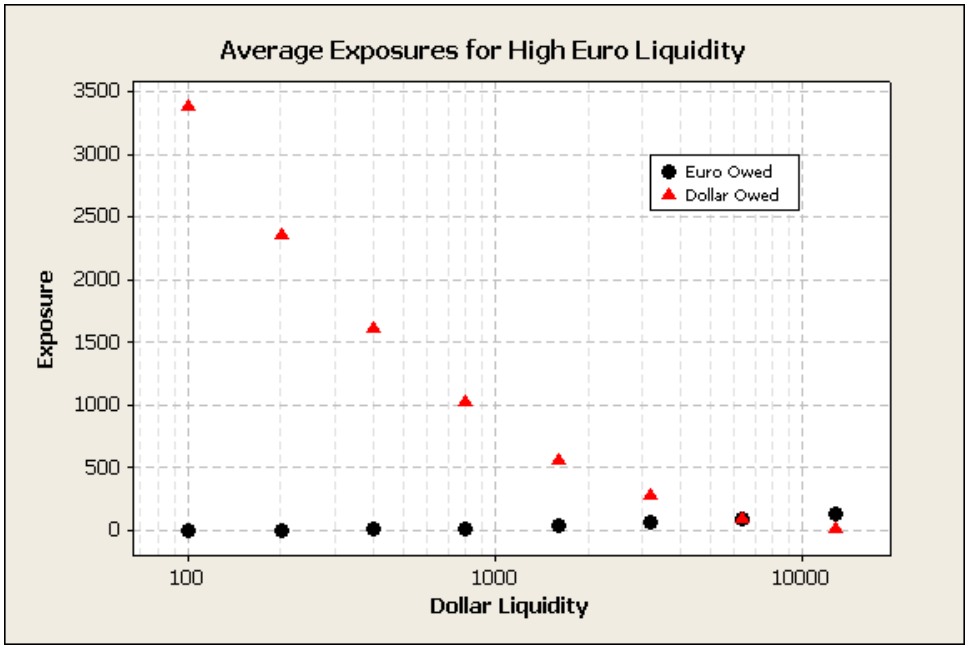

Figure 20: Detailed exposures (euros and dollars owed plotted separately) resulting from the settlement of only one leg of an FX transaction, as a function of the liquidity level in the dollar system, for a high liquidity in the euro system

When liquidity is low in the euro system (black curve on **Figure 19**) however, increasing the liquidity level in the dollar system actually *increases* the total FX exposure. When the level of liquidity in the euro system is low, the number of unsettled dollar legs is low and, thus, settling dollar legs faster has little influence on exposure. Settling dollar legs faster does however increase exposure when the dollar leg settles first. Any decrease in dollar exposure due to the additional dollar liquidity will be more than offset by an increase in the amount of euros owed due to the faster settlement of the dollar leg of the FX transactions.

When liquidity is intermediate in the euro system (orange curve on **Figure 19**), we see a combination of these two effects of increasing dollar liquidity: its tendency to decrease exposure due to unsettled dollar legs and its tendency to increase exposure due to unsettled euro legs. Starting from a low level of liquidity in the dollar system where FX exposures are mostly due to unsettled dollar legs, additional dollar liquidity will at first reduce the total amount of FX exposure. However, as the level of liquidity in the dollar system increases, unsettled euro legs will create greater and greater exposure. This is illustrated in **Figure 21** where the exposures due to pending dollar legs and to pending euro legs are plotted separately.

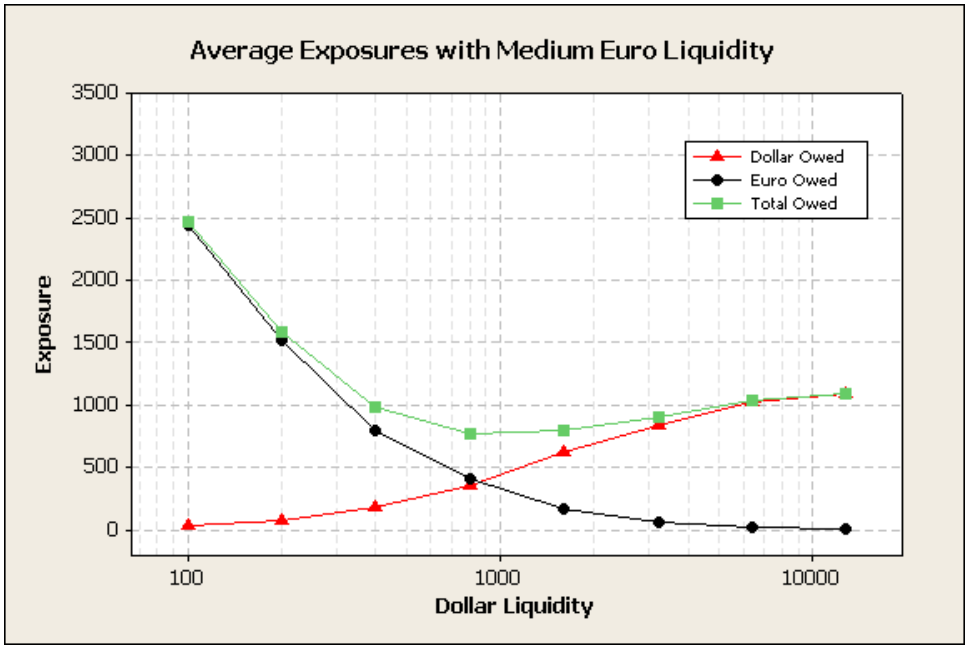

Figure 21: Detailed exposures (euros and dollars owed plotted separately) resulting from the settlement of only one leg of an FX transaction, as a function of the liquidity level in the dollar system, for a medium liquidity in the euro system

We can therefore conclude that in the non-PvP case, an uneven distribution of liquidity between the two systems leads to increased FX exposures. Coordination among Central Banks to ensure similar levels of liquidity in the exchanged currencies could significantly reduce FX credit exposures in both systems.

A similar effect on exposure was observed when the average settlement delay within a currency zone was decreased through an efficient intraday liquidity market (refer to Beyeler et al (2007) for a description of the liquidity market model) during periods in which the other currency zone had a low liquidity level.

5.3 *Influence of FX transaction priority*

Finally, we investigated the influence of the chosen priority level for the FX transactions. As explained above, at high priority, when a global bank lacking liquidity receives a payment, the received liquidity will only be used to settle a local payment if there is no pending outgoing FX transaction leg to settle; at equal priority, all transactions are settled according to their order of arrival, irrespectively of their nature. **Figure 22** provides a comparison of the total FX exposures in the high priority case (red squares) and the normal priority case (black circles), when both systems have the same level of liquidity. The simulations clearly show that using a higher priority for FX payments than for local payments sharply decreases the overall level of FX exposures.

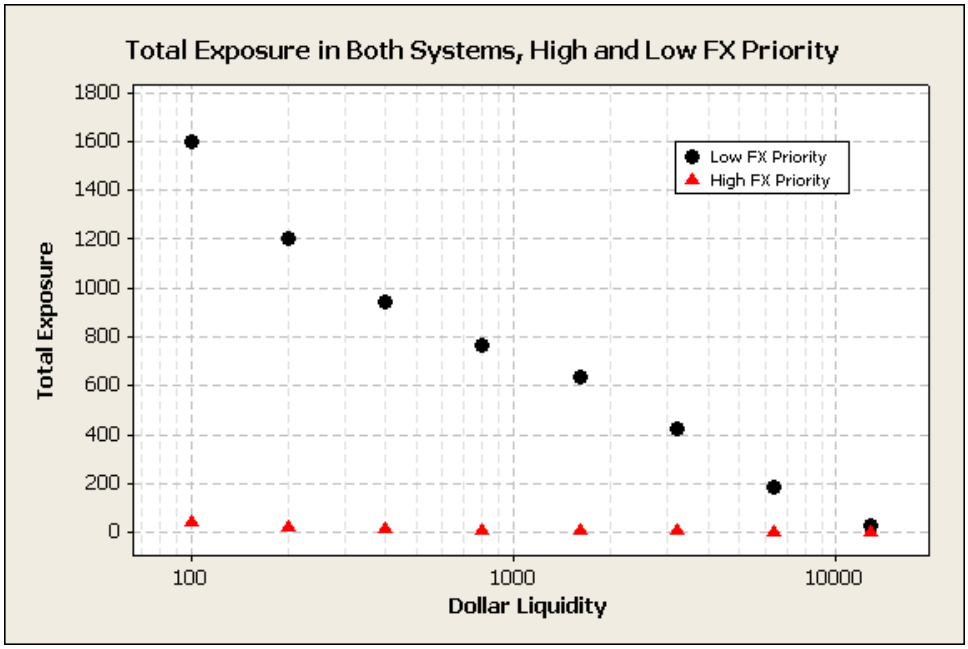

Figure 22: Total exposures (euros and dollars owed) resulting from the settlement of only one leg of an FX transaction, as a function of the common liquidity level in the both systems, for low and high FX priority

6 Conclusion

We developed a parsimonious model of interdependent payment systems by extending the "congestion and cascades" model by Beyeler et al. (2007). Our model captures the rich mechanics of liquidity and delays within a single payment system and the interdependencies between two systems that arise through the participation of large banks in both systems and through their foreign exchange (FX) trading activity. We investigate cases in which FX trades are settled on a gross basis by payment versus payment (in which case both legs of the FX transactions can only be settled simultaneously) and by non-PvP (in which case the two legs of the FX transactions are settled independently).

Foreign exchange transactions link global banks participating in two currency systems through the common inflow of payment and settlement requirements, creating an *institution-based interdependency* between the two systems. The activity of the two systems becomes correlated in the sense that a period of high settlement rate within one RTGS is statistically likely to correspond to a period of high settlement rate within the other RTGS. This happens when liquidity is sufficient to allow the simultaneous settlement of both legs.

The PvP mechanism used to synchronize the settlement of the two transaction legs creates a *system-based interdependency*. With the imposition of PvP, correlation is forced even at low levels of liquidity when the simultaneous release of the FX legs allows other queued payments to be released in both systems simultaneously. Correlation is not present when the two legs are not synchronized with PvP and when liquidity is low. In this case settlement is governed by the internal dynamics of each system separately.

When FX trades are settled non-PvP, some credit exposures are created between the set of global banks that engage in FX trading. Model results show those exposures to be dependent on the level of liquidity present in each system. Moreover, it appears that a structural liquidity imbalance between the two systems leads to very high credit exposures, much like the effects of a time zone difference between the two systems. One system settles the legs quickly and the other slowly, creating exposures for the duration of the time gap. The model shows that these exposures can be drastically reduced by granting FX transactions a higher level of priority than the local payments.

When FX trades are settled PvP, the credit exposures between the global banks vanish. However, the PvP mechanism creates another kind of interdependency between the two systems. Model results indicate that under PvP constraints, the average level of queuing within one system depends not only on its own level of liquidity but also on the liquidity level in the other system. More specifically, when liquidity is decreased within the “less liquid” system, the level of queuing increases significantly within the “more liquid” system. This effect appears especially strong for intermediate levels of liquidity in the “more liquid” system. We also observe that the level of queuing in the “less liquid” system decreases when the liquidity is increased in the “more liquid” system. This interdependency increases with the level of FX activity, and sharply decreases when FX trades are given a higher order of priority than local payments.

What kind of policy conclusions can be drawn from this work? First, it seems that foreign exchange settlement can cause systems in different currencies to develop correlated settlement rates even in normal circumstances as modeled in this paper. Currently the majority of FX trades are settled in the Continuous Linked Settlement (CLS) System which was developed with the intention of minimizing credit exposures arising from the settlement of FX transactions. Starting operations in 2002, CLS settles FX transactions on a gross basis with PvP, but banks post funds

to CLS on a net basis. We saw in our model that the PvP mechanism can eliminate exposures. This was the main reason for developing CLS. We also saw that PvP increases the intraday variability of banks liquidity demands. CLS addresses this issue through net funding - the amount of which the banks know in advance. This probably reduces the liquidity risk compared to the case of pure gross PvP settlement.

However, a substantial percentage of FX trades is still settled outside of CLS by settling the two legs of the trade independently of each other. Our model suggests that prioritizing FX trades over normal payments can reduce exposures significantly. Second, we saw that liquidity differentials between systems can increase exposures and a low level of liquidity in one system can negatively affect the other system or increase its liquidity needs, i.e. the effects spill over to the system operating on higher level of liquidity. Coordination between the central banks might therefore be required to ensure both systems have a similar level of liquidity.

Model results obtained so far can be used to qualitatively describe and document the effect of the interdependencies created by FX trading and the potential effects of the PvP mechanism on the activity of the two systems. Future research on modeling the cross-border spread of a liquidity disruption caused by the technical or financial default of a major participant would be likely to uncover other unexpected consequences of the interdependencies created by FX. The model developed in the paper could also be used to investigate more specific questions, such as the consequences of net funding for the settlement of FX transactions, or the impact of the creation of an intraday FX swap market.

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