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Liquidity Efficiency and Distribution in the LVTS: Non-Neutrality of System Changes under Network Asymmetry

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Abstract

The authors consider the liquidity efficiency of Tranche 2 of the Large Value Transfer System (LVTS T2) by examining, through an empirical analysis, some plausible strategic reactions of individual participants to a systemwide shock to available liquidity in the system. The network structure of the LVTS T2 is found to be asymmetric in terms of the patterns of out-payment flows. It is composed of three subgroups, in which participants within a subgroup are more strongly linked with each other than with participants in other subgroups. Three possible network equilibria are proposed. The equilibria are defined in terms of participant-specific collateral needs and out-payment delays, and result from different relative cost structures involving collateral costs, queuing costs, and payment delay penalties. Each of the conjectural equilibria relate to a dominant strategy for at least those participants most central in the network with respect to liquidity transfer adopted network-wide as a common strategy.

JEL classification: L14, L13, G21
Bank classification: Payment, clearing, and settlement systems; Financial services; Financial institutions

Résumé

Les auteurs étudient l'efficience de la gestion de la liquidité liée aux paiements de tranche 2 du Système de transfert de paiements de grande valeur (STPGV) en analysant empiriquement les scénarios plausibles des réactions stratégiques de chaque participant à un choc systémique qui toucherait la liquidité existante. Les caractéristiques des flux de paiement révèlent la structure asymétrique du réseau utilisé pour les paiements de tranche 2. Ce réseau compte trois sous-groupes de membres, dont les relations sont plus étroites dans chaque sous-groupe qu'avec les participants des autres sous-groupes. Les auteurs proposent trois formes d'équilibre de réseau. Ces équilibres, qui sont fonction des garanties dont a besoin chaque participant et de ses retards de règlement, découlent des différentes structures de coûts relatifs agencées autour des coûts de nantissement, du coût des files d'attente et du niveau des amendes associées aux retards de règlement. Chacun des équilibres potentiels relève d'une stratégie dominante, suivie au moins par les membres les plus influents du réseau (ceux qui remplissent un rôle clé dans les transferts de liquidité) et devenue la stratégie commune à l'ensemble des participants.

Classification JEL : L14, L13, G21
Classification de la Banque : Systèmes de paiement, de compensation et de règlement; Services financiers; Institutions financières

Executive Summary

Recognizing that liquidity transfer is a by-product of a payment transfer and that the availability of liquidity is the main determinant of the immediacy of a payment transfer, recent research in payment settlement systems has begun to focus on liquidity efficiency. Liquidity is defined as claims on Bank of Canada settlement funds, or assets immediately convertible into such claims. Liquidity efficiency in a payments system refers to the minimum amount of liquidity required to settle a given value of payments. It depends in large part on the real-time distribution of liquidity flows among network participants via payment transfers. We consider the liquidity efficiency of Tranche 2 of the Canadian Payments Association's Large Value Transfer System (LVTS T2) by examining, through an empirical analysis, the effects on individual participants of a systemwide shock affecting the adequacy of available liquidity within a settlement cycle.

Two interesting features of potential payment activity within the LVTS T2 arise from this analysis. The first is the high degree of asymmetry in payment linkages among subgroups of network participants. Indeed, the participants in the LVTS T2 can be classified into three subgroups. In terms of payment flows, participants within each subgroup are more symmetrically linked with each other than they are to participants in the other subgroups. Such asymmetry can lead to different preferred payment management strategies, and strategic reactions to network shocks, for different classes of participants. The second feature is more inferential. It suggests that, when there are different operating costs for different payment management strategies, as well as different individual payoffs for each of these strategies for alternative network conditions, the ultimate network outcome is specific to the underlying conditions. In other words, there is no single unique predictable network equilibrium on which to converge following some network-wide shock. Also, some of the plausible strategic equilibria may not be "first-best" for all network participants.

In our analysis, we draw from different strands of network analytic and game-theoretic approaches to participant-based payment settlement, to construct an analytical framework with which to define and evaluate the liquidity-efficiency properties of various possible equilibria in the LVTS T2. The analysis involves the creation of a hypothetical systemwide shock in the form of a one-time migration of payments to the LVTS from another system. The migration challenges the capacity of participants to make all their payments promptly with the same liquidity investments and under the existing settings or usage of the network's liquidity-efficiency mechanisms. We consider a set of feasible reaction strategies based on required adjustments in the parameters of specific liquidity mechanisms in the LVTS T2 that can lead to new network equilibria. The "conjectural" equilibria are defined in terms of participant-specific

collateral needs and out-payment delays. The equilibrium is derived from a common strategy acceptable to all participants but selected by the dominant participants in the network (those most central to the liquidity transfer process in the overall network and in each of the subnetworks). The welfare properties of the conjectural equilibria are based on systemwide liquidity efficiency, minimal out-payment delays, and likely acceptability of liquidity cost cross-subsidies inherent to the collateral pooling mechanism in the LVTS T2.

We examine three conjectural equilibria – each conditioned on a specific relationship among collateral cost, queuing cost, and penalty cost for out-payment delay. When penalty costs are low relative to collateral and queuing costs, the equilibrium is characterized by a high level of out-payment delays with low collateral requirements and no queuing of payments in the LVTS central queue. When penalty costs are high, other conjectural equilibria involve no out-payment delays and either one of: (i) extensive use of the T2 central queuing mechanism when queuing costs are low relative to collateral costs, or (ii) bilateral renegotiation of bilateral credit limits (BCLs) when queuing costs are high relative to collateral costs. The strategies underpinning these latter two equilibria are found to dominate the other possible strategy – raising the systemwide parameter. Based on defined systemwide desirability criteria, the conjectural equilibrium involving the use of the central queue is the most desirable, and the one associated with BCL adjustments is a close second.

Our approach to this analysis tries to circumvent, in a somewhat mechanical way, one of the principal weaknesses of empirical analyses of the LVTS T2 using the LVTS version of the BoF-PSS2 simulator. The simulator is a very useful analytical tool, but it does not encompass any response by participants in terms of payment flow management to a network change or shock. Unless participants' reaction strategies are exogenously linked to the simulator, as in this analysis, or incorporated into a new simulation tool, the simulator cannot adequately simulate a full range of potential network equilibria. Consequently, without the addition of participant reactions, the simulator's predictive capacity for ultimate network outcomes from policy and market shocks is limited. On its own, the simulator can be a poor guide for future policy research and for many policy decisions. Future simulation analyses of the LVTS T2, and related policy analyses, can benefit from a careful description of the behavioural objectives of its participants, relevant operating and costs constraints, feasible strategic choices, and network equilibrium rules and properties.

This leads to a second point. The maxim that good (policy) decisions require good information holds for this type of empirical analysis. More transparency is required in the relative all-in costs individually and network-wide for participants of a range of possible strategies for dealing with network-wide changes and events. Similarly, data that allow estimates of the relative payoffs from alternative strategies to be formulated are equally relevant. Such data can help inform operators, participants, and regulators about the efficiency and stability properties of equilibria achievable within particular settlement network arrangements.

1 Introduction

In payment settlement systems, the principal requirement for making a payment is liquidity and a principal by-product of bilateral payment transfer is a liquidity transfer. Although the original focus for system design was generally on risk control, the focus has recently shifted to liquidity efficiency for participants. New system designs feature liquidity-saving mechanisms to help lower liquidity costs for participants without sacrificing systemic risk control (CPSS 2005). Liquidity in payments systems is defined in terms of central bank funds, either as direct claims on central bank money or other eligible assets immediately convertible into central bank money. Liquidity efficiency in a payments system relates, however, to more than the minimum level of liquidity required to settle a given value and volume of payments. It relates as well to the distribution in the flow of that liquidity through the day, resulting from payment transfers among participants. The Canadian Payments Association's (CPA) Large Value Transfer System (LVTS) is one of the earliest payment settlement systems designed to limit systemic risk while incorporating specific liquidity-efficiency mechanisms.

We examine how a systemwide shock to Tranche 2 of the Large Value Transfer System (LVTS T2) might affect the equilibrium balance between payment delay and liquidity cost for individual network participants. The network is defined by the value of out-payment flows (i.e., links) between all pairs of network participants (i.e., nodes). The paper is essentially an empirical one. The analytical framework draws from a synthesis of recent theoretical work in three separate streams of research: (i) network topology, which describes and measures participant-specific network relationships and interdependencies; (ii) incentive structures for individual participants, based on liquidity costs, queuing costs, and delay penalties; and (iii) the properties of participant-based network equilibria that emerge when individual participants, aware of the network interdependencies, select payment management strategies. In equilibrium, the optimal payment management strategy pursued by one network participant allows all others to maintain their chosen strategies without further adjustment.[1] The resulting analytical framework guides the direction of the analysis and the interpretation of the empirical results. This allows some conclusions to be drawn as to the effects of systemwide changes on individual participant behaviour and the likely network equilibria that could result. It also allows the formulation of some policy lessons with respect to efficiency and stability for the future design and oversight of the LVTS T2.

1. Although not necessary for a network equilibrium, all participants may find the same strategic management approach to be optimal – hence, a "common" strategy equilibrium. Other equilibria – individual strategy equilibria – allow participants to pursue different, individually optimal, strategies.

This paper is organized as follows. The next section outlines the properties of the key liquidity-efficiency and transfer mechanisms in the LVTS T2. Section 3 provides a brief review of the literature that underpins the analytical framework and approach. Section 4 outlines the analytical framework for the study. Section 5 describes the strategy for the empirical analysis and reports on the empirical results in the context of the analytical framework. Section 6 provides conclusions and policy implications.

2 Liquidity Efficiency and Transfer

The LVTS is a dual-stream payment and settlement system characterized by real-time finality of individual payments and guaranteed end-of-day settlement of related net interbank obligations (Arjani and McVanel 2006). Intraday borrowed liquidity, to facilitate real-time payment settlement, is available through collateralized intraday loans from the Bank of Canada. The T1 stream of the LVTS requires full collateralization of intraday loans to fund out-payments, and has liquidity transfer features similar to those of a basic real-time gross settlement system. In the T2 stream, network participants pool their collateral so that a payor can draw on a common collateral pool to acquire the necessary intraday credit from the Bank of Canada to fund its out-payment. The vast majority of LVTS payments, in both volume and value, are T2 payments.

Although minimal required liquidity is a critical element for liquidity efficiency of a payment settlement system, it is not the only critical element. Because of network interdependencies in a payment settlement system, the minimum liquidity required of a participant to make its out-payments through the day depends in part on how the initial aggregate stock of liquidity is redistributed through payment settlements during the day. For example, if liquidity redistribution is tilted toward one participant in the network, other participants would need to invest more liquidity to make their out-payments, or delay some of those out-payments. In this case, the payment settlement system would be a less liquidity-efficient network for its participants as a group than one in which the redistribution of initial aggregate liquidity were to evolve more proportionately to the out-payment needs of all its individual participants.

As a liquidity transfer system, the LVTS T2 is characterized by (i) mechanisms governing participants' liquidity flows from payment settlement, (ii) the mechanics for funding liquidity transfers through payments, and (iii) the nature of the liquidity cross-subsidies among network participants relating to out-payment funding.

2.1 Liquidity transfer mechanisms in the LVTS T2

The LVTS T2 involves three different types of liquidity-efficiency mechanisms. These mechanisms lower the stock of liquidity required by participants to fund a given value and volume of out-payments. In addition, they help govern the distribution of liquidity among network participants and, in doing so, they help limit the prospect that an individual participant can acquire sufficient liquidity through in-payments or collateral draws to pose a threat of gridlock to the system.

The first of these mechanisms are participant-specific caps on net liquidity transfers. The two basic variables in these mechanisms are the net bilateral credit limits (BCLs) that individual participants grant to one another, and a common systemwide parameter (SWP). The maximum aggregate amount of liquidity that a participant can acquire through in-payments from other participants in advance of an out-payment is capped by the sum of the BCLs it grants to others.[2] The maximum value of out-payments that a participant can make to others, in advance of an in-payment, is set by its net debit cap (NDC). A participant's NDC is the product of the SWP and the sum of BCLs granted to it by the others. The NDC limits a participant's capacity to draw from the T2 collateral pool to make out-payments in advance of any in-payment flows. Avoidance of disproportionate liquidity capture by an individual participant in the form of either in-payment hoarding or excess demand for pooled collateral in the LVTS T2 enhances liquidity efficiency systemwide.

The second liquidity-efficiency mechanism in the LVTS T2 is the T2 collateral pool. To this pool, each participant is required to contribute an amount equal to the product of the maximum BCL it grants and the SWP. The sum of these collateral pool contributions allows individual participants to make out-payments with values in excess of their accumulated in-payments but below their NDCs. The participant draws on the collateral pool to acquire intraday credit from the Bank of Canada to fund such out-payments. These intraday loans are immediately paid down through subsequent in-payments, and the collateral acquired from the pool is freed up. The individual participant's contribution to the pool is less than the aggregate value of out-payments – and sometimes even less than the value of individual out-payments – that it can make through that contribution. This results from the propositions that, since out-payments of one participant are in-payments to another, and the distribution caps are not generally binding, the collateral acquired from the pool to fund out-payments from one participant releases collateral back to the pool in the same amount from the recipients of the out-payments. In other words, participants do

2. The BCLs that the LVTS participants extend to each other are also used to determine their individual contingency loss in the event of another participant's default. See Arjani and McVanel (2006) for details.

not all draw on the collateral pool at the same time and the aggregate drawdowns at any point in time are, on average, less than the value of the pool.[3]

The final liquidity-efficiency mechanism in the LVTS T2 is its central queuing mechanism. Out-payments submitted for T2 settlement by a participant that exceed the sender's NDC or the receiver's BCL are parked in the queue until sufficient funds (or counterparty net BCL room) become available to the sender for the out-payment to be settled. The central queue in the LVTS T2 does not allow bilateral payments between a given pair of participants to be divided or reordered over the time of submission (i.e., no first-in, first-out [FIFO] bypass). Even so, the central queue allows some of a participant's out-payments to be held back until the sending and receiving limits for the queued payments have sufficient value to permit these out-payments to settle. In effect, through the central queue, a participant's out-payments that were originally ordered for settlement according to the submission time and the counterparty are reordered over the day, which changes the actual settlement sequence of the submitted payments to their receiving counterparties. The release of one payment from the queue for settlement can cascade through the system to create the conditions that result in the subsequent release of other payments from the queue so as to dislodge any partial gridlock. Aside from the absence of a FIFO bypass, the central queuing mechanism in the LVTS T2 is quite flexible in terms of parameterization with respect to value, volume, and duration of payment queuing.

2.2 Funding out-payments in the LVTS T2

Since the LVTS settles in central bank money, each in-payment to an LVTS participant is essentially a receipt of a claim on Bank of Canada funds transferred from the network participant making the out-payment. The value of this claim, supported by the Bank of Canada's guarantee of settlement on net LVTS payment inflows, adds to the receiver's out-payment financing capacity.[4]

3. In the rare event that the aggregate drawdowns of collateral exceed the total value of the collateral pool at a point in time, the Bank of Canada effectively has a residual uncollateralized intraday credit exposure. This is the basis of its residual settlement guarantee in the LVTS. For an analysis of unanticipated defaults in the LVTS, see McVanel (2005) and Ball and Engert (2007).

4. Since the claims on central bank funds transferred intraday from a payment sender to receiver are guaranteed for delivery of their net settlement value by the Bank of Canada, they are essentially (real-time) contingent claims issued by the Bank. The contingent state is default by a participant in a net funds deficit. The Bank of Canada's contingent credit risk exposure is covered, wholly or in part, initially by the defaulting participant's pre-paid T2 collateral pool contribution and, additionally, by some or all of the remaining value of the T2 collateral pool.

An LVTS participant generally has very limited choice in the funding of individual out-payments in T2. Once a participant's out-payment is submitted to the LVTS T2 and accepted for immediate settlement, it is financed algorithmically by the available combination of in-payments from other participants, its own collateral contribution to the T2 collateral pool, and, if necessary, a portion of the collateral pledged by other network participants to the collateral pool. If, for example, the value of an out-payment in the LVTS T2 is below the available room under a participant's NDC, but exceeds the value of the sender's Bank of Canada claims accumulated through earlier in-payments, the sender draws automatically on the T2 collateral pool to borrow from the Bank of Canada on a collateralized basis.[5]

The principal liquidity cost for an LVTS T2 participant is its collateral pool contribution (CPC). Out-payments fully funded by in-payments are essentially costless to a participant making an out-payment. Granting a low maximum BCL limits a participant's required contribution to the T2 collateral pool and, thus, its liquidity costs in the LVTS. But it also effectively caps the level of other BCLs it may grant. If a participant grants low BCLs, it will receive a limited flow of in-payment liquidity with which to fund its out-payments. If a participant is granted low BCLs by others, its NDC is low, which implies low-value out-payments, and thus a limited draw on the T2 collateral pool.

2.3 Liquidity cross-subsidies in the LVTS T2

In networks where participants are homogeneous in all relevant respects and bilateral linkages are complete and fully symmetric (i.e., identical in directionality and value and volume of payments for all pairs of participants), cross-subsidies would not exist. In networks with collateral pooling, a significant degree of heterogeneity among groups of participants, and incomplete or asymmetric bilateral linkages, cross-subsidies in liquidity costs for funding out-payments will generally exist. As will be shown, the LVTS T2 is such a network.

With two sources of out-payment funding – in-payments and intraday credit backed by draws on the T2 collateral pool – cross-subsidies can involve out-payments funded principally by draws on the collateral contributions of others, or principally by in-payments from the out-payments of others that are funded mainly through their own CPCs. Where there are two distinct classes of participants, large and small for example, the cross-subsidies associated with the two sources of out-payment financing can be bidirectional and offsetting, or unidirectional in favour of one class. For example, large participants may draw relatively heavily on the accumulated CPCs of

5. An individual out-payment can exceed a participant's NDC by the amount of the participant's positive funds positions (i.e., accumulated in-payments) just prior to making the out-payment.

small participants, but deliver to them in-payment flows that are quite sufficient for the latter to fund their out-payments with little need to use the T2 collateral pool. Alternatively, large participants may draw relatively heavily on the T2 collateral pool to fund out-payments to one another, while small participants draw amounts less than their cumulative CPCs to fund out-payments destined principally to each other. In the latter case, the net liquidity-cost subsidy is largely in favour of the large participants, while, in the former, the cross-subsidies are offsetting to a much greater extent.

The nature of the cross-subsidies in liquidity cost is defined largely by the network topology, which in the LVTS T2 is related to the BCLs. Network topology refers to agent-specific network relationships and interdependencies. Since the BCLs are visible to both parties in the LVTS, retaliatory BCL setting can, under some topological conditions, limit "free-riding" with respect to CPCs to the T2 collateral pool and the unintended cross-subsidies in the liquidity cost of out-payment financing among network participants. Cross-subsidies can, however, still exist acceptably for heterogeneous subgroups in the network. To be mutually acceptable, the cross-subsidies between large and small participants would likely need to be sufficiently offsetting.

3 A Review of the Literature

Current research on large-value systems is beginning to focus on how the design of liquidity-efficiency mechanisms influences the size and distribution of payment flows, and consequent liquidity transfers, among network participants. We aim to contribute further to this research by (i) linking the LVTS BoF-PSS2 simulator model used for empirical analysis of the LVTS network to explore possible network equilibria resulting from underlying economic behaviour of network participants, and (ii) relating the largely descriptive measures of network topology to the determination of participant interaction in the determination of network equilibria for payment settlement systems. The settlement system on which the analysis is performed is the LVTS T2, which has some specific design features, as described in the previous section, that relate directly to the liquidity efficiency of the system. Changes in the basic parameters of these liquidity-efficiency mechanisms will have direct implications for payment and liquidity transfers among individual network participants.

The framework for our empirical analysis builds on elements of three different streams of recent theoretical and empirical research on the measurement of participants' behaviour in social and economic networks. Some of the research applies directly to generic payment settlement systems, but can be readily modified to specific systems such as the LVTS T2.

3.1 Trade-offs between liquidity cost and payment delay

One of the key research streams relates to the interrelationship between liquidity and payment flow management by participants in a payment settlement system. Such research considers the trade-off between liquidity cost and settlement delay. The trade-off relationship postulates that the incentives of individual network participants to minimize liquidity cost would limit the amount of liquidity each participant directs toward funding its out-payments. In aggregate, lower liquidity systemwide could delay the pace of payment settlement. Research on this problem considers how the design of various liquidity-efficiency mechanisms might avoid payment delay with even lower aggregate liquidity.

Arjani (2006) estimates the nature of the trade-off between liquidity cost and out-payment delay for the LVTS T2. Implicit in his analysis is the proposition that participants on the trade-off curve, or behavioural frontier, for a given amount of aggregate liquidity in the form of the T2 collateral pool, will settle individual payments arriving throughout the day as promptly as possible. Those that pass the LVTS T2 risk-edits, which relate directly to the liquidity-efficiency mechanisms described in section 2.1, settle immediately upon submission for settlement during the day. The others are queued for delayed settlement. By varying the SWP, Arjani demonstrates that increases in participants' NDCs and the T2 collateral pool (which allows participants to access higher values of intraday credit) reduce the volume and value of out-payment delays. Arjani also shows that a more effective use of the central queuing mechanism in the LVTS T2, to permit the reordering of delayed payments into a sequence generating a low multilateral net value, can reduce out-payment delays at each aggregate liquidity value.

3.2 Network topology

In large-value payments systems, network topology describes participant-based patterns of intraday liquidity flows involving direct bilateral, and indirect multilateral, payment links (Bech, Chapman, and Garratt 2007; Soramäki et al. 2006; and Beyeler et al. 2006). The measures used to describe these patterns of liquidity distribution in payment settlement networks are derived from descriptive metrics among nodes (i.e., participants) in generic network structures.

There are four principal topological features used to describe participant interrelationships in the LVTS T2: completeness of links, symmetry of links, centrality of individual participants, and the velocity of liquidity for individual participants.[6] Each measures, respectively, the relative ranking of individual participants in the network in terms of its degree of bilateral connectivity with other

6. See the appendix for a technical description of these measures.

participants, the value of its bilateral connections in terms of out-payment flows, its importance in the liquidity transfer process within the entire network, and its liquidity efficiency in funding out-payments. The completeness and symmetry measures indicate the degree of heterogeneity among individual participants within the settlement network in terms of their liquidity transfer roles and the efficiency with which they perform that role. Heterogeneity in some relevant properties of network participation suggests that (subgroups of) individual participants may not react identically to a given shock. The centrality measure indicates which participants play the most dominant liquidity transfer roles in the network. Dominant participants have a strong bargaining position in determining the network strategies affecting bilateral and multilateral payment activity. The velocity measure evaluates the liquidity efficiency of the potential strategic network equilibria for each participant and, when decomposed by funding source, indicates the nature of the cross-subsidies in liquidity cost among participants for each of these potential equilibria.

In our analysis, these topology measures indicate the structural conditions governing the feasible set of possible network equilibria, the relative bargaining power of various classes of participants in determining the strategic network equilibrium, and the properties of that equilibrium in terms of its overall network efficiency.

3.3 Strategic payment behaviour

This stream of research proposes that the observed patterns of participant-based payment flows in a settlement network are the result of participants' individual strategic payment behaviour. Participants react to systemwide events and to each other's reaction by adjusting their own strategy for payment flow management. Their individual strategies converge on (or coordinate around) a network (Nash) equilibrium, typically defined as some combination of liquidity investment and out-payment delay for each of the individual participants in the network.

Bech and Garratt (2003) analyze the behaviour of individual participants in a payment settlement network that can lead to different equilibrium trade-offs between liquidity investment costs and the delay of out-payment. Although their initial analysis is developed in the context of a strategic (Bayesian) game involving two homogeneous participants, Bech and Garratt (2006) extend the analysis to a heterogeneous n-person game. In the latter analysis, they outline two possible "pure" reaction strategies to a systemwide event that can result in payment delays: a self-perpetuating strategy and a self-reversing strategy. A self-perpetuating strategy would imply that a participant takes no action to avoid or reverse the payment delays. This strategy suggests that the penalty cost of payment delay is low compared with the effort and liquidity costs of avoiding such delays. The self-reversing strategy implies that the penalty cost is sufficiently high relative to the effort and liquidity costs that a participant will take action to avoid out-payment delays. They describe Nash equilibria within the network arising from these strategies and the conditions under which they are potentially unique and efficient.

For example, when penalty costs for delay are relatively high compared with liquidity costs, all network participants in Bech and Garratt's (2006) model will choose a self-reversing strategy and converge on a unique equilibrium that avoids payment delays. In the case where liquidity costs can exceed delay costs, two network equilibria can exist – one that tolerates payment delay and one that does not. However, under particular conditions relating to the heterogeneity of participants, the coordination of participants on either of these equilibria can face some degree of uncertainty. Bech and Garratt's analysis of these equilibria, and the uncertainty conditions around them, suggest that coordination on a particular equilibrium depends largely on the decision of the largest participant. Its reaction to any systemwide event appears to dominate that of the smaller participants in determining the network equilibrium. Bech and Garratt's results suggest that network participants that play a pivotal role in determining network equilibria are "too big to fail," in a network centrality sense.

While Bech and Garratt suggest that dominant participants in the network, in terms of network centrality, can lead in the determination of the network equilibrium, they provide little explanation as to why other participants would accept such direction. Implicitly, of course, strictly dominant participants control the distribution of liquidity in the network through their out-payment management positions. They can, therefore, penalize less-dominant smaller participants for non-compliance by forcing on them higher liquidity costs or payment delay penalties. The prospect of such retaliation by dominant participants in a settlement network has been examined empirically by Ledrut (2007). Her analysis supports the proposition that dominant participants in a settlement network composed of heterogeneous participants are able to control the network equilibria through the threat of retaliation. She finds that (the threat of) retaliation can be an effective counterparty control in a network when one or more participants fails to make out-payments. However, the degree of reciprocity of this threat between participants depends on the degree of symmetry in value-weighted bilateral links. The more symmetric these links, the more reciprocal is the degree of control through the threat of retaliation. The more asymmetric are these links, the more unidirectional is the disciplinary control from the dominant participant to the less dominant ones.

Martin and McAndrews (2007) also consider the determination of network equilibria when participants are heterogeneous. Their analysis focuses on the effect of strategic complementarities (network interdependencies) in liquidity transfer, and the impact of liquidity-savings mechanisms – specifically, various (parameter) designs for central queuing mechanisms – on the determination of network equilibria, defined again in terms of liquidity cost and payment delay. Martin and McAndrews define a network of participants divided into two types: strategic core participants and non-strategic participants. Each participant makes and receives one payment to and from one of the other participants. Payments within the strategic group may or may not be time critical. If not time critical, they can be made early in the day or late in the day; if time critical, they need to be made before the designated time to avoid a delay penalty. If necessary, participants can borrow intraday to fund their out-payments, but at a cost.

Martin and McAndrews consider first the responses of participants to an idiosyncratic liquidity shock to one participant that cascades through the system due to network linkages. As shown in Bech and Garratt (2003, 2006), a liquidity shock to the system will lead to a multiplicity of possible network equilibria, with coordination of one of the equilibria depending on the delay penalty relative to the expected borrowing cost. Martin and McAndrews then introduce a central queuing mechanism. This allows participants an additional strategic choice (given a known liquidity shock) or in- and out-payment matching mechanism that can reduce liquidity requirements. An out-payment – especially a non-time-critical out-payment – can then be (i) submitted and settled promptly, (ii) delayed internally (in a participant-specific internal cash-management queue) for later submission and settlement, or (iii) centrally queued, to allow the queuing algorithm to determine the timing of the payment, based typically on in-payment matching. With central queuing, even more network equilibria are possible, although some can be strictly dominated by others, in that payments can be made without delay penalties and with lower liquidity cost as a result of queuing. The welfare properties of even the dominant queue-related equilibria depend on the design of the queuing mechanism and the degree to which queued payments are offsetting.

Martin and McAndrews' analysis confirms that the coordination of payment flows among participants can be more difficult the greater the heterogeneity among participants and depending on the nature of their payment flows. The combination of network interdependencies with heterogeneity of participants in a settlement network complicates coordination of network strategies on an efficient and safe network equilibrium relative to systems with weak network linkages or homogeneous participants.

4 The Analytical Framework for the LVTS T2

Some of the elements of these different areas and types of research on networks discussed in section 3 can be modified and brought together to form a useful framework for analyzing the impact of a systemwide liquidity shock to the LVTS T2. Specifically, the literature suggests the following principal elements for the analytical framework: (i) the technical environment for payment settlement, (ii) the objectives and payoffs from participation and the factors conditioning the strategic actions of individual network participants, including heterogeneity and network asymmetry, (iii) the nature of the shock and the information around it, (iv) the feasible reaction strategies resulting from these objectives and constraints of individual participants to a common event, and (v) the iterative process related to individuals' reaction strategies in achieving a network equilibrium and the properties of that equilibrium.

4.1 The technical environment for the LVTS T2 payments

Virtually all time-critical out-payments are settled in the LVTS T1; only non-time-critical out-payments are submitted for T2 settlement. Delay of an out-payment is defined for this analysis as the holdover of that payment until the following day's settlement cycle.

With regard to the payment queuing process, we assume that out-payments are submitted immediately upon receipt of the payment instruction to an internal liquidity-management scheme – the sending participant's own mechanism in which it may queue payments intraday, for a short period, to smooth anticipated liquidity flows. All internally queued payments of a participant are, however, submitted to the LVTS for settlement during the current daily cycle. Since real-time monitoring and payment reordering is costly in terms of resource effort, internal queuing is informationally imperfect in terms of the LVTS T2 bilateral and multilateral net liquidity positions.

Central queuing in the LVTS T2 helps circumvent the informational problems related to costly internal queuing by each participant. That is, some payments released from a participant's internal queue for submission to the LVTS T2 may not pass the system's real-time risk edits. Centrally queued payments are those out-payments submitted to the LVTS for settlement but temporarily rejected by the system's risk controls. The central queuing algorithm resubmits queued out-payments for settlement at a point later in the day when the participant has room under both its NDC and the BCL granted to it by the receiving participant. Payments are queued and resubmitted in the order of their arrival in the queue (i.e., no FIFO bypass). Unlike the current parameterization of the LVTS T2 queuing mechanism that involves a short maximum delay time and a minimum payment value, the queuing mechanism for this analysis requires only that centrally queued out-payments of any value need to be resubmitted for settlement no later than the end of the day's settlement cycle to avoid delay.

According to the assumptions regarding the queuing process, any delayed out-payments would have been centrally queued payments. As indicated in the empirical analysis, centrally queued out-payments are delayed principally because of limitations on NDCs (partly by the design of the experiment but also by the liquidity costs of BCL-setting). Therefore, we assume that a participant will acquire the maximum possible aggregate value of BCLs that it can profitably negotiate and, thus, has the maximum NDC that it can have in the LVTS T2 for a given systemwide parameter.

4.2 Participant's objectives, strategic controls, and payoffs

All network participants are assumed to act individually to minimize the cost of settling out-payments as promptly as possible in the LVTS T2, given the value of liquidity available to each of them. These costs are composed of liquidity costs and queue management costs. Taking the net costs of holding and pledging an additional dollar of collateral as fixed, liquidity costs are defined by the level of each participant's CPC. Queue management costs are internalized for participants (including those involved in the strategic use of the central queue). Consider the marginal queuing cost for each out-payment as a fixed value.

Out-payment delays involve penalty costs that are proportional to the value of the delayed payment. These penalties reflect, for example, the overnight interest rate (plus a premium) paid to customers that originate the payment. Since we are considering only non-time-critical out-payments, receiving participants that anticipated the in-payment for their own out-payment funding may impose retaliatory out-payment delays on the participant delaying the payment.

There are, therefore, three possible costs that a participant must consider when managing its out-payments: (i) the liquidity costs of its CPC, which relates to the value of the largest BCL that it grants, (ii) the costs of out-payment queuing, which relates to the number of out-payments centrally queued, and (iii) the penalty cost of delaying the settlement of a queued payment until the next settlement cycle. Individually, a participant can control these network participation costs by optimizing the level of the BCLs that it grants to other participants in a way that controls the value of its CPC and the cumulative value of in-payments that it can acquire. It can influence the level of out-payment delays by negotiating with other participants to acquire the maximum value of BCLs that they will grant to it. Since their bilateral out-payments are in-payments to that counterparty, which provides the receiver with essentially cost-free out-payment financing, the maximum BCL granted to a participant by another will generally be no less than the expected peak intraday payment received by the granting participant from the sender. By definition, it can be no larger than the largest BCL it grants to a participant, which creates its liquidity cost.

4.3 Nature of the shock and its information structure

To simulate a systemwide shock involving potential out-payment delays, the analysis adopts the same strategy used by Arjani (2006) and varies the SWP from its present level of 24 per cent, in one-percentage-point reductions, to 20 per cent. The SWP reduction lowers each participant's NDC so that the value of out-payments sent, and thus in-payments received, is reduced systemwide. Lowering the SWP also reduces each participant's CPC equiproportionately, and thus the value of the collateral pool to create potential out-payments at each SWP level below SWP 24. Consequently, for some participants, there are now more payments each day than can be settled for the given level of liquidity available.

For the purpose of this analysis, assume that the initial parameterization of the LVTS T2 is SWP 20. Assume also, at least initially, that participants have the same BCL pattern for each SWP level. This assumption is consistent with Arjani's (2006) result of a flat trade-off curve in the 20-24 per cent SWP range. The shock to the system can then be described as the migration of large-value payments from another payment settlement system to the LVTS, equivalent in value and volume to the potential out-payment delays at SWP 20. For a given level of available liquidity in the T2 collateral pool, and the liquidity allocation caps relating to individual participants, the migration results in an implicit systemwide liquidity shortage for the LVTS T2 payment settlement system. It permits us to examine the various strategies for dealing with a liquidity shortage leading to potential out-payment delays.[7]

The migration shock is assumed to be known by participants before the date on which it comes into effect. This assumption allows participants to pursue reaction strategies that might require advance bilateral or multilateral negotiations within the network. All feasible reaction strategies and the operational date of the shock are, therefore, common knowledge, but their likely impact on the payment flows of individual participants is assumed to be private information. Hence, reliable information about which reaction strategies individual participants will actually pursue, and its network impact, is not fully revealed until the settlement cycle on the migration date.

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7. In the past, payment migration to the LVTS encouraged participants to set a high SWP, which was subsequently lowered to limit excessive liquidity costs. Currently, there is a proposal to raise the SWP to minimize (internal) queuing costs for at least some participants, and to minimize the prospect of out-payment delays relating to increases in the value and volume of payments arising in large part from growing financial market activity.

4.4 Possible reaction strategies

Based on Bech and Garratt (2006), individual participants can choose over two general reaction strategies for a systemwide event involving a shock to available liquidity: a self-perpetuating strategy or a self-reversing strategy. The selection of a reaction strategy depends on the relationship between liquidity, queue management, and delay costs. All network participants have sufficient information about their own relative costs to evaluate all strategies available to them before the migration date. As noted in section 4.3, information about the strategic preferences of other participants is imperfect and learned only through observation of their reactions.

For the purposes of this analysis, the self-perpetuating strategy presumes that the delay costs are so extremely low – relative to liquidity costs, in particular – that they can be taken as zero. In this case, a participant would prefer to delay payments rather than to expend more on liquidity and queuing.

In a self-reversing strategy, delay costs are extremely high for the participant, so that out-payment delay is not considered a preferable approach. For the participant, the issue is how to settle all its payments within that daily cycle at the lowest possible cost. For an LVTS participant, there are three options or substrategies to consider for T2 settlement, each of them negotiated. The first is to renegotiate BCLs with the counterparties subject to out-payment delay and settle any "tail" amount of out-payments subject to delay through T1. The second substrategy is to utilize the central queuing mechanism in the LVTS more liberally, which for our analysis involves a full-cycle queuing period with no minimum payment value – and settle any tail amount through T1. While this strategy can be pursued unilaterally during a settlement cycle, it could require multilateral pre-negotiation of the queuing mechanism's value and timing parameters. The third substrategy is to raise the SWP, which would also require multilateral negotiation ahead of the migration date.

The strategic reactions of individual participants in the LVTS T2 depend on their idiosyncratic properties in network participation, which are represented by their relative centrality and efficiency in the network structure, and the common participation objectives and constraints that they share. As shown in the empirical analysis section, the LVTS T2 is complete, but highly asymmetric, in its structure as a consequence of heterogeneity among its participants.

4.5 Potential network equilibria

The equilibrium outcome can be described in terms of each participant's T2 CPC and T1 collateral use, and the value of its out-payment delays. Hence, the network equilibrium is fully described by a matrix of values for each of these outcome variables for each participant.

The literature review in section 3 indicates that multiple equilibria are possible with network asymmetry, which the LVTS T2 exhibits. Since the only idiosyncratic difference among participants considered in this analysis is the heterogeneity in the relative scale of network activity, such equilibria would allow the different classes of participants to select different cost-minimizing strategies. Where there are cross-subsidies involved in liquidity pooling, one subgroup of participants may find it cheaper, for example, to pursue a queuing substrategy and another a BCL renegotiation strategy if it is less burdened by out-payment delays. Indeed, if one subgroup has no out-payment delays, and has very weak out-payment linkages with a subgroup in which all out-payment delays are concentrated, it might well prefer the self-perpetuating substrategy.

To narrow the equilibria possibilities for this analysis, the network game will be simplified based on the proposition in Bech and Garratt (2006) that dominant participants in the network largely determine the network equilibrium, and Ledrut's (2007) support for this proposition, via an implicit threat of retaliation. This analysis will assume that it is the dominant participants in each subgroup that determine the equilibrium. The dominant participants will be identified according to their centrality rankings. The implicit threat of retaliation from the most central participants with respect to network-wide liquidity transfer causes the other participants to adopt the preferred strategies of the former, reducing the set of potential network equilibria to common pure strategy equilibria. For the possible equilibrium based on a common self-perpetuating strategy, all potential out-payment delays at SWP 20 would be tolerated by participants. For the possible equilibria based on common self-reversing strategies, no out-payment delays are acceptable for any individual participant.

5 Empirical Analysis and Results

The sample payment data are submitted to the LVTS BoF-PSS2 simulator in the same sequence that they settled, without delay, at SWP 24.[8] At SWP 20, and the associated CPC for each participant that sums to the T2 collateral pool, the payments submitted to the LVTS T2 can yield

8. The sample data are payment-by-payment data from the first business day in October 2005 until the last business day in October 2006.

three separate payment streams for each participant: a stream of delayed out-payments, a stream of settled out-payments, and a stream of final in-payments. Using these payment streams, the empirical analysis is based on the calculation of: (i) the structure of network participation as measured by the pattern of bilateral payment linkages, out-payment activity, and network centrality, (ii) the outcome of the participant's possible reaction strategies in terms of liquidity requirements and out-payment delays, and (iii) each participant's T2 velocity and collateral pool usage for each adjustment strategy. The centrality measures are used to identify the dominant participants in the network. Their lowest-cost strategies are identified for each set of relative cost conditions and used as the common network-wide strategy. The possible network equilibria arising from the common strategy are examined with respect to their comparative velocity and cross-subsidy implications, to summarize their relative liquidity efficiency and their acceptability across participants, in the context of their common payment management objectives and associated systemwide desirability criteria for potential network equilibria.

5.1 The structure of the LVTS T2 network

The LVTS T2 is essentially a complete network, having the maximum number of bilateral linkages possible, but it is quite asymmetric in the value of the different linkages. Based on the relative values of these linkages, the participants in the LVTS T2 are classified into three subgroups: inner core, outer core, and non-core subgroup.

Chart 1 shows the bilateral out-payment linkages within and between subgroups in the LVTS T2. The thickness of the links within and between the subgroups represents the relative value of their respective bilateral links. Within a subgroup, it is the value of the reciprocal bilateral out-payment links between participants. Between subgroups, it is the value of out-payments, aggregated over subgroup participants, to and from each pair of subgroups. The participants in each of these subgroups have higher-valued out-payment linkages with each other than with participants in the other subgroups.

Although the threshold values for classification of participants bordering on an adjacent subgroup are largely arbitrary, they generally reflect an order of difference in value between the next higher ranked and the next lower ranked participant. Moreover, the classification of participants is supported by a similar rank-ordering process using different metrics for the value of network participation – notably, out-payment activity levels and centrality rankings.

Chart 1
Value of Out-Payment Links by Subgroup
(daily average; $ millions)

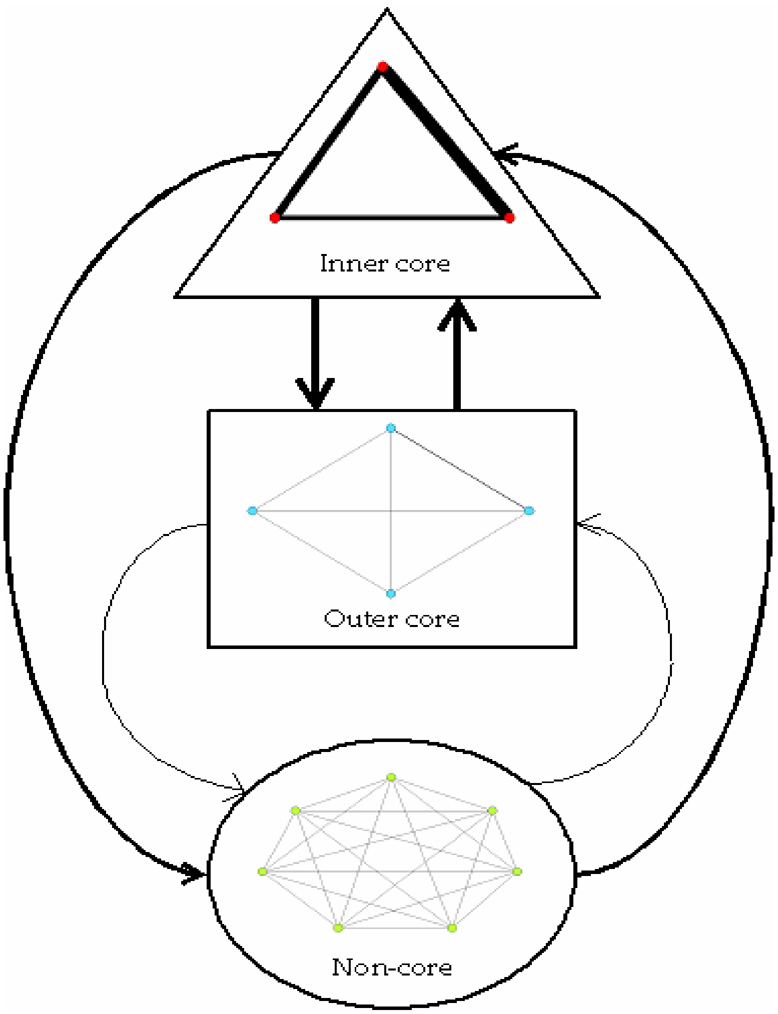
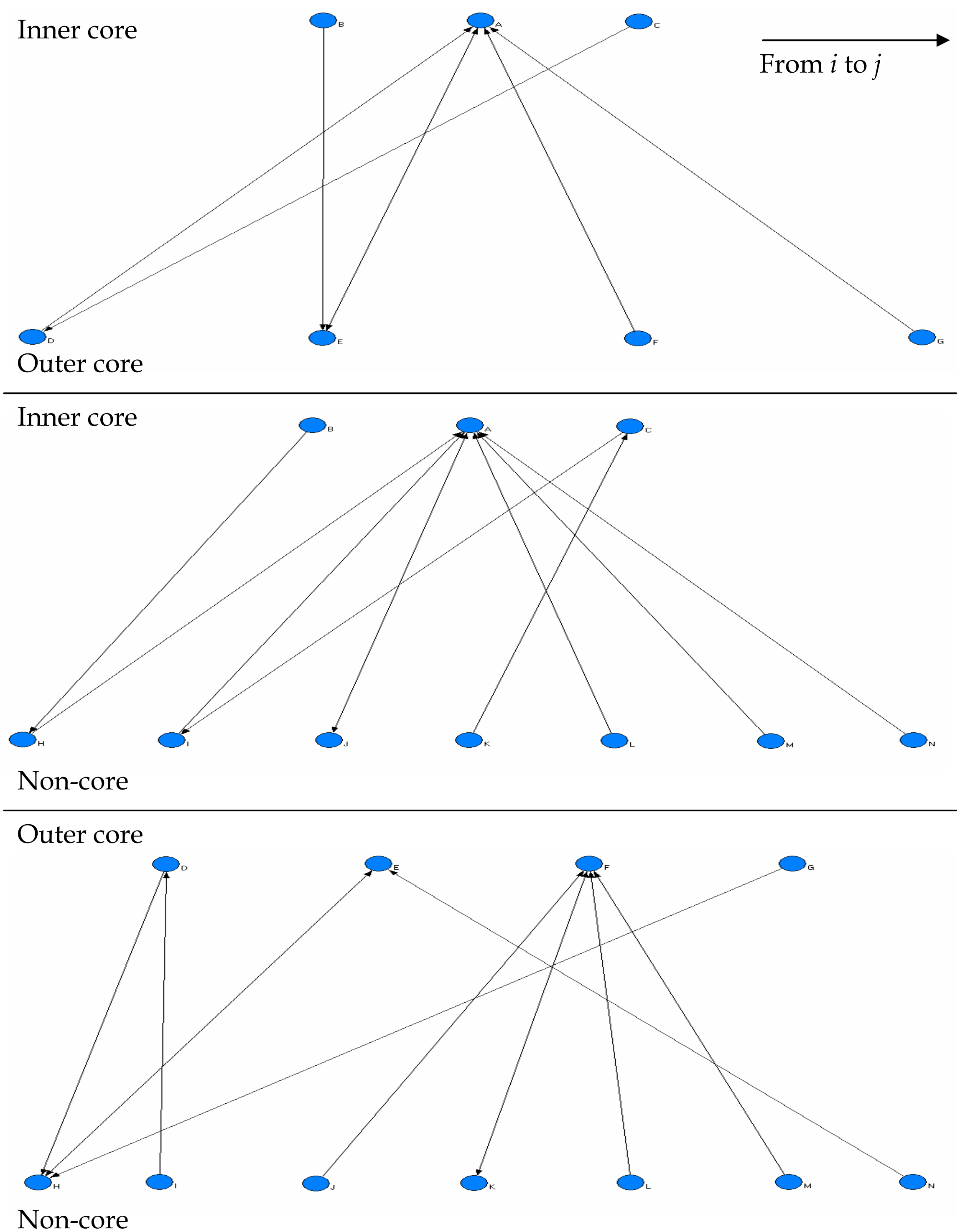


Chart 1 illustrates three important structural properties of the LVTS T2. The value of bilateral out-payments among the inner-core subgroup is substantially greater than those in the other two subgroups. Also, the value of bilateral out-payments among the outer-core participants is slightly greater than those among the non-core participants. Second, the aggregate value of out-payments between pairs of subgroups is relatively symmetric. However, the value of out-payments between the inner-core subgroup and the outer-core subgroup is substantially greater than between either of these two and the non-core subgroup. Hence, the non-core subgroup is only weakly linked with the other two subgroups in the LVTS T2. Finally, even with subgroups, where participants within each subgroup may be more strongly linked with one another than with participants in other subgroups, the LVTS is still a complete, highly connected network, overall.

With respect to the last point, while the value of the out-payment linkages among any two LVTS T2 participants varies from day to day, and may be unidirectional on some days for a given pair, the largest out-payments from a participant in one subgroup are almost always to the same participant in another subgroup. More specifically, as shown in Chart 2 by the number of arrows, there is one participant in each subgroup that is the dominant recipient of out-payments from participants in the other subgroups. Chart 2 shows the largest daily average bilateral out-payment from each participant in a subgroup to a recipient in another subgroup. The dominant recipient in the subgroup is also usually the dominant out-payment participant in that subgroup, when Chart 2 is matched with Chart 1. These data indicate that Bank A in the inner core, Bank E (and possibly Bank F) in the outer core, and Bank H in the non-core are the dominant participants, respectively, in each of these subgroups.

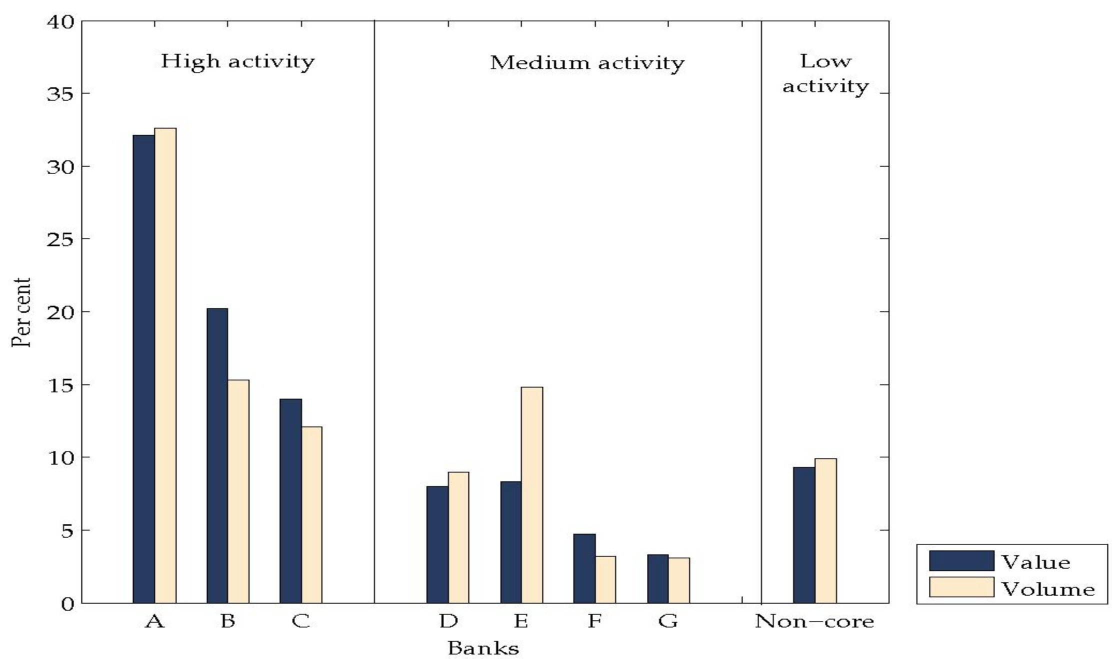
Chart 2
Largest Out-Payment Link between Participants across Subgroups
(daily average; $ millions)



Bolstering the assignment of participants to each of these subgroups is their correspondence with the relative activity ranking of each of these participants in the LVTS T2 (Chart 3) and their respective centrality rankings (Chart 4). The participants identified in the high-, medium-, and low-activity-level groups in Chart 3 correspond to the inner-core, outer-core, and non-core subgroups in Chart 1. Also, the ranking of these participants according to the centrality measures corresponds to the subgroup assignment by relative value of bilateral payment flows.

Based on observable levels of the average daily out-payment value over the sample period (13 months ending October 2006), there is obvious heterogeneity in scale among the individual participants in the LVTS T2. When participants are ranked simply by the value of out-payment activity, there is a direct correspondence between relative activity levels and their ranking according to the value of bilateral linkages in and between the subgroups. In other words, the majority of the value of bilateral out-payments among the highest activity participants, which are inner-core participants, is primarily between each other. The next highest percentage is with one or more participants in the outer-core subgroup.

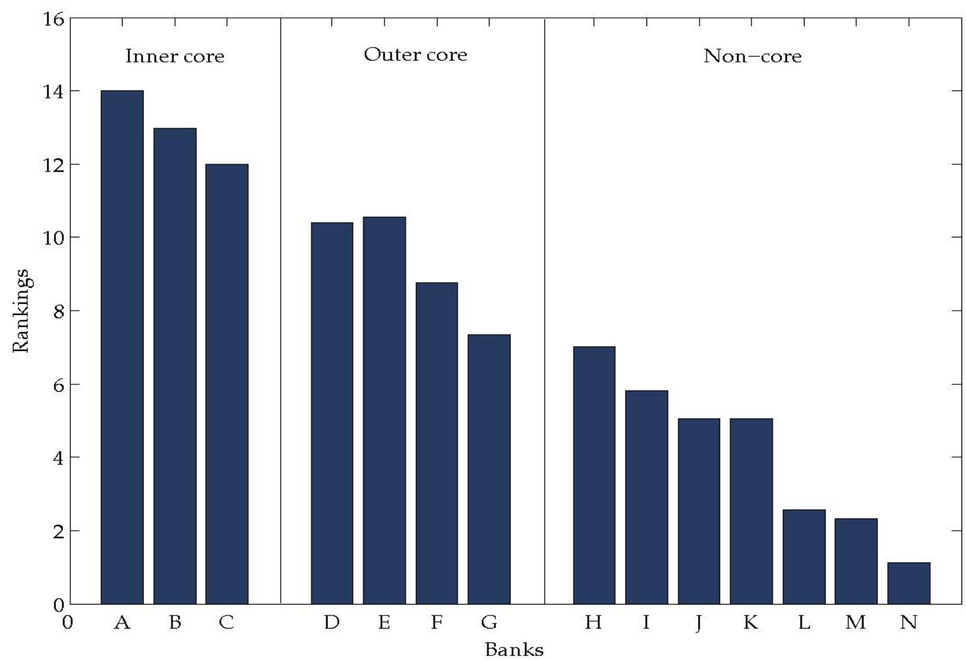
Chart 3
LVTS T2 Activity
(daily average; per cent)



The high-activity subgroup, consisting of only three participants, accounts for two-thirds of the payment value and the highest average payment value. The low-activity subgroup, which, with seven participants, is the largest in size, accounts for around only 10 per cent of the network volume and value.

The centrality and intercentrality rankings in Chart 4 confirm the liquidity dominance of Bank A network-wide for the LVTS T2 (and thus in the inner-core subgroup), and of Banks E and H in their respective subgroups.[9]

Chart 4
Centrality and Intercentrality Rankings
(weighted daily average for SWP 20-24)



There are three points to note about Chart 4. First, these are rank-order numbers, not the actual calculated values. They indicate the average daily rank (highest to lowest) for each of the 14 network participants in terms of value of out-payment over the sample period. Bank A always ranks the highest, and therefore has a "perfect average" of 14. Other participants may change rankings within the local region of their average and thus have ranking values in decimal points. Second, the centrality and intercentrality rankings are identical, even though their calculated

9. See the appendix for a detailed derivation and explanation of the centrality and intercentrality measures.

values are not. Apparently, the out-payment asymmetry among participants is sufficiently large and persistent over the sample period to leave the centrality rankings unaffected by the adjustment for payment feedback loops in the intercentrality measure. Third, the centrality and intercentrality rankings are unaffected by the decline in the SWP over such a short range, although their actual values do change in slightly different proportions. Arjani's (2006) results indicate that, in contrast to much lower SWP values, the trade-off between liquidity costs and out-payment delays is relatively flat when the SWP varies between a level of 20 and 24, which is at the tail end of the trade-off curve. The small value of out-payment delays relative to overall out-payment activity for each participant leaves the rankings unchanged even as the SWP declines.

Taken together, these measures of network structure indicate that if each participant were able to ignore the reactions of other participants to both the network shock and to its particular reaction to it, different participants may not always prefer to adopt the same adjustment strategy, even with common objectives. The strategic reactions of participants, especially those of the most central participants in the network and in their own respective subgroups, can affect other participants' reactions. As a result, at least some participants may adopt a strategy, to avoid possible retaliation, that is individually second-best but acceptable to all other network participants. In this case, such equilibrium payoffs are the best that the individual participants can obtain given the network interdependencies and externalities.

5.2 Impact of the payment shock on subgroups

The shock is defined as a migration of payments to the LVTS T2 that could lead to possible out-payment delays. The shock is constructed by reducing the SWP level from SWP 24 to SWP 20 to determine for each participant which out-payments at SWP 24 would not pass the risk-edits at lower SWPs and are thus subject to delay. Table 1 outlines the allocation of potential out-payment delays across participants, as well as the aggregate impact network-wide, for the different levels of the SWP.

There are three key points to note for the subsequent analysis. First, consistent with the results of Arjani (2006), the aggregate value and volume of potential out-payment delays even at SWP 20 are very small – only a fraction of a percentage point of the average daily value and volume of payments submitted to the LVTS T2 for settlement. Even so, the individual out-payments that could be delayed are fairly large in value. Second, about 80 per cent of the potential out-payment delays originate with participants within the inner-core subgroup. But at higher SWP levels, the value and volume of potential delays decrease more rapidly for the outer-core and the non-core subgroups than for the inner-core subgroup, so that the inner core's share of potential out-payment delays in the LVTS T2 increases moderately up to SWP 24. Consequently, the tighter the available liquidity network-wide, the more widespread are potential out-payment delays over subnetworks.

Table 1
Unsettled Out-Payments
(daily average; per cent of network total)

Participant and subgroup	SWP 23		SWP 22		SWP 21		SWP 20	
	Value	**Volume**	**Value**	**Volume**	**Value**	**Volume**	**Value**	**Volume**
Inner core	**83.7**	**84.3**	**83.3**	**83.4**	**77.7**	**75.9**	**79.5**	**72.9**
Bank A	50.9	73.3	48.2	69.5	47.2	62.4	42.3	59.3
Bank B	18.2	4.3	20.4	4.3	17.1	4.6	21.0	4.6
Bank C	14.6	6.7	14.7	9.6	13.4	8.9	16.2	9.0
Outer core	**15.4**	**9.6**	**12.5**	**12.6**	**16.2**	**18.0**	**14.6**	**21.6**
Bank D	2.1	0.8	2.7	1.4	2.9	2.0	2.4	1.1
Bank E	1.7	0.2	2.4	1.2	3.7	1.6	3.9	2.0
Bank F	1.9	1.9	1.8	2.1	2.7	2.2	2.3	1.8
Bank G	9.7	6.7	5.6	7.9	6.9	12.2	6.0	16.7
Non-core	**0.9**	**6.1**	**4.2**	**4.0**	**6.1**	**6.1**	**5.9**	**5.6**
Total (per cent)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Network Total	**$mil.**	**number**	**$mil.**	**number**	**$mil.**	**number**	**$mil.**	**number**
Daily average	$225.6	6.6	$455.8	12.6	$687.3	18.3	$1,050.7	26.2
Per cent of total submitted	0.16	0.03	0.32	0.07	0.48	0.10	0.74	0.14

Finally, but possibly most critically, the pattern of out-payment delays is quite different, not only between subgroups but also over individual participants within the same subgroup at the lower SWP levels. This pattern is consistent with those in Charts 1 and 2 relating to the concentration of large-value out-payment links across subnetworks between the dominant participants in each subnetwork.

Even though the vast majority of the potential out-payment delays originate with participants in the inner-core subgroup, Chart 1 only hints at which group of participants might suffer the largest potential in-payment losses. Table 2, however, confirms that the potential payment flow losses from out-payment delays are, indeed, also concentrated within the inner core subgroup.

Table 2
Subgroup Distribution of Unsettled Out-Payments
(per cent of value)

	SWP 23			SWP 22			SWP 21			SWP 20		
	Out-payments to											
Out-payments from	IC	OC	NC	IC	OC	NC	IC	OC	NC	IC	OC	NC
Inner core (IC)	60	29	11	64	26	10	58	31	11	64	27	9
Outer core (OC)	85	8	7	76	18	5	83	13	4	83	12	5
Non-core (NC)	94	4	2	86	12	2	88	9	3	86	10	4

The columns under each SWP level indicate the percentage of the delayed out-payments that are in-payment losses to that specific subgroup. The diagonal elements of the submatrices under each SWP value, therefore, show how much of the potential delays in out-payment value originating in that subgroup would be absorbed within that specific subgroup as potential in-payment losses. For example, the inner-core subgroup absorbs 64 per cent of its potential out-payment delays at SWP 20 as in-payment losses, while passing through 27 per cent to the outer-core subgroup and only 9 per cent to the non-core. Conversely, 86 per cent of the out-payment value potentially delayed within the non-core subgroup at the same SWP would show up as in-payment losses to the inner-core subgroup. The non-core subgroup would absorb only 4 per cent of the value of its potential delays as in-payment losses.

The key point is that, while the change in the SWP has an equiproportionate and, thus, a neutral impact on all participants' NDCs and CPCs when bilateral credit limits are held constant, the ultimate effect on out-payment flows and in-payment financing is non-neutral, because of network asymmetry among participants. Most of the effects are concentrated within the dominant inner-core subgroup, but they can spread as well to other subgroups in a disproportionate manner. Hence, the incentives on whether to adjust to systemwide shocks, and the preferred strategy if some choose to adjust, can be very different among subgroups.

5.3 Network equilibria analysis

What network equilibria can arise with the self-perpetuating and self-reversing reaction strategies available to individual participants?

5.3.1 The self-perpetuating strategy

This strategy can arise when the penalty costs of out-payment delays are low in comparison with the queuing costs and liquidity costs of eliminating or even reducing them. Participants might then decide to delay payments rather than adjust their BCLs, CPCs, and queue-management programs. Since the majority of these potential delays are concentrated among the dominant participants in the LVTS T2, and are relatively low, in aggregate terms, in value and volume, the acceptance of out-payment delays to limit queuing and collateral costs when delay penalties are virtually non-existent is not an implausible strategy. Table 3 summarizes the participant-specific outcomes from the common self-perpetuating strategy.

The allocation of T2 collateral costs and out-payment delays is largely consistent in relative terms with the centrality and intercentrality rankings of the individual network participants, which is also reflected in their relative activity levels. Bank A, and others in the inner-core subgroup, have the highest CPCs, the largest value of out-payment delays, and the highest out-payment delay value per dollar of CPC. However, the relative outcomes for other network participants under a self-perpetuating strategy suggest more diversity in their strategic preferences. In the outer-core subnetwork, for example, Bank E, the dominant participant in the subnetwork, and Bank G prefer more out-payment delays and lower collateral costs relative to the other subnetwork participants. In the non-core subnetwork, the pattern is even more diverse, as indicated by the ratio of out-payment delays per dollar of CPC. Some subnetwork participants in the non-core prefer relatively more out-payment delays and lower collateral costs than does Bank H, the dominant participant in the subnetwork. Only a couple of others prefer relatively lower out-payment delays than Bank H per dollar of CPC.

Table 3
Self-Perpetuating Equilibrium at SWP 20

Subgroups and participants	Collateral pool contributions ($ millions)	Out-payment delays ($ millions)	T2 velocity ratio[1]	Collateral pool utilization rate[2]
Inner core				
Bank A	458.0	444.5	102.8	-
Bank B	424.6	220.6	68.4	1.93
Bank C	350.7	170.6	59.0	0.56
Outer core				
Bank D	313.8	25.4	36.4	0.45
Bank E	313.1	41.4	38.1	0.67
Bank F	308.6	23.8	21.7	0.27
Bank G	218.8	63.4	23.2	-
Non-core				
Bank H	235.2	16.8	20.2	0.13
Bank I	205.5	7.9	15.9	-
Bank J	123.2	17.4	22.0	-
Bank K	127.8	4.2	20.1	0.06
Bank L	47.6	7.4	5.8	-
Bank M	24.1	5.9	11.2	0.09
Bank N	18.7	1.2	4.5	-

1. Ratio of the value of the participant's out-payments to the value of its T2 collateral pool contribution.
2. The collateral pool utilization rate is the ratio of a participant's average daily draw on the collateral pool, less its own collateral pool contribution, divided by its own collateral pool contribution. Negative values are set at zero, so that the reported ratio reflects the utilization of other participants' contributions to its own.

Note: See the appendix for a detailed derivation and explanation of the velocity and collateral pool utilization ratios.

The velocity and collateral pool usage measures of participants for this strategy indicate an extensive use of the collateral pool by over one-half of the LVTS T2 participants, and very extensive use by most participants in the inner- and outer-core subnetworks. Interestingly, however, Bank A – the most dominant participant network-wide – uses the collateral pool least among the core participants in this equilibrium. With very low delay penalties compared to collateral costs and, in this case, queuing costs driving individual participants' strategies to an equilibrium, Bank A utilizes in-payments and its own CPC to fund out-payments and delay the rest to limit other settlement management costs. Even so, it manages to settle the highest value and volume of out-payments per dollar of CPC within the overall network. To settle the next highest value of out-payments per dollar of CPC, Bank B must rely on its in-payments and still draw more than double the value of its own CPC from the T2 collateral pool. Nevertheless, it still leaves out-payment delays valued at about one-half those of Bank A.

Although many of the network participants use the T2 collateral pool in amounts above their own CPC to fund some of their out-payments, the pooling effect still implies a cross-subsidy from those that use the pool less intensively (and especially those that use no more than their own CPC to fund out-payments) to those that use it most intensively. The beneficiaries of the cross-subsidy include most of the core participants.

5.3.2 Self-reversing strategies

There are three possible strategies to accommodate settlement of all payments and thus avoid out-payment delays: bilateral renegotiation of BCLs, greater use of the central queuing mechanism, and an increase in the systemwide parameter to SWP 24. The principal incentive leading to the pursuit of these strategies would be high penalty costs for payment delay relative to liquidity and queuing costs. Which of these strategies could lead to a network equilibrium depends on the marginal cost of collateral increases (a one-time renegotiation cost plus pledging and net interest costs) relative to that of central queuing.

Liquidity costs

Table 4 shows the participant-specific collateral costs for each of the self-reversing strategies. The lowest-cost strategy for Bank A and the other network participants is the queuing strategy. By allowing a full-cycle queuing period and eliminating the minimum payment value requirement, a central queuing strategy, with a small residual tail settled through T1, could reduce Bank A’s average daily collateral cost by almost $250 million relative to the T1 settlement.[10] If queuing costs are sufficiently high relative to collateral costs, the strategy involving the renegotiation of BCLs or an increase in the SWP would be more attractive. Of the two, the BCL strategy is the lowest cost for all participants except Bank B. The SWP increase is, indeed, the lowest cost for Bank B only. Based on the proposition that the dominant participants

10. As a precautionary strategy, LVTS participants pledge collateral for T1 settlement in excess of their needs (McPhail and Vakos 2003). For some participants, the T1 settlement of their part of the migration shock would consume all their excess collateral and, for a few, even require a small additional collateral increase.

in the network and each subgroup choose the equilibrium strategy, the strategy involving an increase in the SWP is first-dominated by the other two self-reversing strategies.

Table 4
Collateral Costs for Self-Reversing Strategies
($ millions)

	BCL renegotiation	**Central queue adjustment**	**Increase to SWP 24**
Inner core			
Bank A	501.8	463.4	549.6
Bank B	514.9	424.6	509.8
Bank C	408.8	380.6	421.0
Subtotal	**1,425.5**	**1,268.6**	**1,480.4**
Outer core			
Bank D	356.4	314.0	376.7
Bank E	358.3	313.2	375.9
Bank F	327.5	308.6	370.5
Bank G	234.0	218.8	262.6
Subtotal	**1,276.2**	**1,154.6**	**1,385.7**
Non-core			
Bank H	246.8	235.2	282.4
Bank I	211.7	205.5	246.7
Bank J	141.8	123.2	147.8
Bank K	134.1	127.8	153.4
Bank L	46.1	48.2	53.9
Bank M	25.4	24.1	29.0
Bank N	20.4	18.7	22.5
Subtotal	**826.3**	**782.7**	**935.7**
Total	**3,528.0**	**3,205.9**	**3,801.8**

In sum, there are two possible strategies that can lead to three potential equilibria. The first equilibrium involves a self-perpetuating strategy. It is characterized by very low collateral costs for each network participant and a non-trivial volume and value of payment delays, especially for the dominant participants. It is conjectured that this equilibrium could arise when payment delay costs are extremely low compared with collateral costs and queuing costs. In this conjectural equilibrium, participants may even choose to hide payment delays from the network by queuing them internally if this would reduce payment delay penalties even further. This would be a unique strategic equilibrium under these relative cost conjectures. The other two equilibria are associated with self-reversing strategies, which would arise when bilateral out-payment delays are visible to, or readily estimable by, other network participants and the payment delay penalties are high relative to the liquidity and queuing costs of eliminating them. When liquidity costs are high relative to queuing costs, the equilibrium strategy is to adjust the queuing parameters to allow more liquidity-efficient use of the central queuing mechanism in the LVTS T2. The conjectural equilibrium for this strategy involves the lowest liquidity cost of the self-reversing strategies and no out-payment delays. When queuing costs are high relative to liquidity costs, the equilibrium associated with BCL renegotiation could arise.

Liquidity efficiency and optimality of the strategic equilibria

While any of these strategies could arise, they would generally produce a stable network equilibrium only under the conjectured relative cost conditions and the equilibration assumption that dominant participants select a commonly adopted strategy. The strategies that produce an equilibrium are the most likely to ultimately emerge, given the objectives of the participants and the comparative payoffs from each strategy. However, the fact that these conjectural equilibria can exist does not imply that they are all universally desirable. For this analysis, the systemwide desirability of a conjectural equilibrium is defined by the following four properties: (i) a high degree of liquidity efficiency network-wide, (ii) no out-payment delays, so that all payments are settled within the settlement cycle in which they are submitted, (iii) a mutually acceptable liquidity cross-subsidy scheme among network participants, and (iv) a low strategic operating cost. These criteria indicate that individual network participants satisfy their payment management objectives in terms of cost minimization yet satisfy the prompt settlement needs of clients originating the payments.

In Table 3, the equilibrium relating to the self-perpetuating strategy has a very low collateral cost overall, but one that, in comparison with the queuing equilibrium for the self-reversing strategy, is only slightly lower for some participants and the same for others. Also, the liquidity cross-subsidy of the self-perpetuating equilibrium favours participants in the inner- and outer-core subgroups more than under the self-reversing queuing equilibrium. Furthermore, it leaves delayed payments. Therefore, while it may pay off for the dominant participants in the network to encourage the adoption of the self-perpetuating equilibrium when out-payment delay penalties are virtually zero, it would not be a socially desirable network equilibrium.

Table 5 shows the liquidity-efficiency properties of the self-reversing strategies. With respect to the velocity of participants' T2 liquidity, the queuing strategy is either the most liquidity efficient, or is no less liquidity efficient, than any other strategy for all network participants. All out-payments are settled within the daily cycle with the same or lower collateral than any other self-reversing strategy. It is the most liquidity-efficient strategy for all inner-core participants, and is no less liquidity-efficient than any other for the dominant participants in the other subnetworks.

The liquidity efficiency of the queuing strategy relates largely to a pooling of out-payments that allows their release for settlement to fund, in turn, the recipients' out-payment releases from the queue (i.e., a cascade effect). In effect, queuing allows the formation of an interdependent sequence of bilateral netting among linked pairs of network participants. The result is a quasi-multilateral netting through the queue that leaves only a small tail value of queued but unnetted out-payments to be settled via the LVTS T1. A more effective queuing algorithm for the LVTS T2 that would reorder payments to permit a more efficient multilateral netting process could eliminate some, if not all, of this tail amount.

Not only does the queuing strategy have the lowest liquidity cost, and is the most liquidity-efficient, network-wide, among the self-reversing strategies, it also involves the lowest liquidity cross-subsidy between subnetworks. The cross-subsidy in this equilibrium may be quite acceptable to the LVTS T2 participants, since (i) collateral costs are low for all participants, (ii) potential out-payment delays are avoided, which provides a greater flow of in-payment financing for out-payments by all network participants, and (iii) the cross-subsidy is low compared with the other strategies. If queuing costs are low relative to delay penalties and the costs associated with BCL and SWP renegotiations, the queuing strategy will yield a socially desirable equilibrium.

Table 5
Efficiency Properties of Self-Reversing Strategies
(daily average)

Subgroups and participants	T2 velocity ratio[1]			Collateral pool utilization rate[2]		
	T2 parameter adjustments			T2 parameter adjustments[3]		
	BCLs	Queue	SWP	BCLs	Queue	SWP
Inner core						
Bank A	96.3	103.8	86.6	0.27	0.38	0.15
Bank B	57.9	68.5	57.4	1.49	1.77	1.46
Bank C	51.6	59.3	49.6	0.29	0.61	0.23
Outer core						
Bank D	32.7	36.4	30.4	0.18	0.32	0.09
Bank E	33.9	38.2	31.8	0.39	0.57	0.31
Bank F	20.6	21.7	18.1	0.18	0.24	0.02
Bank G	22.0	23.5	19.6	-	-	-
Non-core						
Bank H	19.4	20.3	16.9	0.05	0.09	-
Bank I	15.6	15.9	13.3	-	-	-
Bank J	20.2	22.1	18.4	-	-	-
Bank K	19.6	20.1	16.8	-	0.04	-
Bank L	5.8	5.9	4.9	-	0.01	-
Bank M	11.3	11.4	9.6	0.23	0.15	0.03
Bank N	4.4	4.5	3.8	-	-	-

1. Ratio of the value of the participant's out-payments to the value of its T2 collateral pool contribution.
2. The collateral pool utilization rate is the ratio of a participant's average daily draw on the collateral pool, less its own collateral pool contribution, divided by its own collateral pool contribution. Negative values are set at zero, so that the reported ratio reflects the utilization of other participants' contributions to its own.
3. Includes collateral used for T1 settlement of residual out-payment delays with BCL and queue adjustments.

Note: See the appendix for a detailed derivation and explanation of the velocity and collateral pool utilization ratios.

However, if queuing costs are relatively high for the dominant participants in the network, they are unlikely to support a queuing strategy. Considering the low collateral costs for the dominant participants, other than Bank B, in the network and subnetwork, and the limited additional collateral cost to that bank, the BCL renegotiation strategy could find support. According to the desirability criteria other than strategic administrative costs, it is already a close second-best to the queuing equilibrium. If the BCL renegotiation costs are sufficiently lower than the administrative costs of the queuing strategy, it will be the socially desirable equilibrium.

The cross-subsidy is greatest for the strategy involving an SWP increase. With an SWP increase, all participants raise their CPCs equiproportionately, but fewer of the non-core participants use the collateral pool beyond their own CPC value.[11] Together with its high collateral costs, the cross-subsidy effect rules out this strategy as one leading to a highly desirable equilibrium, and confirms further its dominated position as a conjectural equilibrium.

6 Conclusions

The analysis in this paper is highly stylized. For example, it refers to potential responses of heterogeneous participants to anticipated small aggregate one-time shocks that have asymmetric effects on the different classes of participants. The potential responses could be different if the shocks were unanticipated, larger, or dynamic. The assumption of a one-time shock combined with the implicit premise of independent one-period games permits the use of a static model for the analysis. Were the model to allow intertemporal effects, such as overnight payment delays with next-day penalty costs or a phased increase in payments over time, optimal strategic choices different than those derived from this model might arise. In this regard, the analytical framework suffers from the absence of endogenous interaction between participants' behaviours and reactions for changes in the key parameters of the the LVTS T2 network (as defined in the LVTS BoF-PSS2 simulator). Also, the absence of available information on internally queued payments forces the construction of potential out-payment delays through artificial means, in this case an SWP reduction. Consequently, the participant-specific results may be influenced by the construction of the artificial systemwide shock and may be specific to the sample period not only in absolute terms but also possibly in terms of some relative relationships.

Nevertheless, even with the limitations noted above, the analysis highlights some key interactions among three critical characteristics of the LVTS T2: (i) the role of out-payments in the liquidity efficiency of network settlement, (ii) the influence of heterogeneity among participants and the associated degree of asymmetry in their network interdependencies on liquidity efficiency, and (iii) the extent of interactive reactions possible among individual

11. Although not reported in the results, the utilization ratio for the collateral pool, u(BCL, SWP), shows a similar pattern. The frequency of use of the collateral pool, which is significantly lower for non-core participants than the others, declines relatively more for non-core participants when the SWP increases.

participants to a systemwide event when arriving at a network equilibrium, which incorporate some measure of network externalities.

The LVTS T2 is a network of three related subgroups of participants. These subgroups are asymmetric in terms of their levels of network activity, liquidity efficiency, and degree of network centrality. The connectivity between the subgroups is largely concentrated in bilateral links between the most central and intercentral participants in each. These few dominant participants in the network, especially those in the inner-core subgroup that account for the highest level of network activity, are the principal source of in-payment financing for out-payments for the whole network. Due to this asymmetry among network participants, even systemwide shocks that seem to be neutral in relative participation effects can result in highly non-neutral outcomes. Individual (asymmetric) participants may have common objectives (notably, cost-minimization of prompt out-payment settlement) and may be aware of their own payoffs from each of the various available adjustment strategies – most of which would require bilateral or multilateral negotiation – and still prefer different strategies. Consequently, there may be a multiplicity of potential network equilibria.

We propose three network equilibria, each of which could exist for a particular relative ranking of collateral costs, queuing costs, and delay costs common to all network participants. One equilibrium involving a self-reversing queuing strategy, which arises with high delay penalties and low queuing costs relative to collateral costs, is, according to the defined criteria, the most desirable systemwide. An alternative possible equilibrium involving a different self-reversing strategy – BCL adjustments – may also arise if its administrative costs are sufficiently low compared with those of the queuing strategy. It would also be socially desirable if the administrative cost saving were to exceed the liquidity cost difference favouring the queuing strategy. The third potential equilibrium involves a self-perpetuating strategy, which has a very low liquidity cost but with significant out-payment delays. It could arise when delay penalties are virtually zero. It would not, however, satisfy the desirability criteria for a network equilibrium, since out-payment delays impose a liquidity inflow loss on clients of the network participants who receive payments, and force the receiving network participants to either delay some of their own out-payments or increase their liquidity costs to make them. Overall, the liquidity efficiency of the LVTS T2 would suffer.

Our analysis highlights a number of critical factors for policy formulation by the operators of the LVTS and its regulators. Understanding the scope and importance of network asymmetries, and the reactions of different classes of participants to systemic shocks, is necessary for determining the likely level and pattern of network participation. Just because it exists, a network equilibrium may not actually be as desirable as some other strategic equilibria. System operators and regulators should, therefore, promote the provision of meaningful information about the overall cost, payment flow, and cross-subsidy effects concerning alternative feasible adjustment strategies. Such transparency is necessary to allow network participants to converge toward a welfare-desirable network outcome. To achieve this goal, system operators and regulators might focus greater attention on: (i) mapping out the critical aspects of the network's topology using a variety of informative metrics and approaches, (ii) considering carefully in their payments policy changes how relevant network asymmetries of different types might drive the final outcomes in terms of their preferred properties, and (iii) innovating and implementing greater flexibility, wherever technologically and economically feasible, into the various LVTS T2 liquidity-efficiency mechanisms – most especially, in relation to this analysis, the central queuing mechanism.

References

Arjani, N. 2006. “Examining the Trade-Off between Settlement Delay and Intraday Liquidity in Canada’s LVTS: A Simulation Approach.” Bank of Canada Working Paper No. 2006-20.

Arjani, N. and D. McVanel. 2006. “A Primer on Canada’s Large Value Transfer System.” Bank of Canada. Available at <http://www.bankofcanada.ca/en/financial/lvts_neville.pdf>.

Ball, D. and W. Engert. 2007. “Unanticipated Defaults and Losses in Canada’s Large-Value Payments System, Revisited.” Bank of Canada Discussion Paper No. 2007-5.

Ballester, C., A. Calvo-Armengol, and Y. Zenou. 2006, “Who’s Who in Networks. Wanted: The Key Player.” *Econometrica* 74 (5): 1403–17.

Bech, M. L., J. T. Chapman, and R. Garratt. 2007. “Which Bank is the ‘Central Bank’?: An Application of Markov Theory to the Canadian Large Value Transfer System.” In *Developing a Framework to Assess Financial Stability*. Proceedings of a conference held by the Bank of Canada, 6–8 November. Ottawa: Bank of Canada.

Bech, M. L. and R. Garratt. 2003. “The Intraday Liquidity Management Game.” *Journal of Economic Theory* 109 (2): 198–219.

———. 2006. “Illiquidity in the Interbank Payment System following Wide-Scale Disruptions.” Federal Reserve Bank of New York Staff Report No. 239.

Beyeler, W. E., R. J. Glass, M. Bech, and K. Soramäki. 2006. “Congestions and Cascades in Payment Systems.” Federal Reserve Bank of New York Staff Report No. 259.

Bonacich, P. 1987 “Power and Centrality: A Family of Measures.” *American Journal of Sociology* 92 (5): 1170–82.

Committee on Payment and Settlement Systems (CPSS). 2005. “New Developments in Large-Value Payments.” Bank for International Settlements. CPSS Publication No. 65.

Ledrut, E. 2007. “Simulating Retaliation in Payment Systems: Can Banks Control Their Exposure to a Failing Participant?” De Nederlandsche Bank Working Paper No. 133.

Martin, A. and J. McAndrews. 2007. “Liquidity-Saving Mechanisms.” Federal Reserve Bank of New York Staff Report No. 282.

McPhail, K. and A. Vakos. 2003. "Excess Collateral in the LVTS: How Much is Too Much?" Bank of Canada Working Paper No. 2003-36.

McVanel, D. 2005. "The Impact of Unanticipated Defaults in Canada's Large Value Transfer System." Bank of Canada Working Paper No. 2005-25.

Soramäki, K., M. L. Bech, J. Arnold, R. J. Glass, and W. E. Beyeler. 2006. "The Topology of Interbank Payment Flows." Federal Reserve Bank of New York Staff Report No. 243.

Appendix

Technical Description of Network Topology Measures

Completeness

According to Soramäki et al. (2006), completeness of interconnectivity among participants is measured by the number of out-payment links that an individual participant has with other participants in the network (the maximum being (N-1) for N participants). The number of links that a participant can have with other individual network participants is the sum of its out-payment links and in-payment links to and from the others. The degree of completeness of a network can then be measured by the average number of out-payment links per participant ($M \leq (N$-1)) relative to the maximum possible number per participant ($N(N$-1)).

Symmetry

Although heterogeneity in a network can be defined by differences in the average number of linkages of individual participants, even complete networks can be asymmetric when the value of these links is considered. Network symmetry is measured by value-weighted links. In this analysis, the bilateral out-payment links of each participant are weighted by the value of out-payments made through these links each day. Ordering pairs of participants by the value of their bilateral out-payment links with each other makes it possible to identify subgroups of participants within a network in which the value-weighted linkages are relatively symmetric among participants within a particular subgroup but quite asymmetric between the subgroups.

Centrality

The centrality of a participant in a network is measured by its relative ranking as a circulator of liquidity through the network via the out-payments it makes in relation to the in-payments it receives. The Bonacich (1987) measure of centrality in a general network can be adapted to a payment settlement network. In the payments system context, the measure considers all the sequences of value-weighted out-payment links, beginning with one network participant's link to another, the second participant's link to a third, and so forth, ultimately leading back to the originating participant. This sequence of bilateral links is called an out-payment path. In the modified Bonacich centrality measure, each of the value-weighted direct and indirect paths from one participant to another is power-weighted by the path length and multiplied by a discount factor also power-weighted by that path length. The discounting represents the fraction of the value diverted by the receiving participant to paths other than those circulating back to the originating participant making the out-payment. Hence, the longer the path, the lower is the amount recaptured by the out-payment originator through in-payments from other participants on the same network path. A participant's centrality measure is the sum of all these possible discounted, value-weighted paths.

Ballester, Calvo-Armengol, and Zenou (2006) modify the Bonacich measure by normalizing the centrality measure around feedback loops; they term this new measure "intercentrality." In adapting the Bonacich measure to a payment settlement network, the normalization is around the participant's liquidity recapture value. The intercentrality measure in a payment settlement network focuses more precisely on the value of liquidity sent by a participant to other network participants relative to the portion of that value recaptured. The longer the path lengths emanating from a participant to others in the network, for a given value of out-payments sent, the greater is its reach throughout the network and, thus, the more central is its intermediary role in value transfer. A participant with large out-payment values and short paths can be defined as central by the centrality measure, while a participant with lower out-payment values and longer paths may be intercentral to the network according to the intercentrality measure. A particular participant can, of course, dominate in the network group according to both measures.

To illustrate the two measures, let G be an n x n (zero) diagonal matrix for which each element is the value-weighted out-payment link between participants i and j. Since the maximum value of out-payments a participant can make before receiving an in-payment is capped by its NDC, each element in the matrix is a function of the vector of BCLs granted to the ith participant and the SWP. Thus, $G(\text{BCL, SWP}) = [g_{i,j}\,(\text{BCL, SWP}); \forall j \neq i]$. The centrality measure is defined as:

$$B(g, p) = [\textstyle\sum_{k=1} \mathrm{p}^{\mathrm{k}} \cdot G^{k}] \cdot i = M(g, p) \cdot i \text{ , which has as a typical element} \tag{1}$$

$$b_i(g, p) = \{[m_{ii}(g, p) + \textstyle\sum_{j \neq i} [m_{ij}(g, p)]\} \text{ for } m_{ij}(g, p) = \textstyle\sum_{k=1} (p^{k} \cdot g_{ij}^{\;k}), \tag{2}$$

where p is the discount factor representing the decay in the value of the out-payment from the ith to jth. In this paper, $p = (1 + r)^{-1}$; $0 \leq p \leq 1$, on the premise that distance and time vary directly and equiproportionately and that r is the average one-day holding-period equivalent of the annualized overnight target rate. It represents the cost of refunding the out-payment decay over the path length.

The intercentrality measure derived from the centrality measure has a typical element:

$$[c_i(g, p)] = \{[b_i(g, p)]^2)/(m_{ii}(g, p)\}. \tag{3}$$

Velocity of liquidity

The velocity of a participant's liquidity in a payment settlement network refers to the value of out-payments sent and settled relative to the value of the initial liquidity investment. When the funding of out-payments involves collateralized intraday borrowing, the value of the liquidity investment will include the (average) value of collateral pledged over the day relative to the (cumulative) value of intraday loans it supports. The velocity of liquidity measures the participant's liquidity efficiency. From an out-payment funding perspective, the liquidity efficiency of a participant's out-payment financing will relate to the sum of the intensity of in-payment use and the intensity in use of the pooled collateral needed to borrow settlement funds intraday, both relative to the participant's own invested collateral.

With collateral pooling as the main liquidity-saving feature of the LVTS T2, a participant can invest a lower amount of collateral into the pool to fund the same amount of intraday credit as in settlement systems without collateral pooling. Consequently, for a given level of in-payments, participants in the LVTS T2 that borrow collateral from the pool beyond their own contributions (CPCs) are able to fund a higher value of out-payments per dollar of collateral invested than those that utilize only some or even all of their own CPCs. A participant's liquidity efficiency in the LVTS T2 is then defined by the velocity measure:

$$V_i\,[\mathrm{BCL, SWP}] = [O_i/S_i] = h(\cdot)\cdot[I_i/S_i] + u(\cdot)\cdot[S/S_i], \tag{4}$$

where

O_i = average daily value of out-payments; $O_i \leq \mathrm{NDC}_i$,

I_i = average daily value of in-payments; $I_i \leq \sum_{j \neq i} \mathrm{BCL}_i$,

S_i = the CPC and $S = \sum_i S_i$ => the aggregate value of the T2 collateral pool,

$h(\cdot) = h(\mathrm{BCL, SWP})$ => the intensity of use for in-payment funding ,

$u(\cdot) = u(\mathrm{BCL, SWP})$ => the intensity of collateral pool use.

Since there is only one equation but two unknowns, [$h(\cdot)$, $u(\cdot)$], additional information is required to estimate the intensity factors. Defining $NP_{i,T+1,t} = (I_i - O_i)$ as the participant's net funds position on day t following its next out-payment ($T + 1$), the following conditions are assumed to hold for:

$NP_{i,T+1,t} \geq 0$, $u(\cdot) = 0 \Rightarrow 0 \leq h(\cdot) = [V_i / I_i] < 1$, and

$NP_{i,T+1,t} \leq 0$, $h(\cdot) = 1$ => in-payments fully utilized and for $0 < u(\cdot) = [(O_i - I_i)/S] \leq 1$,

$u(\cdot) \cdot S \leq S_i$ => utilization of no more than own CPC,

$u(\cdot) \cdot S > S_i$ => additional utilization of the CPCs of other participants.

These conditions are derived from the continuous-netting process and loss-allocation rule in the LVTS T2. To fund a given out-payment, they require that (i) accumulated in-payments in the LVTS T2 net funds position be fully utilized to make an out-payment before the participant can draw on the T2 collateral pool, (ii) the participant draw from the collateral pool to obtain intraday credit only for the amount of the negative net funds position its out-payment will create, and (iii) its draw on the collateral pool fully utilizes its own CPC before acquiring collateral from the remainder of the T2 collateral pool.