EUROPEAN CENTRAL BANK

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RECENT ADVANCES IN MODELLING SYSTEMIC RISK USING NETWORK ANALYSIS

JANUARY 2010

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PREFACE

In October 2009, the ECB hosted a one-day workshop called "Recent advances in modelling systemic risk using network analysis", which gathered together experts from central banks and from international organisations working in the fields of financial stability and payment system analysis/oversight. The aim of the workshop was to exchange views and experiences in modelling and analysing systemic risk in different kinds of networks that are relevant to financial stability and payment systems. The workshop also aimed to improve the awareness of network modelling in general, to enhance knowledge about the possibilities and limitations of this field of analysis, and to exchange experiences in the use and formatting of data, computing techniques and analysis of results that have been obtained in various institutions.

The global financial crisis that erupted in August 2007 clearly illustrated the role of financial linkages as a channel for propagation of shocks. Indeed, the spreading of the financial turmoil from the US sub-prime mortgage market via the securitisation instruments to the banks' off-balance-sheet vehicles and further to the banks' balance sheets and to other financial and non-financial sectors exposed unforeseen counterparty linkages and eroded confidence in a way which further amplified the effect of the initial shocks.

Research in the area of financial network analysis has shown that modelling the interlinking exposures either between financial institutions, among the sectors of the economy or across entire national financial systems, can assist in detecting important shock transmission mechanisms. Simulation exercises using these networks may then reveal that parts of the systems that might not be considered vulnerable to given adverse scenarios could still be affected due to their close interconnection with agents that are directly confronted with the unforeseen events. Policy recommendations could then be targeted towards structural changes that mitigate the adverse consequences that may emerge in closely intertwined systems in times of crisis.

Against this background, and in light of the recent institutional reforms concerning the global and European institutions for macroprudential supervision, improving the analytical capacity of central banks and international organisations entrusted with responsibilities in the areas of financial stability and payment system oversight has become paramount. The presentations and discussions in the workshop that are summarised in this paper provide one contribution to that end. They highlight the potential of network theory to enhance the tools for market infrastructure oversight, counterparty risk management and macroprudential analysis and propose several avenues for future research.

Any opinions expressed by the presenters, discussants, or chairpersons of sessions that are quoted in this paper are their own and do not necessarily reflect the views and opinions of their respective institutions.

INTRODUCTION

Introductory remarks by Gertrude Tumpel-Gugerell, Member of the Executive Board of the ECB

Ladies and Gentlemen,

I would like to welcome you to the workshop on "Recent advances in modelling systemic risk using network analysis" here at the ECB. A workshop on systemic risk that provides an analytical focus on the financial sector as a network of financial agents could not come at a more timely moment.

In 1896 the German sociologist Georg Simmel stated in his book "The Philosophy of Money": "money is the spider that spins society's web". With this, Simmel already at the time pointed to the network aspect of money, how financial innovation can transform the economy and society; and the transformation process as changes in the complexity, size and nature of economic and societal networks.

The recent financial crisis has strikingly illustrated the interconnectedness that characterises the global financial system. In providing a framework for strengthening financial stability, policy makers are currently not only refining the regulatory and institutional set-up, but also looking for new analytical tools that help to better identify, monitor and address sources of systemic risk. Therefore, I believe network analysis can make a relevant contribution and I am delighted that you have come together today to present and discuss new work in this field.

Let me give you three questions (from the perspective of a policy maker) which today's workshop would ideally shed light on:

What are the key channels and systemically important players that need special attention?

How can macro-prudential supervision take the interconnectedness into account?

And can network methodologies provide us with a useful tool in this respect?

With these questions in mind, I have structured my introductory remarks into three parts. I will first give a short assessment of the relevance of systemic risk in the modern financial system. Then I will discuss the use of network theories for the analysis of systemic risk. Finally, I will briefly refer to network applications to payment and financial systems.

SYSTEMIC RISK IN THE MODERN FINANCIAL SYSTEM

Systemic risk refers to the possibility that a triggering event such as a bank failure or a market disruption could cause widespread disruption of the financial system, including significant difficulties in otherwise viable institutions or markets. Preventing these negative externalities from impairing the functioning of the system and from spilling over to the real economy is a crucial element of the mission of central banks and of supervisory authorities.

In the last two years, the functioning of the global financial system has been challenged by an extraordinary sequence of such triggering events. This brought to the fore how complex and interconnected the financial system had become and, consequently, how problems in one part of the system could reach other parts, also very distant ones.

In July and August 2007 the asset-backed commercial paper (ABCP) market collapsed when investors realised that money market mutual funds had invested in paper backed by sub-prime assets. Investors became suddenly distrustful of all forms of private credit, especially structured products and other complex and opaque instruments, and this caused the funding for structured investment vehicles and special-purpose vehicles to dry up. Difficulties faced by conduits and other asset-backed programmes in rolling over their short-term funding forced them to look to bank sponsors for liquidity (this was the case, for instance, for IKB and Sachsen LB in Germany) or to sell assets. A crisis of confidence ensued which gripped money market mutual funds and the commercial paper market, notwithstanding their distance from the US housing market.

Such unstable dynamics, set off by increasing uncertainty about the size of losses in the system and, maybe more importantly, about their exact location, continued in the course of 2008. Then, the collapse of Lehman Brothers in September 2008 transformed a pessimistic and disoriented mood into full-blown panic and paralysis.[1]

The biggest negative surprise following Lehman Brothers' default was its effect on money market funds. When one fund, Reserve Primary, "broke the buck" (that is, the value of investors' money fell below the notional amount invested), the sector was hit by a wave of redemptions that fuelled instability in the credit markets. Again, banks and companies relying on short-term funding through commercial paper or ABCP (i.e. debt backed by mortgages, credit cards and other consumer loans) could not roll over their debt, except at overnight maturities.

The ensuing dynamics in market participants' behaviour clearly illustrate the presence of knock-on effects, negative externalities, and a coordination failure in the market network. Each institution responded rationally given individually available information. However, each rational response had repercussions for the whole system.

The impact of systemic risk depends very much on the collective behaviour of financial institutions and their interconnectedness, as well as on the interaction between financial markets and the macroeconomy. Systemic stability is a public good. The recognition of this public good property underpins the recent emphasis on a macro-prudential approach to regulation and supervision.

From a micro-prudential perspective, a strengthened supervision of individual institutions' risk-taking incentives is also important. A key element of the risk management framework of banks is that they take into account, in terms of credit and liquidity risks, the exposure they have to particular (potentially systemically relevant) counterparties. Systemic risk is, in principle, outside the control of each individual institution. But, by keeping liquidity buffers and capital reserves and by limiting large exposures and addressing dependencies, banks can contribute to an increase in the resilience of the system as a whole.

THE USE OF NETWORK THEORIES FOR THE ANALYSIS OF SYSTEMIC RISK

The financial crisis has reminded us how important it is to look at the links and connections of the financial system. We saw that major disruptions such as failure or a near failure of certain institutions rapidly spilled over to the whole financial system.

Therefore, network theory can help us to analyze the systemic risk of such disruptions (i) by looking at how resilient the system is to contagion; and (ii) what the major triggers and channels of contagion are.

An important aspect of the analysis of systemic risk is that an apparently robust system may in fact be very fragile. This comes from the fact that a high number of interconnections within the network will serve as shock-amplifiers rather than as absorbers.

Another key aspect of the analysis is that within the network of the financial system, there are players with only a few connections, but also players that are highly connected. Obviously, such networks are extremely vulnerable if those highly connected players are disrupted. In fact, when a shock hits the system, the number of affected participants can

1 G. Tett (2009), "Markets 12 months after Lehman collapse", Financial Times, 9 September.

be especially low, but the shock may still propagate system-wide. Payment systems, for instance, are networks with such a property.[2]

Clearly, large and highly connected financial institutions are systemically important. This has important implications for macro-prudential surveillance, and hence for financial stability. Network analysis is crucial for the identification of such systemically important institutions and markets which are critical players in the web of exposures. Monoline insurance providers and AIG provided an example of such critical institutions; key custodian banks or large correspondent banks play a similar role.

Let me add to this, that a particular institution might not only be critical to the functioning of financial markets or market infrastructures because other institutions are financially exposed to it, but also because other market participants rely on the continued provision of its services. For us as policy makers this is a crucial point, as the impact of a failure of a given market player also hinges on the ability of the financial infrastructure to support its resolution and to facilitate the orderly unwinding of positions. So let me now turn to the specific application of network theory to payment and financial systems.

NETWORK ANALYSIS APPLICATIONS TO PAYMENT AND FINANCIAL SYSTEMS

Research in network theory has received relatively little attention in economics until the last decade. Therefore, I am delighted to see that this literature is growing and today's workshop clearly illustrates its growing importance.

The papers from today's program highlight how direct and indirect interlinkages and contagion dynamics among financial institutions, as well as among institutions, markets and infrastructures, can be significantly influenced by three important network characteristics: First, the degree of connectivity, second, the degree of concentration and third, the size of exposures. We see from the papers that network analysis can help to better understand the interlinkages and systemic connections in many different segments of the financial markets, ranging from money markets to networks of credit default swaps (CDSs), and from large-value payment systems to cross-sector exposures in the euro area financial system.

We see that this research gives important insights into the various amplification mechanisms in the global web of financial connections. Such amplification very much depends on a number of factors, such as the size of aggregate macroeconomic shocks, asset price volatility, liquidity risk and financial leverage. Moreover, network analysis can be used to simulate the effect of credit and funding shocks on banking and financial stability by taking into account – beyond the direct balance sheet exposures – also the impact of contingent claims and credit risk transfer techniques.

I am glad that the workshop brings together a wide variety of applications. It demonstrates two key points: first, network analysis is advancing as a common tool for assessing dynamics within the various parts of the financial sector (from payment systems to interbank balance sheet exposures); and second, it reveals that a truly systemic perspective needs to combine the focus on various parts of the financial sector with an analysis of the interlinkages among them, ideally including the interaction with the real economy. This is, of course, an ambitious objective that calls for further research.

CONCLUSIONS

Let me conclude. The recent financial crisis has underscored the need for policy makers and regulators worldwide to track systemic linkages.

2 See M. Pröpper et al. (2008), "Towards a network description of interbank payment flows", DNB Working Paper No. 177, for an analysis of Dutch payment flows; C. Puhr and S. W. Schmitz (2009), "Structure and stability in payment networks – a panel data analysis of ARTIS simulations" in H. Leinonen (ed.), *Simulation analyses and stress testing of payment networks*, Bank of Finland, for the Austrian large-value payment system; and K. Soramäki et al. (2007), "The topology of interbank payment flows", Physica A, Vol. 379, pp. 317-333, for an analysis of Fedwire, the large-value payment system operated by the Federal Reserve.

Network analysis offers a very relevant tool for addressing this challenge. Its focus on interconnectedness and on systemically important market players makes it especially relevant for the assessment of the fragility or resilience of the financial system as a whole. By applying network theories we can benefit from the important progress made in other sciences to monitor and assess systemic risks, direct and indirect linkages, vulnerabilities and contagion. This is because networks allow us to look beyond the immediate "point of impact" of a shock and, hence, also to the spillovers likely to arise from interlinkages in the system. Thus, network analysis can undoubtedly provide useful guidance for the analysis of systemic risk and can be a key tool for the future analysis of such risk.

For us, such analysis will be of crucial importance. As you know a European Systemic Risk Board will be established with the mandate to map financial risks and their concentration at the system level for the macro-prudential supervision of systemic stability. The mandates of other supranational institutions and fora, such as the IMF and the Financial Stability Board, also refer to network aspects of the financial system that have become apparent during the current crisis and that should be taken into account in order to obtain new measures of financial fragility.[3]

Also for the specific field of market infrastructures the relevance of network effects is being taken into account. The market for credit default swaps (CDS) has clearly revealed its systemic importance, as the default of one major counterparty has put the whole system under severe strain. Therefore, I welcome very much that central counterparties for credit default swaps have been established to address first, the high degree of interconnectivity between CDS markets and credit and cash securities markets, second, the high leverage embedded in these financial instruments, and third, the significant concentration of related risks in a small group of major market players. Effective implementation of central clearing of derivatives enables a significant reduction in counterparty risk, hence addressing some of the negative externalities that stem from the over-the-counter network that has formed over the years.[4]

Interlinkages within the financial system are nothing fundamentally new. However, business strategies developed by financial institutions over the last 20 years and financial innovations have made the system much more interconnected, complex and opaque than it was in the past.

I believe that policy makers and regulators of today will be judged in the future on the basis of the regulatory measures and analytical tools they have applied to address the root causes of the crisis. A key challenge is to transcend a purely national or sector-specific perspective and to take an approach that matches the global nature of financial networks. A key prerequisite for network analysis as a surveillance tool remains, however, the availability of relevant data. This holds true especially on a cross-border basis, but also at bank level. Going forward, regulators and overseers should continue to develop ways to systematically collect and analyse data. The crisis has clearly demonstrated that data confidentiality must not stand in the way of improvements in systemic risk analysis and assessment by policy makers.

Once more, I welcome you to this workshop and I wish you productive and enriching discussions on this very relevant topic.

3 See IMF (2009), "Global Financial Stability Report", Chapter II on *Assessing the Systemic Implications of Financial Linkages*, April, and E. Nier et al. (2007), "Network models and financial stability", Journal of Economic Dynamics and Control, Vol. 31, pp. 2033-2060.

4 See also ECB (2009), "OTC derivatives and post-trading infrastructures", September.

DETAILED SUMMARY OF THE THEMES

SESSION I – ANALYSIS OF NETWORK TOPOLOGY, RECENT ADVANCES AND APPLICATIONS

The first session of the workshop, chaired by **Ignazio Angeloni**, provided an overview of the techniques and the methodologies of network analysis and of recent applications aiming to model and better understand the interconnectedness of financial and payment systems. The first presentation, made by Kimmo Soramäki,[5] provided the audience with a general introduction to the topic, as well as with concrete applications, illustrating the potential of this tool for policy purposes. The title – "Is network theory the best hope for regulating systemic risk?" – refers to the recent argument made by some policy makers and economists that network topology could represent a new and key tool for taking into account contagion and systemic risk.[6] The second paper, presented by Sheri Markose, provided an in-depth empirical mapping of the financial network created by credit default swap (CDS) obligations among US banks, and between banks and non-regulated entities (monoline insurers and hedge funds) involved as protection buyers and protection sellers. The long-term aim of this research is to establish fully digital and database-driven network mappings of key financial sectors for systemic risk modelling and assessment.

INTRODUCTION TO THE TOPICS

Kimmo Soramäki organised his presentation around three policy questions:

1. How can we measure the systemic importance of a bank?

2. Can regulators promote a safer financial system by affecting its topology?

3. Is it possible to devise early warning indicators from real-time data?

Soramäki provided a brief overview of the general findings of network theory that make straightforward the potential for its application to the analysis of *financial networks*. Networks are broadly defined as collections of *nodes* (banks) and *links* (in the form of credit and financial relationships). The links that exist between the nodes affect the attributes of the nodes (for example, banks' balance sheets are affected by existing links with other banks), and the structure of the links affects the performance of the system as a whole. There are a number of common properties shared by many large and complex networks that are of particular interest for policy makers today, as they allow for a better understanding of recent financial network dynamics. These are as follows:

- The "robust yet fragile" property of scale-free networks, i.e. of systems where the probability of finding a node with a high degree (high number of links) is very low, while the probability of a node having a few connections is very high. This property refers to the robustness of a connected network in the case of random removal of a node (given the high frequency of low-degree nodes), versus its fragility in the case of a targeted attack directed against one of the few highly connected vertices (which could represent, for instance, a financial hub).

- The "strength of weak ties", which refers to the relative importance – in terms of availability/dissemination of information – of *weak versus strong* connections in shaping the topology of the network.

- "Homophily", i.e. the concept that certain attributes tend to set up clusters of nodes.

- The "small world phenomenon", by which the number of links covering the distance between any two nodes tends to be relatively low (or network paths are short). This might have interesting implications for episodes of

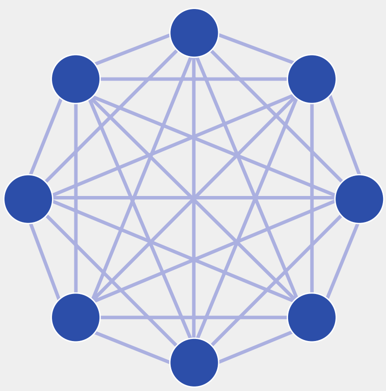
5 Kimmo Soramäki has recently created a website www.financialnetworkanalysis.com, which aims to gather research in this relatively unexplored field of financial economics.

6 See, for instance, IMF (2009), "Global Financial Stability Report", Chapter II on *Assessing the Systemic Implications of Financial Linkages*, and A. G. Haldane (2009), "Rethinking the financial network", speech delivered at the Financial Student Association, Amsterdam, in April.

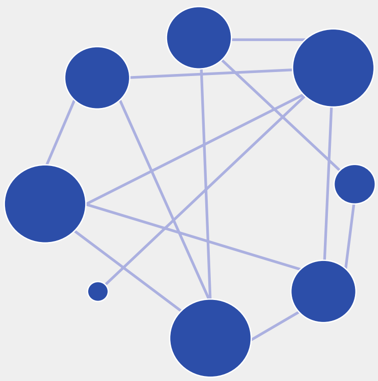
contagion in many real world small networks, since the number of affected nodes above which epidemics propagate system-wide is especially low (and it can be zero).[7]

Chart 1 Types of networks

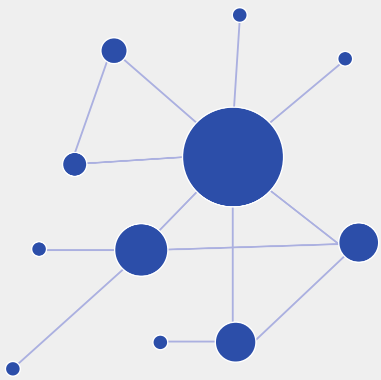
Complete network



Random network



Scale-free network



Source:

In applying these findings to financial networks one needs to consider the process taking place in the network and behaviour of the nodes in the particular field of application.[8]

A crucial characteristic of the structure of network processes is their *centrality* (i.e., in a broad sense, the relevance of the position of a node in the network).[9] Centrality might give an insight into which nodes should be considered of "systemic importance". However, Soramäki also made clear the limits of available centrality measures, since, although able to capture the type of flow-processes in the network, they do not currently capture any complex behaviour by the vertices, i.e. the drivers behind each node's choice to set up certain links and the magnitude of the links that are set up.

The lack of behavioural aspects is perhaps the main criticism addressed to network analysis by many economists today. The resulting mechanical representation of how the structure is created and evolves over time cannot fully capture feedback loops and endogenous responses which are, however, at the core of financial networks' developments. Indeed, the current crisis has shown how network processes can change in a sudden and unpredictable fashion. "Agent-based modelling" (relying on algorithms and simulations) is one recent approach devised to tackle this shortcoming.[10]

7 M. Bech, W. E. Beyeler, R. J. Glass and K. Soramäki in "Network topology and payment system resilience", BoF Simulation Seminar, 23 August 2006, provide evidence on how the "small world" property might affect interbank payment flows after the occurrence of a payment outage at a large bank. They show that scale-free, long-tailed networks display the highest rate of liquidity absorption after such a shock (the rate of absorption being the rapidity with which a certain amount of liquidity is *absorbed by/sent to* the distressed bank).

8 S. Borgatti (2005), "Centrality and network flow", *Social Networks*.

9 "Centrality" may be measured by the number of links that terminate upon a node (*in degree*), by the distance from other vertices (*closeness*), or by the existing connections to central nodes. A measure of centrality particularly suitable for financial networks is the *betweenness* centrality of a node, defined as the number of shortest paths that pass through the node.

10 An "agent-based model" (ABM) is a computational model for simulating the actions and interactions of autonomous individual agents with a view to assessing their effects on the system as a whole. A key concept in an ABM is that simple decision-making rules can generate complex behaviour at the system level.

For instance, Soramäki discussed a model of a real time gross settlement (RTGS) payment system with 15 banks introducing behavioural rules for each bank's decision about (i) the share of payments it has "queued" at any moment, and (ii) the size of net exposure it wants to have towards a single counterparty in relation to the total value of sent payments. Running simulations on the basis of these rules, the authors study how the centrality of a failing bank (removed for the whole day from the network) correlates with additional liquidity demand from the whole system. The more non-linearities the system exhibits due to bank behaviour or liquidity constraints, the weaker is the correlation of the failure impact with the centrality measures.

Concerning the possibility for policy makers to promote safer topologies, Soramäki referred to CLS, the world's largest settlement system for foreign exchange trades, as an example where the financial links of an institution are severely restricted for the purpose of financial safety. CLS is not allowed to have any non-FX settlement related links to the financial infrastructure. Another example is the introduction by regulators of sectoral barriers to banking, such as those introduced by the Glass-Steagall Act in 1933. A recent case in point is the introduction of central counterparty clearing for CDSs. Soramäki expanded on this last example by outlining research that he has done on the topology of the network that develops around the central counterparty (CCP).[11] This work studies the impact of different network structures – determined by the extent of tiering (i.e. the number of banks that participate directly in the CCP) and the concentration of clients across first tier (direct) clearers – on the maximum exposure of the CCP. The results show that the higher the level of tiering (i.e. the lower the number of members clearing directly in the CCP and the higher the number of indirect participants) and the higher the level of clients' concentration, the lower the CCP's maximum expected exposure. However, high tiering (for a given concentration) makes CCP's exposures more dispersed and increases the likelihood of larger exposure concentrations relative to a "star" format network (i.e. relative to the limiting case where clearers are all direct).

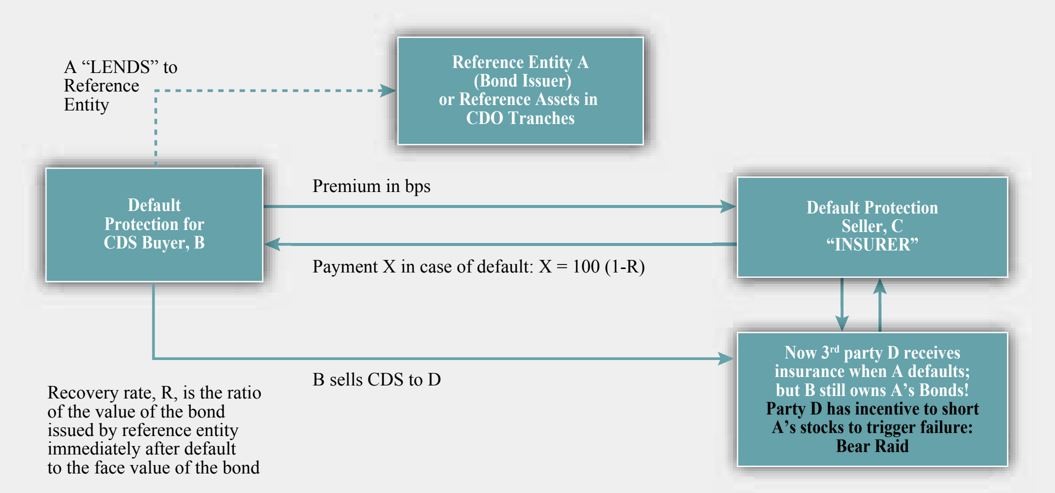
Finally, as regards the scope to devise early warning indicators from real data, Soramäki raised the possibility of central banks constructing such indicators – e.g. increased riskiness or worsened liquidity conditions of banks – by using the same kind of network techniques used by credit card companies on customers' payment behaviour to detect card frauds. For instance, payment data could be used to detect features in the timing of payments sent to and from the bank, in net outflows across different systems, in the bank's money market activity or in the volume of cash withdrawals/deposits made by the public, factors which are rather common across available examples of failed banks.

THE CDS NETWORK

The paper by **Sheri Markose**, Simone Giansante, Mateusz Gatkowski and Ali Rais Shaghaghi, "Too interconnected to fail: financial networks of CDS and other credit enhancement obligations of US banks", responds in part to Soramäki's agenda of key policy questions. The authors apply agent-based modelling to a financial network and use simulation results to devise an operational measure of systemic risk. The focus on CDSs stems from the "unique, endemic and pernicious role" that these instruments had in the current crisis. The authors argue that incentives provided by the credit risk transfer (CRT) scheme included in the Basel II accord could have contributed to the rapid expansion of this market. One potential consequence of banks' ability to reduce regulatory capital requirements by using CRT techniques has been the growing popularity of synthetic securitisations, with the consequent dispersion of products and risks worldwide in complex chains of insurance and reinsurance against credit default risk (see Chart 2). According to the authors, the large amounts outstanding and the relatively high concentration

11 M. Galbiati and K. Soramäki (2009), *Central counterparties and the topology of clearing networks*, forthcoming.

Chart 2 The CDS chain structure and bear raids 1)



Source: S. Markose (Workshop presentation, 2009).
1) CDS on single and multiple reference entities.

of risks to a few dominant players has brought to the fore the "too interconnected to fail" paradigm. To avoid such problems in the future, Markose et al. suggest setting up stress testing exercises for new financial instruments and propose such stress tests for the US CDS network.

The authors reconstruct their network using CDS linkages among the top 25 US banks and the external non-bank insurers. Market shares are taken as a proxy for actual bilateral exposures. Specific "small world" network properties and the loss impact suffered by each participant (in terms of core capital loss due to the failure of a major player) from its activity in the CDS market are computed.[12] This allows the authors to investigate the robustness of a topology in which the top five US banks accounted for 98% of the reported CDS gross notional value at the end of 2008, while the non-bank entities had the highest clustering of links with the top four banks.

According to the results of agent-based simulations presented in the paper, bailouts of institutions with very large numbers of links – notwithstanding their possible technical insolvency – could not be averted: the simulations show how a credit event at one such critical hub could have brought down part of the whole CDS market, with a consequent impact on the whole financial system.

The analysis reveals the presence of "super-spreaders" in the CDS network, i.e. large protection sellers who are highly "central" in the market in terms of clustering and connectivity measures, and whose capital bases – although comfortably fulfilling regulatory requirements – could be considered low when account is taken of the system-wide capital loss they may impose if they are assumed to fail in these simulation exercises. The same experiment is then simulated on a random (i.e. not *hub-clustered*) network. It is worth noting that, although the random graph has no nodes which are highly connected and also has lower network concentration or clustering, the consequences of its unravelling when hit by a shock may be more severe

12 The authors conduct two experiments. In both, they use a 20% reduction of core capital as a threshold to identify bank failures induced by the default of a triggering bank. The first test considers only the loss of CDS cover due to the failed bank suspending its guarantees as a counterparty. In the second experiment, the triggering bank is itself a CDS reference entity, which activates obligations from other CDS market participants. Furthermore, loss of cover owing to the triggering bank's default on exposures to special purpose vehicles and owing to other credit enhancements is considered.

(22 banks out of 25 fail rather than only five as in the previous case). At the same time, the dynamics that bring down the system develops over several consecutive rounds (following the demise of the triggering bank), and not just after the first one. This might have important implications for regulators and central banks aiming at promoting a safer financial system, and suggests the need to be cautious in promoting any form of "ideal" network topology.

Markose and her co-authors emphasise the need to incorporate institutional rules and behavioural aspects to obtain an adequate modelling of systemic risk and financial contagion. In particular, they discuss how agent-based models can address the failure of other economic tools to take into account systemic risk, heterogeneity in agents' strategies, and interconnectedness of relationships, that make the system prone to non-linear and extreme non-Gaussian dynamics when hit by a shock.

As regards regulatory solutions to the implicit "too big to fail" insurance enjoyed by large market players, the authors argue in favour of a price/tax to be imposed/levied on super-spreaders – possibly identified on the basis of the proposed "systemic risk ratio" (SRR) – to reflect the negative externalities imposed by these market participants on the whole system.[13] More generally, a price on the operations of "systemically important" players is regarded as an adequate measure to provide banks and especially non-banks (e.g. non-regulated monolines in CDS markets) with more aligned incentives to engage in over-supply of a given financial activity or instrument. Overall, based on their evidence, the authors suggest that it might be beneficial if the large negative externalities that arise from the possible demise of a big player in the CDS network were taken into account when banks are allowed to reduce capital on assets that have CDS protection.

Finally, welcoming the recent introduction of central counterparty clearing (CCP) in CDS markets, Markose et al. propose the use of agent-based stress-tests to estimate the amount of capital that a CCP should hold and the use of network indicators to make members' contributions to the CCP's capital or clearing fund proportional to their potential systemic impact. The authors also mention the possibility of changing the existing requirements on initial and on variation margins that market participants are required to post and hold as part of their risk controls.

MAIN COMMENTS AND DISCUSSION

Commenting on both papers, **Johannes Lindner**, discussant for this first session, agreed with the presenters on the crucial importance of agent-based modelling for understanding financial networks and especially their complex dynamics under distressed conditions. He said that this would be decisive in further strengthening of financial network analysis and would allow its establishment as an additional analytic tool for policy makers and regulators.

While recognising the potential of this new instrument, the discussant also pointed out the importance of a clearer categorisation of which shocks and crisis dynamics could be best understood using network analysis rather than other tools. For instance, network statistics computed after past failures of a market participant could be more useful inputs to early warning indicators designed to predict the impact of sudden idiosyncratic shocks on a financial entity than variables which capture the build-up of macro imbalances over time. Moreover, he mentioned how network analysis and simulations, even if "agent-based", might be less suited to capturing certain market imperfections, such as incomplete markets and asymmetric or imperfect information.

Lindner agreed that there was an opportunity to exploit today's computer-power to map network structures. To this end, he stressed the importance of getting access to data not only at the level of individual networks, but especially across networks and across national

13 For each trigger bank or non-bank CDS provider, the SRR estimates the percentage loss in aggregate core capital resulting from its collapse.

borders. Even acknowledging the limits to mapping complex adaptive systems in a unitary framework, the development of a comprehensive network perspective remains a key requirement for policy makers and regulators.

For instance, concerning the empirical reconstruction of the CDS network provided by Markose et al., Lindner recognised its merit as a good first approximation of bilateral exposures in the market. However, depending on data availability, a cross-check with actual bilateral exposures among participants, as well as the inclusion of Europe and/or other markets would be important in order to obtain a more reliable basis for policy implications.

An important point raised by many participants was whether network measures could represent an appropriate tool to identify systemically important market players and how these measures could be integrated in the existing toolbox of regulators. This is strongly related to the issue of how to address institutions' systemic importance and, therefore, of how regulators could encourage safer topologies. On this aspect, Markose et al. argue in their paper that imposing a "tax" on the operations of critical players could be one way of providing financial institutions with more aligned incentives and hence contain risks. Moreover, concerning the very recent move towards central counterparty clearing in CDS markets, Lindner concurred with Soramäki and Markose that this is a key example of how improvements in the infrastructure and encouragement from public authorities can affect the robustness of the financial system.

A CCP reduces counterparty risk, increases market liquidity and strengthens transparency. However, it also concentrates systemic risk. This makes the establishment of a strict risk management framework and adequate oversight by regulators essential. Similar to the need to regulate systemic risk and systemically relevant market players in the financial sector more broadly, the risk concentration in a CCP requires the combination of different risk controls – participation requirements, initial and variation margins, and financial resources (i.e. CCP's own capital or clearing fund) – to address the risks stemming from its participants.

Concerning the possibility of imposing a price on the operations of systemically important players, the subsequent discussion revealed that, from the point of view of regulators and overseers, a key operational issue would concern the exact definition of a critical participant (should authorities use a binary indicator or should different layers of "criticality" be considered?) and the way in which network connectivity could be taken into account in addition to traditional balance sheet or activity measures (i.e. size and volumes/values). One of the participants put forward the proposal to integrate existing risk management tools (e.g., CoVaR analysis) with network measures for regulatory purposes.[14]

A main caveat raised during the discussion on the identification of key market players concerned the inadequacy of indicators that are solely based on participants' exposures in a particular market/instrument. Ignazio Angeloni, chairman of the session, pointed out how such "narrow-view" indicators could actually provide a misleading picture on the criticality of a certain participant. In fact, an institution which is relatively small in one particular market could still be "central" in the network due to its uneven exposure to a large and highly connected player. Its demise might then still have a large impact on other participants in the system.

The particular usefulness of network tools for visualising direct linkages among market players and, depending on data availability, links across different markets is generally acknowledged. However, some participants

14 See IMF (2009), "Global Financial Stability Report", Chapter II, and M. Brunnermeier et al. (2009), "The Fundamental Principles of Financial Regulation," Geneva Reports on the World Economy, 11.

to the workshop expressed doubts about the scope of network analysis alone to understand the identity of factors driving the expansion of a financial market/instrument over time, or how a certain institution becomes a "key" player for a given market. Such an understanding is critical for regulators. The endogeneity of a market structure – which is the outcome of a dynamic process taking place over time – makes any policy intervention extremely difficult. On this part, while acknowledging this difficulty, Soramäki emphasised his conviction that this should not prevent the regulators from trying to use all the tools available to them to devise mechanisms that have the potential to mitigate risks ex ante and, therefore, to make the financial system safer.

SESSION II – INTERDEPENDENCIES AMONG INSTITUTIONS, SECTORS AND SYSTEMS

The second session of the workshop, chaired by **Paul Mercier**, brought together two papers on the theme of interdependencies among institutions, sectors and systems.

The experience of the recent crisis has shown that even the failure of relatively small but well connected entities can have unforeseeable negative financial consequences through contagious effects. For researchers, this poses new challenges as a better understanding of the structure and the functioning of financial networks is key to preventing risks inherently present in the system.

Following this line of investigation, the presentation given by Morten Bech enhanced the understanding of settlement behaviour of Fedwire participants before, during and after the failure of Lehman Brothers. Network analysis provides an adequate toolbox to analyse and visualise the daily changes of settlements in the Fedwire network as well as the increased behavioural coordination of its participants.

In contrast to the application of network analysis based on individual payments, Olli Castrén presented a paper looking at sector level interdependencies in the euro area financial system. Network analyses of this kind have so far been conducted on firm level and on country level, leaving an unexplored gap at the intermediate stage.

FEDWIRE SETTLEMENTS

The first paper of the session, entitled "Payments, crunch and easing" by **Morten Bech** and Ian Adelstein, uses network analysis to explore the changing pattern of Fedwire settlements following Lehman Brothers' bankruptcy.

The authors introduce a threefold concept by distinguishing between market, funding and settlement liquidity. While the focus of the paper lies in the latter, it also points to existing links between settlement and funding as well as settlement and market liquidity, emphasizing possible economic implications that can result from such interlinkages.[15]

In order to find out how major Fedwire participants changed their behaviour in terms of delayed settlements, the authors consider two shocks that actually materialised. Firstly, the impact of the failure of Lehman Brothers on liquidity and payment flows is explored. The injection of liquidity into the financial system by the Federal Reserve following the bankruptcy of Lehman is considered to be the second shock to Fedwire.

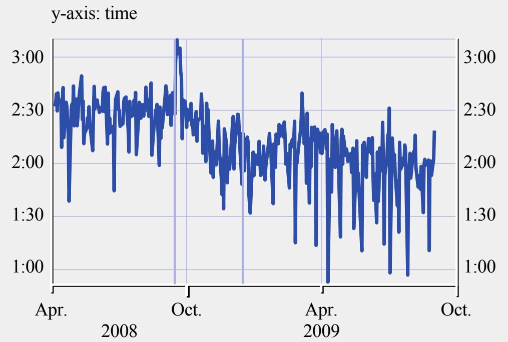
Focusing on payments settled in the system, Bech and Adelstein identify changing liquidity conditions by looking at different patterns of settlement timing on a daily basis from the end of March 2008 until 1 September 2009. Settlement liquidity in Fedwire is measured using data about the degree of daily settlement delays, dividing the period of interest into pre-crisis, crisis (Lehman's default) and post-crisis periods.

The authors find that prior to the collapse of Lehman Brothers the average settlement time was around 2:30 p.m. whereas it averaged as late as 3:10 p.m. in the two weeks following this major bankruptcy. During the last period under consideration, as a result of the liquidity injection by the Federal Reserve, settlements were undertaken considerably earlier – on average at 2 p.m. (see Chart 3).

However, settlements in Fedwire typically vary due to calendar effects. In order to net out such influences, the authors run a regression using dummies for days that are known to have different settlement timings. The actual delay due to non-calendar effects is then to be found in the regression residuals which provide a net measure of average settlement timing.

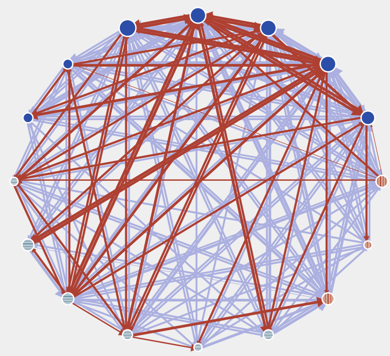
15 Bech and Adelstein point to the failure of Bear Stearns in March 2008 as one prominent example of how lacks in settlement liquidity can negatively affect the availability of funding liquidity for all market players.

Chart 3 Average time of Fedwire settlements



Source: M. Bech and I. Adelstein (2009).

Chart 4 Fedwire settlement delays on September 17, 2008



Source: M. Bech and I. Adelstein (2009).

The results support previous findings in terms of time-shifts of settlements prior to, following and during the period of acute impact of Lehman Brothers' bankruptcy.

After operationalising the variables at hand, the authors employ network techniques to visualise the deteriorated degree of liquidity in Fedwire. The analysis is narrowed down to all business days in September 2008 and to a core set of 16 Fedwire participants. By doing so, the paper keeps its focus on the actual period of interest, as well as on the turbulences caused by the shock event to other actors in the same financial environment. The authors showed that, until 12 September 2008, settlement behaviour was normal. However, this changed dramatically throughout the two weeks following 15 September, the day Lehman Brothers filed for bankruptcy. After that date, significant degrees of delay within Fedwire are observed, reaching a peak on 17 and 19 September with the majority of links reflecting overdue payments (see Chart 4). According to the authors, this observation can be considered an indicator of the effect of a systemic shock to the network.

Bech and Adelstein conclude their paper with an analysis of the coordination of settlements among Fedwire participants in the light of a changing liquidity environment. Using daily time series of the correlations of the 75th percentile settlement times across 72 Fedwire participants, they examine the differences in settlement coordination for three distinct periods, i.e. pre-crisis, crisis and post-crisis.

Based on correlation matrices, a distribution of correlations for each single period is obtained. In line with the findings of the former part of the paper, it is again the period immediately after Lehman Brothers' default that differs from both the baseline and the post-crisis period, showing a higher degree of correlation in settlement timing.

The robustness of these results is underlined by applying the method to a subset of 16 major Fedwire participants. The results show that these display an even stronger tendency to coordinate behaviour, and they actually seem to be driving the heightened coordination in the "crisis" period.

To further illustrate their results, Bech and Adelstein make use of network techniques to visually highlight the differences in coordination settlements throughout the three periods under consideration.

EURO AREA FINANCIAL NETWORKS

The second presentation was given by **Olli Castrén** on a joint paper with Ilja Kristian Kavonius entitled "Balance sheet contagion and systemic risk in the euro area financial system: a network approach".

At the beginning of his presentation, Castrén briefly summarised the work already done on the topic at the macro level as well as at the micro level. He pointed to the fact that an analysis of accounting-based balance sheet interlinkages at sector level has never been conducted before. In addition, he argued that, in order to incorporate elements of risk into the analysis, it is necessary to construct "risk-based balance sheets" which also include volatility of asset values.

The authors use quarterly non-consolidated data from 1999 onwards on euro area financial accounts (EAA), based on the methodological framework established in the European System of Accounts 1995 (ESA95). By doing so, they analyse a closed system of assets and liabilities spread among seven distinct sectors.[16] Since these data do not contain any information about the counterparties of the instrument issued by a given sector, the "maximum entropy" technique is used to approximate these allocations. Finally, matrices of bilateral exposures, reflecting the amounts of assets and liabilities as well as the instrument category they belong to, were constructed for inter as well as intra-sectoral balance sheet relationships.[17]

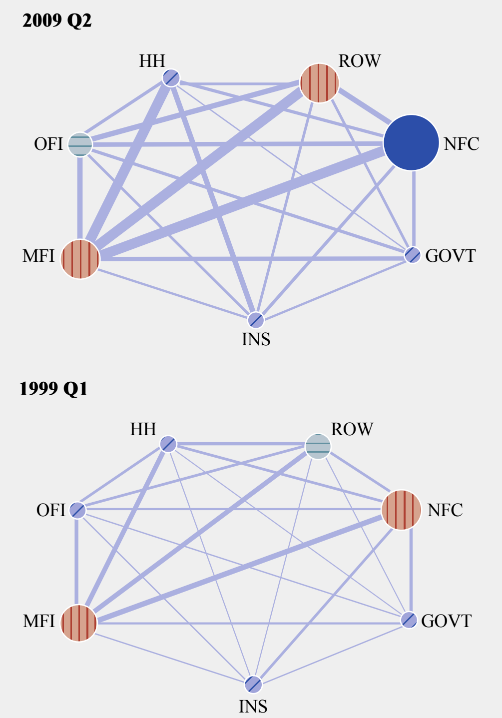
With this information to hand, a complete network linking all sectors together by summing up assets and liabilities for a total of eight instrument categories is obtained. Castrén presented snapshots of these networks of balance sheet gross exposures in the euro area at instrument level for the first quarter of 1999 and for the second quarter of 2009 respectively (see Chart 5).

Comparing these snapshots, three main developments become evident:

1. an overall increase in balance sheet exposures suggesting a higher level of interconnectedness in the euro area financial system;

2. the "hub" position of the banking sector, as revealed by the large weight of its links to counterparties; and

Chart 5 Cross-sector balance sheet gross exposures in the euro area financial system



Sources: O. Castrén and I.K. Kavonius (2009).

3. the increasing importance of the other financial intermediary sector over the past ten years.

In fact, networks which are derived from the balance sheet exposures do not only help to visualise the units of analysis and the links between them. Network analysis also offers features that allow the modelling and tracing of contagious effects and knock-on events in the system. Making use of this quality, the paper first considers a simplified three sector model and assumes an unanticipated net income shock resulting in a deficit for one of the sectors' profit and loss accounts.

16 The set of sectors consists of the following: households, non-financial corporations, banks, insurance companies and pension funds, other financial intermediaries, government, and the rest of the world.

17 The intra-sectoral exposures can thus be found on the matrix diagonal.

Then, mark-to-market accounting is assumed, leading to a faster transmission of the shock throughout the network, i.e. to the balance sheet of the other sectors.

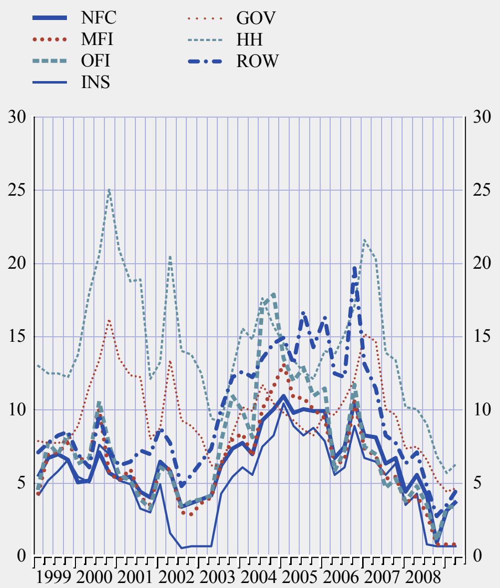
To demonstrate how a similar shock could be transmitted in the network of sectoral balance sheet exposures, the authors introduce a cash-flow shock in the non-financial corporations (NFCs) sector that causes a 20% mark-to-market drop in the value of shareholders' equity. In the first round, above all, the NFCs sector itself as well as the other financial intermediaries (OFIs) and the government sectors are those most heavily affected. In the subsequent rounds, the most affected sectors are those which hold large amounts of equity issued by those sectors which were adversely affected by the initial shock in the first round.

In this context, Castrén emphasised that, in a multi-period framework and when hit by a shock, agents are expected to rebalance their accounts by deleveraging, disinvesting or similar actions – a scenario not incorporated in the current analysis. Nevertheless, the presented network can be used to simulate the effects of such actions once relevant rules and thresholds are specified and modelling problems have been overcome.

In the second part of the paper, contingent claims analysis (CCA) is applied to enhance the framework by accounting for the accumulation and transmission of risk exposures in the financial system, thus overcoming its current deterministic character. Risk-based balance sheets at sector level can be constructed by applying CCA, thus making it possible to conduct a macro financial risk analysis as the propagation of risk exposures across sectors can be examined.

Castrén and Kavonius use the "distance-to-distress" measure obtained from CCA (see Chart 6) to capture how risk exposures in sectors that were not directly struck by the initial NFC cash-flow shock considered above were also affected via contagion across balance sheet items.

Chart 6 Sector level distances-to-distress for the euro area financial system



Source: O. Castrén and I.K. Kavonius (2009).

The authors find a large discrepancy in impacts and argue that this could stem from the non-linear character of the changes in risk exposures as a reaction to volatility shocks in sectors that are characterised by high leverage. Furthermore, they state that, owing to these non-linearities in risk exposures, the interconnections may serve as risk-spreading shock amplifiers in a crisis situation, whereas they are assumed to perform the functions of risk sharing and shock absorption in normal times.

Concluding his presentation, Castrén emphasised that more research needs to be conducted in order to refine propagation mechanisms in such networks.

MAIN COMMENTS AND DISCUSSION

The discussant of the second session, **Goetz von Peter**, commented first on the paper presented by Castrén. He emphasised the innovative approach of conducting a systemic risk analysis on the European sector level, a unit of analysis not yet examined.

At the same time, he recommended clarifying the significance of cross-holdings between some sectors. This brought Von Peter to a general concern: the high degree of data aggregation. In the construction process, existing heterogeneity within each sector is averaged out, inevitably resulting in a loss of information. Consequently, the question of the extent to which such balance sheets remain interpretable arises. In particular, sector-wide balance sheets might be misleading, as solvent units are unlikely to support failing units in the same sector.

Von Peter went on to state that, although the authors acknowledge such data limitations, they do not always explain what this means for the results. In addition, the application of the maximum entropy technique by construction leads to a complete network, obviating the inclusion of statements on degree distribution or the like.

In review of the paper presented by Bech, Von Peter underlined the insights gained in studying a unique event (the Lehman Brothers bankruptcy) in the data-rich environment of Fedwire. He commended the focus on settlement liquidity as an interesting choice and praised the inclusion of behavioural aspects.

However, further exploration is needed on the selection of parameter thresholds in the paper, as they appear to be of a rather arbitrary nature. Improvements can also be made by stating precisely whether it was the type of payment or the type of participant that led the authors to conclude whether or not there was discretion in when the payment needed to be sent. More importantly, Von Peter questioned the use of correlations to quantify coordinated delays, as they only deliver information about the tendency of participants to move together, whether late *or early*. Furthermore, he felt that further exploitation of the network structure that the authors had constructed would be desirable. For instance, considering transitive relationships (e.g. clustering) would help explain why delayed incoming payments would lead a bank to also delay sending payments. Additionally, the discussant posed an open question on whether delays are indeed the main feature of stress. Other aspects, such as volumes of payments and failures, may be equally important for assessing tensions.

The subsequent discussion by the workshop participants mainly focused on the changing nature of networks, which needs to be taken into consideration. Furthermore, the use of aggregated data was discussed, as macro level networks are well connected by construction, making the application of some network topology measures somewhat uninformative. It was also pointed out that network properties become increasingly non-linear the more aggregated the data are. This leads to interpretational biases, as the underlying structure between the network components is not correctly captured. Another suggestion concerned the inclusion of robustness tests in both papers. This can be done, for example, by altering the definition of nodes and edges in order to check whether similar results are obtained.

SESSION III – INTERBANK CREDIT, MARKETS AND LIQUIDITY MANAGEMENT IN LARGE VALUE PAYMENT SYSTEMS

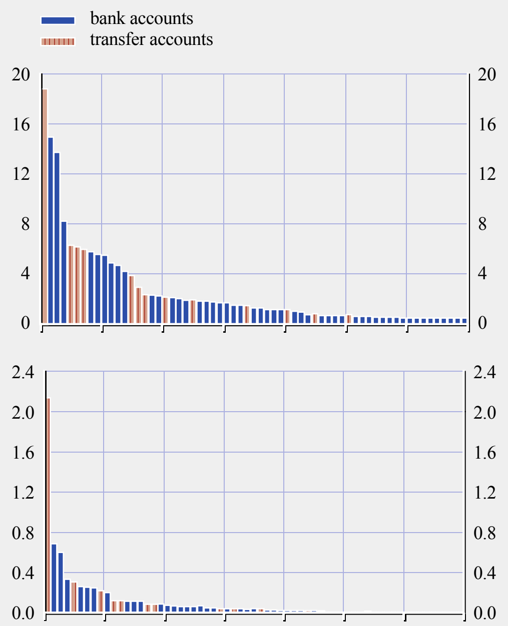
The speakers of the third session, chaired by **Daniela Russo,** presented two applications of network analysis to large value payment systems (LVPS). Both papers were motivated by the need for the national central banks (in this case, the Oesterreichische Nationalbank and De Nederlandsche Bank) to gain a better understanding of the robustness of the domestic payment system. To this end, both papers analyse the topology of the payment network and perform a set of simulations in order to assess its stability when a highly connected participant is removed from the system (in the Dutch case, which was presented by Iman van Lelyveld) or with an operational incident at one participant's account (in the Austrian case, which was presented by Claus Puhr). These exercises allow the authors to assess the relevance of contagion for the domestic LVPS (respectively ARTIS for Austria and TOP for The Netherlands) and the systemic importance of some players.

THE AUSTRIAN LVP SYSTEM

The failure of a large domestic bank prior to the crisis motivated **Claus Puhr** and his co-author, Stefan W. Schmitz, to start an exploratory analysis of ARTIS liquidity data using different econometric techniques. Their aim was to eventually extract some early warning signals from actual payments data. In the paper presented at the workshop, "Structure and stability in payment networks: a panel data analysis of ARTIS simulations", network topology and counterfactual simulations are used to quantify the contagious impact of unsettled payments resulting from an incident at an individual bank level (namely from the inability of a participant to submit payments for the whole day).

The results of 63 different operational stress scenarios, for the period from November 2005 until November 2007, reveal that only a few accounts are systemically important in terms of number and value of contagious defaults that they might cause per day (see Chart 7).[18]

Chart 7 Average number & value of simulated contagious defaults per day



Sources: C. Puhr and S.W. Schmitz (2009).

Also, transfer accounts cause significantly more contagion than bank accounts (due to their centrality in the network) while, unexpectedly, operational shocks on days with higher transaction activity cause lower contagion.[19] This last and somewhat counterintuitive result is possibly related to the uncovered decreasing time trend in the number of simulated contagious defaults per day over the period from November 2005 to November 2007. This seems to suggest that the Austrian system has become more stable over these two years.

In the last part of the paper, the authors use a panel data analysis to assess the relative significance of network topology indicators in explaining the high variation of contagion – as measured by (i) number of banks with unsettled payments;

18 A "contagious default" occurs when a bank that does not receive a payment is in turn unable to send payments for that day.

19 "Transfer accounts" are ARTIS accounts held by other Eurosystem central banks at the Oesterreichische Nationalbank. All national TARGET components are directly linked by transfer accounts. All transactions to and from the respective country and Austria are routed via these accounts.

(ii) number of unsettled payments, at the end of the day, due to an operational incident at another participant and (iii) value of unsettled payments, at the end of the day, due to an operational incident at another participant – both in the cross-section (i.e., among ARTIS participants) and across days.[20] The results show that, out of more than a hundred indicators at network and node level, the best measures for the identification of systemically important accounts in ARTIS are the number and volumes of (contagious) defaulted payments that a bank can cause. That is, following an incident at one participant's account, the ensuing liquidity loss and the level of aggregate liquidity available in the system offer the most convincing explanations.[21]

THE DUTCH LVP SYSTEM

The second speaker, **Iman van Lelyveld**, presented "Interbank payments in crisis", a joint work with Marc Pröpper and Ronald Heijmans on the topology of the domestic LVP system (TOP) and on the broader implications network topology might have for financial stability.

First, the paper presents an intraday analysis of transactions processed and values transferred through TOP from June 2005 to May 2006. The authors then study the changes in the structure of the network over time in terms of commonly used network measures. These are size (number of active nodes); connectivity between banks (the ratio of actual to possible links); clustering (the probability of two neighbours of a node also sharing a link); and network correlations (whether nodes that make payments to many counterparties also receive payments from many).

They find that the Dutch network is small in terms of both nodes and links, compact (with banks that are on average only two steps apart) and sparse in terms of connectivity over the period under analysis, for all the different time-snapshots used (1 hour, 1 day, or 1 year). Moreover, it is characterised by a few highly connected nodes linked to several nodes with relatively few connections. Interestingly, on a short time scale, not all of these most highly connected nodes correspond to the largest Dutch banks. For instance, one of the most connected hubs is a clearing institution. According to the presenter, this clearly indicates that network measures do provide an additional tool to assess the criticality of a participant from a systemic point of view, and to better evaluate the performance of the system.

The paper provides new evidence of the influence of the chosen time frame in the analysis of network properties. In fact, due to finality of payments in RTGS systems, links are extremely short-lived. This implies that the chosen time horizon is crucial when assessing the results. In the case of TOP, a ten-minute slice of recorded flows is already sufficient to characterise the structure of the whole system.

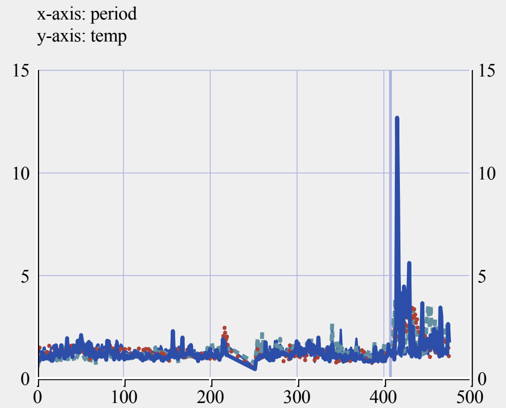
In the second part of the paper, the authors study the vulnerability of the system to the removal, one by one, of the ten most highly connected participants. Looking at the impact of these removals on network properties and on settled volumes and values makes it possible to measure indirectly the role of highly connected players (either banks or clearing institutions) in the stability of the network.

Finally, the authors try to investigate the effects of the recent financial crisis on the payment system by monitoring traditional activity measures as well as network properties in the period from June 2006 to December 2008. Consistent with the results of the previous paper, indicators in the Dutch payment system network also seem to add relatively little to the analysis once volumes and values are taken into account.

20 *Number* and *value* refer, respectively, to the total number and total value of payments that could not be settled by banks that did not experience an operational incident.

21 The authors selected 44 indicators at network level and 71 at node (stricken bank) level. Both univariate and multivariate analysis showed the existence of a significant correlation between node-indicators and (contagious) unsettled payments. In particular, higher *node-degree* and *connectivity* and lower *average path length* are significant in explaining higher contagion. Among network-level indicators, *betweenness centrality* – the average of all individual nodes' betweenness centralities (see the definition in footnote 9) – turns out to be particularly helpful in predicting contagious defaults in the Austrian interbank market.

Chart 8 The impact of the failure of Lehman Brothers [1]



Source: I. Van Lelyveld et al. (2009).
1) Developments of gross turnover and of a set of network measures from 1 January 2007 to 31 December 2008.

The monitoring exercise reveals the absence of any noticeable disruptions in the Dutch payment system until the migration to TARGET2 was achieved in September 2007. A drastic change in the reconstructed network is clear after the collapse of Lehman Brothers (see Chart 8). However, the migration to TARGET2 does not allow for an appropriate disentanglement of crisis effects.

MAIN COMMENTS AND DISCUSSION

Cornelia Holthausen, discussant for this session, highlighted the scope for further comparison of systems that, however heterogeneous in terms of volumes processed and number of participants, might nonetheless share a common structure. The striking similarity between the results on the Austrian LVPS and those obtained from analyses looking at the US Fedwire system suggests that comparisons among payment systems might be especially useful as a source of policy recommendations for the enhancement of network stability.

A key comment made by the discussant about both presentations concerned the absence of behavioural assumptions. Convincing behavioural aspects are excluded from a standard simulation analysis, where only the static consequences of each simulated scenario are considered and nodes do not react to the simulated triggering event. Holthausen argued that until adaptation in behaviour in response to shocks is not contemplated by network models the latter will not represent an appropriate tool for the assessment of systemic risk and of systems' resiliency to shocks. This is because the current models "miss" the kind of strategic, non-cooperative, and self-reinforcing feedback loops that are crucial in the development of a financial crisis.

Another key issue raised in the discussion is the need for improvements in data and information-sharing across national borders and across today's numerous interdependent systems and markets. These are critical in order to gain a thorough understanding of interactions existing in the global financial system and, therefore, to extend the network framework currently used for the analysis of payment systems to the study of broader questions about financial stability.

Beyond the lack of any adaptation in behaviour following a shock, Holthausen questioned the appropriateness of some of the assumptions on which the presented papers rely on (e.g. the inability of a troubled institution to send any payment on a given day or the absence of strategic delays in settlement). In order to build a meaningful link between the analysis of network properties and systemic stability, elements such as the identity of market players, changes in the set of the most active banks over time or the potential scale of financial obligations which are not reflected in actual payments should not be overlooked. This is of the utmost importance in making network research results a reliable basis from which to draw regulatory implications.

Holthausen made an additional general remark to papers in this emerging field of financial network research, namely the need to identify more clearly the scope of the analysis at hand for policy recommendations. On this point, Puhr mentioned the importance of good business continuity arrangements, especially at the most important/connected nodes, as one of the main implication of the presented paper.

In the case of an operational failure at one account, allowing for alternative ways of settling at least the largest payments would greatly reduce the systemic impact of the incident.

In agreement with the discussant, and notwithstanding his confidence as regards the contribution network theory can make to the analysis of the functioning of "the plumbing" of the financial system, Van Lelyveld expressed some scepticism when it comes to the use of networks for the purpose of studying the vulnerability of the system. In fact, for broader financial stability questions, more information is needed about *what motivates* participants' payment decisions, especially in reaction to a shock, and about the way changes in agents' choices might eventually reinforce one another in a non-cooperative way. Van Lelyveld pointed out how strategic behaviour is probably less relevant in small networks, where participants know each other.

In the ensuing discussion the importance of tailoring existing measures to the specific application and objective at stake was highlighted. The discussion following the first session had highlighted the need to set up a careful categorisation of which particular measures are the most appropriate for the analysis of each specific type of shock. The discussions in the current session converged on the idea that the choice of the most appropriate time window for each specific issue at hand is an additional important issue to be considered in simulation exercises using financial networks.[22]

Concerning the expansion of the scope of network analysis to study financial stability, the chairman, Daniela Russo, pointed out how interdependencies *across* different systems and markets are potentially more important for financial stability than interdependencies *within* the system. This is the case because these types of links have the potential to dramatically change the behaviour of market participants. Russo pointed out how, especially in a crisis situation, the behaviour of a player who is active in many different systems might be affected not only by a shock per se, but even more so by existing interdependencies among the systems in which it operates. As a consequence, the same player will behave differently in each system, even if it faces no liquidity hoarding or other strategic motivation.

22 In particular, some participants argued that the resilience of the system to shocks is probably best analysed using a one-day snapshot, while shorter time windows would be more appropriate for capturing behavioural aspects and the sudden evaporation of trust that characterises financial crises.

SESSION IV – SYSTEM-LEVEL LIQUIDITY EFFECTS AND NETWORKS IN EARLY WARNING MODELS

The presentations of the fourth session, chaired by **Mauro Grande**, dealt with balance sheet interconnections between economic entities and the potential risk stemming from these links when shocks occur. Both papers have a similar analytical scope as they disentangle the web of claims and obligations present in the financial system in order to gain insights into the contagious effects that can be rooted in tight financial relationships. They differ, however, substantially regarding the units of analysis and the aggregation level at which the analysis is carried out.

The first paper, presented by Sujit Kapadia, takes into account the intricacy of financial systems as it examines the relationship between firms, domestic banks and international banks. The chosen network approach captures a large portion of the links between financial agents, a feature not often found in existing network models.

In contrast, the second presentation by Juan Solé and Marco Espinosa examined consolidated claims and liability relationships across national banking systems. In their paper, simulations based on idiosyncratic shocks are analysed, leading to the identification of systemically important as well as particularly vulnerable banking systems. Furthermore, the contagion paths, and thus the spreading of risk throughout the system, are explored using network techniques.

FINANCIAL RELATIONSHIPS BETWEEN FIRMS, DOMESTIC BANKS AND INTERNATIONAL BANKS

The first presentation was given by **Sujit Kapadia** on "Complexity and crisis in financial systems", a joint paper with Kartik Anand, Simon Brennan, Prasanna Gai and Matthew Willison.

Kapadia started with a brief overview of network theory concepts and their applications in economics, stating that tipping point properties and fat-tailed loss distributions are particularly important features of the current paper. The model used in the paper mainly consists of three distinct layers that are interconnected through cross-holding exposures of loans and equities:

1. a core of interacting domestic banks constituting a complete network;

2. a set of international banks, typically well connected to their immediate neighbours; and

3. a group of firms operating independently of each other but borrowing both from domestic and international banks.

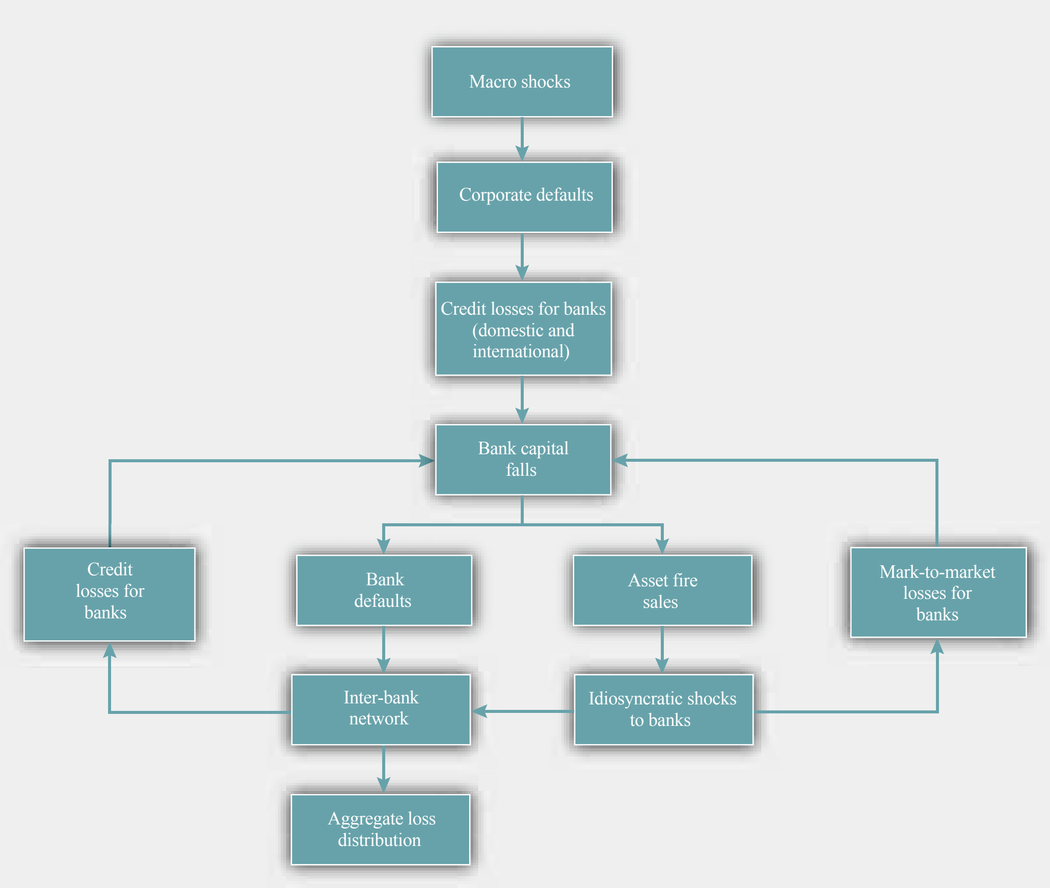
The linkages among these entities can be summarised in a single restricted matrix, representing a large part of banks' balance sheet items.[23] Initially, a macro shock hits the system leading to corporate defaults that trigger credit losses for both types of banks under consideration, potentially causing their default. To let banks compensate for the capital loss suffered, the possibility of fire sales is incorporated into the model. This distress sale of assets might lead to mark-to-market losses which can trigger further fire sales in the system, provoking an even larger negative impact on the participants of the system. On the other hand, financial entities primarily suffer credit losses as a result of a bank default, an event that can have knock-on effects, again leading to further defaults of other banks (see Chart 9).

Concluding the explanation of the basic model and its specific features, the authors describe the calibration of the model, using data from 17 UK banks, 120 foreign banks and 50.000 firms, stemming from various sources.

In a baseline scenario, an idiosyncratic rather than aggregate shock was considered, driving, on average, 220 firms into bankruptcy. This causes an average asset loss of 0.15% to domestic banks and 0.12% to international banks, which does not threaten the stability of the system.

23 The matrix takes on a restricted form because it is assumed that firms do not lend and that financial institutions only hold equity in firms and not in each other.

Chart 9 Mapping shocks to systemic risk



Source: S. Kapadia et al. (2009).

As a second step, the smallest shock that can bring down the entire system is considered. The simulation shows that the system collapses in 0.4% of the cases when (on average) 2700 firms default whereas in 99.6% of cases it does not. These findings underline the tipping point property which is characteristic for such networks when put under stress, i.e. a sudden increase in distress in the loss distribution.[24] The authors find that adding fire sales to the scenario increases the vulnerability of the system to much smaller macro shocks.

In the next step, the authors relax the assumption of homogeneity across banks in terms of the sizes of their capital buffers (4% for all banks) and instead allow the buffers to vary between 4% and 24% across institutions. This softens the tipping point property of the loss distribution but, when the average size of collapsing firms is given a sufficiently large value, the entire system may still default as in the previous simulations.

The presentation went on to draw a link to the current crisis and to highlight the increased vulnerability of complex financial systems to Lehman Brothers-type system-wide breakdowns. Additionally, the model also emphasizes the potentially amplifying effects of mark-to-market losses, an observation which has been

24 Kapadia pointed out that, although in this scenario a 100% loss given default for inter-bank loans was considered, this sort of bi-modal loss distribution prevails even after this assumption is relaxed.

made also in the context of the most recent turmoil. In this regard, Kapadia draw attention to declining capital buffers and increasing leverage in recent years. The authors argue that these developments, among others, can be partially held responsible for making the system more vulnerable to instability. The introduction of systemic capital requirements might therefore deserve more consideration, also in the light of recent experiences.

At the end of his presentation, as a potential avenue for future research, Kapadia pointed to the need to incorporate liquidity risk into the modelling of systemic risk in financial systems.

ASSESSING CROSS-BORDER LINKAGES

The second paper presented dealt with the topic "Network analysis as a tool to assess cross-border financial linkages" and was presented by **Juan Solé** from the IMF, on behalf of his co-authors Marco Espinosa and Kay Giesecke.

At the beginning of his presentation, Solé stressed the potential of network analysis to become an important tool for cross-border surveillance. For regulators, it provides a metric to identify institutions that are potential sources of contagion. Furthermore, it can help to track contagion paths and offers a metric that can be used to find out when and whether a financial entity is "too connected to fail" in times of financial stress.

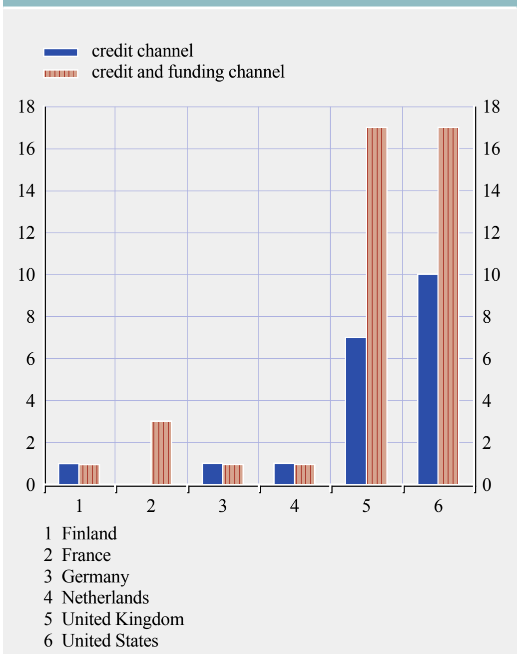
In order to present the methodological framework of the paper, Solé introduced a stylised bank balance sheet identity that makes it possible to follow "movements" of balance sheet items when a shock event occurs. In the paper, the authors first consider a pure idiosyncratic credit shock and then extend the analysis to a credit-plus-funding shock. These simulations are carried out for two different datasets. The first one contains solely on-balance-sheet items whereas the second one adds elements of risk transfer.[25]

In both simulations, the main aim is to trace the path of contagion among banking systems by following the transmission of the initial shock throughout the network. In addition, it is possible to identify systemic players within the network, i.e. those banking systems whose failures cause immense stress to their counterparties in the network. The financial distress triggered by those players can trigegr not only to the default of other banking systems, but also the collapse of all systems under consideration. Another feature of the analysis is that capital impairment on a country-to-country basis can be easily displayed in a matrix form, providing useful information about actual counterparty risks.

As a result of the first simulation, which applies the first dataset, the UK and the US banking systems are identified as important entities causing three and four rounds of contagion respectively, as well as 44.6% and 80% loss of all capital in the system (see Chart 10). Due to

25 The data is taken from the BIS consolidated banking statistics (www.bis.org) which provides quarterly data on immediate borrower basis (on-balance-sheet items) and on ultimate risk basis (including risk transfers).

Chart 10 Induced banking system failures



Source: J. Solé (Workshop presentation, 2009).

their close linkages to the countries from which the shocks were assumed to originated, Belgium, the Netherlands, Sweden and Switzerland are found to be the most vulnerable to these particular shocks. Their banking systems fail in at least three out of the fifteen hypothetical simulations in which they were themselves not considered as the trigger country.

The analysis of the second simulation – the credit-plus-funding event – largely confirms the results from the first exercise.[26] Again, the banking systems of the United Kingdom and the United States take on systemic roles, triggering even more hypothetical defaults than before. Surprisingly, the collapse of the French banking system now induces three hypothetical defaults compared with none in the former scenario (see Chart 10). Solé et al. argue that this might reflect the important role of this country as liquidity provider in the system and that it shows the usefulness of including scenarios that account for different types of stress. The authors also demonstrate that the incorporation of the funding channel into the model increases the overall vulnerability of the network in terms of defaults and capital impairments.

However, looking at the transmission of a shock using the second dataset, i.e. including risk transfers, the results change. The resilience to shocks of Belgium, Sweden and Switzerland improves relative to the previous case. Furthermore, the French banking system becomes more important, inducing three hypothetical failures in both scenarios. Additionally, the relevance of the German banking system in the credit-plus-funding-shock simulation increases dramatically. Its collapse hypothetically causes five other banking systems to fail. These new findings lead the authors to conclude that, although the data on risk transfers used in the paper is of bilateral nature only, the additional insights gained from its use are noteworthy.

At the end of his presentation Solé concluded with reflections on the policy implications of the presented work. First, he mentioned that, with an increasing interconnectedness of financial institutions, a better understanding and monitoring of direct and indirect linkages is needed. Network analysis is one tool to assess this problem. However, as some participants voiced doubts concerning its empirical practicability, Solé referred to Chapter II of the April 2009 IMF Global Financial Stability Report, where basic models of this kind are outlined.[27]

Furthermore, he emphasised that information about off-balance-sheet items and non-bank financial institutions, as well as other financial entities, need to be better incorporated into network analysis. However, since this is often not possible due to data limitations, he appealed for more joint surveillance as well as data sharing between countries in the future.

MAIN COMMENTS AND DISCUSSION

In his discussion of the two papers, **Diego Rodríguez Palenzuela** underlined the renewed importance of network analysis as a scientific field and highlighted the value in exploring different approaches within the field. Influences from innovative concepts in economics are needed, given the shortcomings of the established paradigm in economic theory in terms of foreseeing the depth of the recent crisis.

In this regard, he commended the efforts made by the authors to take into account the complexity of the financial system, as both papers provide a contribution for a better understanding and monitoring of systemic risk. Regarding the first paper, Rodríguez Palenzuela welcomed the effort to incorporate heterogeneous bank balance sheets, as this is a first step away from the prevailing undifferentiated maximum entropy technique. He also complimented the authors for showing how macroeconomic shocks, asset market liquidity and network structure can cause system-wide credit losses and contagion via interaction.

26 The authors assumed a 50% haircut in the fire sale of assets and a 65% roll-over ratio of interbank debt (M. Espinosa, J. Solé, and K. Giesecke (forthcoming) "Network analysis as a tool to assess cross-border financial linkages", page 20).

27 This chapter in the IMF Global Financial Stability Report of April 2009 was also written by J. Chan-Lau, M. Espinosa-Vega, K. Giesecke and J. Solé.

As regards possible improvements, the discussant suggested the exploitation of real data to conduct stochastic rather than deterministic parameter calibrations, given that assuming, for example, zero recovery rates is rather restrictive. This is also true for the assumption that bank debt is completely illiquid. By construction, this rules out the possibility that banks might be able to soften the impact of a shock through the replacement of debt with equity.

Another suggestion was made on the price impact of fire sales as well as the selection of the trigger point that leads banks to start the selling of assets in the model. These distress parameters are modelled to be constant in the paper, whereas a varying adjustment depending on the state of the economy would be more suitable. The same is true for the parameter reflecting the amount of firms defaulting, since the underlying process driving the bankruptcies in the models is not fully elaborated. Hence, an early warning signal derived from the framework of the analysis would be rather rigid due to the underlying constant values of its parameters. Furthermore, Rodríguez Palenzuela questioned whether a log-normal distribution can correctly capture the fat tails correctly. He suggested using other distributions to install a more flexible structure in the model.

As regards the second paper, the discussant praised its usefulness in assessing cross-border financial stability risk using aggregated data. However, Rodríguez Palenzuela proposed incorporating country-specific default probabilities for first and second rounds instead of simple country defaults. In his view, this would permit a more efficient analysis of vulnerabilities. Moreover, a cross-check using other indicators or approaches to examine the robustness of the results was recommended.

The discussant concluded his presentation pointing to the need for further elaboration in the field of network analysis, especially regarding the unspecified role of time, the lack of fundamental theorems, the definition of a central measure for system risk and the unexplored nature of market failures. Until these challenges are dealt with, it is hard to see network analysis to be applied more broadly for policy calibration.

In the subsequent discussion, comments focused on the exploratory character of network analysis.

In particular, the question whether and on what basis capital surcharges can be imposed upon systemically important firms or banks remains a challenge for policy makers. Adding to this, Solé stressed the point that financial institutions are usually not aware of how interconnected they are. Consequently, they do not fully internalise – by setting aside additional capital buffers – the network externalities they might cause.

In addition, attention was drawn to the fact that network analysis, based on bank balance sheet models, often does not cause many players to default in the simulations unless large shocks are considered. However, as could be observed during the recent crisis, contagion leading other financial institutions to come close to bankruptcy does not necessarily need to be based on a large initial shock. Therefore, future models need to account for this, e.g. by incorporating risks stemming from high leverage.

Based on these comments, Kapadia pointed to the need for more research on liquidity risk to be conducted, as this has been a main feature in the current crisis. Confirming the importance of liquidity, Espinosa emphasised that they had already included such risk in their simulations. In the analysis, this indeed led to more contagious defaults and made banking systems generally more vulnerable to shocks.

Furthermore, a consensus emerged in the discussion that difficulties remain concerning the communication to decision makers as they may not be fully familiar with network analysis and hence are frequently not convinced of its usefulness. Nevertheless, network modelling can help to identify entities that are "critical" for the stability of financial systems, providing decision makers with arguments for policy discussions. In this context, the important role of the research community in making network analysis a useful tool for policy advice and to adapt it properly to supervisors' toolboxes was underlined.