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Exploring agent-based methods for the analysis
of payment systems: A crisis model for StarLogo TNG

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EXPLORING AGENT-BASED METHODS FOR THE ANALYSIS OF PAYMENT SYSTEMS: A CRISIS MODEL FOR STARLOGO TNG

Luca Arciero⁺, Claudia Biancotti^{*}, Leandro D'Aurizio^{*}, Claudio Impenna⁺

Abstract

This paper presents an exploratory agent-based model of a real time gross settlement (RTGS) payment system. Banks are represented as agents who exchange payment requests, which are settled according to a set of simple rules. The model features the main elements of a real-life system, including a central bank acting as liquidity provider, and a simplified money market. A simulation exercise using synthetic data of BI-REL (the Italian RTGS) predicts the macroscopic impact of a disruptive event on the flow of interbank payments. The main advantage of agent - based modeling is that we can dynamically see what happens to the major variables involved. In our reduced-scale system, three hypothetical distinct phases emerge after the disruptive event: 1) a liquidity sink effect is generated and the participants' liquidity expectations turn out to be excessive; 2) an illusory thickening of the money market follows, along with increased payment delays; and, finally 3) defaulted obligations dramatically rise. The banks cannot staunch the losses accruing on defaults, even after they become fully aware of the critical event, and a scenario emerges in which it might be necessary for the central bank to step in as liquidity provider. The methodology presented differs from traditional payment systems simulations featuring deterministic streams of payments dealt with in a centralized manner with static behavior on the part of banks. The paper is within a recent stream of empirical research that attempts to model RTGS with agent – based techniques.

JEL Classification: C63; E47; G21.

Keywords: agent-based modeling, payment systems, RTGS, liquidity, crisis simulation.

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1. Introduction¹

This paper presents an agent-based model of a real-time gross settlement system (RGTS), especially designed to simulate how interbank flows of liquidity evolve under critical conditions. We mainly seek to offer a methodological contribution, showing how the chosen modeling approach can be employed alongside other tools to study the generation and propagation of systemic risk in payment systems.

This topic is of growing interest due to the sharp increase in both cross-border payment activity and institutional attention to security and safety issues. In the context of RTGS systems, single large-value operations are settled one by one and immediately on condition that sufficient liquidity is held in participants accounts, with several rules enforced in order to provide participants with adequate funds to execute payments throughout the day. The system runs smoothly under ordinary conditions and is also well-suited to cope with common temporary liquidity shortages deriving from normal upswings of reserve stocks. However, mechanisms can be severely strained by negative financial or operational shocks affecting single participants or a group of them, resulting in danger to the entire system. This is why in the recent past oversight authorities (primarily central banks) have promoted substantial research into how these situations arise and which parts of the system they affect most and in which order, with special reference to the most critical stage of the payment process: interbank settlement.

A well-established line of research uses traditional simulation techniques for the analysis and monitoring of settlement systems, with a view to the containment of typical credit, liquidity, and operational risks. Different tasks can be performed with different input data and simulation methods: historical data of payments submitted by banks can be used for “what if” analyses under different settlement mechanisms, while stochastic inputs can be used either for theoretical studies or for models aimed at extrapolating the consequences of particular behavioral assumptions on small-scale settings. Along these theoretical lines, the Bank of Finland pioneered the construction of large-scale simulation models for settlement systems by building an ad hoc algorithm, where a deterministic stream of payments is accepted as an input and dealt with in a

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centralized manner under different hypotheses on the operating rules. Bank behavior is taken as given, or is made able to evolve in a predetermined manner. At present, the Bank of Finland simulator is widely used to evaluate the functioning of large-value payment systems under stressful conditions (see Bedford et al., 2005; Arnold et al., 2006; Hellqvist and Koskinen, 2005; Lublóy and Tanai, 2007; Glaser and Haene, 2007; Heijmans, 2007).²

Compared with these earlier experiences, agent-based modeling, especially suitable for highly decentralized, highly parallel complex systems, is an innovative technique that has been introduced in this field only recently. Banks are seen as agents acting independently, and the system evolves as a result of their interaction. In some cases, behavior adaptation based on changing scenarios is allowed (see Fioretti, 2005; Alentorn et al., 2006; Galbiati and Soramäki, 2007). Each agent features a vector of attributes and, most importantly, a set of simple micro-level rules governing its behavior both in isolation and in relation to other agents. Agents can be defined and initialized in many ways and separate groups of agents governed by ad - hoc rules are a possibility. Agent-based modeling permits the step-by-step analysis of transitions from one equilibrium to another following a shock. This appears to be particularly attractive since interesting stylized facts are likely to emerge along the path to a new equilibrium, rather than simply once it is reached.

Our paper explores these recent developments and seeks to build a knowledge base and an algorithmic representation for the core behavioral rules of banks participating in an RTGS system. This is a crucial stepping stone towards any model with actual operational relevance, since the results of any simulation are only as good as the assumptions made on the traits and behavior of its elements, and these assumptions are typically best formulated and tested in a small-scale setting like ours.

Compared with previous agent-based exercises, our model's main novelty is its explicit introduction of a money market, which plays a fundamental role in the evolution of the system

² Beside this strand of studies based on a simulation approach, some authors have analyzed the effects of disruptive events under an econometric perspective. Among others, McAndrews and Potter (2002) use a panel approach to estimate how the US banks participating in the US RTGS system Fedwire changed their strategy in term of payment submission during the 9/11 crisis. Payment systems can also be represented as a complex network, with banks as nodes and mutual liabilities/claims defining the arches; this kind of modeling is static, in the sense that the time dimension is not directly taken into account. Network theory has been exploited to study the main features of real interrelations among banks (Boss et al., 2004), making it possible to understand the system's level of concentration, i.e. whether few banks are responsible for the bulk of the links. The consequences of catastrophic events are simply modeled by removing a specific node and measuring the performances of the rest of the network.

after a critical event blocks or limits the activity of a participant. At first, when banks are not aware of the event, they continue to direct payments towards the non-operational counterparty and to expect payments from it; as a result, a certain quantity of liquidity is siphoned from the system and liquidity expectations are inflated. In turn, this yields an illusory thickening of the money market, driven by the granting of interbank loans based on incorrect expectations and not backed by actual liquidity; delays in payments start accumulating. When news of the critical event spreads across the system, banks adjust their expectations and start making decisions that are consistent with the new scenario. Under a reasonable parameterization of the model, this is not enough to curb the adverse domino effect triggered by the sequence of delays, which results in a flow of losses on the part of banks.

The paper is organized as follows. Section 2 illustrates the basic functioning of an RTGS system and highlights the importance of preventing systemic risk. Section 3 contains a brief methodological overview of agent-based modeling, and explains why it is especially relevant to the problem at hand; literature related to the simulation of payment systems is also reviewed. Section 4 presents our model, section 5 the parameterization and section 6 is devoted to the results. Section 7 concludes and suggests proposals for future work. The appendix contains some examples of StarLogo TNG programming.

2. Real-time gross settlement systems and systemic risk: an overview

In modern exchange economies, the smooth functioning of economic activity is heavily dependent on the reliability and the efficiency of payment systems. Cash transactions are steadily diminishing; consumers and firms generally settle their obligations through banks or other financial intermediaries, by means of instruments such as checks, money orders and electronic transfers. The intermediaries themselves initiate numerous payment flows for their own treasury operations or for other reasons. The volume and value of transactions passing through payment systems are ever-increasing, driven by financial liberalization and innovation and by the globalization of the real economy. In the European Union alone, interbank payments amounted to 57 times annual GDP in 2005, up from 40 times at the end of the 1990s. Payment systems are increasingly interconnected, and their technical and functional complexity is high. Independent of the originator of a transfer and of the underlying instrument, each payment order enters an integrated process, going from the initial decision to transfer funds to a counterparty up to

settlement in central bank money, i.e. an interbank flow of liquidity across the accounts banks hold at the central bank.

The costs associated with disruptions in payment systems are also climbing rapidly, since any interruption in the orderly functioning of the structure due to major unexpected (even catastrophic) events is bound to affect an increasingly large number of transactions and the high degree of interdependence between participants facilitates the emergence of pernicious domino effects. Central banks play a twofold role in settlement systems, which are public goods in nature, both as operators and overseers, and therefore have an interest in fostering financial stability and in studying the effects of these systemic risks so as to prevent major disruptions or at least to minimize their consequences.

Large-value operations represent a major potential source of systemic risk, which is best kept under control by the utilization of RTGS systems (see fig. 1 for a description of their basic functioning): they settle such transactions one by one and immediately and for this reason they have progressively been adopted by the majority of payment systems in the world³, starting from the second half of the 1990s.

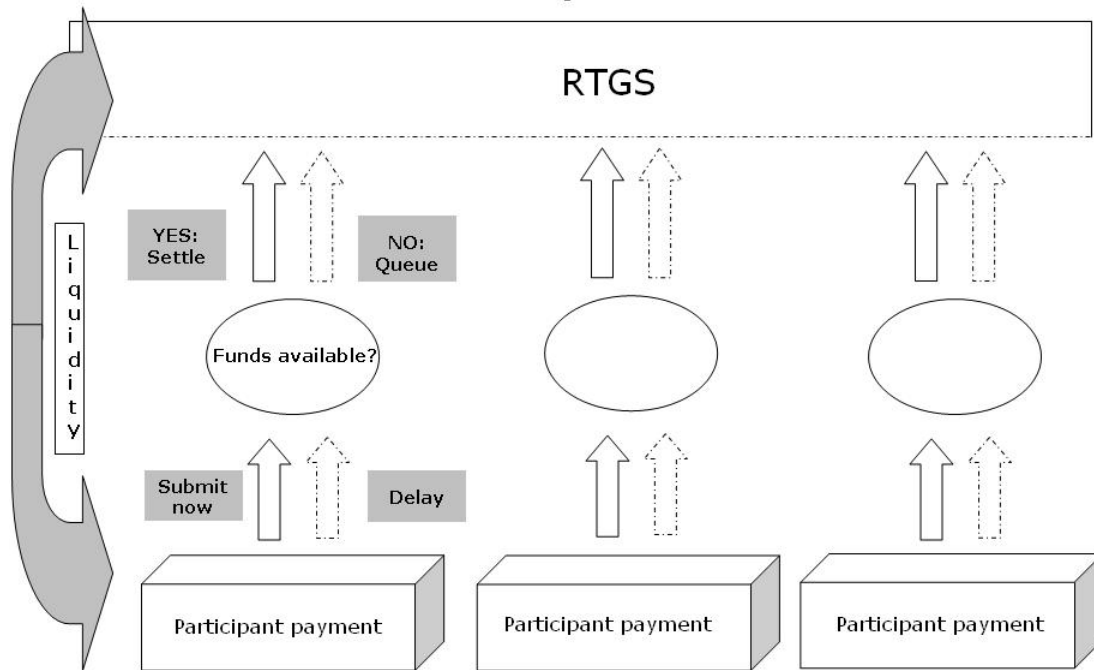
Several intraday liquidity sources are available to banks to fund their outflows. Within an RTGS system, each participant normally relies on a continuous flow of incoming payments from its counterparties. Moreover, it can obtain central bank intraday credit, which entails a cost that may be explicit (when such credit is subject to a fee) or implicit (when the provision of funds is not priced but is conditional on the availability of collateral). Alternatively, funds can be borrowed in the unsecured interbank market from other banks. According to the actual and expected availability of such resources, each bank makes the strategic decision as whether to submit a payment promptly or delay it, thus affecting the overall time pattern of flows in the RTGS. In this respect banks continuously face a trade-off between liquidity and delay costs. By releasing payments timely, banks satisfy customer and counterparty needs and benefit from a sound reputation, but can incur high liquidity costs, to the extent that they borrow from the

³ The alternative settlement mode to RTGS is the deferred net settlement (DNS) model, in which only net positions among banks are settled on their accounts at the central bank (usually once a day, in the late afternoon). This system requires banks to hold less intraday liquidity, but exposes the payment system to higher risks of financial distress, since banks extend intraday credit to their debtors until the net settlement phase is successfully completed. A default by a bank unable to fund its net debit position could trigger a domino effect within the system. A comprehensive description of RTGS system's design and activity in the most industrialized countries can be found in Bank for International Settlements (2005).

money market or the central bank. On the other hand, banks can play on the intraday dynamics of the money market more effectively by choosing to delay payments, at the expense of increased systemic uncertainty and their reputation.

Figure 1

Basic functioning of an RTGS environment



Once a payment is submitted to the system it is settled immediately if funds are available or is queued if funds are lacking. The payment will be settled automatically once the shortage is overcome; banks can no longer affect the process at that point. It is worth noting that the tools and practices mentioned (delays, intraday liquidity, queues) are commonly used by system participants to cope with ordinary intraday liquidity upswings. The question is what could be the effects of an uncommon financial or technical shock or disruptive event on the functioning of an RTGS system. Such an event may induce prolonged, pathological illiquidity during the day, with potentially severe consequences for the smooth operation of the RTGS system, for financial stability and, ultimately, for economic activity.

3. Complexity, agent-based modeling and payment systems

The main difficulty in representing payment systems for analytical purposes is that the behavior of a system as a whole is more than the sum of the behavior of its parts. For example, how and in what order participants transfer funds to each other is as important for the outcome of the settlement process as the amount, originator and destination of each transaction. In other words, payment systems exhibit organized complexity, a term routinely used in systems theory and introduced to economists by Friedrich von Hayek in his 1974 Nobel Lecture: “Organized complexity means that the character of the structures showing it depends not only on the properties of the individual elements of which they are composed, and the relative frequency with which they occur, but also on the manner in which the individual elements are connected with each other.”

According to Wolfram (1994), the main difference between complex and simple systems is that the elements, interactions and dynamics of a complex system, while coherent in a recognizable way, generate structures admitting surprise and novelty which cannot be defined a priori based on the properties of the elements. The appearance of these structures is generally called emergence (Goldstein, 1999).⁴ In most systems, emergence is associated with self-organization (Corning, 2002): independent individuals pursuing independent goals can generate regular patterns of collective behavior.

Emergence is sometimes quite easy to predict in a general sense; for example, independent drivers leaving for work all at the same time will generate a traffic jam, and independent stock traders scared by a disastrous news item will precipitate a slump in stock prices. Even when this is the case - and it is not for most complex systems - the specifics of emerging behavior cannot be conceivably studied without resorting to numerical methods. In a world with many elements and many interactions, these have a major advantage over analytic models based on systems of equations and typically focused on the properties of equilibria: they allow researchers to analyze transition dynamics of many simultaneous processes without excessive computational burden.

⁴ The word was first used in this sense by the psychologist George Henry Lewes (1875), who distinguished between "resultants" of a system, "homogeneous and commensurable" with its components and "emergents", occurring "when, instead of adding measurable motion to measurable motion, or things of one kind to other individuals of their kind, there is a co-operation of things of unlike kinds". The emergent "is unlike its components insofar as these are incommensurable, and it cannot be reduced to their sum or their difference".

Agent-based modeling is especially suitable for highly decentralized, highly parallel complex systems: most economic and social systems fit this definition (Gilbert and Terna, 2000). Each agent, i.e. each individual element of the system, is represented by way of a vector of attributes and, most importantly, a set of simple micro-level rules governing its behavior both in isolation and in interaction with other agents. The modeler is given complete control over the way agents are defined and initialized, and can even specify and maintain separate groups of agents or define super-agents from aggregations of simple agents. If we accept the definition of a complex adaptive system as a system made up of agents that interact and reproduce while adapting to a changing environment (Holland, 1995), agent-based simulation techniques can also provide a useful framework to represent system dynamics in the presence of learning. Once created, agents live for a certain period in a world where time and space explicitly exist, and evolve in parallel. Since the very first applications, such as von Neumann's self-replicating machine (1966) and Conway's game of life (Gardner, 1970), this approach has turned out to be very powerful, allowing the emergence of credible macro-level dynamics under minimal assumptions on individual behavior.

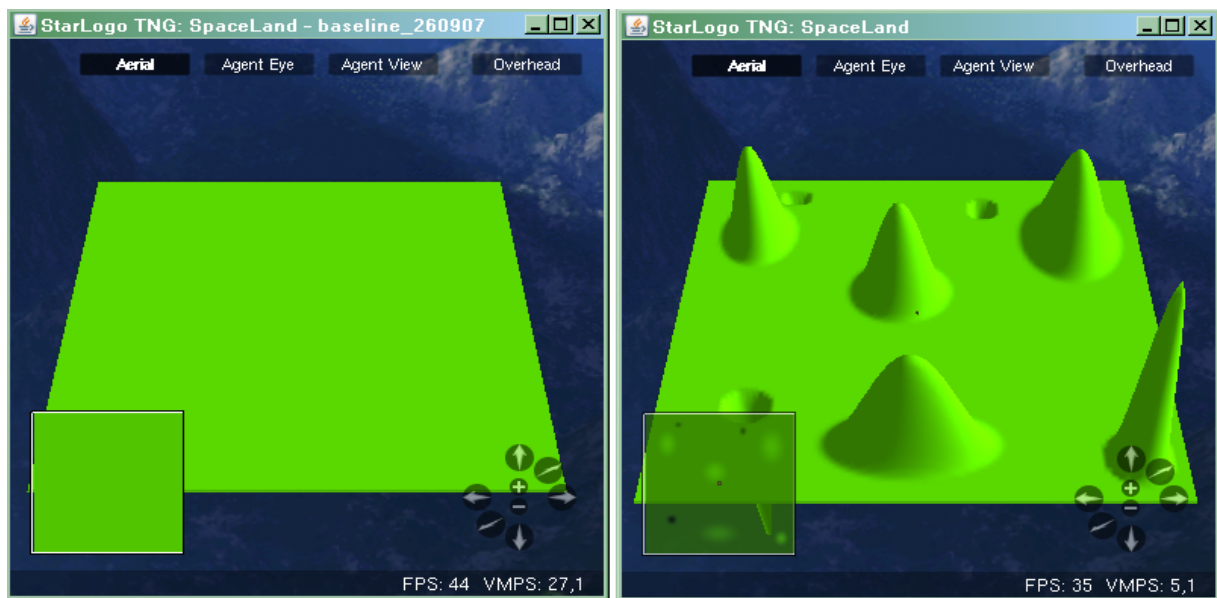
In this paper, we build on the small set of recent and innovative studies, referenced in Section 1, that look at payment systems through the lens of agent-based modeling. The behavior of commercial banks and of the central bank can be realistically described (at least in the short run) in terms of a simple and consistent set of rules, governing a core set of decisions. Given a flow of payments, banks mainly choose in which order to submit these payments to the system and how to obtain the liquidity necessary to meet obligations, subject to known constraints. The set of available strategies can be described in the language of game theory (Bech and Garrat, 2003) and translated into algorithms with ease. The great flexibility of this approach makes it suitable for a system like this, which evolves over time: payment systems change, the banking sector consolidates (both domestically and internationally); some types of bank disappear, others gain prominence; occasionally, entire countries join a given system or withdraw from it; new financial instruments emerge; rules may change, at least partly.

4. The model

Our model is built upon the widely used simulation tool StarLogo – The New Generation (TNG).⁵ The simulation can be seen on the screen evolving on a pseudo-physical world⁶ (Figure 2), with time taken by an internal clock⁷.

Figure 2

StarLogo TNG pseudo-physical world, standard and user-modified



The building blocks of StarLogo programming are breeds and agents. In mathematical terms, breeds are sets of homogeneous agents, upon which certain operators are defined. Breeds can contain an unlimited number of agents, while each agent can belong to one and only one breed at any given moment (though breed change is allowed). In computer programming language, breeds can be defined as abstract sets of variables and functions, representing agent features and behavioral rules respectively. Behavioral rules come in two varieties, perpetual and timed, the former dictating the ordinary behavior of agents belonging to a breed for the entire duration of the simulation and the latter being activated on command for a specified number of

⁵ StarLogo is a software platform, freely available for download at <http://education.mit.edu/starlogo-tng/>, developed at the Massachusetts Institute of Technology originally for educational use, that permits simple graphical programming of agent-based models. It is an evolution of the Logo language, born in the 1960s as a simplification of the LISP language for functional programming.

⁶ The physical world is called terrain, having the default representation of a thin parallelepiped, that can be altered by the programmer. Each point of the terrain is identified by a standard set of three-dimensional coordinates.

⁷ Time is kept by the internal StarLogo clock; it starts at zero and progresses in terms of StarLogo seconds, standard units whose physical duration depends on the hardware used to run the simulation.

seconds. Agents are defined temporally and spatially, meaning that they are born in a certain moment with a specific set of coordinates and they can move. They can also “die”, i.e. disappear and cease performing any activity.⁸

The first step is the creation of one or more breeds: this operation entails choosing a name for the breed and an “avatar” that defines its identifying features in terms of numerical, Boolean and string variables and describes its theoretical behavior in a number of circumstances. The next step is the definition of a different set of rules – also called ‘setup’ rules, normally governing the start of the simulation – so as to create agents.⁹

For example, a stylized model of an epidemic in a human population could be constructed with a few simple steps: a single breed called “Man” is created, and a single Boolean variable called “healthy” is introduced. Two perpetual rules are defined. First, at each tick of the clock, all agents make a random movement. Second, when two agent collide, if the variable “healthy” has the same value for both, nothing happens; if, on the contrary, “healthy” is false for a man and true for the other, the healthy one is infected by the sick one, i.e. its value for “healthy” is changed to false. The setup rules for our simple example could be as follows: at the onset of the simulation, generate ten agents of the breed “Man”; scatter them by assigning a random set of coordinates to each one; draw a number between one and ten for each; if the number is less than five, set the variable “healthy” to true; otherwise, set it to false. The model could be complicated in a number of ways: for example, the breed could feature an additional numerical variable called “birth date” for the breed “Man”, recording the value of the clock at the moment of instantiation of each individual man, and survival probabilities could be defined for agents conditional on birth date and health status.¹⁰

In the StarLogo TNG environment, there are several ways of triggering an action on the part of a specific agent, both to itself and with reference to other agents; for example, routines can be designed such that each healthy individual is aware of any sick one existing near him and can attempt to “kill” him, with a given probability of success.

⁸ This can be triggered by the elapsing of a certain number of seconds or by the occurrence of a certain event.

⁹ In computer science terms this activity is called instantiation of abstract breeds into concrete individuals.

¹⁰ The evolution of the percentage of healthy men in the population as time elapses could be monitored with different types of graphs, or written in a global variable uniformly available to all agents or made visible for instant appraisal in a dedicated window.

The preferred trigger for interaction in the StarLogo TNG environment are collision procedures, available by default for each pair of breeds A and B, including the possibility of $A = B$. They instruct the computer as to what should be done when an agent of breed A occupies the same position as an agent of breed B. The ease of use of collision procedures, coupled with their inherent recognition of the relevance of space and time, makes them central to any programming exercise conducted with StarLogo TNG.

Compared with other platforms for agent-based simulation, StarLogo TNG has the advantage of simplicity. Standard graphical blocks for most logical and mathematical operations, as well as dedicated blocks for variable definition, are already provided to combine and parameterize at will, so that non-trivial routines can be implemented quickly and without having to write any traditional code. As an obvious flip side, it is difficult, and sometimes downright impossible, to implement very complicated routines in an efficient way, a circumstance that is aggravated by the current unavailability of vector algebra and of a number of common random distributions in the environment. For these reasons, StarLogo TNG is especially appropriate to models such as the one we present in this paper, built with the intention of gaining a full understanding of how the single parts of a system work, not of simulating a life-size world. However, we are aware that an operational model will have to be integrated with different tools.

We model a stylized version of a the “plain vanilla” RTGS system outlined in Section 2, excluding advanced liquidity management tools such as optimization and centralized queues. The model includes seven breeds of agents: banks, the central bank, payment requests, defaulted operations, interbank loan requests, crisis events and “craters”, representing banks hit by such events and accordingly unable to perform any operation for a given time. One StarLogo second corresponds to one real-life minute. The logical flow of the model is outlined below, while the following section discusses the parameterization in detail.

During the setup phase, representing the opening of operations, banks are endowed with a starting level of cash and collateral. During the day, for every tick of the clock, each bank “hatches” a certain number of new agents, representing aggregations of all payment requests to be sent to a single counterparty at that moment (Figures A.1 and A.2). Once hatched, each payment request proceeds to cross the terrain at fixed speed towards its destination (Figure A.3).

For computational reasons, the RTGS system is treated as direct-debit based, with payments always requested by the payee. For greater realism compared with agent-based

simulations that classify payments only on the base of their size and arrival time, payment requests in our model are assigned individual deadlines, ranging from “upon reception” (time-critical payments) to a certain number of minutes after reception. Amounts, deadlines and counterparties are determined through a random draw, whose features can vary depending on the desired scenario. Upon arrival, it is queued until its deadline expires and triggers the settlement routine. We remark that this submission rule allows for the implicit modeling of the settlement delay costs banks incur: for each operation, the delay cost is assumed to be a discontinuous function of time with a jump at the payment deadline, being lower than liquidity costs until the deadline and higher afterward.¹¹

From the moment a payment request is generated and until it is settled, its amount is incorporated in the expectations of a liquidity change for both the originating and receiving bank. We therefore assume that at each moment banks are perfectly informed on all payment requests concerning them either as payer or payee; at time t banks are able to calculate their future liquidity up to the time T , where $T-t$ is the maximum lifespan of a payment request generated at t . The expectation is constantly updated as new payment requests enter the world.

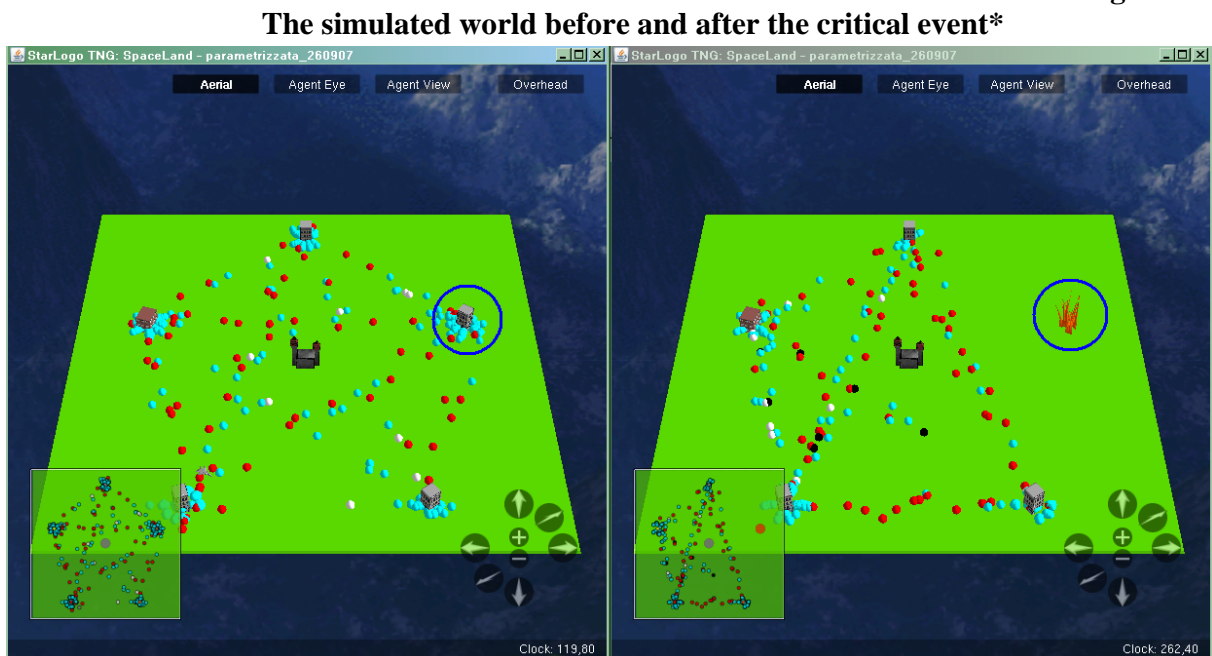
When the settlement process starts, the intended payer tries to meet its obligation immediately. If the cash balance it holds at the moment is not sufficient, it tries to pledge collateral with the central bank, which provides liquidity based on 100% percentage. In addition, a major innovation of our model is the explicit introduction of an interbank money market. If collateral is also insufficient the bank tries to borrow on the money market (“short” bank), looking for a lending counterparty (“long” bank). The short bank i randomly draws a potential counterparty k from all the other banks. Bank k agrees to the loan if the condition $p_t^{ij} \leq E [L_T^k]$ is met, where p_t^{ij} is the payment request, j is the bank that originated it, and $E [L_T^k]$ is the expected cash balance for k at time T (put simply: the bank does not lend money, if the lending makes future expected liquidity negative). In other words, the loan to cover p_t^{ij} is or is not granted on the basis of both present cash balances and future liquidity expectations, as determined by other outstanding payments initiated by or sent to the potential lender.

¹¹ Though not game-theoretically founded, this rule satisfactorily reflects the fact that banks schedule a large share of outgoing payments according to institutional intraday deadlines (cut-offs). These cut-offs are agreed with customers, who initiate payments, with the receiving bank, when the payment arise from interbank trades (see e.g. the guidelines of the Euro Banking Federation for money market related payments), or are established by the system rules (e.g. for payments related to monetary policy operations).

When a loan request is refused the payment request p_{t}^{ij} “bounces”, and the “short” bank looks for another lender. A counter keeps track of the number of bounces per request: when they exceed a certain threshold - a function of the number of possible available counterparties - the bank that has to settle the payment is unable to obtain sufficient funds from anyone. The request is cancelled and flagged as a defaulted obligation and its amount is recorded as an instance of insolvency by the “short” bank and as a loss by the intended payee bank. Liquidity expectations for both ends of the transaction are adjusted accordingly.

Disaster is simulated through the introduction of an agent of the “disruptive event” breed. A bank picked at random becomes utterly inactive (it neither makes nor receives payment requests, nor does it operate in the interbank market as lender or borrower). Initially (in the first thirty minutes after the disruption has taken place) no agent is aware of it and all surviving banks continue their routine activity. A random process then makes the banks aware of disaster, with the probability of awareness increasing over time. Once a bank is aware, it stops requesting payments from the inactive bank, no longer considers it as a counterparty for loan requests, transforms all payment and loan requests pending towards it into defaulted obligations and updates losses and expected liquidity (Figure 3).

Figure 3



* The simulated world is depicted one second before (left) and 140 seconds after (right) a critical event hitting the circled agent. In the “after” scenario, enough time has elapsed since the disruption to allow all banks to exclude the inactive bank from the flow of payment requests, represented by colored spheres moving on the terrain.

Depending on the simulated scenario, the central bank monitoring module may also be activated, although we do not use it in our simulation. When it is active, with a given lag following the disruption the central bank starts checking whether banks are delaying their payments beyond some pre-determined normal threshold. If a bank shows an excessive number of delays, the central bank supplies it with a sufficient amount of cash. The intervention routine stops when the number of delays is back below the threshold.

5. Parameterization

We use a set of summary statistics extracted from real data to calibrate the model. Data are drawn from the statistical archives that the Bank of Italy maintains in order, among other things, to perform its oversight function, in compliance with international standards.¹² They refer to the month of July 2007. More than 100 banks participate in BI-REL directly; we collapse them into five agents.¹³ The aggregation is necessary because the preliminary modeling step presented in the paper is aimed at capturing the essential traits of the agents' interactions, which can be best dealt with by focusing on a small number of agents. Each of our agents of the breed "banks" is therefore a "superbank" of sorts, incorporating banks that appear homogeneous in terms of payment traffic, opening balances, and collateral.¹⁴

Table 1 describes the five agents as they are in the real world. Superbanks 1 to 4 are aggregations of Italian banks, while superbank 5 is the aggregation of the Italian branches of foreign banks. The Bank of Italy collects elementary data for each payment channeled in the BI-REL system, including information on the counterparties involved, the type of payment¹⁵ and the time at which it is submitted, settled or canceled. We transform this mass of data into a simplified archive, containing aggregate per-minute payment flows submitted by the five fictitious superbanks, plus those generated by their interactions with the central bank and participants located outside the country which will be neglected.

¹² Notably, the 2001 BIS Core Principles for Systemically Important Payment Systems and the consequent framework of the European System of Central Banks.

¹³ The five agents do not include non-banks (i.e. the central bank, central securities depositories and other clearing agents, as well as banks not directly participating in BI-REL, but using EU RTGS linked to it).

¹⁴ The reduction in the number of agents, forced by computational limitations, impacts on the evolution of the complex system. The BI-REL system is, however, quite concentrated; two superbanks, for example, correspond to actual single banking groups, with a high level of internal coordination in the payment system.

¹⁵ Broadly speaking, the "type of payment" attribute indicates whether a transaction is initiated by a bank customer or stems from the bank's own activity in the financial market.

Payments involving individual banks belonging to the same superbank (intragroup flows), which amount to about 40 per cent of the total given in Table 1, are not considered. This does not present substantial drawbacks for the model, as most of these payments occur over the counter and are channeled through internal accounts rather than through BI-REL.

Data on cash balances refer to the fiat money banks hold at their RTGS accounts at the start of the operational day, while data on collateral are estimated on the basis of the maximum amount of collateral pledged at the central bank during the day.

Table 1

Main scenario
(€ millions)

| Agent number | Average payments settled daily | Large ^a payments settled (% of the total) | Average end-of-day liquidity | Average end-of-day collateral |
|--------------|--------------------------------|--|------------------------------|-------------------------------|
| 1 | 18,384 | 3.0 | 5,302 | 2,648 |
| 2 | 22,669 | 6.6 | 3,583 | 3,947 |
| 3 | 13,718 | 3.1 | 4,780 | 2,766 |
| 4 | 18,451 | 8.8 | 2,211 | 850 |
| 5 | 43,339 | 7.5 | 439 | 10,119 |
| Total | 116,562 | 5.0 | 16,315 | 20,329 |

^a Payments are defined “large” if their amount exceeds the 95th percentile of the total distribution of flow values.

For our methodological purposes we just need to extract some stylized facts from the data observed and reproduce them within the simulation through a series of random draws.

To begin with, real-life payment distribution is highly concentrated (Figure 4), with payments larger than the 95th percentile accounting for 85 per cent of the total amount exchanged and those above the 99th percentile alone for 50 per cent. The average payment (2.9 million euros) is therefore scarcely representative of the data mass, and such a high concentration makes kernel estimates of the underlying density function very unreliable. In other words, the relevant feature of the payment distribution is that it is formed by a great mass of payments of relatively small values and an isolated cluster of unusually large ones; also, huge payments tend to be spread among participants.

The daily amounts of collateral and cash show a high degree of variability and do not follow easily detectable patterns of correlation (Lütkepohl and Krätzig, 2004) according to an

exploratory analysis of the two series using the Johansen test of cointegration rank, not shown here for brevity (Figure 5); this could be explained by the fact that cash is also held to satisfy Eurosystem reserve requirements. Finally, the time series of daily payments is not correlated with either collateral or cash flow, which accords with the fact that the vast majority of payments to settle during the day are satisfied by liquidity obtained in the course of the day.

Figure 4

**Concentration curve for payments submitted by the five superbanks
(percentages)**

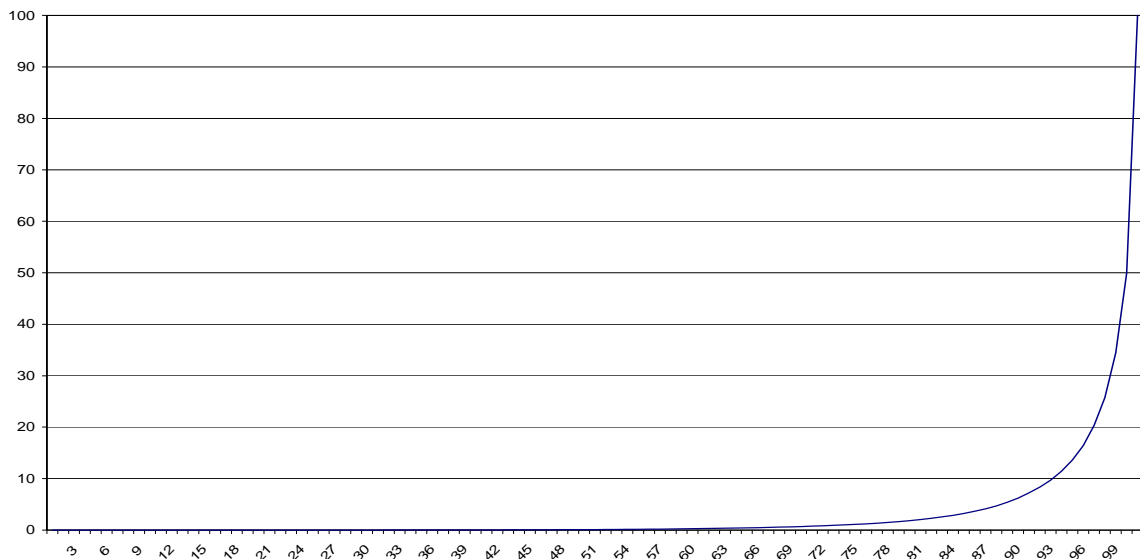
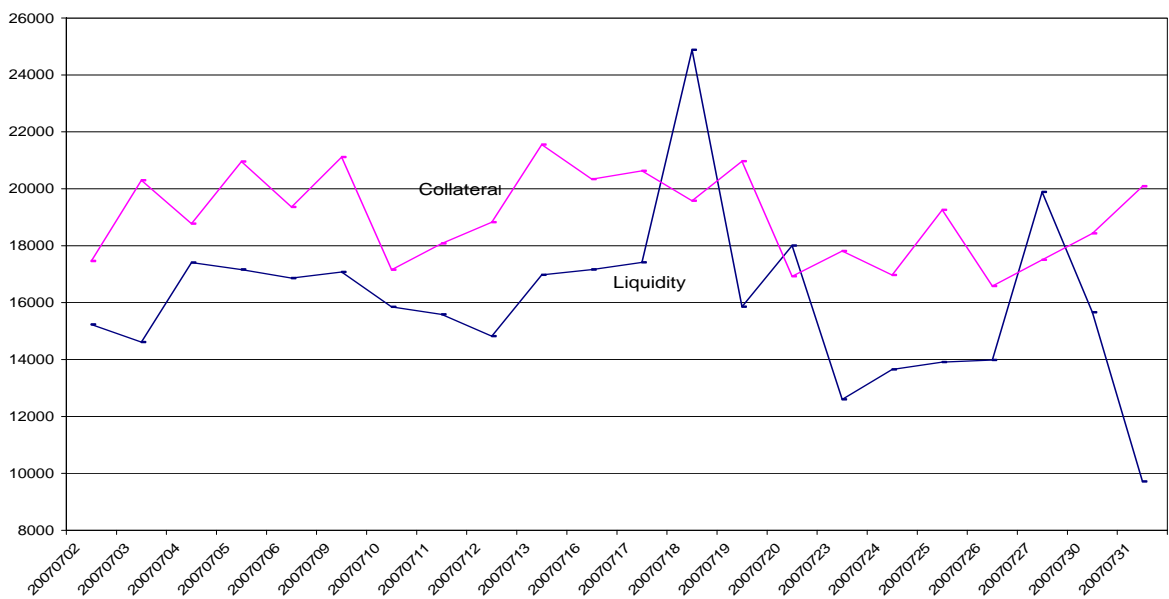


Figure 5

**Total daily amounts of collateral and liquidity
(€ millions)**



We reproduce these features as follows. Before the generation of payment flows, each fictitious system participant is initially endowed with liquidity and collateral. We first decrease the real daily amounts in our dataset by the share of payments for which the payee is not among the five units considered. These reduced amounts are further shrunk to take into account that they are also used to settle payments made by two participants belonging to the same superbank. We then compute for each of the five macro entities i the means μ_{Li} , μ_{Ci} and the standard deviations σ_{Li} , σ_{Ci} of these final amounts of liquidity and collateral. The starting levels of liquidity and collateral are approximately generated as realizations of two uniform distributions defined in the intervals $[\mu_{Li} - \sigma_{Li}, \mu_{Li} + \sigma_{Li}]$, $[\mu_{Ci} - \sigma_{Ci}, \mu_{Ci} + \sigma_{Ci}]$.

When it comes to generating payment flows, we emulate reality through a sequence of two per-minute draws from a uniform distribution for every participant: the first decides whether a payment request is to be submitted and the second, conditionally on the payment being submitted, decides its size class (small or large).

The probability of submitting a payment in the typical minute reproduces the average empirical frequency; on average, 98 per cent of submitted payments are small. The final size of the payments is decided by an additional random draw from a uniform distribution, centered on the appropriate class mean for payment size. The class means take into account that we want to simulate only payments taking place between the superbanks entities, and therefore neglect cross-border payments and those to and from the central bank.

6. Results

The simulation results are briefly described: insofar as they appear to be realistic, they can confirm the robustness of the proposed methodology, although they are just a first stepping-stone for real-scenario analysis because of the highly stylized context used.

Figures 6.1-6.5 depict the model predictions. The five panels represent the global evolution of liquidity levels, liquidity expectations (expressed as differences between current liquidity and liquidity as estimated after the settlement of all payment flows currently existing in the system), money market thickness, delays and losses incurred by banks in settlement activity.

Under normal operating conditions, the total liquidity follows quite a steady pattern, whereas the average expected liquidity is zero by definition, since we are modeling a closed world with five agent and what a single agent expects with the “plus” sign exactly corresponds to the same amount with “minus” sign for another. Only a modest percentage of the banks’ required

liquidity is covered by money market trades, very close to the current true 5-7 per cent of the Italian banking system.

When the disruptive event occurs and one of the banks is rendered unable to perform any transaction, the system evolves through three distinct phases. At first, when no agent is aware of what happened, the average expected liquidity jumps from zero to large positive values, since the banks in operation keep on sending payment requests to the inactive one, incorporating the future settlement of such requests in their expectations. Such future settlements will obviously remain unfulfilled, resulting in failure of the regular counterbalancing mechanism for expectations, and illusions of short-run liquidity increase for all its counterparties.

This ushers in the second phase, marked by a sizable boom in money market transactions. Banks experience a lack of liquidity, because they do settle all requests from the inactive bank that were pending at the time of the disaster but their own requests towards it are not settled. After consuming their entire endowment of collateral in exchange for central bank money, they try to remedy the lack of liquidity by turning to the money market. Since loans are granted based on both current and expected liquidity, and expected liquidity is artificially inflated for the reasons stated above, all banks are willing to lend to other banks: the thickness of the interbank market increases sharply, and as the actual liquidity fails to come in, delays accumulate.

The third phase sets in as banks start to become aware of the disruptive event. One by one, they realize that a bank is not operational anymore and adjust their liquidity expectations accordingly. Money market activity slows down and losses accumulate.

Whether the system goes back to normal functioning, aside from the accumulated stock of defaulted obligations, depends on the relative impact of the disruptive event and its consequences compared with the total amount of liquidity in the system. According to our model, the system would not be able to react autonomously, i.e. without bailouts from the central bank, which were not implemented in the simulation.

7. Conclusions and further research

In this paper we present an agent-based model of crisis simulation for a simplified RTGS payment system. The model's predictions approximate the macro-features of reality, showing the sequential intraday effects of an unexpected negative shock affecting a participant. The event first affects the liquidity stock and expectations of other participants. Then, the turbulence spills over in the interbank market and finally, when it has become visible in payment system activity,

necessitates adequate central bank intervention. Overall, the results shown suggest it could be worth further exploring the possibility of including agent-based modeling in the set of analytical tools that central banks use in their oversight activity and in the analysis of stability and resilience of financial systems. The model is related to stress testing techniques, commonly employed by supervisory authorities and individual banks in quantifying the effects of extreme financial or operational events. Stress testing methodologies share many traits with agent-based modeling, such as the focus on a given set of institutions, while behavior is governed by a pre-defined set of rules and generates feedback or “second round” reaction effects. However traditional stress tests may put too little emphasis on market-wide conditions, being more focused on firm-specific levels, and accordingly underestimate some liquidity risks originating in new financial products and techniques. Agent-based simulation may be especially suitable as a remedy to these shortcomings, since it is flexible enough to accommodate increasing complexity in the behavior of financial networks such as settlement systems.

Our framework can be improved in several directions, so as to better reflect real RTGS and money market environments. The payment submission process can be refined by moving from a direct-debit to a credit-transfer based system, where payments are submitted by the payer. The number of banks should be enlarged, and some source of uncertainty could be introduced by relaxing the independence assumption underlying payment generation and the hypothesis of common knowledge of environmental variables. Moreover, banks could be assigned an end-of-day target in terms of cash balances, to mimic the inter-day liquidity management optimization they pursue during the maintenance period for required reserves.

As for the central bank, the fact that it autonomously makes and receives payments in real – life RTGS systems, together with its well-known liquidity supplier function, needs to be considered. Modeling of the money market can be refined to take into account the role of overnight interest rates in influencing banks borrowing and lending decisions. The rest of the world could be introduced at least as an external shocking agent, also to account for the significant (and increasing) real-life share of cross-border payment traffic.

Time patterns of the relevant variables during the simulation
(disruptive event indicated by the vertical line)

Figure 6.1

Total liquidity

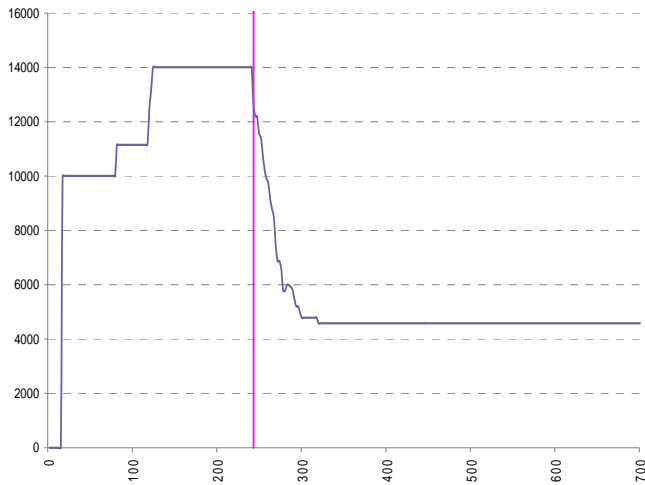


Figure 6.2

Average expected liquidity

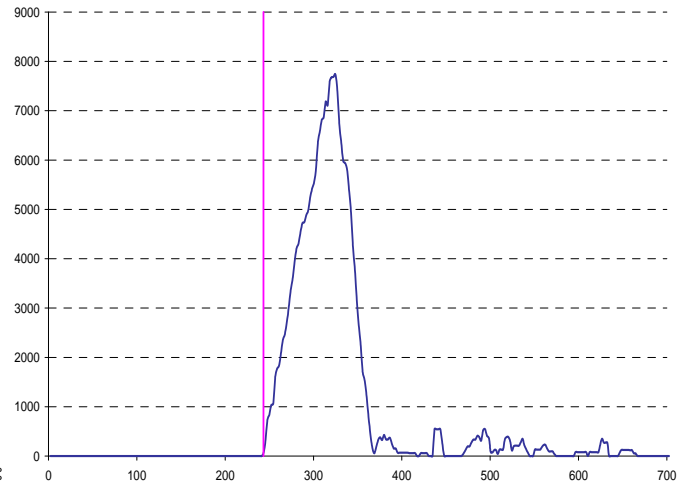


Figure 6.3

Number of lending operations

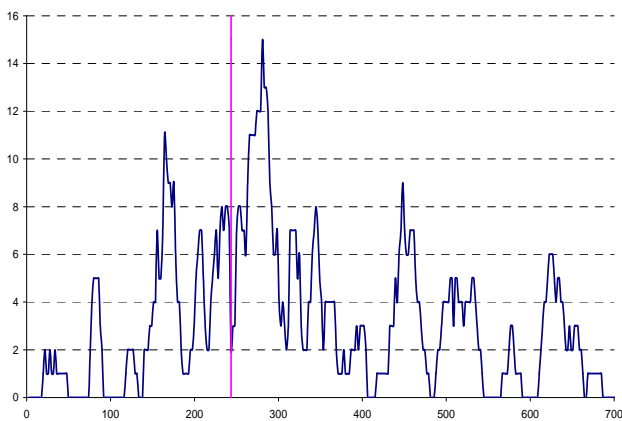


Figure 6.4

Number of delays

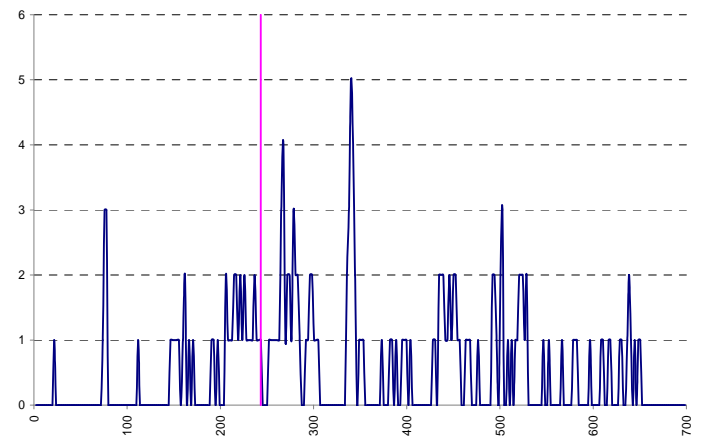
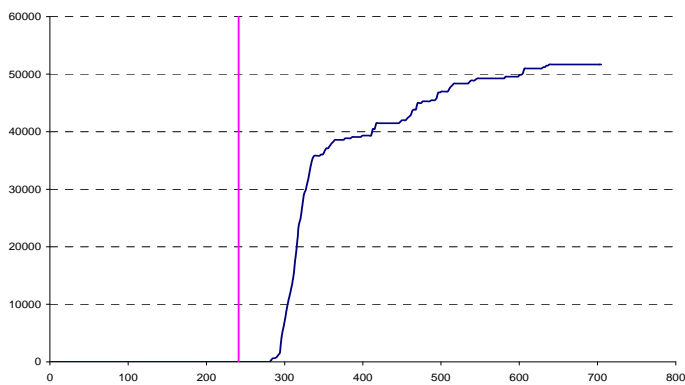


Figure 6.5

Total losses



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Appendix - The main building blocks of StarLogo TNG programming

Figure A.1

Timed Run block for payment generation*



*Each agent of the breed “Banks” is instructed to execute the procedure “PaymReqBank” repeatedly for 600 seconds.

Figure A.2

Agent procedure for payment generation, initial steps*

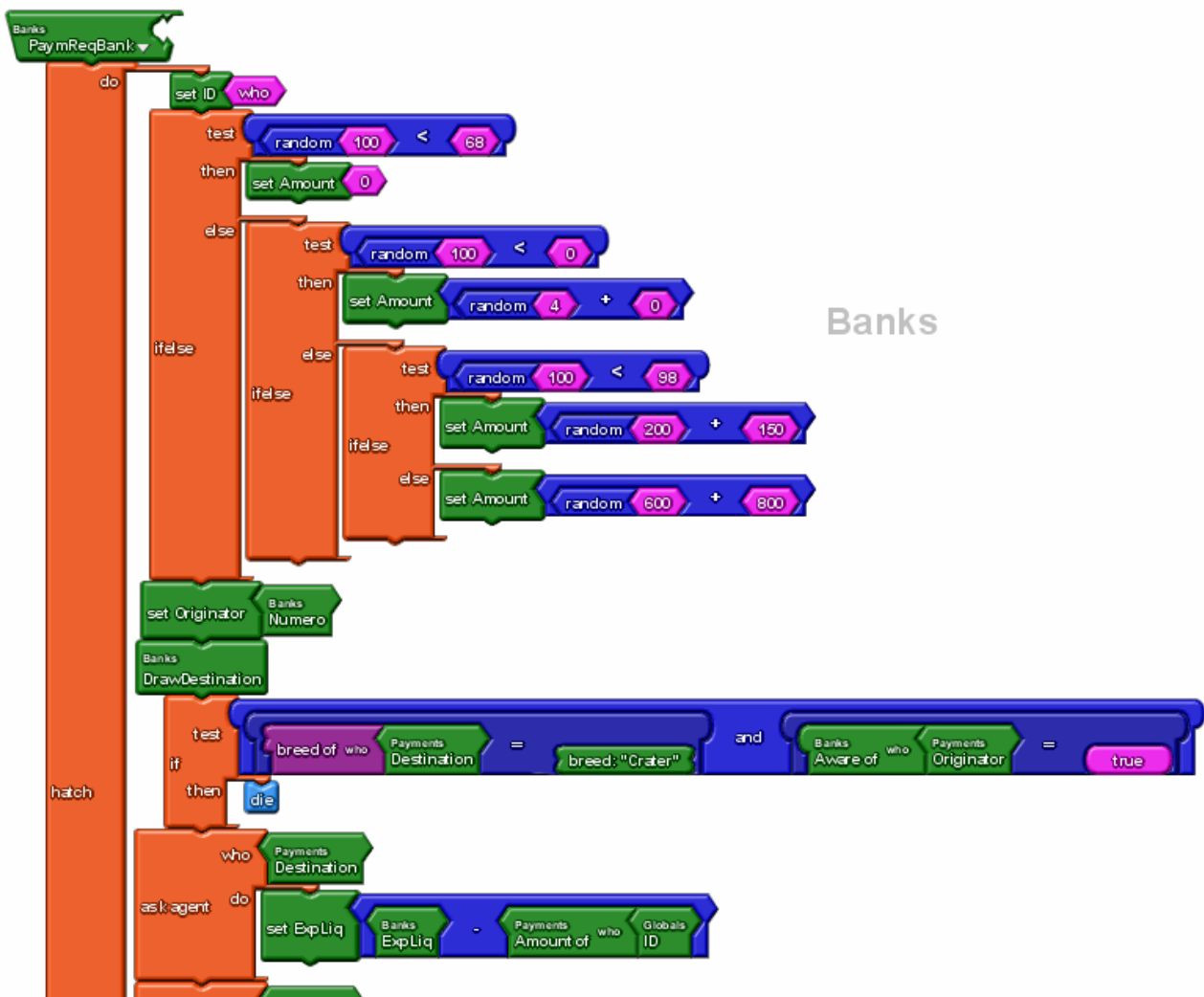
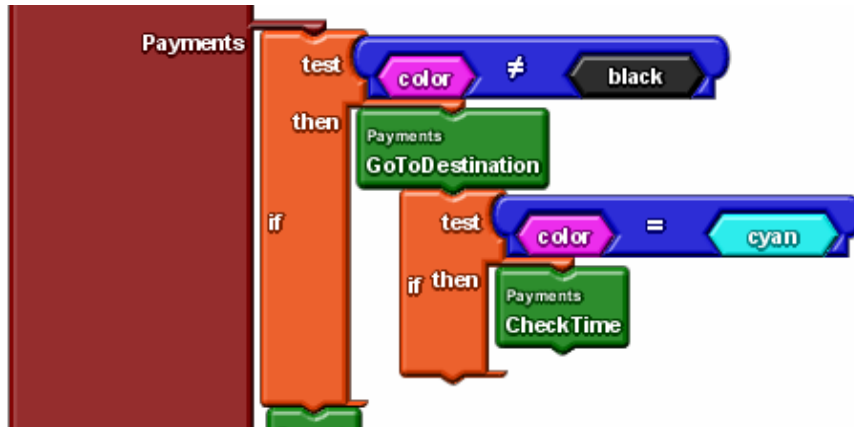


Figure A.3

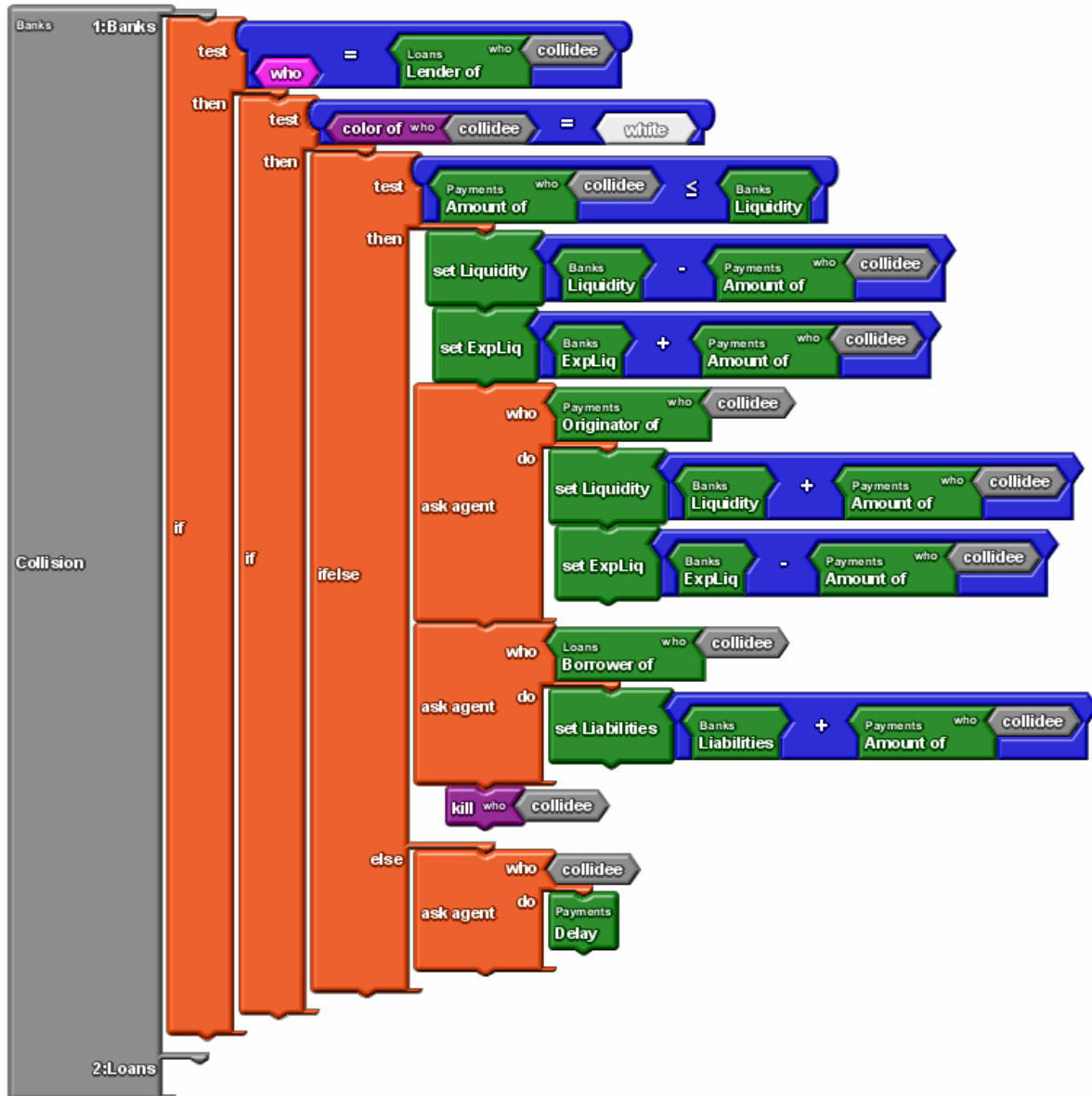
Perpetual Run block and agent procedure for the movement of payments*



* These sets of blocks control the movement of payment requests over the terrain. The CheckTime procedure runs simultaneously to the GoToDestination one and ensures that requests are flagged as time-critical when their deadline expires.

Figure A.4

Collision block for banks and interbank loan requests*



* The potential lender communicates its willingness to act as such when the borrower generates the loan request, but the loan is granted only upon collision, i.e. after the request has crossed the terrain separating borrower and lender. The mechanism allows for revision of the lender's liquidity expectations during the interval between loan request and the time the loan is made.

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