Network Model Simulation and Stress Testing of PvP Systems

Jorge Cruz Lopez
Financial Network Analytics (FNA)
University of Western Ontario

Gabriel Rodriguez Rondon
Financial Network Analytics (FNA)
McGill University

Giuseppe Matera
Financial Network Analytics (FNA)

Jordan Cambe
Financial Network Analytics (FNA)

Carlos Leon
Financial Network Analytics (FNA)

Bank of Finland
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1. Introduction

What do we do?

- **Objective:**
  - To develop a methodology to simulate single currency and payment-versus-payment (PvP) transactions.

- **Motivation:**
  - PvP transactions are common in foreign exchange (FX) trades, crypto-currency to fiat currency trades, and crypto-currency to crypto-currency trades. In addition, we expect that PvP transactions will be used for exchanging central bank digital currencies (CBDCs) across jurisdictions (see CPMI et al., 2021).
  - In 2020, the G20 set as a key priority the enhancement of cross-border payments, which includes facilitating the adoption of PvP (see CPMI, 2020; CPMI, 2022).
  - Most models in the literature focus on single-currency transactions (see Chiu and Lai, 2007)

- **Applications:**
  - Synthetic data
  - System architecture
  - Scenario analysis
  - Stress testing

How do we do it?

- **Overview of Methodology:**
  - Our simulation approach takes the Soramäki and Cook (2013) method as the basis for generating a payments network.
    - This method creates directed, weighted, scale-free networks, such that arches or links, which represent payment orders, are generated based on the preferential attachment of nodes, which represent market participants.
  - We generalize this method by taking into account the time partitions used in Cruz Lopez, Kahn and Rodriguez Rondon (CKR, 2021), which allows to incorporate the following features:
    - Intraday variation in volumes, values
    - Intraday variation of in the number of active market participants
    - Heterogeneity across market participants with respect to the value of payment order submissions
    - The option to simulate batches of trading days with carry over balances that can be complemented with overnight flows
  - We also generalize this method by extending the model to include **PvP transactions**.
    - To the best of our knowledge this is the first PvP simulator

What do we get?

- **Preliminary Results:**

  - Our model can simulate systems with a wide range of characteristics
    - Different number of participants
    - Wide ranges of volumes and values
    - Different settlement and risk management structures

  - It can generate counterfactual scenarios for stress testing

  - Importantly, we can obtain the probability and impact (on variables of interest) of each scenario

Figure 1: First Leg: USD Payments

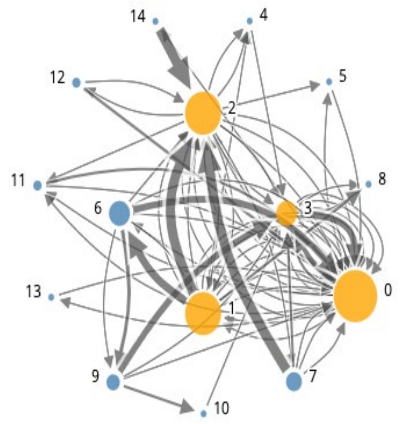
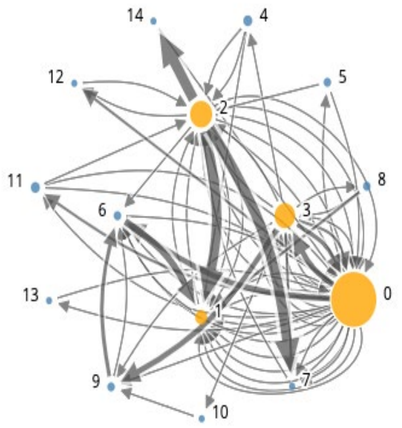


Figure 2: Second Leg: EUR Payments



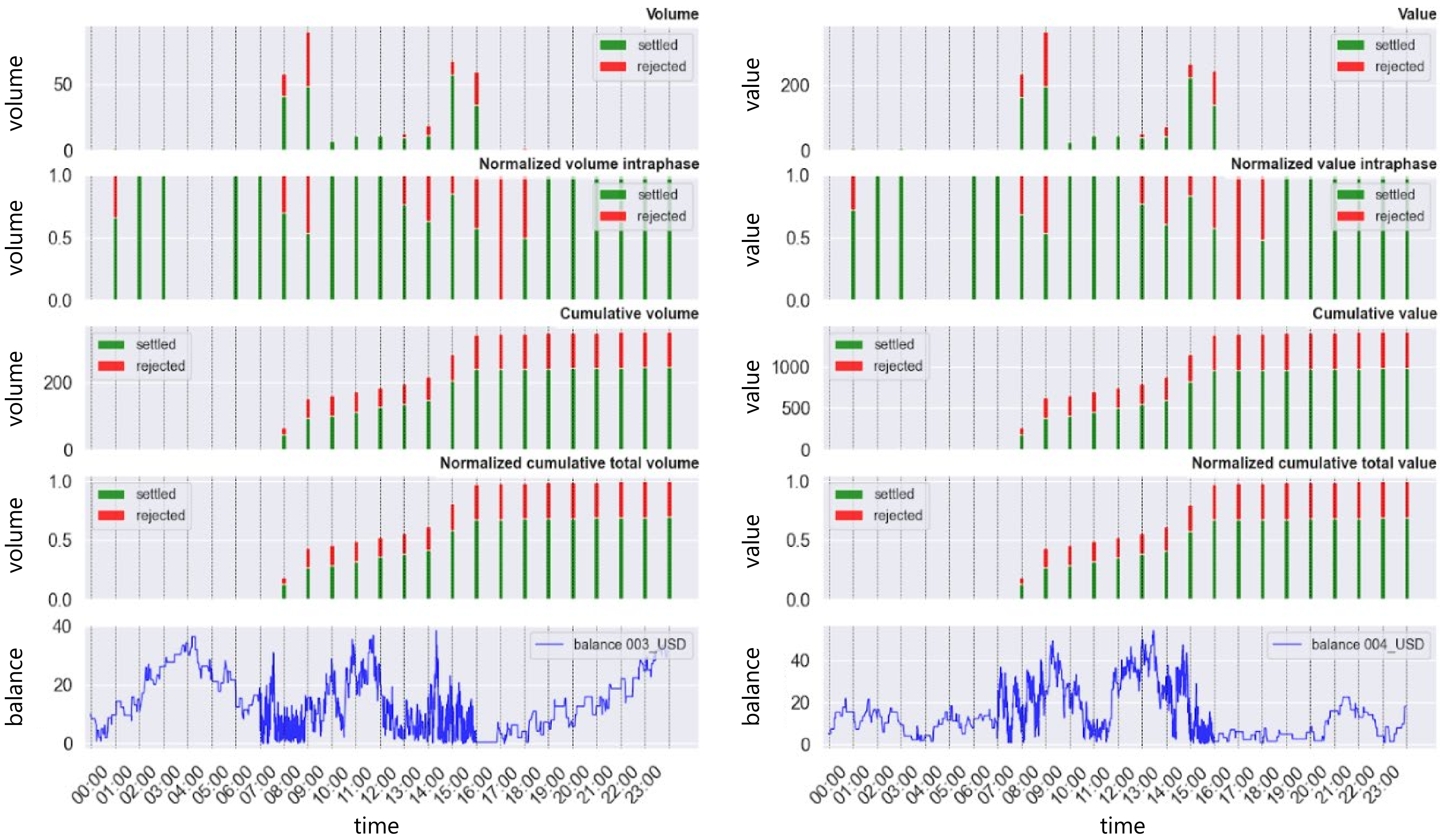
What do we get?

Figure 3: Example of synthetic payments data

id	datetime	sender	receiver	value	priority	currency	settled	rejected	settl_status	sub_period
20220817090000_02_03_GBPEUR_01	2022-08-17 09:00:00.139016331	participant-2	participant-4	58.63	0	GBP	2022-08-17 09:00:00.139016331		0	0
20220817090000_03_02_GBPEUR_02	2022-08-17 09:00:00.139016331	participant-4	participant-2	69.23	0	EUR	2022-08-17 09:00:00.139016331		0	0
20220817090002_00_02_GBPEUR_01	2022-08-17 09:00:02.846642976	participant-3	participant-2	104.64	0	GBP	2022-08-17 09:00:02.846642976		0	0
20220817090002_02_00_GBPEUR_02	2022-08-17 09:00:02.846642976	participant-2	participant-3	123.55	0	EUR	2022-08-17 09:00:02.846642976		0	0
20220817090002_02_05_USDEUR_02	2022-08-17 09:00:02.225522542	participant-3	participant-6	91.11	0	EUR	2022-08-17 09:00:02.225522542		0	0
20220817090002_05_02_USDEUR_01	2022-08-17 09:00:02.225522542	participant-6	participant-3	92.97	0	USD	2022-08-17 09:00:02.225522542		0	0
20220817090008_01_02_USDGBP_01	2022-08-17 09:00:08.819607024	participant-3	participant-1	376.91	0	USD	2022-08-17 09:00:08.819607024		0	0
20220817090008_02_01_USDGBP_02	2022-08-17 09:00:08.819607024	participant-1	participant-3	312.84	0	GBP	2022-08-17 09:00:08.819607024		0	0
20220817090021_00_01_GBPEUR_02	2022-08-17 09:00:21.458116283	participant-3	participant-1	168.80	0	EUR	2022-08-17 09:00:21.458116283		0	0
20220817090021_00_02_USDGBP_02	2022-08-17 09:00:21.186144672	participant-2	participant-1	105.84	0	GBP	2022-08-17 09:00:21.186144672		0	0
20220817090021_01_00_GBPEUR_01	2022-08-17 09:00:21.458116283	participant-1	participant-3	142.96	0	GBP	2022-08-17 09:00:21.458116283		0	0
20220817090021_02_00_USDGBP_01	2022-08-17 09:00:21.186144672	participant-1	participant-2	127.52	0	USD	2022-08-17 09:00:21.186144672		0	0
20220817090023_00_01_USDEUR_01	2022-08-17 09:00:23.201984491	participant-1	participant-2	97.54	0	USD	2022-08-17 09:00:23.201984491		0	0

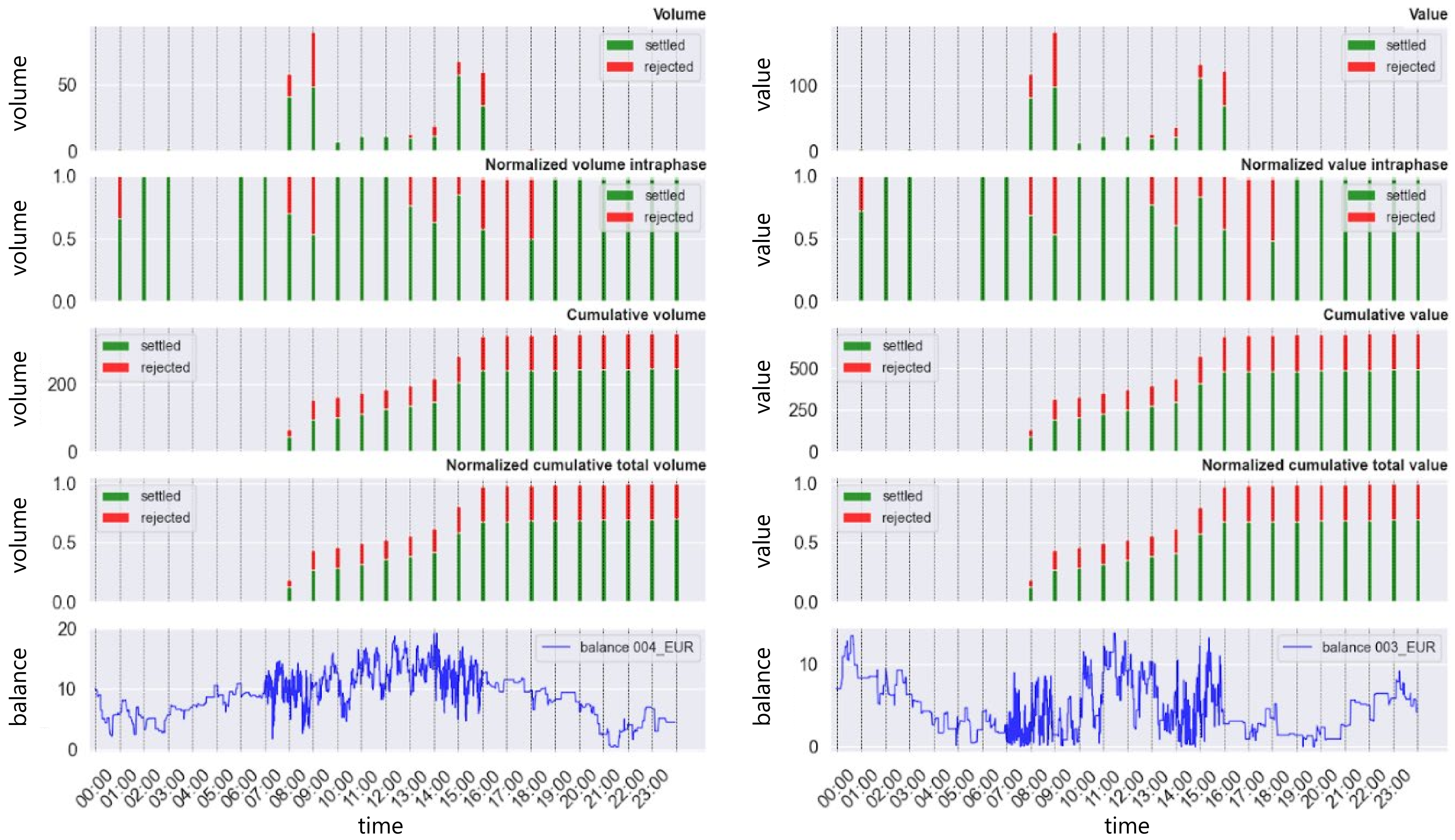
What do we get?

Figure 4: Example of Simulation Results
Payments from a large participant to a large participant in USD



What do we get?

Figure 5: Example of Simulation Results
Payments from a large participant to a large participant in EUR



Where do we fit in the literature?

- **Leon (2012)**
  - Provides a method for simulating payments data **based on volumes** using a correlated Poisson distribution. Correlated volume of payments are then interpreted as a sign of coordination across market participants and values are assigned by means of a historical (non-parametric) bootstrap procedure.
  - Does not model volumes and values jointly, which may lead to incorrect identification of events or coordination (e.g., a slowdown in the payment flows of the system could be caused by a participant that reduces the value of its payments to others without altering its volume)
- **Soramäki and Cook (2013)**
  - Simulates a payment network using the method in Barabási and Albert (1999) for scale-free networks. Distribution of volumes is determined by throughput guidelines and timing is assigned using a uniform distribution.
  - Matches network properties well but does not preserve some economic properties (e.g., timing, coordination, correlations, etc. at the bilateral and multilateral levels)
- **Cruz Lopez, Kahn and Rodriguez Rondon (CKR, 2021)**
  - Models the behaviour of individual market participants using impulse response functions to the actions of other participants in the system
  - This approach can model important economic features at the participant, pair, group and system levels:
    - Liquidity rationing
    - Bilateral coordination of participants
    - Multilateral coordination of participants
    - Queuing and liquidity saving mechanisms (LSMs)

A quick word on synthetic data

- **Why do we need synthetic data?**
  1. **Privacy:** Anonymize private and confidential data while preserving statistical features of original data
  2. **Access:** Allow academics and other professionals to work in relevant problems without the "red tape"
  3. **Innovation:** Development of new models and improvement of existing ones

Figure 6: Daily Value

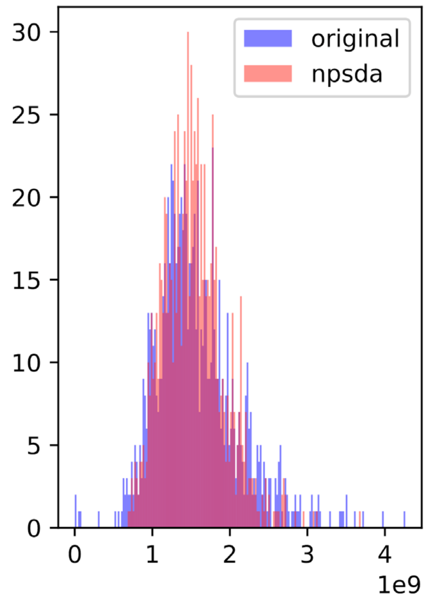
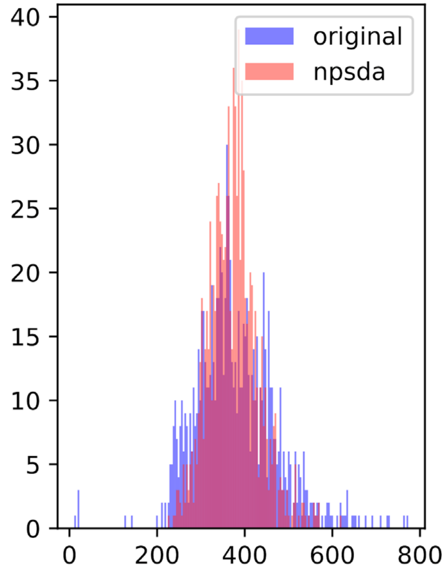


Figure 7: Daily Volume



2. Methodology

Soramäki-Cook Method

- **Context:**
  - Soramäki and Cook (2013)
  - Based on an extension of Barabási-Albert model (Barabási, A.-L., and Albert, R. (1999)) for generating random scale-free networks. This method has two important features: (1) growth and (2) preferential attachment

- **Key Features:**
  - Growth: network starts with only a few nodes (participants) and more nodes are gradually added to the system.
  - Preferential attachment: more connected nodes (participants) are more likely to receive new links (payments). Newly added nodes are therefore more likely to connect to nodes with many existing links.
  - Match volume & connectivity for full day
  - Value is assigned using a truncated log-normal distribution

- **Limitations:**
  - Does not allow for intraday variation (e.g., volume, value and number of participants)
  - Does not allow for heterogeneity of participants with respect to value
  - Does not take into account settlement protocols (ignores interactions between the system architecture and the generation of payment orders)
  - Does not model changes in participant behaviour resulting from stress scenarios and/or changes in system configuration

Generalizing Single Currency Payments

- **Step 1:** Set initial balances or unconstrained balances
- **Step 2:** Split the day into periods (e.g. 24 periods of one hour)
- **Step 3:** For each period:
  1. Generate payment orders (links) following the Soramäki, Cook (2013) method
  2. Assign values using (heterogeneous) truncated log-normal distributions (by participant type) for each payment order
  3. Assign time to each payment order
  4. Sort payment orders chronologically
  5. Run the settlement protocol
  6. Update balances for each participant
- **Step 4:** Repeat step 3 until full day has been generated

Integrating PvP Transactions

- **First Leg:**
  - We use our single currency method presented in slide 13 to generate single currency networks (e.g., USD) for the first leg of the FX transaction.
  - We generate one network for each currency pair (e.g., USD-CAD, USD-JPY, etc.) for which trading is allowed in the payment system.
- **Second Leg:**
  - For each first leg, single-currency network, we generate the network of corresponding payments (i.e., the second leg) using a realized or simulated FX rate for the corresponding date
  - Note: Dividing the model by periods, allows us to introduce intraday variation in exchange rates
- **Settlement:**
  - We settle both legs of the transaction using a real time gross settlement (RTGS) protocol. However, other protocols, including queues, can be implemented.

PvP Modeling Assumptions

- The distributions of payment value all follow a truncated lognormal distribution
- A participant can only send a payment order in a given currency once it has had a positive balance in that currency
- The timing of payment arrival within each period follows a uniform distribution
  - There is no "hard wired" correlation in the timing of payments between participants
  - But this can be changed (e.g., by adding correlated arrival times)
- Each currency pair is independent from the other currency pairs
  - That is, each payment in a given currency pair is generated independently of the other currency pairs
  - Again, this can be changed (e.g., by adding a multivariate distribution of volumes and values across currency pairs)

USD-EUR PvP Network

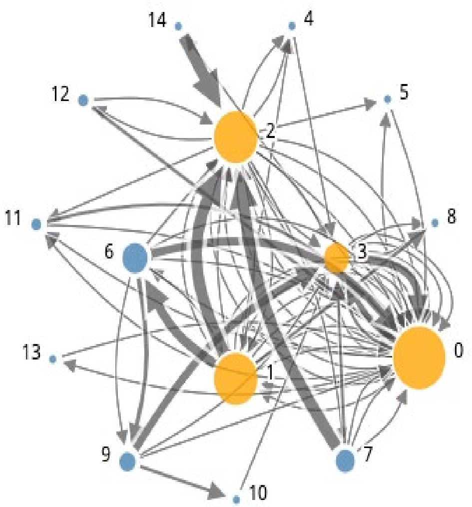


Figure 8: First Leg: USD Payments

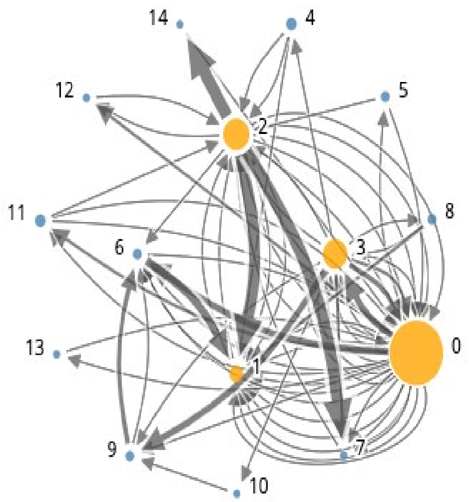


Figure 9: Second Leg: EUR Payments

Table 1: Description of network components

Network Component	Representation
Node Size	Volume sent during the period
Node Colour	Orange for core Blue for periphery
Edge direction	Payment order flow (from-to)
Edge width	Value

3. Applications

3.1. Simulation

Parameters

- **Currency pairs**
  - n, number of participants
  - n_0, number of core participants
  - Exchange rates
  - Daily volume
  - Parameters of payment value distributions:
    - Average payment value,
    - standard deviation,
    - maximum payment value

Table 2: Description of network components

Currency pair	Rate	n_0	n	Daily volume
USD/EUR	0.98	3	8	10,000
USD/GBP	0.83	3	8	10,000
GBP/EUR	1.18	3	8	10,000

Table 3: Description of network components

Currency pair	stats	Large-Large	Small-Large	Large-Small	Small-Small
USD/EUR	average	200	100	20	10
USD/EUR	std	10%	10%	10%	10%
USD/EUR	max	2,000	1,000	200	100
USD/GBP	…	…	…	…	…
…	…	…	…	…	…

Parameters

Table 4: Volume throughput profile

Start time	End time	Proportion
00:00:00	08:00:00	0.1
08:00:00	10:00:00	0.3
10:00:00	14:00:00	0.2
14:00:00	18:00:00	0.3
18:00:00	23:59:59	0.1

Parameters

Table 5: Ranking of participants

Bank id	USD/EUR	USD/GBP	GBP/EUR
participant-1	0	2	1
participant-2	1	0	2
participant-3	2	1	0
participant-4	3	3	3
participant-5	4	4	4
participant-6	5	5	5
participant-7	6	6	6
participant-8	7	7	7

Parameters

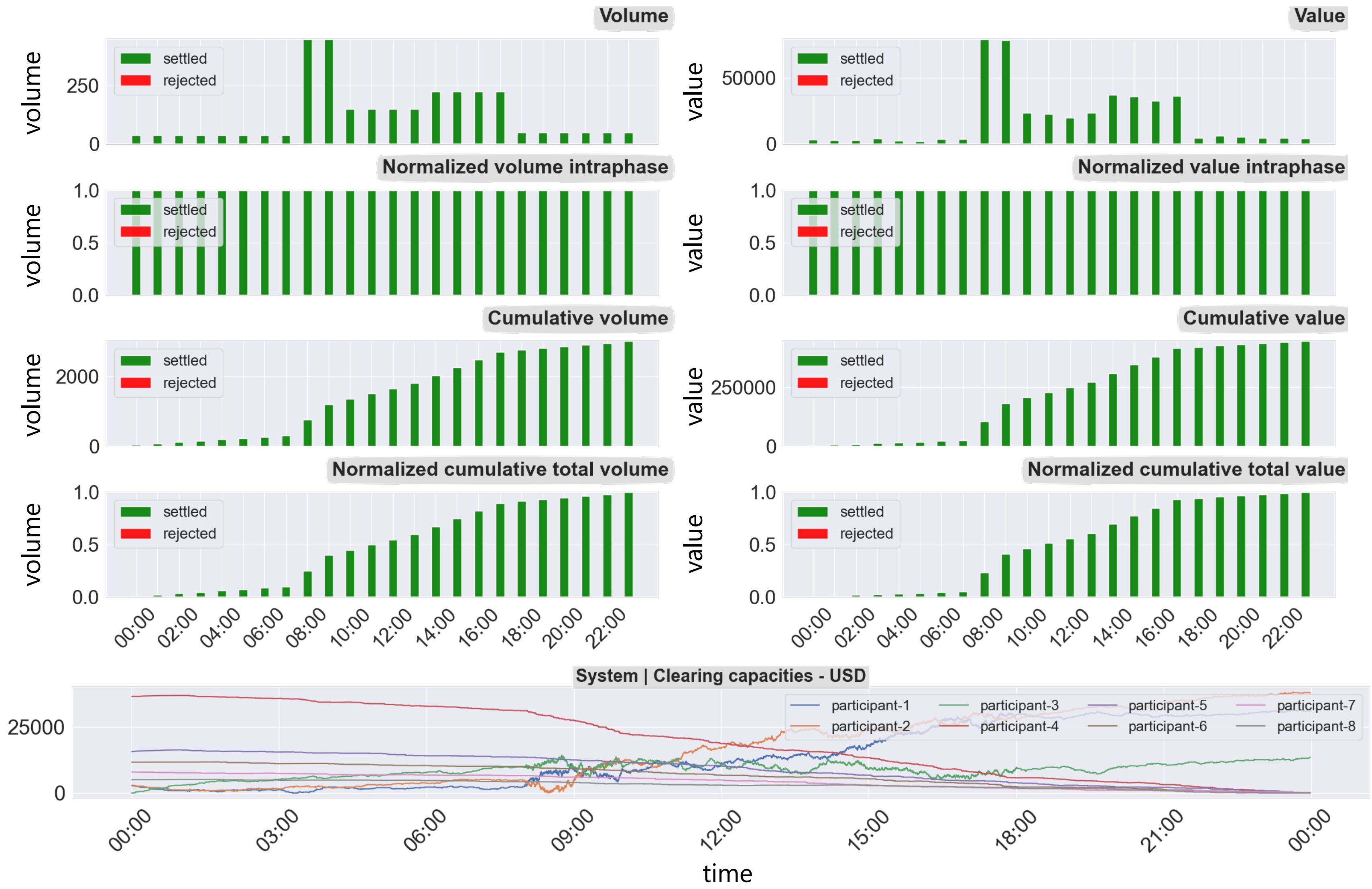
Table 6: Clearing capacities

The liquidity needs of each participant in each currency are given as their initial clearing capacities

Bank id	USD	EUR	GBP
participant-1	2,894.81	46,114.88	3,216.26
participant-2	2,767.82	9,056.09	22,409.38
participant-3	0	25,161.62	0
participant-4	36,480.6	349.4	0
participant-5	15,656.97	0	4,721.45
participant-6	11,645.17	0	1,890.04
participant-7	7,945.66	0	404.84
participant-8	4,968.62	130.67	433.55

Results

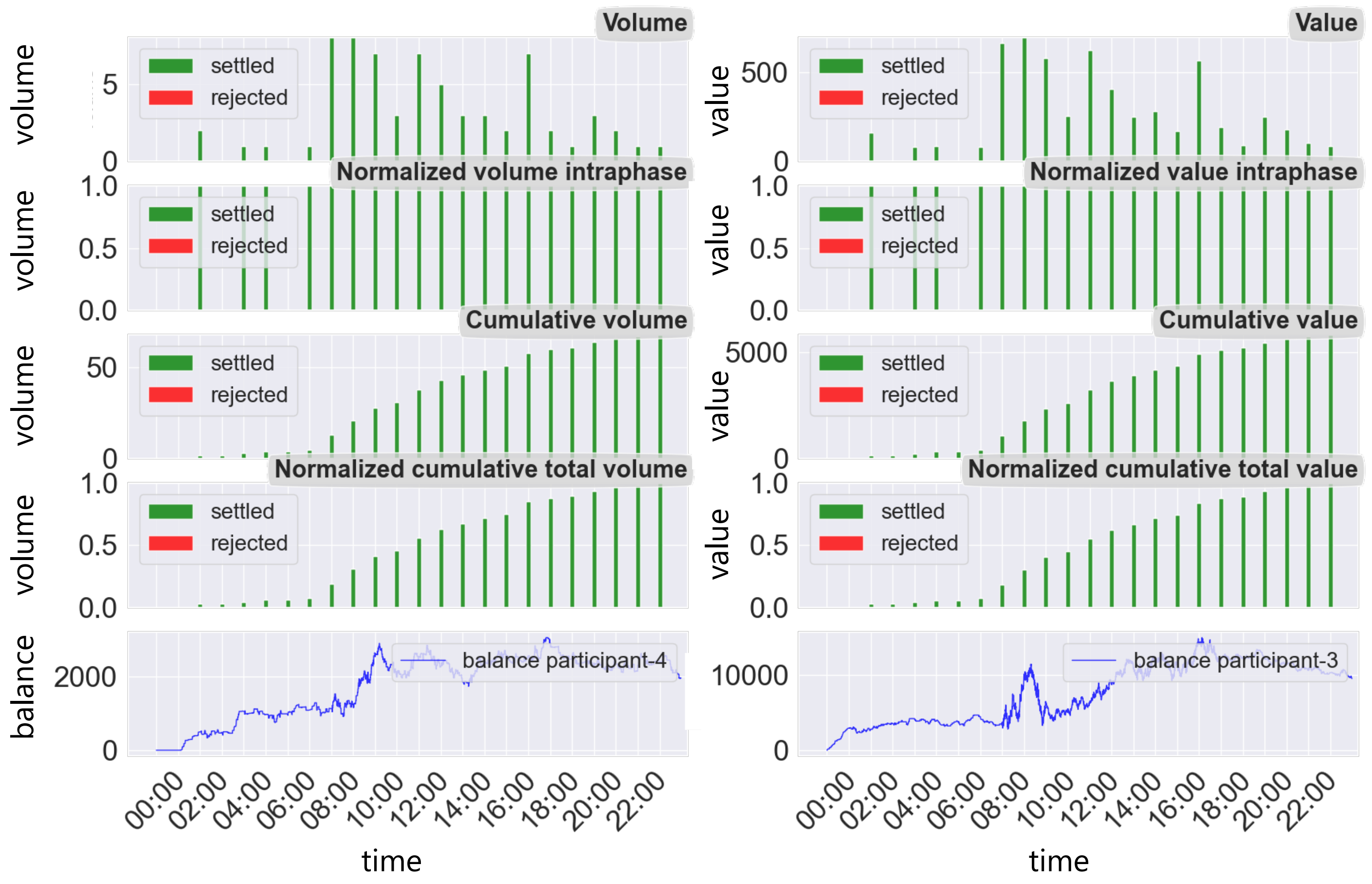
Figure 10: System level statistics USD/EUR in USD



- **Left Panel: Volume Statistics**
- **Right Panel: Value Statistics**
- **Statistics:**
  - Gross volume and value settled and rejected
  - Normalized volume and value settled and rejected in the period
  - Gross cumulative volume and value
  - Normalized cumulative volume and value

Results

Figure 11: Bilateral level statistics GBP/EUR in GBP
Participant 4 – Participant 3



- **Left Panel: Volume Statistics**
- **Right Panel: Value Statistics**
- **Statistics:**
  - Gross volume and value settled and rejected
  - Normalized volume and value settled and rejected in the period
  - Gross cumulative volume and value
  - Normalized cumulative volume and value
  - Balance of sender
  - Balance of receiver

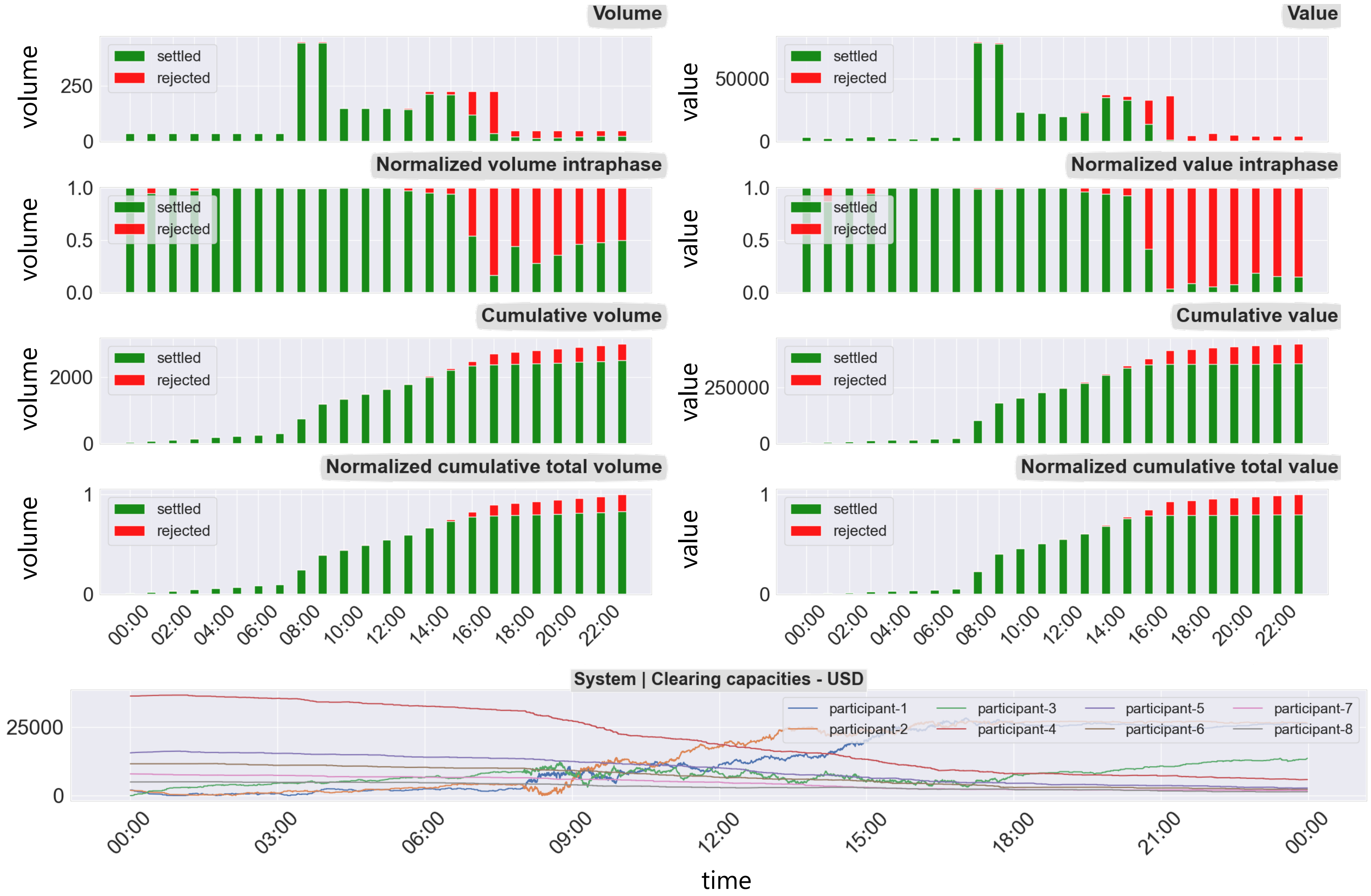
3.2. Stress Testing

Possible Stress Variables

- Number of participants and core participants
- Daily Volume
- Parameters of the payment value distribution (truncated lognormal distribution)
  - Location
  - Standard deviation
  - Maximum
- Throughput profile
- Clearing capacities
- Participant Outage

Results

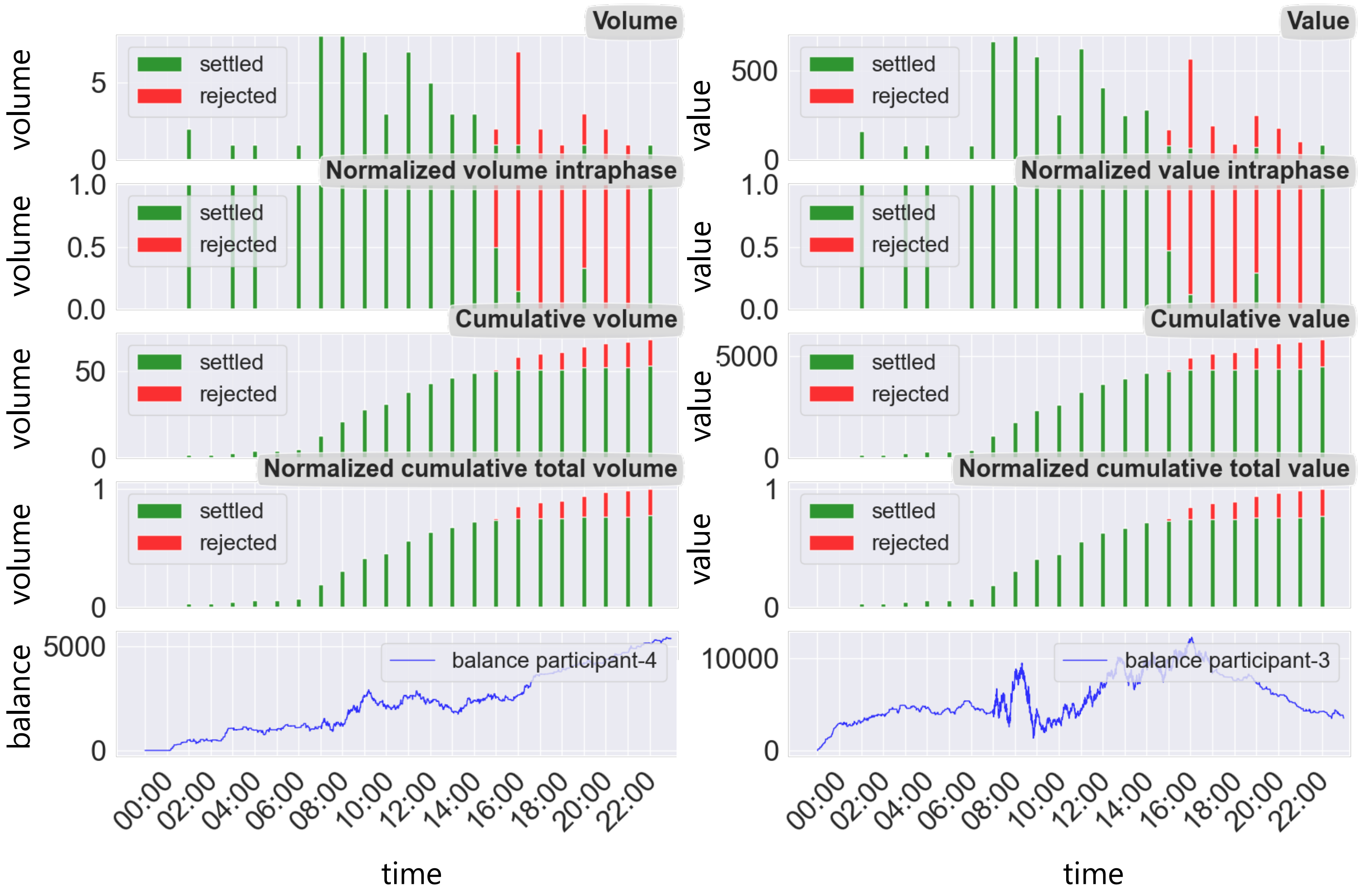
Figure 12: System level statistics USD/EUR in USD



- The three core participants only provide 70% of their liquidity needs
  - A large proportion of payment orders are rejected after 16:00

Results

Figure 13: Bilateral level statistics GBP/EUR in GBP
Participant 4 – Participant 3

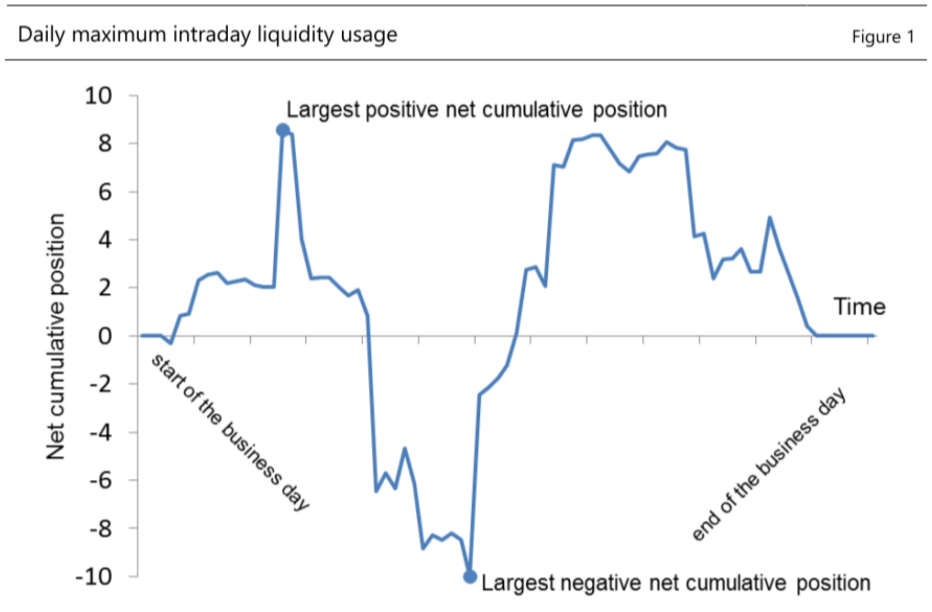


- We can explore how the liquidity shock cascades across participants and currencies

3.3. Example of Commercial Application

Assessing Benefits of Consolidation

- Determining Liquidity Requirements in a multicurrency PvP system
  - For each participant:
    - **Step 1:** Determine the largest negative net cumulative position (LNNCP) in each currency
    - **Step 2:** Convert all LNNCPs to a common currency (e.g. USD)
    - **Step 3:** Sum the converted LNNCPs to get the overall LNNCP. It is the overall liquidity requirement for the day.



Source: BCBS 248

Assessing Benefits of Consolidation

Table 7: Example of a payments file

From	To	Amount	Currency
1	2	10.00	EUR
2	1	10.10	USD
1	3	5.00	USD
3	1	4.95	EUR
1	4	10.00	USD
4	1	9.90	EUR
1	24	10.00	USD
24	1	8.33	GBP
1	23	25.00	GBP
23	1	29.75	EUR
1	22	5.00	GBP
22	1	6.00	USD

Assessing Benefits of Consolidation

Table 8: Consolidated values across all currency pairs for Participant 1

	EUR	USD	GBP	Consolidated Values in EUR
Liquidity Requirements	10.00	14.90	21.67	50.53
Value Cleared	10.00	25.00	30.00	70.45

- The liquidity needs of Participant 1 decrease due to the benefits of consolidation.
  - As the number of currency pairs in a system increases, more implicit netting happens.

Table 9: Values for each currency pair taken individually for Participant 1

	EURUSD		EURGBP		USDGBP		Consolidated Values in EUR
	EUR	USD	EUR	GBP	USD	GBP	
Liquidity Requirements	10.00	4.90	0.00	25.00	10.00	0.00	54.50
Value Cleared	10.00	15.00	0.00	25.00	10.00	5.00	70.45

3.4. Events of Interest

Events of Interest

- We can model the following events of interest:
  - Gridlocks
  - Slowdowns
  - Operational disruptions at the participant and system levels (cascading)
  - Exogenous shocks (can be idiosyncratic, systematic or systemic)
  - Liquidity sinkholes (for single currency payments)

4. Conclusions & Next Steps

Conclusions

- We develop a methodology to simulate LVPS and PvP systems
- Importantly, our method allows us to obtain the distributional properties of variables of interest in the three relevant dimensions of variation
  - Cross-sectional
  - Intraday (time series)
  - Calendar (time series)
- We can also asses the impact of scenarios or events of interest on these distributional properties (as opposed to on a single point estimate)
- Therefore this methodology can help us to better understand system architecture and events of interest, as well as to improve monitoring and regulation.
  - For example, we can now set liquidity requirements as a quantile of a distribution (similar to VaR) that can be stress tested under different scenarios for which we obtain probabilities

Conclusions

- Practical applications:
  - Synthetic Data
    - Preserves data anonymity while allowing us to develop new risk management systems and operational algorithms
  - Developing standardized stress testing scenarios
    - Endogenous and exogenous shocks at the participant or system levels
  - Assessing system architecture and operational limits
    - Different LVPS configurations
    - LSMs and queue configurations

Next Steps

- Additional Scenarios
  - Assessing the impact of events of interest
  - Assessing the impact of system configuration changes
  - Assessing the impact of regulatory changes
- Liquidity Rationing
- Queuing Systems

Figure 14: Volume vs Clearing Capacity

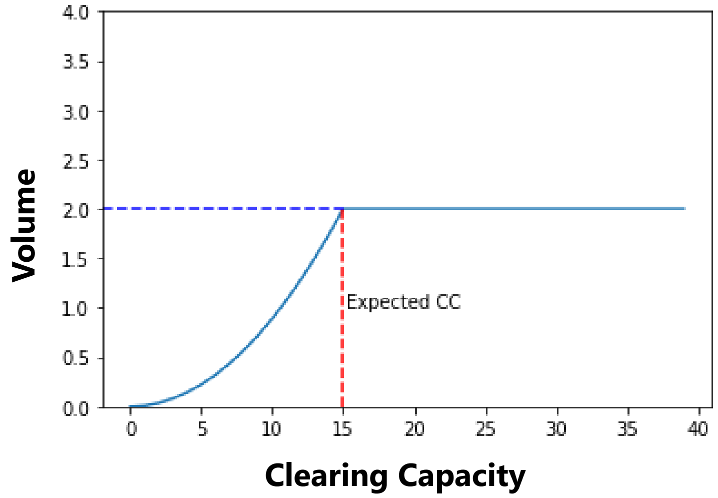
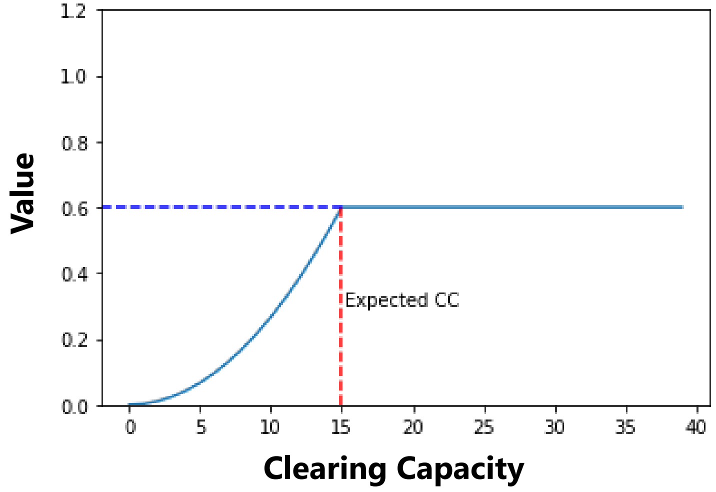


Figure 15: Value vs Clearing Capacity



Thank you!

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