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Central Counterparty Default Waterfalls and Systemic Loss

Samim Ghamami
University of California Berkeley Center for Risk Management Research, New York University Courant Institute, and New York University Department of Finance and Risk Engineering
samim_ghamami@berkeley.edu

Mark Paddrik
U.S. Department of the Treasury Office of Financial Research
Mark.Paddrik@ofr.treasury.gov (corresponding author)

Simpson Zhang
Office of the Comptroller of the Currency Market Risk Analysis Division
Simpson.Zhang@occ.treas.gov

Abstract

Central counterparty (CCP) default waterfalls act as the last lines of defense in over-the-counter markets by managing and allocating resources to cover payment defaults. This article examines the impact of variations in waterfall design on financial system losses in the presence of payment network dependencies and frictions in the cleared and noncleared portion of the system. Through the development of a structural model, we draw several theoretical conclusions about the effectiveness of CCP default waterfalls under severe payment stress. These findings are empirically quantified by testing the model using supervisory data for the U.S. credit default swap market.

I. Introduction

Central counterparty (CCP) clearing in over-the-counter (OTC) financial markets has grown substantially since the 2007–2009 financial crisis, as regulators encouraged measures to reduce the risk of large market participant defaults creating financial instability.[1] CCPs provide resiliency to these markets through their

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[1] While nearly nonexistent in 2007, CCP Clearing now comprises more than 70% of new interest rate derivatives and index credit default swaps volume in the United States as of 2020 (Financial Stability Oversight Council (2020)).

"default waterfalls," which are financial resources that cover losses generated by the defaults of member firms. However, assessing the effectiveness of a default waterfall is difficult due in part to the complicated network of OTC payment obligations and frictions in partially cleared markets. The Mar. 2020 COVID crisis emphasized these concerns, as many CCPs were forced to re-evaluate their waterfall resources in the face of market stress.

Determining the default waterfall resources necessary to maintain CCP integrity under severe market distress is at the heart of this issue (Cont (2015), Duffie (2015)). This article proposes a theoretical model that measures the impact of changes in the risk management policies of a CCP while accounting for spillovers from the noncleared portion of the market and the presence of payment frictions. This approach allows us to draw several theoretical conclusions on the resilience of CCP default waterfalls and the impact of network dependencies under a severe variation margin payment stress. These findings are then empirically evaluated with a unique and comprehensive data set from the U.S. credit default swap (CDS) market that encompasses a cleared segment with a single large CCP and a sizable noncleared segment.

This work addresses two important and related questions in the existing CCP default waterfall literature. First, how do changes in a CCP's default waterfall elements (e.g., initial margin and the guarantee funds) affect the CCP's resilience to a market shock and the extent of firm losses in the financial system? Second, how do changes in the network of payments and the severity of frictions alter CCP waterfall effectiveness and financial system resilience for a fixed level of default waterfall resources? Our novel theoretical model and comprehensive empirical data set allow for an exploration of these two topics within a unified framework.

Motivated by the substantive cross-country heterogeneity in CCP default waterfall resource levels globally, we start by examining the consequences of variations in the relative amounts of clearing members' segregated initial margin (IM) accounts and mutualized guarantee fund contributions.[2] We show theoretically that guarantee fund contributions provide improved CCP stability and lower systemic losses, an aggregate measure of financial losses, compared to an equivalent dollar amount of IM. While works like Wang, Capponi, and Zhang (2022) have highlighted that guarantee funds provide increased CCP stability over IM in systems with only cleared payments, our result is the first to show it generically lowers financial system losses when including both cleared and noncleared payments.

These theoretical findings are empirically reinforced by comparing the effectiveness of waterfall resourcing levels across regions. We calibrate the default waterfall elements of the CCP in our empirical setting to the average waterfall proportions of different regions, holding all else equal. By then applying a series of market shocks based on the Federal Reserve's Comprehensive Capital Analysis and Review (CCAR) stress test, our results show significant stability variation across waterfall structures. For instance, if we calibrate to the average European CCP's waterfall, we find the CDS CCP can withstand a 13% greater stress relative to if it were calibrated to the North American CCP average.

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[2] In Appendix A of the Supplementary Material, we also consider variations to CCP end of waterfall mechanisms.

In addition, systemic losses are 5% lower with the European CCP calibration when the CCAR stress is applied.

To address the second question, we quantify the impact of payment network structures and market friction variations on CCP stability and systemic losses for fixed default waterfall setups. An important factor that can erode CCP stability is client clearing, whereby a CCP member sponsors a client's cleared positions (Paddrik and Young (2021b)). Despite client-cleared positions collectively representing half of CCP risk exposure and having had a substantive role in past CCP failures,[3] the literature has often ignored the positions of clients. However, our empirical treatment of client obligations shows that ignoring these positions risks overestimating CCP stability, as the CCP's resilience is lowered by 44% when client positions are considered, holding all else equal.

Beyond the CCP, there is a substantive noncleared portion of derivative markets which can pose an indirect risk to CCP waterfall effectiveness, as the payments from these positions can alter a member or client's ability to make payments. Unlike the previous risk management literature, such as Amini, Filipović, and Minca (2020), we take into account the network of noncleared payments in our model and analysis. According to our estimates, failing to include noncleared payments overestimates CCP stability by more than 58% for a fixed default waterfall.

Finally, frictions exist in the processing and settlement of OTC payments, including portfolio netting limitations, collateral illiquidity, and rehypothecation restrictions. While these impediments are typically negligible, under periods of financial distress they degrade CCP stability and compound financial system shortfalls, as noted in Duffie and Zhu (2011) and Duffie, Scheicher, and Vuillemey (2015). Our work furthers the literature on these effects by testing a range of payment frictions. Most notably, we find that netting limitations created by currency or portfolio mismatches have the largest impact on CCP stability and systemic losses. For example, even a minimal, but realistic, level of netting limitations more than doubles the amount of mutualized resources required for the CCP to remain solvent and increases financial system losses by 30% over a benchmark with no netting frictions included.

A. Literature Review

Due to the historical rarity of CCP defaults, the effectiveness of default waterfalls has not been well-tested. As discussed in the survey paper by Menkveld and Vuillemey (2020), prior studies of CCP failures have been limited to a few historical cases.[4] Although industry groups, such as the International Swaps and Derivatives Association (ISDA), and standard-setting bodies, such as the Committee on Payments and Market Infrastructures (CPMI) and International Organization of Securities Commissions (IOSCO), have provided qualitative discussions on the

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[3] The importance of client clearing was seen in the role it played in the *Caisse de Liquidation des Affaires en Marchandise* default in 1974 (Bignon and Vuillemey (2020)). Though not as consequential, in Mar. 2020 this risk was once again realized when a client defaulted at CME clearing, leaving its clearing member an estimated $200 million in losses (Mourselas and Smith (2020)).

[4] Kroszner (1999), Cox (2015), and Bignon and Vuillemey (2020) examine in depth a few historical examples of large clearing member defaults at derivatives CCPs.

merits of default waterfall designs (ISDA (2013), CPMI-IOSCO (2017)), there has been limited theoretical modeling of these mechanisms or empirical examination. In addition, the default waterfall literature has so far remained silent on the implications of payment spillover effects from noncleared trades.

This article is the first to consider the impact of the noncleared portion of the market on default waterfall effectiveness and to use position-level market data to assess the impact of contagion on the CCP's default waterfall. By providing a flexible and detailed methodology for assessing the impact of payment spillover effects on CCP stability, our work helps to fill in the gaps in previous studies. For instance, unlike the theoretical works of Biais, Heider, and Hoerova (2012), Amini et al. (2020), and Wang et al. (2022) that investigate optimal counterparty risk exposures through trade-offs in CCP risk-sharing, this article focuses on the network of exposures, capturing direct and indirect effects of CCP loss spillovers. Unlike Capponi, Cheng, and Sethuraman (2017) which examine the CCP's role in attracting less risky membership and the consequences for risk-sharing in the default waterfall, we take a structural approach to estimating the full financial system's losses by combining the effects of the several layers of the waterfall with those of client clearing and noncleared positions. Our focus on aggregate losses and counterparty externalities bears similarities to Acharya and Bisin (2014), Ghamami (2015), and Ghamami and Glasserman (2017), although these papers do not consider network effects or payment frictions in their analysis.

Concerns over the conflicting objectives of CCPs in determining their waterfall structures is an area of significant interest to the literature (see Murphy (2017), Cox and Steigerwald (2018), Cerezetti, Cruz Lopez, Manning, and Murphy (2019), Huang (2019), and Huang and Takáts (2020b)). As commercial enterprises with profit-making incentives, CCPs compete for the clearing business of members and their client positions (Glasserman, Moallemi, and Yuan (2016)). This tension is likely to drive how much and where waterfall resources are allocated, as raising collateral has direct short-term costs for participants and could disincentivize participation in central clearing. Our article complements these works by empirically quantifying the magnitude of the stability benefits provided by default waterfall resources, which must be balanced against the costs imposed on clearing members.

Several papers in the literature have also studied the exposures that CCPs may face from tail risks. For instance, Huang, Menkveld, and Yu (2021) find that the composition of CCP exposures can be fundamentally different for tail risks, with evidence of elevated crowding. Menkveld (2017) proposes a measure for computing the tail risk of CCPs by considering correlations in member returns. Faruqui, Huang, and Takáts (2018) describe how the balance sheets of CCPs and their largest clearing members are linked through the use of the CCP's default waterfall in times of stress. Our article contributes to this topic by developing a comprehensive financial system model for the stress testing of CCP tail risks, which we empirically test with system-wide counterparty position data. Our results underscore how tail risks can be exacerbated by payment spillovers and market frictions, as well as how CCP default waterfalls can be structured to help insulate against these effects.

This work also complements research on CCP margin requirements and the impact of collateral in OTC markets. For instance, Cruz Lopez, Harris, Hurlin, and Pérignon (2017)) propose a new methodology to estimate initial margin requirements called CoMargin. This method assesses margins based on the correlations in tail risk of a given market participant with other market participants. We empirically test the stability benefits provided by CoMargin against traditional initial margin models, and we find that CoMargin provides additional protection to the CCP over the other methods. However, as several CCPs required margin re-evaluations during the COVID-19 period (see Huang and Takáts (2020a), Paddrik and Young (2021a)) creating procyclical liquidity stress, there is a need to reassess the effectiveness of the types of resources in the default waterfall. In a similar spirit as Ghamami, Glasserman, and Young (2022), which highlights the benefits of pooling collateral in a multi-stage network model, we find that greater pooled resources in the CCP's default waterfall reduce network contagion.

Finally, this article contributes to the literature on how market frictions affect the performance of central clearing. For instance, Benos, Huang, Menkveld, and Vasios (2019) discuss how netting frictions can lead to a clearing cost basis across different CCPs, and Glasserman et al. (2016) examines how liquidity costs are impacted by margining across multiple CCPs. In contrast, our work focuses on a single CCP and addresses how the network of cleared and noncleared payment obligations is impacted by market frictions such as rehypothecation restrictions, netting inefficiencies, and fire sales. Our analysis of fire sales in Appendix B of the Supplementary Material complements Kuong (2021), which considers how CCPs can mitigate fire sales with a focus on short-term debt markets.

This article proceeds as follows: Section II provides background and empirics on CCP default waterfall design. Sections III and IV describe the model and the measurement of systemic loss. Section V presents theoretical results on how a CCP's default waterfall affects systemic loss. Section VI presents the calibration and quantitative results using U.S. CDS market data, and Sections VII and VIII provide counterfactual analysis of different waterfall resourcing and payments network features, respectively. Section IX concludes.

II. CCP Default Waterfall Structure

A CCP's recovery plan to deal with a firm's default is known as its default waterfall. The default waterfall provides a detailed list of resources that the CCP will use in attempting to recoup losses from defaults. While the exact rules of default waterfalls vary across CCPs, their overall structures are similar and follow standard industry guidelines (ISDA (2013), ISDA (2015)). Figure 1 provides a flow diagram of the typical stages of a default waterfall.

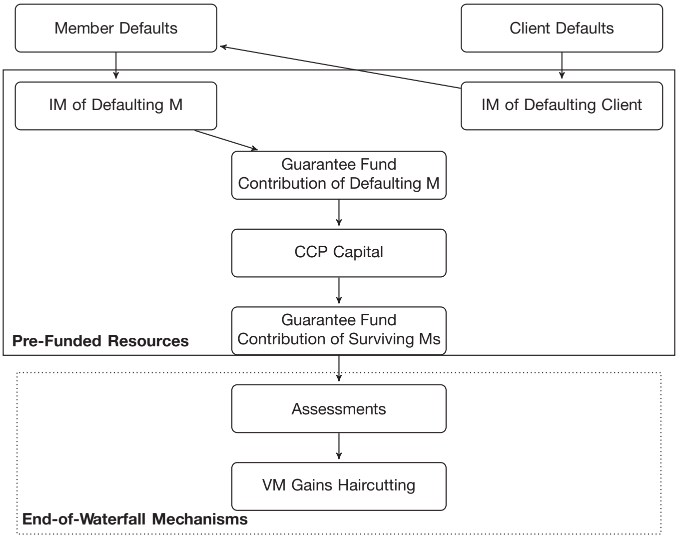
A. Client Clearing Obligations

Client clearing allows clients (i.e., nonclearing members) to participate in central clearing by having a clearing member clear positions on their behalf. As CCPs set stringent capital requirements and mandate waterfall contributions for membership, many client firms are excluded from meeting membership standards. By having a member clear a client's positions, the member guarantees the client's obligation such that the CCP is not directly exposed to the client's counterparty risk.

FIGURE 1

Stages of CCP Default Waterfall

Figure 1 depicts the series of resources and mechanisms in the waterfall which will be accessed if previous ones are insufficient to cover total default losses in the event of a clearing member (M) or client default. The solid arrows depict the most common set of waterfall resource contingencies. A defaulting clearing member or client's obligation is first covered by their initial margin (IM). Positions of defaulting clients are the responsibility of the associated clearing member, who has to cover any shortfalls in variation margin (VM) payments owed for those positions. If the clearing member cannot fulfill this obligation, the clearing member may be placed into default. If the clearing member's IM is insufficient to cover its obligations, the resources of the waterfall stages will be applied. *Source*: Authors' creation.



Though not typically thought of as part of the CCP's default waterfall, the member's guarantee plays an important role in the chain of resources used to cover default losses. Before any waterfall resources can be used, client clearing obligations require members to take over the defaulting client's payment obligations.[5] Client clearing does not affect the use of default waterfall resources later in the waterfall, but it merely provides an extra layer of guarantee by the member. While client clearing helps reduce CCP risk, a member's client clearing guarantee creates additional downside risks for the member during times of market stress. This feature could cause members to default on their obligations, resulting in additional spillovers throughout the network and increasing systemic losses.

B. Default Waterfall Resources and Mechanisms

If a member defaults, the resources of the default waterfall can be deployed to cover lost payments and close the member's position. The first stages of default waterfall resources are present in nearly all CCPs, and they are known as the "pre-funded" waterfall stages because these resources are contributed before any

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[5] Client positions were historically held in omnibus clearing accounts, causing inter-client counterparty risk and making porting positions difficult in the event of a member's failure. However, with the mandated introduction of clearing to OTC derivative markets, client positions have now been segregated to add additional layers of protection to clients and to facilitate client porting.

payment shocks or defaults occur. The amount available to use is thus independent of the shock size.

The first default waterfall resource is the initial margin (IM) of the defaulting clearing member. IM is held at the CCP in case a clearing member defaults. IM can only be used when the clearing member does not fulfill its payment obligations. The IM contribution amount is usually set at a certain Value-at-Risk (VaR) level, such as 99%, but may also be based on additional components like jump-to-default, concentration, and liquidity (Capponi et al. (2022)). IM is also collected for noncentrally cleared transactions. However, the margin period of risk (MPOR) used in bilateral versus centrally-cleared IM calculations differs, with derivative CCPs typically using a 5-day MPOR while bilateral trades typically use a 10-day MPOR.

The second default waterfall resource is the guarantee fund contribution of the defaulting clearing member. Guarantee fund contributions are collected from all clearing members and held at the CCP. A clearing member's contribution is usually proportional to their portfolio's relative level of risk. The CCP's guarantee fund is typically sized according to the "Cover 2" rule, which states that the guarantee fund should cover the default of the two largest clearing members of the CCP. The guarantee fund is more versatile than IM because it can be applied to cover the losses of any clearing member, but this versatility also opens up nondefaulting clearing members to losses.

The next stage is the CCP's capital contribution.[6] This is commonly referred to as "skin in the game" and is intended to reduce moral hazard on the part of the CCP. CCP capital contributions are generally 10–1,000 times smaller in relative magnitude compared to the aggregate IM. Their contribution to CCP stability is thus relatively limited. The final stage of pre-funded resources is the guarantee fund of the surviving clearing members. This stage acts as a form of loss mutualization, as it can use resources from members that have not defaulted.

If the pre-funded resources are entirely deployed, a few different end-of-waterfall mechanisms can be implemented either to raise fresh funds, via "assessments," or reduce obligations, via "variation margin gains haircutting" (VMGH). Assessments allow the CCP to request additional funds from nondefaulting clearing members, whereas VMGH allows the CCP to temporarily reduce the variation margin payments on its obligations. These mechanisms have rarely been used in practice and may have alterations made to them to further support the CCP.[7]

C. Empirical Comparison of CCP Default Waterfall Resources

Though CCPs use the same types of default waterfall resources and mechanisms globally, the amount of resources collected at each stage varies significantly

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[6] This stage may come in one or two parts depending on the CCP. Some CCPs allow for a second part that comes after the guarantee fund stage. We use one part in the analysis for simplicity, but having a second part would not materially change the model.

[7] For the sake of focus, we discuss these additional mechanisms and empirically analyze them, in Appendix A of the Supplementary Material. We compare CCP assessment rules, specifically the cap on assessments as a function of the guarantee fund contribution sizes, and whether CCP rules permit usage of VMGH and initial margin haircuts (IMH). Each choice of rules can have a significant effect on the size of the shock the CCP can withstand.

TABLE 1

Waterfall Resources by CCP Asset Class

Table 1 presents the mean percentage of pre-funded resources collected at each stage, and the maximum assessment a CCP can make on its clearing members relative to the guarantee fund size, grouped by the asset class a CCP clears. Looking across CCP types, the initial margin makes up the majority of resources collected, ranging from 70% to 81%, followed by the guarantee fund with 13% to 22%. The CCP's contribution is minimal, ranging from 1% to 9%. More generally, we find that no particular asset class appears to have any unique preference in assigning resources. *Source*: CCPView Clarus Financial Technology; authors' analysis.

	Interest Rate	Currency	Commodity	Credit	Equity
No. of CCPs	13	12	16	6	13
Pre-Funded Resources					
Initial margin	79.2	73.6	77.2	77.9	81.1
Guarantee fund	19.2	21.8	13.7	20.1	13.4
CCP capital	1.6	4.6	9.1	2.0	5.5
End-of-Waterfall Resources					
Assessments	86.5	96.9	75.8	60.2	124.9

TABLE 2

Waterfall Resources by Jurisdictional Region

Table 2 presents the mean percentage of pre-funded resources collected at each stage, and the maximum assessment a CCP can make on its clearing members. The maximum assessment is measured relative to a member's guarantee fund size and averaged by the continental jurisdiction a CCP resides. Looking across CCP jurisdictions, we see wide variation in pre-funded resources and assessments, suggestive of jurisdictional regulatory preferences influencing CCP's default waterfall allocations. *Source*: CCPView Clarus Financial Technology; authors' analysis.

	Asia	Europe	North America	Oceania	South America
No. of CCPs	27	20	12	2	2
Pre-Funded Resources					
Initial margin	69.2	74.0	85.2	90.1	97.7
Guarantee fund	18.7	25.3	13.5	2.2	2.2
CCP capital	12.2	0.7	1.3	7.7	0.1
End-of-Waterfall Resources					
Assessments	75.5	122.3	77.5	300.0	73.6

in practice. To highlight the differences empirically, we collected a unique data sample of default waterfall resources from the Principles for Financial Market Infrastructures filings of 60 global CCPs from the fourth quarter of 2017. The data identifies a large degree of heterogeneity in how different CCPs design their waterfall resources.

We summarize the variation in CCP resources in Table 1, which shows the average percentage of resources for different stages of the default waterfall across CCPs grouped by asset class. Commodity CCPs make the highest percentage of capital contributions, whereas Interest Rate CCPs make the lowest percentage. Credit CCPs have relatively high levels of IM and guarantee funds but low levels of capital contribution relative to other CCP asset classes. This waterfall structure shifts the losses from the CCP onto the clearing members. The table also shows the maximum assessment limit as a percentage of total guarantee funds.[8] These values are due to caps on assessments set by each CCP as a function of guarantee fund size.

Table 2 shows a similar summary grouped by the location of the CCP. There does not seem to be a global consensus on the optimal waterfall design for

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[8] Some CCPs allow for a greater assessment amount if there are multiple clearing member defaults versus a single clearing member default.

minimizing systemic risk or ensuring incentive compatibility for CCP members. The ratios vary dramatically across regions. Asian and European CCPs have significantly lower percentages of IM than North American CCPs. European CCPs have larger levels of guarantee funds, while Asian CCPs have larger CCP capital. The differences across regions can have an important impact on CCP resilience under periods of market stress, which will be examined in Section VII.

III. Model of CCP Default Waterfall

CCP stress can arise in many forms. For instance, a substantial shock such as the one developed in the annual Comprehensive Capital Analysis and Review (CCAR) can lead to a situation where some firms owe much more variation margin (VM) than they expect to receive. These VM obligations are supposed to be satisfied in short order of a call, typically within a few hours, and can put severe stress on the firms' trading desks. This stress may prevent a firm from fulfilling all its obligations to its counterparties. This, in turn, increases the stress on the firm's downstream counterparties, amplifying the impact of the shock through the network of CDS exposures. The model assumes that payments are all made simultaneously as margin payments are made intra-day, though in reality it may take several days or weeks for some portfolio liquidations. In the next 2 sections, we introduce a network model that incorporates payment contingency and shows how the different components of the CCP waterfall can be included in the model.

A. Basic Setup and Payments

The setup employs the framework of Glasserman and Young (2015), which in turn builds on the model of Eisenberg and Noe (2001). There are $N+1$ agents in the market, with 0 indexing the CCP and $i \in 1,\ldots,N$ indexing the non-CCP firms. Each pair of counterparties i,j can have a set of contracts between them, which are assumed to be in a single asset class such as CDS. The contracts can be bilateral or centrally cleared.

There are three types of non-CCP firms in the model: clearing members M, clients C, and bilateral firms B. These firms differ in their use of central clearing. Clearing members can clear through the CCP directly. Clients cannot clear through the CCP directly but can instead submit trades through a clearing member. Clearing members pass through the payments received or owed from the client to the CCP, and clearing members must cover any shortfalls in these payments out of their funds. Denote C_k as the set of client firms of a clearing member k, and M_i as the set of clearing members of a client firm i.[9] Finally, some nonmembers are purely bilateral firms that do not participate in any centrally cleared transactions and instead engage only in bilateral transactions (see Figure 2 for an example).

Given a market shock, a VM payment obligation is created for each contract. The VM payments on contracts between every pair of counterparties create a single net VM payment that needs to be made between the pair. The net VM payment obligation is written as an obligation matrix $\overline{P}=(\overline{p}_{ij})_{i,j \in N_0}$, where $\overline{p}_{ij}$ is the net

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[9] In the data, we do not observe the identity of the clearing member that a client uses, but we assume that the client clears through the clearing member with which it has the most bilateral transactions.

FIGURE 2

Example Network of Cleared and Noncleared Obligations

Figure 2 depicts the four firm types in the payments network: the CCP, clearing members (M), clients (C), and bilateral firms (B). The links represent obligations, both direct (solid) and client clearing (dashed). These firms differ in their use of central clearing. Clearing members may clear through the CCP directly. Clients cannot clear through the CCP directly but must instead submit trades through a clearing member. Clearing members pass through the payments received or owed from the client to the CCP, and clearing members must cover any shortfalls in these payments out of their funds. *Source*: Authors' creation.

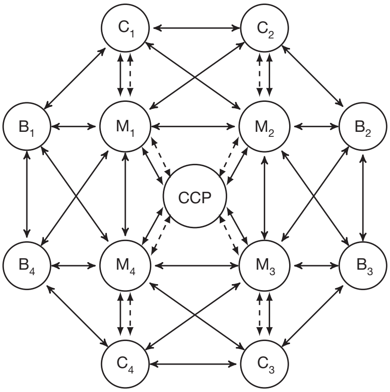
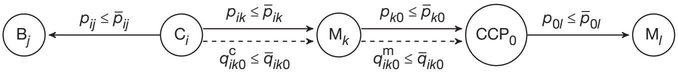


FIGURE 3

Example of Payment Obligations and Realized Payments

Figure 3 shows the types of obligations that could occur between four types of firms, both bilateral and client cleared. The figure helps to illustrate the dependencies that firms can have on one another, as clearing member k's ability to pay CCP 0 may depend on client i's ability to fulfill its obligations. In the figure, if the realized payments from client i, $p_{ij}, p_{ik}, q^c_{ik0}, q^m_{ik0}$, are less than its obligations, clearing member k and pure bilateral firm j will suffer direct losses. Additionally, the impact of client i's realized payments may lead to clearing member k reducing its payments, causing potential losses to the CCP as well. *Source*: Authors' creation.



amount of VM owed by node i to node j in the aftermath of the shock. The indices of the first row and column of this matrix are denoted as 0 to account for the CCP. Note that if $\overline{p}_{ij}$ is positive then $\overline{p}_{ji}$ is 0. Further, $\overline{p}_{ii} = 0$ for all i. For a given market shock, firms may only be able to satisfy part of their payment obligations due to shortfalls in funds. We denote the actual VM payments made between firms using the realized payment matrix $P = (p_{ij})$ (see Figure 3 for an example).

Client-clearing transactions in the network induce a set of corresponding client clearing obligations. The net VM client-clearing obligations are denoted by the 2 matrices $\overline{Q} = (\overline{q}_{ik0}, \overline{q}_{0ki})_{i \in C, k \in M}$. In this notation, $\overline{q}_{ik0}$ denotes the net amount owed by client i to the CCP through clearing with member k, and $\overline{q}_{0ki}$ denotes the net amount owed by the CCP to client i through clearing with member k.[10] Note again that if one of these obligations is positive then the other is 0. Because client clearing

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[10] The CCP does not net the transactions of a client that clears through multiple different clearing members. The client is in effect treated as a different entity across each clearing member with which it clears.

must involve a clearing member as an intermediary, $\overline{q}_{ik0}$ is fulfilled by having client i submit a payment to clearing member k, q^{c}_{ik0}, and that clearing member k then submitting a payment to the CCP, q^{m}_{ik0}. The reverse obligation $\overline{q}_{0ki}$ is fulfilled by the CCP submitting a payment to clearing member k, q_{0ki}, and clearing member k submitting a payment to client i, q^{m}_{0ki}. A clearing member must pass through any payments that it receives in the course of client clearing, even if the clearing member is in default. Therefore, $q^{m}_{ik0} \geq q^{c}_{ik0}$ and $q^{m}_{0ki} \geq q_{0ki}$. As a result of this mechanism, even if the clearing member is in default, the client account or the CCP may not be in default. This setup is chosen to accurately capture the rules for client-clearing obligations that are used in practice. The description of how the payment amounts are determined in equilibrium is addressed in the next few sections.

1. Initial Margin and Capital Buffer

In most transactions, IM is held to cover deficiencies in VM payments. IM that i holds from counterparty k is denoted as z_{ki}. This IM value is always positive unless the counterparty k is the CCP itself as the CCP does not post IM, so $z_{0i} = 0\ \forall i$. In the event counterparty k fails to pay VM to i promptly, the position will be closed and the IM will be applied to the shortfall in VM payments. The value of IM held is calculated on a portfolio level using a historical lookback.[11] This reduces the payment obligation of k to i, and thus the pro rata payment that k must make to i is also reduced proportionally by the amount of VM that is taken.

For client clearing transactions, IM is held by the CCP for a transaction with client i clearing through clearing member k. This IM is denoted by z_{ik0}, as the IM is used to cover shortfalls in payments if the client is unable to cover its obligations. The IM is considered part of the passthrough payment by the clearing member to the CCP to assist with the member's obligation to cover the client's payment. The passthrough payment of clearing member k must be weakly greater than the amount it receives, $q^{m}_{ik0} \geq \left(q^{c}_{ik0} + z_{ik0}\right)$. The CCP does not post IM for the client clearing obligations that it owes.

Beyond IM, firms are assumed to hold some quantity of assets on hand, which we term as "capital buffer," $b_i > 0$. This b_i is a function of the firm's risk management policies, non-CDS positions, or available cash. Firms apply their capital buffers to help cover their VM obligations and deal with net payment losses.

Generally, collateral in the financial system can be treated as cash, particularly in the case of cleared IM, as CCPs require IM to be in sovereign bonds or currency. As a result, if collateral z_{ij} is seized by node j from node i, node i's payment obligation is reduced by exactly z_{ij}. However, in the noncleared derivatives market, a wide range of less liquid securities including corporate bonds, foreign-denominated bonds, and equities are accepted as collateral and can be converted to short-term cash through repurchase agreements if necessary.

2. Payments for Bilateral Firms

The simplest payment equation to derive is for bilateral firms, where each firm i makes payments p_{ij} to each counterparty j conditional on the payments that it

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[11] VM and IM are estimated following the formulation of Luo (2005) and applying the framework adopted by Paddrik, Rajan, and Young (2020).

receives from each counterparty k, p_{ki}. The resources available to firm i to cover its outgoing payments are its capital buffer b_i, the payments from each counterparty k, p_{ki}, and the IM that i holds from each counterparty k, z_{ki}. The total obligations of firm i to its counterparties are $p_i \equiv \sum_{k \neq i} \overline{p}_{ik}$. If this exceeds the resources of firm i, it will not be able to fully pay its counterparties. It will thus need to reduce its payments to its counterparties proportionally.

For a bilateral firm $i \in B$, we define the stress at i, s_i, to be the amount by which i's payment obligations exceed the incoming payments from i's counterparties and IM held[12]

$$s_i = \left[\underbrace{\sum_{j \neq i, 0} \overline{p}_{ij}}_{\text{Obligations}} - \underbrace{\left(\sum_{j \neq i, 0} \left(\left(p_{ji} + z_{ji} \right) \wedge \overline{p}_{ji} \right) + b_i \right)}_{\text{Resources}} \right]^+ . \tag{1}$$

Let $\overline{p}_i = \sum_{j \neq i} \overline{p}_{ij}$ be the total payment obligations of i to all other nodes. In the following definitions, we restrict attention to the nodes i in the system such that $\overline{p}_i > 0$. The others do not have payment obligations and thus do not transmit payment shortfalls. In the CDS market that we consider, such firms would be buyers of CDS protection (not sellers) and under a market stress they would not be likely to have VM obligations. Shortfall and payment equations are thus not necessary for such nodes.

We will assume that the stress of firm i is transmitted to i's counterparties pro rata the size of its payment obligations, defined by the "relative liability" of node i to node j as $a_{ij} = \overline{p}_{ij} / \overline{p}_i$. Thus, the payment functions $p_{ij}(p)$ for a bilateral firm i are given by $p_{ij} = \overline{p}_{ij} - a_{ij} s_i$ where $0 \leq p_{ij} \leq \overline{p}_{ij}$ for all $0 \leq i, j \leq n$.

3. Payments for Client Firms

Client firms have similar payment functions as bilateral firms, but they also have client-clearing transactions with the CCP. Recall that for these transactions, clients need to form a sponsor relationship with a clearing member, which then intermediates transactions with the CCP. If the client owes money to the CCP, the client pays the clearing member, who then passes the payment onto the CCP. If the client is owed money by the CCP, the CCP pays the clearing member, who then passes the payment onto the client. Clients also post IM to cover shortfalls in their payments. However, the CCP does not post IM for the client.

The total resources of a client firm i are given by the sum of its payments received from bilateral and client-clearing transactions along with its capital buffer. The total obligations of client i are given by the sum of its bilateral and client clearing obligations. If this amount exceeds the resources of firm i, it will not pay its counterparties in full and will instead pass on partial payments.

For a client firm $i \in C$, we define the stress at i, s_i, to be the amount by which i's payment obligations exceed the incoming payments from i's counterparties and IM held

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[12] In general, $x \wedge y$ denotes the minimum of two real numbers x and y.

$$(2)\quad s_i=\left[\underbrace{\sum_{j\neq i,0}\overline{p}_{ij}+\sum_{k\in M_i}\overline{q}_{ik0}}_{\text{Obligations}}-\underbrace{\left(\sum_{j\neq i,0}\left(\left(p_{ji}+z_{ji}\right)\wedge\overline{p}_{ji}\right)+\sum_{k\in M_i}q^m_{0ki}+b_i\right)}_{\text{Resources}}\right]^+.$$

Unlike bilateral firms, clients also have clearing payment obligations. Similarly though, when the client faces stress, their payments are reduced pro rata the total payment obligations owed by the client across all types of transactions.

Denote $\overline{p}^g_i=\sum_{k\neq i}\overline{p}_{ik}+\sum_{k\in M_i}\overline{q}_{ik0}$ as the sum over all payment obligations for client i. These combined payment obligations help derive client i's relative payment liability to different firms:

$$(3)\qquad a_{ij}=\overline{p}_{ij}/\overline{p}^g_i\quad\forall j\neq i,\qquad a^c_{ik0}=\overline{q}_{ik0}/\overline{p}^g_i\quad\forall k\in M_i.$$

The stress of client i is transmitted to i's counterparties pro rata the size of its combined payment obligations. Given any vector $p\in\mathbb{R}^{2n+2}$ such that $0\leq p_{ik}\leq\overline{p}_{ik}$ for all $0\leq i,k\leq n$, the payment functions $p_{ik}(p)$, $q^c_{ik0}(p)$ for a client firm i are given by

$$(4)\qquad p_{ij}=\overline{p}_{ij}-a_{ij}s_i,\qquad q^c_{ik0}=\overline{q}_{ik0}-a^c_{ik0}s_i.$$

4. Payments for Clearing Members

Clearing members may engage in bilateral trades, centrally cleared trades, and client-clearing trades. Each of these three types of trades entail different obligations and resources for the clearing member. The total obligations of clearing member k to its counterparties are given by $\sum_{i\neq k}\overline{p}_{ki}+\sum_{i\in C_k}(\overline{q}_{0ki}+\overline{q}_{ik0})$. If this amount exceeds the resources of clearing member k, it will not pay its counterparties in full. Member k's stress is given by

$$(5)\quad s_k=\Bigg[\underbrace{\sum_{i\neq k}\overline{p}_{ki}+\sum_{i\in C_k}(\overline{q}_{0ki}+\overline{q}_{ik0})}_{\text{Obligations}}-$$
$$\underbrace{\left(\sum_{i\neq k}((p_{ik}+z_{ik})\wedge\overline{p}_{ik})+\sum_{i\in C_k}\left(\left((q^c_{ik0}+z_{ik0})\wedge\overline{q}_{ik0}\right)+q_{0ki}\right)+b_k\right)}_{\text{Resources}}\Bigg]^+.$$

The way that a clearing member k passes on stress differs, however, as centrally cleared payments must be passed through when given to it by a client i for the CCP, $\left((q^c_{ik0}+z_{ik0})\wedge\overline{q}_{ik0}\right)$, or the CCP for a client i, q_{0ki}. If these amounts are sufficient to cover the original obligations, $\overline{q}_{ik0}$ and $\overline{q}_{0ki}$, respectively, then the clearing member makes the payment in full. However, if the amount received by the clearing member is less than the obligation, the clearing member must cover the remainder out of its funds or be in default. If the clearing member is under stress, then any remaining obligations are cut pro rata based on the clearing member's stress.

Define $\overline{p}_k^r = \sum_{i \neq k} \overline{p}_{ki} + \sum_{i \in M_k} \left(\overline{q}_{0ki} - q_{0ki} + \left[\overline{q}_{ik0} - q_{ik0}^c - z_{ik0} \right]^+ \right)$ as the sum of the remaining payments over all entities. Because the passthrough payments must always be made, they are deducted when determining the clearing member's relative liability.

$$a_{ki} = \overline{p}_{ki} / \overline{p}_k^r \quad \forall k \neq i, \qquad a_{0ki}^m = \left(\overline{q}_{0ki} - q_{0ki} \right) / \overline{p}_k^r \quad \forall i \in C_k, \\ a_{ik0}^m = \left[\overline{q}_{ik0} - q_{ik0}^c - z_{ik0} \right]^+ / \overline{p}_k^r \quad \forall i \in C_k. \tag{6}$$

The stress of clearing member k is transmitted to k's counterparties pro rata as defined by the payment functions for clearing member k

$$p_{ki} = \overline{p}_{ki} - a_{ki} s_k \quad \forall i \neq k, \qquad q_{0ki}^m = \overline{q}_{0ki} - a_{0ki}^m s_k \quad \forall i \in C_k, \\ q_{ik0}^m = \overline{q}_{ik0} - a_{ik0}^m s_k \quad \forall i \in C_k. \tag{7}$$

So far we have defined the payment functions for all entities other than the CCP. In equilibrium, the payments received by such firms and the payments made by these firms must be balanced. Firms that are under stress cut their payments pro rata, while unstressed firms make their payments in full. The equilibrium payment vector accounts for contagion effects from one firm failing to pay its counterparties and propagating stress further down the network. Such contagion effects have the potential to be very large, as shown by Paddrik et al. (2020). We define the impact of the CCP's equilibrium payment functions and received payments in the next section.

B. CCP Default Waterfall

The CCP's payment function presented in this section will consider the pre-funded stages. The CCP's payment obligations are given by $\sum_{k \in M} \left(\overline{p}_{0k} + \sum_{i \in C_k} \overline{q}_{0ki} \right)$. The resources that the CCP has available come from the CCP's default waterfall and the VM payments it receives. As described in the introduction, the pre-funded layers of the CCP default waterfall consist of the following stages: IM of defaulting clearing members, guarantee fund contributions of defaulting clearing members, CCP capital, and guarantee fund contributions of surviving clearing members.

IM is the first stage used in the default waterfall and covers shortfalls in the payments of clearing member obligations, including a clearing member's client clearing obligations. z_{k0} denotes the IM collected by the CCP from clearing member k. Including IM, the CCP receives total resources from clearing member k of:

$$\left(p_{k0} + \sum_{i \in C_k} q_{ik0}^m + z_{k0} \right) \wedge \left(\overline{p}_{k0} + \sum_{i \in C_k} \overline{q}_{ik0} \right). \tag{8}$$

The next several stages of the default waterfall utilize the guarantee fund of the CCP. Funds are first taken from contributions of the defaulting clearing members. If the defaulted member's funds are insufficient to cover the CCP stress, the CCP's capital contribution b_0 is deployed, followed by the remaining guarantee fund contributions of all nondefaulting clearing members.

Let γ be the total size of the CCP's guarantee fund, where each clearing member k contributes an amount γ_k to the guarantee fund. Thus, the total guarantee fund is equal to $\gamma = \sum_{k \in M} \gamma_k$. The guarantee fund contributions γ_k are a function of the risk of the portfolio of each clearing member. The contribution γ_k is approximated as a proportion of clearing member k's IM held by the CCP, z_{k0}[13]:

$$\gamma_k = \gamma \frac{z_{k0}}{\sum_{j \in M} z_{j0}}. \tag{9}$$

The CCP also provides its own capital contribution to cover losses, denote by b_0. This capital contribution is used after the guarantee fund of defaulting clearing members and before the guarantee fund of nondefaulting clearing members. As the CCP pre-funds these stages of the default waterfall, the resources are fixed and independent of the sudden market shock.[14]

The CCP's stress is 0 if it can cover its payment obligations without using up its capital b_0 and the guarantee fund contributions of all clearing members γ.[15] If the pre-funded waterfall layers are insufficient, the CCP suffers stress, s_0, given by the following equation:

$$s_0 \equiv \left[\sum_{k \in M} \left(\overline{p}_{0k} + \sum_{i \in C_k} \overline{q}_{0ki} - \left(p_{k0} + \sum_{i \in C_k} q^m_{ik0} + z_{k0} \right) \wedge \left(\overline{p}_{k0} + \sum_{i \in C_k} \overline{q}_{ik0} \right) \right) - \gamma - b_0 \right]^+ . \tag{10}$$

Given that the CCP suffers a stress s_0, the combined payment obligation for the CCP is equal to $\overline{p}^g_0 = \sum_{i \neq 0} \overline{p}_{ki} + \sum_{k \in M} \overline{q}_{0ki}$. This combined payment obligation is used to derive the CCP's relative payment liability to different firms:

$$a_{0k} = \overline{p}_{0k} / \overline{p}^g_0, \qquad a_{0ki} = \overline{q}_{0ki} / \overline{p}^g_0, \tag{11}$$

$$p_{0k} = \overline{p}_{0k} - a_{0k} s_0 \quad \forall k \in M, \qquad q_{0ki} = \overline{q}_{0ki} - a_{0ki} s_0 \quad \forall k \in M. \tag{12}$$

Similar to other firms, the CCP prorates its outgoing payments proportionally based on its level of stress. This assumption is in line with the VMGH protocol most CCPs implement if no new payment resources can be raised.

C. Existence and Uniqueness of Payment Equilibrium

Compared with well-established network models, such as Eisenberg and Noe (2001) and Glasserman and Young (2015), our model features the additional complexities of IM, client clearing obligations, and CCP default waterfall obligations. To analyze this financial system, we define the mapping function $\Phi(p, q)$ on

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[13] In practice, γ is chosen to equal the expected loss to the CCP if the two largest clearing members were to default, after accounting for the clearing members' contributions of IM z_{k0}. For the purposes of this model, we use public disclosures of γ, which we discuss in Section VI.A.

[14] Clearing members must eventually replenish the IM and guarantee fund contributions that are used, but this will usually come later. The Principles for Financial Market Infrastructures regulations require that the IM and guarantee fund payments be replenished by the start of the next business day to ensure compliance with the cover two rule.

[15] In Appendix A of the Supplementary Material, we analyze the impact of including the end-of-waterfall mechanisms to cover the remaining stress.

$[0, \overline{P}] \times [0, \overline{Q}]$ as the set of all the p and q payment functions for all firms in the system. A payment equilibrium (p^*, q^*) for the system is defined as a fixed point of this mapping function such that $\Phi(p^*, q^*) = (p^*, q^*)$. For this setting we find that:

Theorem 1. There exists a unique payment equilibrium, $\Phi(p^*, q^*) = (p^*, q^*)$, for the financial clearing system.

A key challenge to demonstrating that a unique equilibrium exists for our model is the presence of contingent resources, like IM or client clearing. IM in particular presents an issue for standard uniqueness arguments as in Eisenberg and Noe (2001), as it represents an additional firm resource outside of the capital buffer. IM being contingent on a firm's payments could conceivably lead to multiple payment equilibria that vary in the amount of IM used. A key insight of the proof is to show that IM can be reframed into an alternative system that treats it as capital held by an auxiliary node.[16,17]

In the empirical applications in Sections VI–VIII, we will compute the unique equilibrium by choosing values of the capital buffers $\{b_0, b_1 \ldots, b_n\}$ and then recursively computing the fixed point of this system by taking the limit of the sequence $(p^1, q^1) = \Phi(\overline{p}, \overline{q}),(p^2, q^2) = \Phi(p^1, q^1),\ldots,(p^{n+1}, q^{n+1}) = \Phi(p^n, q^n),\ldots$ This "fictitious algorithm" always converges to the unique equilibrium of the network model.[18]

IV. Measuring Systemic Losses

A guiding principle in the mandated introduction of central clearing to OTC derivatives markets is the belief that CCPs improve risk management for large exposures and reduce the consequences to the financial system of a large counterparty's default. A social planner concerned with financial system risk must consider the consequences of waterfall structures on the losses suffered by firms within the financial system. Although a full social welfare analysis can involve many dimensions that are beyond the focus of our study, firm losses are clearly one relevant dimension of social welfare calculations. We define our main loss measure as "systemic loss", the total of bankruptcy losses that creditors suffer, following the interpretations applied by Eisenberg and Noe (2001) and Glasserman and Young (2015).

However, unlike the measures used in these works, which only consider the shortfall of payments, systemic losses include the contingency shortfalls that arise due to client clearing obligations and mutualized default waterfall resources.

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[16] The proof of Theorem 1, in Appendix C of the Supplementary Material, describes how this technique allows several standard methods to then be used to show the existence and uniqueness for the financial system.

[17] We note that a key assumption for our existence and uniqueness result to hold is that surviving nodes cannot free and repurpose their IM posted to failing nodes. Ghamami et al. (2022) show that with IM freeing a payment equilibrium may not exist in a one-period network payments model, but existence can still be guaranteed with a suitably specified 2-period model.

[18] In Appendix D of the Supplementary Material, a description of the fictitious algorithm is provided along with an explanation of how it is used to calculate the equilibrium payment vector in the empirical settings.

Clearing members are responsible for defaulted obligations of their clients, as well as the defaulted obligations of other members through their guarantee fund contributions to the CCP. Thus, clearing members become creditors of these defaulted firms and can suffer payment shortfalls in periods of market stress.[19] Including such shortfalls in the systemic loss measure helps capture the overall level of payment disruption to the system felt across all firm types from the shock.

We next discuss how losses are calculated among the individual participant types, followed by how the total systemic losses can be derived. These measures will allow us to later empirically estimate the stability implications of different default waterfall structures.

A. Losses for Different Types of Firms

The total losses for each type of firm x are denoted by l_x. For a purely bilateral firm i, losses in a given payment equilibrium are composed only of bilateral losses. These bilateral losses are equal to the difference in expected payments versus received payments plus IM in bilateral transactions.

$$l_i = \underbrace{\sum_{j \neq i} \left[\overline{p}_{ji} - \left(p_{ji} + z_{ji} \right) \right]^+}_{\text{bilateral}}, \quad \forall i \in B. \tag{13}$$

For a client firm j, losses in a given payment equilibrium are composed of bilateral plus client-clearing losses, which occur when clients do not receive their full obligations in client-clearing transactions.

$$l_j = \underbrace{\sum_{i \neq j} \left[\overline{p}_{ij} - \left(p_{ij} + z_{ij} \right) \right]^+}_{\text{bilateral}} + \underbrace{\sum_{k \in M_j} \left(\overline{q}_{0kj} - q^m_{0kj} \right)}_{\text{client clearing}}, \quad \forall j \in C. \tag{14}$$

For a clearing member k, losses in a given payment equilibrium are composed of bilateral and direct clearing, client clearing, and waterfall losses, which occur when waterfall contributions are used to cover obligations of a separate defaulting clearing member. We denote the waterfall losses by $\widehat{\gamma}_k$.[20]

$$\begin{aligned} l_k = & \underbrace{\sum_{i \neq k} [\overline{p}_{ik} - (p_{ik} + z_{ik})]^+}_{\text{bilateral and cleared}} + \\ & \underbrace{\sum_{i \in C_k} \left(\left[\overline{q}_{ik0} - \left(q^c_{ik0} + z_{ik0} \right) \right]^+ + \overline{q}_{0ki} - q_{0ki} \right)}_{\text{client clearing}} + \underbrace{\widehat{\gamma}_k}_{\text{waterfall}}, \quad \forall k \in M. \end{aligned} \tag{15}$$

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[19] An example of this type of payment shortfall for clearing members is seen in the default of a clearing member of Nasdaq OMX CCP in late 2018, which caused clearing members to become creditors to the order of €107 million.

[20] Refer to Appendix E of the Supplementary Material for a detailed description of how these losses can be calculated.

B. Losses for the CCP

The losses of the CCP differ from those of other types of firms. The CCP's losses can come from 2 channels. First, the CCP has a capital contribution of b_0 that it could lose if used in the default waterfall. The amount used in equilibrium is denoted as $\widehat{b}_0$, which is equal to the amount the CCP needs to cover after the received payments, IM, and the own default fund contributions of defaulting clearing members:

$$(16)\quad \widehat{b}_0 = \min\left(\sum_{k\in M}\left(\overline{p}_{0k} + \sum_{i\in C_k}\overline{q}_{0ki} - \left(p_{k0} + \sum_{i\in C_k} q^m_{ik0} + z_{k0} + \gamma_k\right)\wedge\left(\overline{p}_{k0} + \sum_{i\in C_k}\overline{q}_{ik0}\right)\right), b_0\right).$$

The CCP can also suffer losses from payment shortfalls that exceed its total waterfall resources (IM, guarantee fund, and capital contribution). Since the CCP has a balanced book, the remaining shortfall in the payments it receives, after using its default waterfall, is equal to the equilibrium stress that it suffers. Recall that s_0, defined in equation (10), denotes the stress of the CCP. The CCP's losses given a payment equilibrium are thus $l_0 = \widehat{b}_0 + s_0$.

C. Systemic Losses

The aggregate loss for all firms in the system is the systemic loss. This term is denoted as L and captures the total shortfall in payments received across all types of firms.

$$(17)\quad \begin{aligned} L = {} & \sum_{i\neq 0}\left[\sum_{j\neq i}\overline{p}_{ji} - \sum_{j\neq i}\left(\left(p_{ji} + z_{ji}\right)\wedge\overline{p}_{ji}\right)\right] \\ & + \sum_{k\in M}\left[\sum_{i\in C_k}\left(\overline{q}_{ik0} - \left(q^c_{ik0} + z^0_{ik}\right)\wedge\overline{q}_{ik0} + \overline{q}_{0ki} - q_{0ki}\right)\right] \\ & + \sum_{i\in C}\left[\sum_{k\in M_i}\left(\overline{q}_{0ki} - q^m_{0ki}\right)\right] + \sum_{k\in M}\left[\overline{p}_{k0} + \sum_{i\in C_k}\overline{q}_{ik0} - \left(p_{k0} + \sum_{i\in C_k} q^m_{ik0} + \gamma_k\right)\right]^+ . \end{aligned}$$

Equation (17) is derived by summing equations (13), (14), and (15) and l_0 across all clearing members, clients, bilateral firms, and the CCP. Note that L is decreasing in all of the payments made in the system. Therefore a waterfall structure that increases the payments made in equilibrium will also lower systemic losses. This metric is what we will employ in our theoretical and empirical analysis, along with the individual losses defined above for the different types of firms.

V. Theoretical Results

Waterfall allocation variations and network structure differences can have important implications for financial system resilience. In this section, we provide two theoretical results that highlight the impact of each factor on systemic losses. Our first result assesses the effects of changes to the default waterfall via changes in the ratio of mutualized versus segregated funds. Our second result evaluates the impact of changes to the network structure via changes in client clearing on CCP resilience and systemic losses.

A. Prefunded Resource Ratio

An important aspect of default waterfall design is how to allocate pre-funded default waterfall resources, as pre-funded resources are held in either segregated accounts, like IM, or in mutualized accounts, like the guarantee fund and CCP capital. How pre-funded resources are allocated across these accounts impacts the CCP's resilience, and it is thus important to determine a satisfactory resource allocation. We find the guarantee fund is generally more effective at preventing systemic losses than an equivalent amount of IM. While works like Wang et al. (2022) have highlighted that guarantee funds provide increased CCP stability in a system with only cleared trades, our result is the first to show it generically lowers aggregate financial system losses when considering both cleared and noncleared trades.

Theorem 2. Given a shock and a fixed level of CCP pre-funded resources, CCP stress and systemic losses weakly decrease as any member's contribution of mutualized funds relative to their contribution of segregated funds is increased.

The intuition behind this result is that a mutualized account dollar is more flexible than a segregated account dollar, and it is thus more useful to the CCP for preventing losses. While IM can only cover the losses at a single clearing member, the guarantee fund can cover the losses for all clearing members. Thus one unit of guarantee fund will provide the CCP with more stability than one unit of IM, all else equal. In turn, this increased resilience lowers losses throughout the system caused by the CCP's payment default under severe stress. Note that this result also implies that simultaneously increasing every member's guarantee fund to IM contribution would improve CCP stability and weakly decrease systemic losses.[21]

Although overall systemic losses are lower if guarantee fund contributions are increased across all members, not all clearing members may benefit from this change. In particular, nondefaulting clearing members could suffer greater waterfall losses from additional guarantee fund contributions. Thus, these clearing members could prefer a lower guarantee fund to IM ratio, although it would likely result in greater systemic losses for them as a group. As such, tensions may exist between CCPs and their members in choosing the waterfall structure (ABN AMRO Clearing et al. (2020)).

B. Client Versus Direct Clearing

Our next result regards the use of client clearing by the CCP. Client clearing obligations are one of the 2 types of exposures a CCP faces. Unlike members who

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[21] Simply varying the average guarantee fund to IM ratio across members does not ensure that the CCP is more resilient. For instance, assume a CCP suffers a member default, and in advance, the proportion of guarantee fund contributions of the defaulting member was increased, while the proportion of a solvent member's contributions was reduced. Even if the average guarantee fund to IM ratio is higher after the change, the CCP's overall resilience is reduced.

directly clear positions, client-cleared positions have an additional layer of payment protection, as the client-clearing member is liable for its client's payment in the event of default. This contingency influences the amount of pre-funded default waterfall resources needed for the CCP to remain solvent against a given market shock, as well as the level of overall systemic losses.

Consider a member k, and suppose that a client clearing obligation of this member is changed to a direct clearing obligation. That is, for a client i of member k the clearing obligation $\overline{q}_{ik0}$ or $\overline{q}_{0ki}$ involving client i and member k is changed into a direct obligation between the CCP and client i. In the direct clearing obligation, the client firm i makes the payment directly to the CCP without the member having a contingent obligation to cover it, or vice versa if the CCP owes the VM payment. Assume that the VM obligation amount between the client and the CCP is the same as before. The new direct clearing obligation is denoted as $\overline{p}_{i0}=\overline{q}_{ik0}$ or $\overline{p}_{0i}=\overline{q}_{0ki}$. The client also provides the CCP with IM equal to the original amount, $z_{i0}=z_{ik0}$, if it owes the obligation, and as usual the CCP does not provide IM if it owes the obligation. Finally, assume that guarantee fund resources are held constant, so the CCP's overall waterfall resources are equivalent.

If one compares the equilibrium in which a client clearing obligation exists against the equilibrium of the network in which this obligation is changed to a direct clearing obligation, we find:

Theorem 3. Given a fixed market shock, if the client clearing obligation of any client i of a member k is converted to a direct clearing obligation, then

- the CCP requires weakly more pre-funded resources to maintain solvency,
- though if the CCP is solvent under both settings, systemic losses are weakly lower in the direct clearing network.

This result highlights the trade-off between having direct clearing versus client clearing in the system. Client clearing allows for greater stability to the CCP by requiring less pre-funded resources for solvency. However, direct clearing allows for lower systemic losses if the CCP does not default. This is because client clearing exposes clearing members to contingent obligations, which place additional stress on members and could result in spillover effects that increase losses throughout the network. The improvement to CCP resiliency from client clearing thus does not imply that systemic losses are also reduced, and in fact, they could be increased.

Note that the result is silent about what happens should the CCP default. In Section VIII, we examine how relative losses under client clearing versus direct clearing are impacted by the shock size. We show that as the empirical data emphasizes member losses over client losses under more severe stresses, direct clearing is found to be worse against smaller shocks but better against larger shocks.

VI. Implementation for the U.S. CDS Market

To address the two research questions posed and verify our theoretical findings, we empirically calibrate the model using data from the U.S. credit default swap (CDS) market. The market provides an ideal setting as it is actively cleared by

TABLE 3

Average Values for CDS Participants and Counterparty Network

Table 3 presents summary statistics on the four types of firms, CCP, Members, Clients, and Bilateral firms, in the credit default swaps market as of Oct. 3, 2014. The statistics present the mean (standard deviations) number of CDS reference entities traded, and gross notional and net notional positions divided by whether the CDS contract was cleared or remained bilateral (noncleared). Gross notional and net notional figures are presented in $ millions, with positive (negative) net notional values referring to CDS protection purchases (sales). Standard deviations for all values are in parentheses. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation, and CCPView Clarus Financial Technology.

		Reference Entities		Gross Notional		Net Notional		
	No.	Cleared	Bilateral	Cleared	Bilateral	Cleared	Bilateral	Counterparties
CCP	1	435	–	6,688,393	–	0	–	389
Member	30	141	1,051	98,843	473,078	38	1,775	162
		(145)	(839)	(132,625)	(628,684)	(10,706)	(20,687)	(177)
Client	364	4	35	2,127	3,555	−3	−280	6
		(5)	(78)	(6,817)	(15,510)	(3,614)	(9,227)	(4)
Bilateral	534	–	12	–	1,305	–	116	3
		(–)	(32)	(–)	(13,795)	(–)	(1,269)	(3)

one CCP, ICE Clear Credit, though a sizable noncleared portion of the market exists.[22] We can thus use this market setting to analyze systemic losses and the consequences of changes in the default waterfall or central clearing rates without facing concerns about CCP competition (Glasserman et al. (2016)) or membership distribution (Murphy and Nahai-Williamson (2014)).

The analysis employs CDS transaction and position-level data from the Depository Trust & Clearing Corporation (DTCC), which includes all CDS contracts that involve at least one U.S. counterparty or a U.S. reference entity. The data are made available through a confidential regulatory data collection by the Office of Financial Research. Table 3 provides a summary of market participant positions and counterparty relationships as of Oct. 3, 2014, the date that corresponds to the stress scenario we discuss in the subsequent section. In accordance with previous empirical literature (D'Errico, Battiston, Peltonen, and Scheicher (2018))), we find a core-periphery network structure with the CCP intermediating a few highly interconnected clearing members (30) and many sparsely connected clients (364) and bilateral firms (534).

Table 3 shows the distribution of CDS positions and contract types intermediated through the network. Clearing members and bilateral firms are generally purchasers of protection, whereas clients are sellers. This is consistent across both cleared and bilateral positions. It suggests that clients may pose a risk under a stress scenario because they would be required to make more payments than they would be likely to receive. The large standard deviations for the net notionals is also notable as it indicates that there is significant heterogeneity in positions, which makes broad generalizations difficult.

One limitation of the DTCC data is a lack of information on each client's clearing member sponsor. While the data indicates the notional position that each client firm has with the CCP, it does not indicate the clearing member that the

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[22] The CCP is a privately held, for-profit company that cleared more than 97% of the notional value of CDS contracts on the date of the analysis. The only other CCP in this market is CME Clearing, which in 2014 cleared less than 3% of the contracts and has since exited the market.

position is cleared through. We assume that each client clears through the member that is their predominant trading partner.[23] In cases where clients have historically traded with multiple clearing members, we assign the clearing member with which the client has historically held their largest exposures against. This assignment rule divides the client firms across the clearing members relatively evenly, with a range of 7–37 clients across the 30 clearing members.[24]

A. Calibrating the Model and Financial System Shock

We calibrate the parameters of the model based on the historical CDS positions, prices, and market conventions of the data period. To calibrate the amount of IM posted, we adopt the historical portfolio-at-risk measure with respect to the margin period of risk presented in Duffie et al. (2015) and validated in Capponi et al. (2022). The method proposed in these works is the most closely aligned with actual CDS margining practices, which account for the asymmetric distribution of CDS payments by applying a maximum shortfall estimate based on a 1,000 day lookback and an additional jump-to-default add-on based on the gross outstanding short notional. We will refer to this method in the text as "MS Plus Short."[25] In the case of bilateral margin and cleared margin, a 10-day and 5-day margin period of risk are applied, respectively, following the regulatory guidelines (BCBS and IOSCO (2015)). For further accuracy, we use public 10-K filing amounts for ICE Clear Credit, as presented in Table 4, to equally scale the modeled portfolio IM and guarantee fund estimates of each account to the aggregate reported values of the CCP's default waterfall.[26] Client clearing IM is calculated using the same method

TABLE 4

Principal Elements of the Waterfall Structure of ICE Clear Credit

Table 4 presents the waterfall resources and assessment power of ICE Clear Credit as of Dec. 2014. The initial margins and the guarantee fund are made up of U.S. Treasuries and cash (USD, CAD, EUR, GBP, JPY). *Source*: SEC EDGAR 10-K Filing.

Tranche	Total Amount
Initial margins	$14.1 billion
Guarantee fund	$2.4 billion
CCP capital	$50 million
Member assessments	Up to 3 times Nondefaulting members' guarantee fund contributions

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[23] This assumption is in line with empirical evidence by the European Central Bank on client clearing (Kahros, Pioli, Carraro, Gravanis, and Vacirca (2021)), which shows that the vast majority of clients clear through only one clearing member.

[24] From public quarterly reporting, ICE reports that only 13 of its clearing members provide client-clearing services.

[25] Further details on the calculation for VM, IM, and capital buffers are presented in Appendix F of the Supplementary Material.

[26] Several additional factors beyond portfolio volatility are considered in the ICE Clear Credit model which we cannot compute, such as liquidity, default, concentration, and correlation. Some CCP risk models have also introduced correlation uncertainty risk charges. See Li and Cheruvelil (2019) for details on how CDS portfolio risk measures can change across correlation regime shifts.

for simplicity, though in practice members can charge higher IM to clients than the CCP.[27]

The capital buffers are calibrated using weekly inflows and outflows of VM at the firm level from 2010 to 2016 following the method in Paddrik et al. (2020). The method involves first computing for each firm a time series of its net VM payments divided by its gross notional portfolio value at each date. Then, the largest negative change in this ratio over the period of observation for each firm is multiplied by the gross notional portfolio value on the date of the shock. The product of these terms is assigned as the capital buffer. The method inherently assumes that larger capital buffers are held by firms with historically higher VM payment variance.

Finally, a stress scenario on the portfolios of CDS positions is applied to estimate a matrix of VM payments. Specifically, we apply the Federal Reserve's 2015 Comprehensive Capital Analysis and Review (CCAR) severely adverse global trading book shock, which prescribes a sudden widening of credit spreads for corporate, state, municipal, and sovereign debt according to their rating class (Federal Reserve Board (2016)). This systemic shock is applied to the positions data and widens CDS spreads in line with the largest historically observed single-day spread increase.[28] The widening of credit spreads results in a series of netted VM payments that need to be settled between firms in the system.

Table 5 summarizes the estimated aggregate VM payments owed between firm types based on the calibrated CCAR shock. Each group owes roughly as much as it is collectively owed, in contrast to what the notional position summaries suggested regarding clients. This difference in client positions and VM flows highlights why notional position size on its own does not capture the riskiness of a firm. Overall, the VM flows suggest no group is a collective risk to this financial system. However, it is worth noting that if payments from clients to the CCP are not fulfilled, these payment obligations become the clearing members' responsibility. Given the scale of client clearing payment obligations relative to those of members, there is a sizable amount of payments that members would become responsible for if the CCP or several clients were to default.

TABLE 5

Variation Margin Payments Under 2015 CCAR

Table 5 presents the aggregate variation margin payment obligations owed (in $ billions) by each firm type (rows) to each firm type (columns) under the 2015 CCAR. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.

		To				
		CCP	Members	Clients	Bilateral	Total
From	CCP	–	1.556	7.191	–	8.748
	Members	1.712	5.249	6.029	3.198	16.188
	Clients	7.036	6.157	0.008	0.003	13.204
	Bilateral	–	2.051	0.003	6.036	8.090
Total		8.748	15.013	13.231	9.237	

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[27] A robustness test of the consequences of higher client clearing margin charges is performed in Appendix G of the Supplementary Material.

[28] The date of Oct. 3, 2014, is selected because the 2015 CCAR scenario is designed to be implemented on positions from this week.

B. Estimating CCP Reliance and Systemic Loss

We use the calibrated model to compute equilibrium payment vectors and firm losses under a range of shocks scaled using the 2015 CCAR scenario. A scaling factor $\alpha > 0$ is applied to all VM payments under the CCAR scenario, which linearly scales the VM obligations of each firm in the model. We use this method to compute the value of systemic losses L at each value of α.

Figure 4 presents the losses of each of the firm types as a function of α, up until the CCP's pre-funded resources are completely subsumed at an $\alpha \approx 1.13$. Not unexpectedly, member losses comprise the majority of the losses. At lower levels of α, most if not all losses are concentrated on clearing members, with only 9% and 18% of the total losses of \$12.5 billion suffered by bilateral and client firms at the original CCAR shock ($\alpha = 1$). We break down the sources of these member losses below. Also of note is the nonlinearly increasing scale of losses as α increases, indicating that contagion plays a significant factor at high shock levels. Due to payment contagion and spillover effects, losses grow rapidly as the default of one firm causes its counterparties to default. The extent of these spillovers is affected by the degree of interconnectedness within the network and the various types of payment obligations that exist within the network. At the largest shock levels, the increasing impact of these spillovers causes losses to grow rapidly among client and bilateral firms.

As a stress event is likely to cause losses to swell across different avenues, we further break down member losses by type. Figure 5 separates the losses suffered by clearing members into those suffered from noncleared positions, client clearing, and the CCP's waterfall. The most notable finding is the large degree of client-clearing losses generated by client-clearing obligations at all levels of α. This illustrates the risk that these indirect contingent obligations pose for clearing members. A second takeaway is the large contribution of bilateral-driven losses when α approaches 1. This result re-emphasizes the outsized impact that bilateral

FIGURE 4

Aggregate Losses to the CDS Market Under the 2015 CCAR

Figure 4 plots the aggregate amount of systemic losses (in \$ billions), split on firm type, under variations of the 2015 CCAR severely adverse global shock scenario. At lower multiples of the shock scenario most if not all losses are concentrated on clearing members and only 9% and 18% of the total losses of \$12.5 billion are suffered by bilateral and client firms at the original CCAR stress. The aggregate losses are nonlinearly increasing with the shock multiplier, indicating that contagion is playing a factor. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.

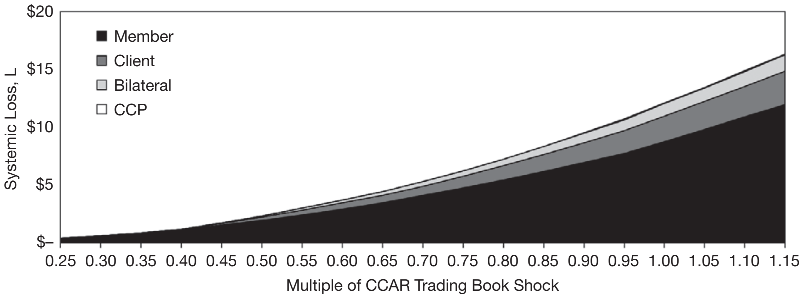
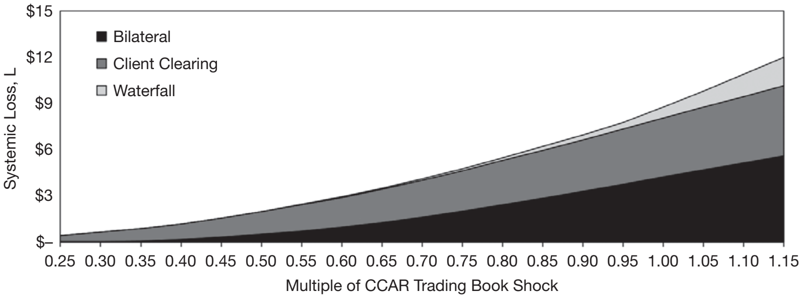


FIGURE 5

Member Losses Under the 2015 CCAR

Figure 5 plots the aggregate amount of clearing member losses (in $ billions), split by cause, under variations of the 2015 CCAR severely adverse global shock scenario. At lower multiples of the shock scenario most if not all losses are caused from covering client failures from client clearing positions. At higher multiples, aggregate losses are caused mainly from noncleared positions, and there are growing losses caused from the use of shared waterfall resources. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.



(i.e., noncleared) losses have on reducing CCP resilience. Finally, clearing member losses from the default waterfall (i.e., mutualized losses) make up a relatively minor proportion of total losses at small shock sizes, but waterfall-related losses grow more substantially at larger shock sizes as VM payment obligations begin to outsize CCP-held IM.

VII. Counterfactual Analysis of Default Waterfall

In this section, we address our first research question regarding how changes in a CCP's default waterfall elements affect the CCP's resilience to a market shock and the extent of firm losses in the financial system for a fixed payment network. We empirically test the theoretical findings presented in Theorem 2, as well as findings from other academic works, on the U.S. CDS CCP's default waterfall structure. By combining the theoretical model with supervisory data, we are able to quantify the economic significance of waterfall design choices. However, as the U.S. CDS CCP's default waterfall and network of payments are not necessarily representative of all CCPs and financial systems, the counterfactual analysis presented is mainly designed to demonstrate how structural design choices can operationally influence CCP resiliency and losses.

A. Impact of Initial Margin Allocation

We first study how to structure waterfall resources to increase CCP resilience and reduce systemic losses. This can be accomplished by either collecting resources from those most likely to cause losses and/or by ensuring that the resources collected effectively protect CCPs from payment shortfalls. In this section, we empirically address both avenues by conducting counterfactual tests of IM model methods and quantifying the benefits of mutualized waterfall resources highlighted in Theorem 2.

We start by considering IM, the first line of defense in the case of a member payment default. As IM is pre-funded and not encumbered by any outside risks, effectively estimating the margin required for each defaulting firm to cover its payment obligations relieves pressure on the later stages of the default waterfall. A CCP has advantages in assessing IM due to its centrality and transparent view of member positions. As a CCP observes a significant portion of the transactions in the financial markets it purveys, it is more capable than other firms at estimating the impact of defaults. Effectively setting margins by the CCP to protect against first-order contingent losses (i.e., the losses which are mutualized in the waterfall) helps improve CCP resiliency and ensures that the consequences of payment failure fall mainly on the defaulter.

The IM model applied throughout this article follows the MS Plus Short approach which accounts for asymmetries in CDS payments due to jump-to-default (see Duffie et al. (2015)). We compare it against an alternative IM technique suggested by Cruz Lopez et al. (2017) for CCPs, CoMargin. CoMargin is defined as the margin required to cover a clearing member or a client's portfolio conditional on one or several other members being in financial distress. This method thus accounts for the interdependencies in tail risks between clearing members.

To understand the implications of using CoMargin over the CCP's current IM model, we re-estimate the IM contributions of members and clients for their direct-cleared and client-cleared positions using the CoMargin method, while keeping bilateral IM consistent with the original MS Plus Short method. The CoMargin IM is empirically estimated by calculating a conditional VaR for each member and client based on the dates when the 2 largest clearing members suffered their collective largest losses (at a 5% level).[29] Although the CoMargin calculation suggests increasing IM in absolute terms, we scale total IM contributions across all members and clients to be equal to the resources in Table 4. This helps keep consistency and focuses the comparison on the distributional effects of the IM models.[30]

Table 6 presents the distributional characteristics of the two models on CCP member and client accounts. CoMargin requires more IM from member accounts and less from client accounts on average. The standard deviation of the CoMargin initial margins is also larger for both member and client accounts, signifying greater variance in the tails of the distribution. Table 6 additionally presents the impacts of the two margin models on CCP resilience and systemic losses. The table compares the CCP's resilience (guarantee fund usage) and systemic losses under three levels of stress (α) of the 2015 CCAR Global Market stress test.

The counterfactual results show that systemic losses are lower under CoMargin than MS Plus Short, although CCP resilience is relatively comparable between the two and the guarantee fund is exhausted under $\alpha = 1.2$ in both cases. An analysis of member losses shows that much of the reduction in systemic losses accrues to members. In particular, dramatic reductions in the client clearing losses suffered by

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[29] More details on this estimation are provided in Appendix G of the Supplementary Material.

[30] Note that the changes in IM model also affect the distribution of guarantee fund contributed by each member. This is in order to keep consistency with the base model, as our estimation of guarantee fund is proportional to our estimation of IM as explained above.

TABLE 6

CCP Initial Margin Model Distribution and Loss Effects

Table 6 presents two CCP initial margin setting models: maximum shortfall that accounts for jump-to-default risk (MS Plus Short) and CoMargin. For each model, we apply a normalized allocation percentages across an equal quantity of aggregate initial margin. The tables present mean and (standard deviation) initial margin held by each cleared account (in $ millions). Given the differing allocations of margin, we provide the estimated systemic loss (in $ billions) under three CCAR shock levels (α = 0.5, 1, and 1.5). Additionally, the percentage of guarantee fund resources used is provided to reflect on the capacity of the CCP to cover payments in full using collected resources. Finally, the α level at which guarantee fund resources are completely exhausted. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.

	Initial Margin Models					
	MS Plus Short			CoMargin		
Member accounts		197 (260)			224 (334)	
Client accounts		29.9 (163)			28.3 (178)	
CCAR stress (α)	0.5	1	1.5	0.5	1	1.5
Systemic loss	2.34	12.04	27.51	0.95	9.30	24.10
Member loss	*1.96*	*8.77*	*18.66*	*0.56*	*7.07*	*17.0*
Member loss: Client clearing	*1.45*	*3.82*	*7.25*	*0.42*	*2.04*	*5.67*
Guarantee fund usage	0.48	39.84	100	1.36	37.44	100
Guarantee fund exhausted (α)	1.13			1.18		

members highlight the distributional advantages of CoMargin for client IM collection. This improvement is due to CoMargin requiring higher margins from risky client accounts that default under the CCAR shock. As a result, sponsoring clearing members suffer fewer losses as they take over the payment obligations associated with defaulting client portfolios. These results suggest CoMargin does provide an advantage over the MS Plus Short method, even if it does not greatly relieve pressure on guarantee fund resources. Ultimately, this exercise highlights why it is important to encourage CCPs to determine initial margins with respect to systemic loss consequences. Analysis that conditions on member defaults, or contingent client obligations, can yield improvements in margining.[31]

B. Impact of Mutualized Resource Ratio

Next, we examine the impact of varying the ratio of IM to mutualized funds (i.e., guarantee fund and CCP capital contribution) on CCP resilience.[32] In practice, CCPs across regions have settled on different ratios of mutualized funds to IM. For example, our analysis of public CCP disclosures finds that guarantee funds and CCP capital make up on average 31% of the total default waterfall for Asian CCPs and 26% for European CCPs, but only 15% for North American CCPs (see Table 2). To test the implications of these different choices on CCP resilience, we perform a counterfactual analysis that compares the impact of variations in this ratio on the "default frontier" for the CDS CCP. The default frontier indicates the minimum

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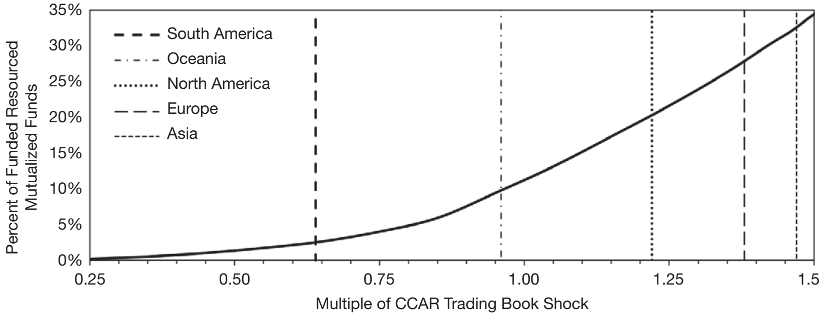
[31] Note that the analysis does not take into account any endogenous actions by firms that may occur if there were a switch to the CoMargin method. As described by Cruz Lopez et al. (2017), a switch to CoMargin could result in incentives to merge positions among members or to move contracts off the CCP. Such actions could alter the effectiveness of CoMargin relative to the other methods.

[32] In Appendix A of the Supplementary Material, we evaluate Initial Margin Haircutting (IMH), which allows the CCP to use the IM of nondefaulting clearing members at the end of the waterfall.

FIGURE 6

CCP Default Frontier and Waterfall Allocation

Figure 6 plots the CCP's default frontier, the point at which the CCP would either need to implement assessments or reduce its payments, under multiples of the 2015 CCAR severely adverse global shock scenario. As the shock increases in size, a larger percentage of mutualized funds are needed to maintain payments. The vertical lines represent the level of shock resilience the CCP would have at each of the regional average levels. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.



percentage of mutualized funds to total pre-funded resources needed to maintain payment continuity for a fixed level of total pre-funded resources, as a function of the shock size. By keeping the total level of waterfall resources and other features of the model fixed, this analysis isolates the impact of changes in the relative amounts of mutualized versus nonmutualized resources (i.e., guarantee fund vs. initial margin).

Figure 6 presents the default frontier for the CCP and highlights the average mutualized resource percentage for each region. If the CCP's default waterfall implements a mutualized funds ratio according to the regional averages, holding all else in the model equal, the European and Asian regional averages provide much greater resilience to the CCP, as the pre-funded resources cover shocks up to $\alpha = 1.38$ and $\alpha = 1.47$, respectively. Stated differently, we find that adopting the larger guarantee fund proportion of European CCPs allows the CCP to withstand a 13% greater market shock relative to the North American region's average waterfall, which would only protect the CCP up to an $\alpha = 1.22$. These increases in CCP resilience are substantial when compared to the prior initial margin model analysis, as changing to CoMargin only increases CCP resilience by less than 5% of α. Overall, these results align with our theoretical expectations of greater CCP stability as the percentage of mutualized funds is increased.

Beyond CCP stability, we find that greater mutualized resources decrease the systemic losses suffered by the financial system. For example, if we once again compare the North American setup to the European setup, we find that systemic losses are 5% lower for the European waterfall setup at an $\alpha = 1$. This difference grows as the level of α increases. These results are thus in agreement with Theorem 2, as they imply that higher levels of mutualized funds provide benefits to clearing members by increasing the resilience of the CCP and ensuring a lower systemic loss for the financial system.

As noted earlier, this analysis keeps all other elements of the financial system constant. In reality, clearing members may react to changes in guarantee fund requirements or other waterfall elements by modifying their participation in central clearing or other aspects of their portfolio (see Huang (2019)). If the costs of clearing outweigh the benefits, then clearing members may reduce their clearing activities. However, it is not entirely clear whether members would be more or less likely to participate under an increase in the guarantee fund to IM ratio. While increasing the guarantee fund further encumbers member pre-funded resources, it also provides them the benefit of improved CCP stability. Members may also base their clearing choices on idiosyncratic external factors such as positions in other markets, and regulations also affect the extent to which members may change their clearing decisions. In Appendix I of the Supplementary Material, we provide a stylized counterfactual analysis showing that against larger market shocks systemic losses are likely to be lower with greater levels of mutualized waterfall resources, in part due to limitations on the clearing decisions of members.

VIII. Counterfactual Analysis of Payments

In this section, we focus on our second research question of how changes in the network of payments and the severity of frictions alter CCP waterfall effectiveness and financial system resilience for a fixed level of default waterfall resources. We empirically test the theoretical findings presented in Theorem 3, as well as findings from other academic works. By combining the theoretical model with supervisory data, we are able to quantify the economic significance of changes to payment networks and market frictions.

A. Assessing Indirect Payment Obligations

While CCPs generally reduce the complex web of payment obligations, they remain susceptible to payment spillovers from the nondirect clearing obligations of members, which we denote as “indirect obligations”. The structural model presented in this article incorporates these indirect obligations along with protective pre-funded resources to provide a fuller assessment of CCP resilience and the financial system’s losses. To assess the impact of these indirect payment obligations on CCP stability, we compare a pared-down version of the model with no payment contagion to the full model.

Table 7 presents a measure of CCP resilience under variations in the shock size by computing the usage of CCP guarantee funds. The table presents three model settings that differ in the types of firms and payments included in the financial system and by extension the payment spillovers possible. The first model includes members and their centrally cleared payment obligations, with the obligations of a member’s sponsored client accounts combined with the obligations of the member’s house accounts.[33] The second model considers both member and client centrally cleared payments, where the member and client accounts are now segregated

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[33] The first model nets all member house accounts and client-cleared accounts into a single VM payment obligation between the member and CCP. These combined CCP-cleared payment obligations are the only payment types included when estimating the financial system’s VM payment obligations. All member IM and capital buffer estimates are held consistent with the full model specification.

TABLE 7

Indirect Payment Obligation Contingency on CCP Resilience

Table 7 presents the consequences of the three CCAR 2015 shock levels ($\alpha = 0.5$, 1, and 1.5) on CCP resilience, as measured by percentage of guarantee fund resource usage. Three model formulations are considered that differ in the type of payment transactions in the system: i) member-cleared payments, ii) member and client-cleared payments, and iii) all member, client, and bilateral payments (cleared and noncleared). *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.

	Member Cleared Payments			Member and Client Cleared Payments			All Firms and Payments		
No. of firms		30			394			928	
No. of payment obligations		23			387			3,890	
CCAR stress (α)	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5
Guarantee fund usage (%)	0	0	0	0	7.04	47.46	0.48	39.84	100

and the members must cover the shortfalls of clients if required.[34] Finally, the third model is the full structural model that includes all firms and payment types in the data set. While the total value of the guarantee fund is kept the same in each setting, the number of firms and payment obligations increase dramatically when moving from one model to the next.

The guarantee fund usages under the different models highlight how CCP resilience deteriorates due to payment contagion as more firms and payments are included in the system. With only member-cleared payments, guarantee fund usage is 0, even at $\alpha = 1.5$. By adding client payments, guarantee fund usage is nearly 50%, while including all firms and positions completely exhausts the guarantee fund at $\alpha = 1.5$. The consequences on guarantee fund usage emphasize the importance of accounting for client clearing and bilateral positions when assessing CCP stability.

Furthermore, we estimate the shock size that would cause the CCP to default in each scenario, assuming no CCP assessment powers. Our tests show that the default thresholds for α are 2.56, 1.78, and 1.13, respectively. Thus, the difference between the member-only and client-inclusive results is a 44% decline in CCP resilience. Adding the noncleared portion to the cleared market then results in an additional 58% decline in CCP resilience. These results highlight the importance of considering the whole network of payments in tests of CCP stability.

B. Client Clearing Exposure Risk

Client clearing makes up a significant proportion of outstanding CCP exposures, with 45% of average CCP IM covering client positions as of 2017.[35] Due to the contingent obligations placed on members in case of client default, these positions can influence CCP and financial system resilience as Theorem 3 asserts. While Figure 5 highlights the magnitude of client clearing losses that members can suffer under a severe market shock, the spillovers of this format of clearing on the rest of the financial system require further analysis.

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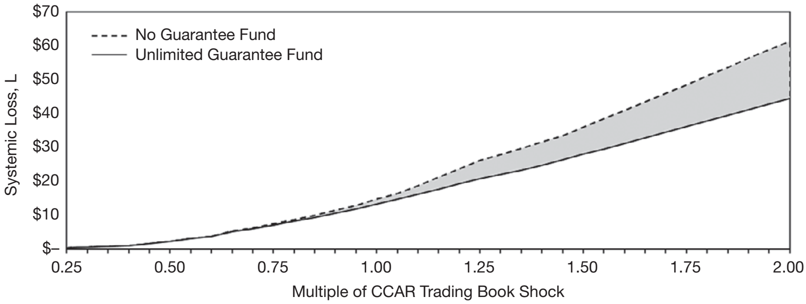
[34] The second model only considers member and client-cleared payment obligations when estimating the financial system's VM payment obligations. All member and client IM and capital buffer estimates are held consistent with the full model specification.

[35] At the time of our empirical setup, we estimate 50% of the CCP's IM is dedicated to client positions.

FIGURE 7

CCP Clearing: Direct Clearing Versus Client Clearing

Figure 7 plots aggregate systemic losses (in $ billions) under variations of the 2015 CCAR severely adverse global shock scenario (α). The two curves represent the level of systemic loss under two different formulations of clearing: client and direct. The two vertical lines represent the α levels at which the CCP would no longer be able to sustain full payments if no new resources were collected, that is, the minimum shock size at which $\dot{s}_0$ goes from 0 to positive in equation (10), under each respective clearing formulation. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.



To empirically test the impact of client clearing, we formulate a counterfactual payment network in which all clients are made direct clearing members.[36] The total pre-funded default waterfall resources under this new structure are assumed to be the same as before. However, the "client" members must now contribute to the guarantee fund based on their portfolio risk, in place of the contributions made by their previous sponsoring clearing members.[37] We vary the shock size α and compute the systemic loss under each setting. Figure 7 empirically compares these two clearing settings and quantifies the economic significance of Theorem 3.

Notably, the CCP defaults at a significantly lower shock level under the direct clearing formulation ($\alpha = 1$) than under the original client clearing formulation ($\alpha = 1.13$). The additional payments made to the CCP by members in case of client default helps to provide additional resiliency to the CCP. However, systemic losses under direct clearing are lower than under client clearing if the CCP does not default. This finding is most pronounced at small α levels. While these results highlight the trade-off between greater CCP resilience and greater systemic losses, the magnitude of the economic impact is not very large.

Figure 7 also provides different insights on losses for the case when shocks are high enough to cause the CCP to default. Recall that the theoretical analysis concluded that either clearing setting could be superior in this case. The empirical results are consistent with this conclusion, as the size of the shock ultimately determines which clearing structure causes more systemic losses. This is highlighted by the fact that the two curves cross one another multiple times.

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[36] Note that this counterfactual exercise assumes all clients would qualify to be members when in reality few clients would be eligible. Rather the focus of the exercise is on the structural consequences of such a material change on the waterfall, CCP resilience, and systemic losses.

[37] The new client guarantee fund contributions are subtracted from each client's capital buffers, while the members' excess contributions are added to their capital buffers, to keep the total amount of resources in the financial system consistent.

Direct clearing results in more severe systemic losses than client clearing at intermediate shocks above $\alpha = 1.13$, but it is superior to client clearing at the most extreme shocks ($\alpha > 1.75$). At high shock levels, the CCP exhausts its default waterfall and must reduce its payments through the use of VMGH. With client clearing, members would then need to cover the obligations owed by the CCP to their clients. Covering these additional obligations consumes member resources and may cause members to pay less to their bilateral counterparties. Large spillover losses can thus arise in the bilateral market as a result of client clearing, whereas with direct clearing the spillovers would not be as significant because clearing members are more important than clients to this market. Client clearing, therefore, results in more systemic losses than direct clearing at high shock levels.

Finally, note that in some markets client clearing does not require a contingent payment from the member to the client in case of CCP default. If the member-to-client contingent obligation is removed, our analysis shows that client clearing always produces lower systemic losses than direct clearing. The benefits of client clearing are thus improved as it not only raises CCP resilience but also reduces systemic losses.

C. Assessing Payment Frictions

Payment frictions are another source of risk for the financial system, as they can impede the ability of the financial system to clear payments. While CCPs help reduce some frictions by centralizing payments and netting offsetting portfolios, many frictions continue to persist. The model, though not built with frictions included, provides a vehicle to assess the severity of various intraday market frictions that may go unaccounted for in traditional stress testing.

The base model uses a classical set of payment assumptions, in line with Eisenberg and Noe (2001), whereby we assume: i) margins are held in cash, ii) payments are in a single form of currency and can be fully netted, and iii) defaulting firms use a pro rata payment rule if full payments cannot be made. However, in reality, margins can be held in rehypothecated assets that have restrictions, payments can be made in several currencies which prevents full netting, and firms may use a binary payment rule whereby they either make full payments if possible or no payments otherwise.

Table 8 presents the consequences of each of these frictions when introduced to the model. Margin rehypothecation restrictions and payment netting constraints

TABLE 8

Payment Frictions on CCP Resilience and Systemic Losses

Table 8 presents the consequences of the CCAR 2015 shock for four model scenarios, one benchmark, and added three frictions, for systemic losses (in $ billions) and CCP resilience (guarantee fund usage percentage). The three frictions scenarios include i) a limit on initial margin rehypothecation of 20% which reduces the initial margin that can cover intraday payments, ii) reduced portfolio payment netting which increases the size of intraday payments required, and iii) a binary payment rule whereby a firm either pays in full or not all. *Source*: Authors' calculations using data provided to the OFR by the Depository Trust & Clearing Corporation and Markit Group Ltd.

	Benchmark	20% of Rehypothecation Margin Inaccessible	Portfolio Payment Netting of 80%	Binary Payment Rule
Systemic loss ($B):	12.04	13.48	15.81	23.92
Guarantee fund usage (%):	39.84	82.73	100	51.36

impede the CCP's ability to cover its outgoing payments, as guarantee fund usage increases by more than double when these frictions are included. However, neither friction greatly changes the level of systemic losses in the broader financial system. By contrast, the use of a binary payment allocation rule by defaulting firms leads to the opposite effect, causing a near doubling of systemic losses but just a minor increase in guarantee fund usage. The result indicates that this friction has a more significant impact on losses in the bilateral portion of the market than in the centrally cleared portion. More broadly, each of these results highlights how frictions can compound spillover effects in financial systems when under periods of severe stress.[38]

IX. Conclusion

The design of the default waterfall is essential to a CCP's ability to fulfill its payment obligations and reduce financial system losses under periods of severe stress. However, estimating CCP stability and its consequences is difficult due to the highly interconnected nature of firms and the spillover effects that arise from contagion and payment frictions. This article addresses this challenge by incorporating default waterfall elements into a network model that assesses losses among firms for centrally cleared, client cleared, and noncleared OTC derivatives positions. We derive several findings from the model and perform counterfactual analyses to evaluate the economic significance of spillover effects and default waterfall design.

Our analysis demonstrates that payment spillovers and frictions can significantly impair payments to CCPs under periods of market stress. Additionally, we find that client clearing, while not a direct risk to a CCP's default waterfall, does cause significant strain on clearing members and may translate to intensified systemic losses. Our evaluation of CCP default waterfall design shows that though well-designed margin models can allocate loss more apropos of risk, higher guarantee fund ratios are ultimately more effective at increasing CCP resilience under severe stress. While higher guarantee fund ratios could disincentivize clearing by imposing greater capital costs and loss-sharing risks on members, regulatory mandates have generally limited clearing participation options.

The contributions and findings made in this article highlight several additional areas for further research. First, a better understanding is needed of the consequences of a CCP's failure on other CCPs and markets. CCPs are likely to affect one another through their shared membership, similar collateral, and mutual demand for

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[38] Appendices G and J of the Supplementary Material detail the implementation of these three frictions in the model and how each is impacted by variations in stress. Additionally, collateral illiquidity and payment prioritization effects are examined in Appendices B and K of the Supplementary Material, respectively. The former reveals the significance of collateral spillover effects, which can intensify systemic losses through the fire sale channel under extreme stress conditions when there is no liquidity provider of last resort. The latter shows that CCP payment seniority increases the resilience of the CCP as it receives more payments, but it does not necessarily decrease systemic loss due to greater bilateral-market driven losses.

liquidity. A disruption in clearing member payments across multiple CCPs may create contagion and collateral fire sales. Additionally, these risks could propagate across other markets. For example, interest rate and currency swaps are commonly used in conjunction with other derivatives contracts and may thus be affected by payment spillover effects.

Second, further analysis is needed to address the strategic choices of firms in OTC markets. Firms may strategically adjust their clearing decisions in response to changes in the CCP's default waterfall. For instance, firms may alter their trading strategies and the riskiness of their portfolios. Additionally, firms may be strategic about making their payments, taking into account features such as the market power or liquidity of counterparties. During a crisis, members and clients may also prioritize specific payments to take advantage of differences in payment delivery options. Such decisions are likely to influence the flow of payments across the financial system in unexpected ways.

Supplementary Material

To view supplementary material for this article, please visit http://doi.org/10.1017/S0022109022001351.

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