‘Smart’ Settlement

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Abstract

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Keywords: Market design, trade settlement, blockchain, vertical differentiation
JEL Codes: D43, D47, G10, G12

1 Introduction

How fast should trades be settled? Most transactions are nowadays finalized with a two- or three-day delay. For example, the Securities and Exchanges Commission (SEC) proposed in September 2016 to shorten the settlement cycle in the United States from three to two business days.[1] In a trading environment where quotes are updated with nanosecond frequency (Menkveld, 2016a), a delay measured in days feels dated. Each trade is processed by a number of different institutions from execution on the exchange until settlement: (i) a trade repository which registers and notarizes it, (ii) a central counterparty (CCP) that provides netting, (iii) a custodian bank that safeguards the assets, and (iv) a central securities depository (CSD) that settles the trade (see, e.g., Collomb and Sok, 2016, p. 80, for a detailed scheme of post-trade infrastructures).

Technological innovation may soon transform the post-trade process. Distributed ledger technologies (DLT), such as the Blockchain, are poised to shorten and simplify the settlement cycle. Blockchain technology uses a distributed messaging protocol (a "ledger") to create consensus across counterparties: all transactions are entered into a single, immutable shared record.[2] The decentralized and open-source nature of Blockchain, while cryptographically encrypted and secure, allows trades to be validated almost instantaneously through market consensus. Consequently, the usefulness of a long settlement chain diminishes. Figure 1 illustrates the settlement chain under both a traditional and a Blockchain market infrastructure.

[insert Figure 1 here]

Blockchain-driven settlement attracted significant regulatory interest. The consensus is that distributed ledger technology has the potential to eliminate the need for multiple records of a single trade and consequently reduce the number of intermediaries (ECB, 2016; ESMA, 2016; Brainard, 2016). Savings are estimated to be economically important: An Oliver Wyman (2016) report estimates worldwide post-trade and security servicing costs at USD 100 billion.

Malinova and Park (2016, p. 1) refer to Blockchain as "the technology that enables frictionless transfer of value." In the context of security settlement, the friction Blockchain

[1] See SEC Proposes Rule Amendment to Expedite Process for Settling Securities Transactions.

[2] Originally, Blockchain technology was instrumental for cryptocurrencies such as Bitcoin. To prevent fraud and double-spending, cryptocurrencies require many anonymous agents to reach a consensus for each trade.

removes is not necessarily the *existence*, but rather the *rigidity* of a positive time-to-settlement. While immediate settlement is indeed an option under Blockchain settlement, industry leaders stress the importance of flexible times-to-settlement. Blythe Masters, CEO of Digital Asset Holdings, focuses on the "*the possibility of giving customers the choice of how fast they want to settle*." In the same spirit, Fredrik Voss, the Vice President of Blockchain Innovation at Nasdaq states that "*I can even think that we [..] allow participants to select the pace at which they want to settle, which has been challenging to do in the market today*." Anecdotal evidence suggests immediate settlement is not necessarily optimal: the Moscow Stock Exchange reverted in March 2013 from a T+0 (same day) to a T+2 settlement cycle to reduce transaction costs related to inventory management.[3]

Blockchain-driven settlement allows for flexible time-to-settlement. Since such flexibility will most likely be specified through a computer protocol referred to as a smart contract, we introduce the concept of "smart" settlement to describe such DLT-embedded optionality.

Our paper asks two questions. First, what is the optimal time-to-settlement – in particular, under which market conditions is immediate settlement optimal? Second, and perhaps more importantly, who should "exercise" the embedded option, i.e., decide on time-to-settlement? One possibility is a market design where exchanges set a single time-to-settlement for each security, perhaps time-varying as a function of changing market conditions. Alternatively, traders can decide on the length of the settlement cycle themselves: Blockchain technology may allow for a "three-dimensional" order book, where each trader specifies not only the desired price and quantity, but also a preferred settlement time.

We build a model with flexible time-to-settlement. There is a single riskless traded asset. A trader receives an exogenous (positive) private value shock and requests a quote from an intermediary who owns the asset. The quote has *two* components: both a price and a time-to-settlement. The price is paid immediately, whereas the asset is delivered at settlement.

There are two economic frictions in the model: search costs and counterparty risk. If traders agree on *immediate settlement*, the asset is transferred from the intermediary to the buyer and gains from trade are realized. However, traders may also choose *delayed settlement*. On the one hand, the intermediary might exogenously default between trade and settlement,

[3] The sources for this paragraph are `https://goo.gl/FBvwki` for the Blythe Masters interview and `https://goo.gl/mv68il` for the Fredrik Voss interview. See also Moscow Targets March Move to 2 Day Settlement.

and consequently fail to deliver the asset. Therefore, the buyer's exposure to counterparty risk increases in the time-to-settlement. On the other hand, between trade and settlement, the intermediary searches for sellers with a negative private value for the asset. The probability of finding a negative-value seller increases in time-to-settlement. The intermediary is better off as time-to-settlement increases as she is less likely to use her inventory. Keeping default risk fixed, gains from trade increase in time-to-settlement. Therefore, the intermediary quotes a lower price and liquidity improves. We interpret the intermediary's search friction as inventory management costs: immediate settlement creates the need for a (high-frequency) market-maker to hold costly inventory in order to trade.

The optimal time-to-settlement depends on the trade-off between the intermediaries' default and counterparty search rates. First, optimal time-to-settlement decreases in default rate. Buyers with relatively small private values favour better liquidity (i.e., paying a small price) over low counterparty risk, and have a preference for delayed settlement. Buyers with relatively large private values choose immediate settlement to eliminate counterparty risk, and are willing to pay a higher price for the asset. It follows that immediate settlement is not necessarily a panacea for market quality, as it over-emphasizes counterparty risk relative to liquidity for a subset of traders.

We focus on a market where duopolist intermediaries compete in both price and time-to-settlement. If time-to-settlement is fixed, intermediaries engage in Bertrand competition over prices and earn equilibrium expected profits of zero. Endogenous time-to-settlement, however, allows intermediaries to offer different price-"quality" menus, where contract quality is proxied by the intermediary's probability of default. A longer time-to-settlement corresponds to higher default risk, consequently to lower contract quality. Naturally, immediate settlement corresponds to the highest possible contract quality (i.e., zero non-settlement risk).

In equilibrium, duopolist intermediaries offer different times-to-settlement, that is, different levels of counterparty risk. This vertical differentiation strategy allows intermediaries to relax Bertrand price competition and have positive expected profits. Intermediary H offers a high-quality (low counterpary risk) and high-price contract, whereas intermediary L offers a low-quality (high counterparty risk) and low-price contract.

The quality wedge between the two contracts is mirrored by a marginal cost wedge between the two intermediaries. The marginal cost for an intermediary is her expected payment upon settlement. A longer time-to-settlement reduces marginal cost in two ways. First, the probability of making a payment is lower, since the intermediary is more likely to default. Second, the probability of the intermediary selling her own asset is lower, since she is more likely to find a negative value seller before settlement. Since the two channels interact, marginal cost decreases faster than linearly in time-to-settlement (i.e., a convex relationship). In contrast, counterparty risk increases linearly in time-to-settlement.

The properties of the equilibrium depend on the ratio between default and search rates. Specifically, a threshold result emerges. For a low enough default rate, both intermediaries offer delayed settlement, have equal market shares, and earn equal rents. We refer to this scenario as the *delayed-settlement* equilibrium. If the default rate exceeds a threshold, the high-quality intermediary H offers immediate settlement, whereas the low-quality intermediary L offers delayed settlement – an *immediate-settlement* equilibrium emerges. For any default rate that exceeds the threshold, intermediary H has a higher market share and earns a larger profit than intermediary L.

To understand the equilibrium result, we note that intermediary H offers a better quality (lower counterparty risk) contract than intermediary L, but intermediary L is able to quote a lower price due to a lower marginal cost. For low enough default rate, it is suboptimal for H to offer immediate settlement since L can more than compensate by offering a contract with sufficiently low marginal cost (i.e., a high enough time-to-settlement) to attract a higher market share.

A higher default rate increases both the quality and the marginal cost wedge between intermediaries. However, since marginal cost depends on both default and search rates, it increases less in default rate. For intermediary H, a higher default rate has a positive net effect: Consequently, H can differentiate her contract more aggressively and quote a lower time-to-settlement (even higher quality). Conversely, for intermediary L a higher default intensity has a negative net effect: L differentiates her contract less aggressively, and also quotes a lower time-to-settlement to reduce the quality gap. There is an important feedback effect: if H quotes a lower time-to-settlement to increase the quality wedge between intermediaries, it also benefits intermediary L as the marginal cost gap widens at the same time.

As long as the default rate remains below a threshold, both intermediaries quote strictly positive times-to-settlement. The difference between the quoted times-to-settlement is constant, and the quality gap increases at the same rate as the default rate. A higher default rate offers a larger scope for contract differentiation. Consequently, both intermediaries' profits increase in the default rate.

When the default rate reaches a threshold, intermediary H offers immediate settlement, i.e., the highest-quality contract. The feedback effect breaks down: intermediary H can no longer improve quality if the default rate increases above the threshold. Therefore, intermediary L no longer benefits from a larger marginal cost gap. Since the marginal cost is convex in time-to-settlement, any attempt of L to reduce the quality gap decreases her marginal cost advantage more than proportially. Intermediary L is consequently worse off: as default rate increases beyond the threshold, she loses market share and expected profits drop. In contrast, both intermediary H's market share and profits increase in the default rate. Consequently, there is a flight to quality effect if the default rate exceeds a certain level.

Intuitively, the duopoly game is not unlike a boxing fixture. Our "boxers," the two intermediaries, start the match in the centre of the ring. An increase in default rate changes the aggressiveness of the two combatants as they begin to slide towards one of the corners: H and L become more, and respectively less, aggressive. However, until they reach the corner, the boxers are still evenly matched, with none attempting a decisive blow in fear of retaliation. In the context of our model, if the default rate is still low, H will not offer an immediate settlement contract. Once the boxers reach the corner, the most aggressive one can fully exploit the advantage and win the fight. In the model, the high-quality intermediary earns both a higher market share and a larger profit once the default rate exceeds a threshold. One important insight is that, even if both intermediaries increase profits at the same rate as default rate rises, a higher default rate still offers a latent advantage to the low-counterparty risk intermediary.

If intermediaries' choose contracts sequentially, as in a Stackelberg entry model, then for low enough default rates they are indifferent between offering a high- or a low-quality contract. Consequently, two symmetric delayed settlement equilibria emerge. For default rates that exceed the threshold, the first entrant always chooses immediate settlement, i.e., to offer the high quality contract.

Our model yields two policy-relevant insights. First, if time-to-settlement is endogenous, intermediaries' rents increase in default risk. This could weaken the intermediaries' incentives to improve their risk management, shifting the burden towards clearing houses or regulatory bodies.

Second, we show an optimally-set unique time-to-settlement improves welfare relative to the duopoly setting. The result suggests exchanges should use distributed ledger technology to set one single time-to-settlement for all trades in a particular security. Such time-to-settlement should incorporate information on counterparty risk and search costs, potentially in a dynamic way as a function of market conditions. The solution implements higher welfare than a market setup where intermediaries endogenously choose when to settle trades, as the latter design encourages rent-seeking behaviour.

Our paper contributes to a small, yet active literature on the applications of distributed ledger technologies (such as Blockchain) on financial markets. Harvey (2016) explores the mechanics of blockchain technology and provides a complete overview of developments in cryptofinance. Malinova and Park (2016) focus on the transparency of holdings in a blockchain-driven market. They find that fully transparent holdings maximize welfare, despite a higher risk of front-running. Lee (2016) speculates on how blockchain trading will affect high-frequency trading strategies, short-selling, and how regulators need to adapt to the new technology. In a similar spirit, Brummer (2015) focuses on legal implications of technological transformations in securities markets. Yermack (2016) discusses corporate governance application and argues that greater transparency will alleviate information asymmetries across different groups of stakeholders in a firm.

Vertical differentiation is first introduced in an industrial organization setting by Gabszewicz and Thisse (1979) and Shaked and Sutton (1982, 1983). A number of recent microstructure papers study vertical differentation mechanisms on financial markets. Closest to our paper, Li and Schürhoff (2015) argue that dealers on OTC markets incur search costs to find suitable counterparties. Central dealers have lower search costs and are more efficient in matching buyers and sellers. However, they charge a premium for providing fast liquidity. The authors use execution speed as a measure of trading quality. In our model, we focus on counterparty risk instead. Moreover, our setup allows time-to-settlement to have an effect on both the quality and the cost of a contract. Neklyudov and Sambalaibat (2015) argue that OTC core dealers specialize in clients with frequent trading needs, whereas periphery dealers specialize in attracting buy-and-hold clients. Pagnotta and Philippon (2015) discuss vertical differentiation at the level of trading platforms, and show that market venues have an incentive to choose different trading speeds to attract different clienteles.

Our paper also relates to the literature on search frictions in asset pricing, starting with Diamond (1982). Duffie, Gârleanu, and Pedersen (2005) argue that bid-ask spreads decrease if investors can find each other at lower costs. Lagos and Rocheteau (2009) discuss the effect of search frictions on the distribution of asset holdings. Gehrig (1993) studies the case of a monopolistic market-maker in a one-period trading game. Vayanos and Wang

(2007) focus on portfolio choice and find a "clientele" effect. They start with two assets with identical payoffs and find that in equilibrium liquidity concentrates in one asset, which carries a liquidity premium. Short-term traders choose to pay the premium and invest in the liquid asset. Cujean and Praz (2015) study endogenous liquidity risk in the case where an asset is traded on markets both with and without search frictions. On limit order markets, Hendershott and Menkveld (2014) document that intermediaries adjust prices in response to inventory shocks that cannot be immediately reversed.

Finally, we contribute to a strand of literature studying counterparty risk. In the aftermath of the 2007-2009 financial crisis, several papers focus the impact of a central clearing counterparty on market quality (Acharya and Bisin, 2014; Acharya, Engle, Figlewski, Lynch, Subrahmanyam, Acharya, and Richardson, 2009; Pirrong, 2009). Loon and Zhong (2014) document that counterparty risk is priced by the market and that the introduction of a CCP in 2009, following the Dodd-Frank Act, led to a decrease in counterparty risk in the CDS market. Duffie and Zhu (2011) discuss economies of scope from having a single CCP across all asset classes. To control systemic risk, Menkveld (2016b) proposes a collateral system that internalizes the global effects of highly correlated portfolios across traders, i.e., the "crowding risk."

A central counterparty's main impact on counterparty risk is due to netting existing positions, that is through the *size* of risk exposure. Distributed ledger technology furthermore allows for immediate or flexible settlement, allowing to fine-tune the *length* of risk exposure. Our paper complements the existing counterparty risk literature by focusing on the latter channel through endogenous time-to-settlement.

2 Model

Asset. A single riskless asset is traded in an over-the-counter market. The common value of the asset is v. There are gains from trade as agents have hetereogenous private values for the asset.

Agents. There are three types of agents: a unit-measure continuum of buyers $\mathbf{B}$, two intermediaries ($\mathbf{I}_1$ and $\mathbf{I}_2$), and a large number of sellers $\mathbf{S}$. All agents are risk-neutral. At the start of the game, each intermediary and each seller are endowed with one unit of the asset, whereas buyers do not hold the asset.

Buyers are indexed by their private values. Buyer i has an additional private value of $(\theta_i - 1)\,v$, where θ_i is uniformly distributed (namely, has unit density) on $[1, 2]$ – in the spirit of, e.g., Constantinides and Duffie (1996). Sellers have a negative private value of $-v$: therefore, their total utility from holding the asset is zero. Intermediaries have no private value. Common and private values of all agents, as well as initial asset holdings, are tabulated below.

Agent type	Common value	Private value	Asset value	Initial holding
Buyers B_i	v	$(\theta_i - 1)\,v$	$\theta_i v$	0
Intermediary $I_{1,2}$	v	0	v	1
Sellers S	v	$-v$	0	1

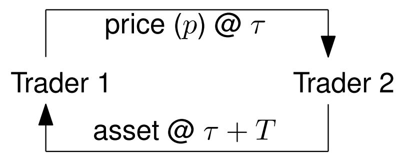
Market contact rate. Intermediaries are present on the market at all times. Buyers and sellers arrive asynchronously as in, for example, Grossman and Miller (1988) or Duffie, Gârleanu, and Pedersen (2005). In particular, buyers only contact the market at $t = 0$; in contrast, sellers only contact the market at $t > 0$. Consequently, both buyers and sellers need to trade through the intermediary to realize the gains from trade.

Intermediaries contact sellers at random: Within a time interval of length T, an intermediary meets a seller with probability λT, where $\lambda > 0$. We refer to λ as the intermediary's *search rate*. It follows that the probability of a trade between an intermediary and a seller increases in the time interval T. Each intermediary searches within its own pool of potential sellers, that is, intermediaries do not compete to attract seller order flow.

Default risk. The default rate for each intermediary is $\delta > 0$. That is, within a time interval of length T, the intermediary exogenously defaults with probability δT. If an intermediary defaults, she does not need to settle any outstanding unsettled trades. Finally, intermediary defaults are also uncorrelated.

Assumption 1: We assume $\delta \in \left[\frac{4}{7}\lambda, 2\lambda\right]$ to ensure all equilibrium probabilities are well-defined.

Trading. A trade contract on the OTC market is a pair (p, T), where p is a price and T is the time-to-settlement. If τ denotes the time of the contract, the price is paid at τ and the asset is transferred at $\tau + T$.[4]



Intermediaries have full bargaining power. Since sellers have a zero valuation for the asset, the price on the intermediary-seller contract is zero, and immediate settlement is always weakly optimal.[5] We focus therefore on the non-trivial trade contracts between intermediaries and buyers.

Intermediaries offer buyers a take-it-or-leave-it contract (p, T). We consider two market designs. In the first model setup, times-to-settlement is endogenous to the trading process. Intermediaries set contract terms sequentially. First, at $t = -2$, they arrive in random order at the market and choose times-to-settlement T. Second, at $t = -1$, intermediaries decide on prices p. In the alternative market design, the exchange (modeled as a social planner) sets a unique settlement time T at $t = -2$, with intermediaries choosing prices at $t = -1$.

Contract terms are common knowledge at all times. At $t = 0$, buyers arrive to the market and choose one of the two contracts offered by intermediaries. Finally, contract terms are not renegotiable. This is a realistic assumption: In practice, trades on the blockchain are likely to be implemented through automatic and immutable "smart" contracts.

[insert Figure 2 here]

The game ends either when all trades are settled, or when at least one counterparty to each unsettled trade is in default. The complete timing of the model is illustrated in Figure 2.

[4]The model is robust to using the assumption of payment-for-delivery settlement (where both the price and the asset are transferred at $\tau + T$), as long as the buyer incurs a loss conditional on seller's default. The assumption is not unrealistic. In the current setup, such loss is represented by the price itself – however, it can stand for lost interest on the margin account, or otherwise foregone investment opportunities. Further, we assume the seller always fulfills her obligations at $\tau + T$ conditional on survival: In a richer setup, this could be modeled through the threat of reputation loss in a repeated game.

[5]Since the seller default risk is zero, both the intermediary and the seller are indifferent across all settlement times starting from immediate settlement and up to the buyer-intermediary contract settlement time.

3 Optimal time-to-settlement

The optimal time-to-settlement on a given transaction maximizes gains from trade between a buyer and an intermediary. To build intuition, throughout this section we focus on a single trade contract (p, T) between one buyer (with private value $\theta_i v$) and one intermediary. In Section 4, we allow for strategic interaction between the two intermediaries and discuss the competitive equilibrium.

The expected utility for buyer i from contract (p, T) is:

$$U_{\mathbf{B}_i} = \underbrace{(1-\delta T)}_{\text{Settlement probability}} \theta_i v - p. \tag{1}$$

With probability δT, the intermediary defaults before settlement. Consequently, with the complementary probability $1 - \delta T$, the intermediary does not default and the trade is settled (either the intermediary uses her own inventory or she finds a seller). Conditional on settlement, buyer i receives the asset with private value $\theta_i v$. Finally, at $t = 0$ the buyer pays the contract price p.

The expected utility for intermediary $\mathbf{I}$ from contract (p, T) is:

$$\begin{aligned} U_{\mathbf{I}} &= p + \underbrace{(1-\delta T)}_{\substack{\text{Settlement}\\ \text{probability}}} \left[\underbrace{\lambda T}_{\substack{\text{Intermediary}\\ \text{finds seller}}} v + \underbrace{(1-\lambda T)}_{\substack{\text{Intermediary}\\ \text{does not find seller}}} 0 \right] - \underbrace{(1-\delta T)\, v}_{\substack{\text{Opportunity cost}\\ \text{from no trade}}} \\ &= p - (1-\delta T)(1-\lambda T)\, v. \end{aligned} \tag{2}$$

The intermediary receives and consumes p at $t = 0$. With probability δT, $\mathbf{I}$ defaults before T and does not make any further payment. With probability $(1 - \delta T)$, the intermediary survives until settlement. Conditional on survival, with probability λT, the intermediary finds a seller and keeps the asset worth v. If the intermediary does not find a seller within the time interval T, she sells her inventory and has no further utility from holding the asset. Finally, the reservation utility at horizon $t = T$ for the intermediary is her opportunity cost from not trading, that is, $(1 - \delta T)\, v$ – the common value of the asset conditional on survival at time T.

Equivalently, the intermediary's utility is the difference between the price p received at $t = 0$ and the expected own inventory outflow. The intermediary settles one unit of the asset worth v from her own inventory if and only if she (a) does not default and (b) does not find a seller until settlement. The joint probability that the intermediary survives *and* does not find a seller is $(1 - \delta T)(1 - \lambda T)$.

From equations (1) and (2), it follows that the trade surplus between buyer i and an intermediary is

$$\text{TradeSurplus}_i = U_{\mathbf{B}_i} + U_{\mathbf{I}} = v \underbrace{(1 - \delta T)}_{\substack{\text{Settlement} \\ \text{probability}}} \underbrace{[\theta_i - (1 - \lambda T)]}_{\text{Conditional gains from trade}}. \tag{3}$$

Since the price is simply a utility transfer between buyer and intermediary, it does not affect trade surplus. First, the probability of an intermediary-seller meeting increases in search rate λ: A larger λ increases the likelihood of the "most efficient" asset transfer (i.e., between a negative-value seller and a positive-value buyer). Consequently, trade surplus increases in λ. Second, gains from trade only materialize upon settlement, when the asset is allocated to the highest valuation agent. It follows that trade surplus decreases in the intermediary default rate δ. Naturally, trade surplus increases in buyer's private value θ_i. Finally, since $\theta_i \geq 1$ and $\lambda T \leq 1$ (i.e., a probability), it follows that the trade surplus is non-negative.

The relationship between time-to-settlement and trade surplus is non-monotonic. First, there is a *counterparty risk effect* as the settlement probability decreases in time-to-settlement. Second, there is a *trade efficiency effect* in the opposite direction: since an intermediary-seller meeting is more likely for higher T, the conditional gains from trade increase in time-to-settlement. Figure 3 plots the resulting concave relationship between trade surplus and time-to-settlement for two values of the default rate δ.

[insert Figure 3 here]

Proposition 1. (Optimal time-to-settlement) *The optimal time-to-settlement between buyer i and an intermediary is $T_i^\star$, where*

$$T_i^\star = \max\left\{0, \frac{\lambda - \delta(\theta_i - 1)}{2\delta\lambda}\right\}. \tag{4}$$

Further, the optimal time-to-settlement is implemented by Nash bargaining between buyer and intermediary, irrespective of their relative bargaining powers.

The proofs of all lemmas, propositions, and corollaries are in Appendix B. Proposition 1 characterizes the optimal time-to-settlement. Two insights emerge. First, both immediate and delayed settlement may be optimal, as Figure 3 illustrates. Immediate settlement is optimal if the default rate δ is relatively large. Second, Nash bargaining is sufficient to implement the optimal time-to-settlement. In particular, the result does not depend on the relative market power of the intermediary. The contract (p, T) depends on relative bargaining powers only through the trade price. Intuitively, the buyer and the intermediary first choose time-to-settlement to maximize gains from trade and then share the surplus according to their relative bargaining power: for example, a higher bargaining power for the intermediary translates into a higher price paid by the buyer. There is, however, a caveat: The Nash bargaining result in Proposition 1 (a) requires that the contract terms are set *after* the intermediary and the buyer meet (which is not true in quote-driven markets), and (b) abstracts from strategic behaviour in a multiple-intermediary market.

Corollary 1. *The optimal time-to-settlement $T_i^\star$:*

(i) increases in the intermediary's search rate λ,

(ii) decreases in the default rate δ, and

(iii) decreases in the buyers' private value θ_i.

Corollary 1 presents further comparative statics. First, the optimal time-to-settlement increases in the search rate λ. A higher search rate, all else equal, implies a stronger positive trade efficiency effect. Consequently, the likelihood of an efficient asset transfer increases for any time-to-settlement. It follows that a social planner can set a higher T, and therefore increase counterparty risk, without reducing welfare.

Second, the optimal time-to-settlement decreases in the default rate. A higher default rate implies a stronger negative counterparty risk effect on trade surplus. Consequently, a social planner sets a lower T to increase the likelihood of settlement.

Third, the optimal time-to-settlement decreases in the buyer's private value. The efficiency of a buyer-intermediary trade, if the intermediary does not meet a seller, is the difference between $\mathbf{B}_i$ and $\mathbf{I}$'s private valuations, that is, $\theta_i - 1$. Conversely, the efficiency of an intermediated buyer-seller trade is $\theta_i - 0 = \theta_i$. For high buyer valuations, the efficiency gap is narrower, that is, $\frac{\theta_i - 1}{\theta_i}$ increases in θ_i. Therefore, buyers with high valuations are relatively more concerned about counterparty risk than about an inefficient trade. The counterparty risk effect dominates, and the optimal time-to-settlement decreases in $\mathbf{B}_i$'s private valuation.

The top panel of Figure 4 illustrates the optimal time-to-settlement as a decreasing function of default rate.

[insert Figure 4 here]

For a high enough default rate, the counterparty risk exceeds a "tolerance threshold" $\widetilde{\delta}$. For any $\delta > \widetilde{\delta}$, immediate settlement is optimal. Since high-valuation buyers are relatively more sensitive to counterparty risk, immediate settlement becomes optimal for a lower default rate, that is, $\widetilde{\delta}$ decreases in the private value θ_i. From equation (4), it follows that

$$\widetilde{\delta} = \frac{\lambda}{\theta_i - 1}. \tag{5}$$

Counterparty risk and price. To illustrate the relationship between default rate and price, we assume the intermediary has full bargaining power in her relationship with the buyer. From Proposition 1, the time-to-settlement is still $T_i^\star$. The intermediary sets the price $p^\star$ such that the buyer's participation constraint is binding, that is,

$$U_{\mathbf{B}_i} = \left(1 - \delta T^\star\right) \theta_i v - p^\star = 0. \tag{6}$$

From equations (4) and (6), it follows that the intermediary sets the price

$$p^\star = \min\left\{\frac{v}{2\lambda}\theta_i \left[1 + \delta\left(\theta_i - 1\right)\right], v\theta_i\right\}. \tag{7}$$

The bottom panel of Figure 4 plots the price in equation (7) as a function of default rate δ. The salient feature is that the price $p^\star$ *increases* in default rate. This is in contrast to price behaviour in a market with fixed time-to-settlement. If time-to-settlement is constant, counterparty risk increases in the default rate. Therefore, a higher default rate translates into a lower settlement probability. The buyer needs to be compensated for the additional counterparty risk and pays a lower price.

On a market with flexible time-to-settlement, a higher default rate leads to faster settlement. Therefore, counterparty risk increases at a lower rate than in a market with fixed time-to-settlement. A new channel emerges: faster settlement corresponds to a lower probability of finding a seller, and therefore to decreased trade efficiency. The intermediary sets a higher price to compensate for the increase in her expected costs, as she is most likely to trade against her own inventory. This channel is absent in a fixed time-to-settlement market, as T does not respond to a change in default rate: Consequently, the likelihood of finding a seller is independent from the likelihood of settlement.

From Figure 4, the immediate-settlement price is always higher than, or equal to, the price if the time-to-settlement is $T^{\star}$. Since with immediate settlement the intermediary always trades against her own inventory, the counterparty risk is zero: Trades are always settled. The intermediary charges the full gains from trade, that is $v(\theta_i - 1)$. We interpret a lower price as higher market liquidity, as it implies a lower transaction cost for the buyer. It follows that, for low default rate (i.e., $\delta < \widetilde{\delta}$) immediate settlement leads to sub-optimal liquidity. A social planner would only completely eliminate counterparty risk for a high enough default rate.

4 Competitive equilibrium

We search for subgame-perfect Nash equilibria in pure and mixed strategies. In particular, an equilibrium consists of a pair of price and time-to-settlement contracts (p_1, T_1) and (p_2, T_2) offered by intermediaries, and a choice for each buyer i at $t = 0$ to trade either of the two contract or to not trade. We use backward induction to search for the equilibrium. Section 4.1 focuses on a market design with flexibile time-to-settlement. Intermediaries quote T_i at $t = -2$, and therefore times-to-settlement are endogenous to the trading process. Section 4.2 discusses the benchmark market design where time-to-settlement is set ex ante by the exchange, i.e., it is exogenous to the trading process.

4.1 Flexible time-to-settlement

In this Section, we focus on a market design where intermediaries decide on times-to-settlement at $t = -2$. Without loss of generality, one intermediary offers a longer time-to-settlement than her competitor.[6] Let intermediary L (for low quality) offer settlement period T_L. Intermediary H (for high quality) offers a shorter time-to-settlement $T_H < T_L$. Longer delay between the trade and settlement decreases the intermediary's survival probability, thus exposing buyers to greater counterparty risk. At the same time, it gives the intermediary more time to locate a seller, thus decreasing the expected payment upon settlement, that is the marginal cost of delivering the asset.

Definition 1. Survival probability differential (scaled by the common value) between the two intermediaries is defined as

$$\Delta s = s_H - s_L, \tag{8}$$

where $s_j \equiv (1 - \delta T_j)\, v$ for $j = L, H$.

Definition 2. Marginal cost differential between the two intermediaries is defined as

$$\Delta c = c_H - c_L, \tag{9}$$

where $c_j \equiv (1 - \delta T_j)\,(1 - \lambda T_j)\, v$ for $j = L, H$.

It is worth noting that there are two components to the marginal cost c_j: (i) the probability of payment and (ii) the probability that an intermediary finds a counterparty before the contracted settlement time T_j. An increase in T_j has therefore a *convex* (i.e., higher than linear) effect on marginal cost as both the likelihood of defaulting *and* the likelihood of finding a counterparty increase – that is, the two independent channels that drive changes in marginal cost. On the other hand, changes in T_j affect the survival probability s_j (i.e., the quality of the contract) at linear rate δ.

Figure 5 plots the survival probability and marginal cost as a function of time-to-settlement. The top panel illustrates the convexity of marginal cost for one intermediary. The bottom panel focuses on the bivariate case and plots survival probability and marginal cost *differentials* as a function of both intermediaries' time-to-settlement. Again, the salient feature is the non-linearity of changes in the marginal cost differential.

[insert Figure 5 here]

[6] We prove in Proposition 2 that, if time-to-settlement is flexible, intermediaries never set equal times-to-settlement.

We proceed to solve for equilibrium by backward induction. First, we deduce buyer's demands (given prices and times-to-settlement), then describe price choices (given time-to-settlement), and finally discuss the time-to-settlement choices of the intermediaries. We look for an equilibrium in which the market is covered, i.e. there is nonnegative demand for services of both intermediaries.

The buyer's choice at $t = 0$. As a first step, we characterize the demand faced by each intermediary by finding the marginal (indifferent) buyer $\mathbf{B}_m$ who is indifferent between trading with intermediary H or with intermediary L. That is,

$$U_{\mathbf{B}_m}(p_H, T_H) \;=\; U_{\mathbf{B}_m}(p_L, T_L). \tag{10}$$

From equation (1) and condition (10), the marginal buyer $\mathbf{B}_m$ must have valuation parameter $\theta_i = \bar{\theta}$ such that

$$\bar{\theta} \;=\; \frac{p_H - p_L}{\Delta s}. \tag{11}$$

As in Shaked and Sutton (1982), the indifferent buyer is determined by the ratio of price and "quality" differences. Buyers with $\theta_i \geq \bar{\theta}$ will trade with intermediary H. Buyers with $\theta_i < \bar{\theta}$ and $\theta_i > \max\{1, p_L/s_L\}$ will buy the asset from the intermediary L.[7]

We can therefore state the demands faced by the two intermediaries,

$$\begin{aligned} D_L(p_L, p_H) &= \frac{p_H - p_L}{\Delta s} - 1, \text{ and} \\ D_H(p_L, p_H) &= 2 - \frac{p_H - p_L}{\Delta s}. \end{aligned} \tag{12}$$

Buyers with a relatively high private valuation will be willing to pay a higher price for fast settlement and will buy the asset from intermediary H, while buyers with a relatively low private valuation will buy the asset from intermediary L, who offers a lower price. By lowering the price, an intermediary can attract more buyers.

[7]Here p_L/s_L is the valuation parameter of the buyer who is indifferent between buying the asset from the low quality intermediary or not buying it at all. Requiring that $\theta_i > 1 > p_L/s_L$ ensures that traders with the lowest valuation are interested in buying the asset and thus both intermediaries have non-negative demands. Assumption 1 guarantees that, in equilibrium, $1 > p_L/s_L$.

Price competition at $t = -1$. We now proceed to find the equilibrium in the price-setting subgame, taking time-to-settlement of the two intermediaries as given. In Nash equilibrium, intermediaries choose prices to maximize their profits (given the price set by the other intermediary), that is

$$p_j^\star = \arg\max_{p_j} \underbrace{(p_j - c_j)}_{\text{Mark-up}} \underbrace{D_j(p_j, p_{-j})}_{\text{Demand}}.$$

Lemma 1. *For a given time-to-settlement pair (T_L, T_H), the Nash equilibrium prices charged by the two intermediaries are*

$$p_L^\star = c_L + \frac{1}{3}\Delta c, \tag{13}$$
$$p_H^\star = c_H - \frac{1}{3}\Delta c + \Delta s > p_L^\star.$$

Lemma 1 characterizes Nash equilibrium prices in the Bertrand price competition subgame. The intermediary with the lowest time-to-settlement contract charges a higher price, but both intermediaries charge prices above their respective marginal cost. The equilibrium price gap

$$p_H^\star - p_L^\star = \Delta s + \frac{1}{3}\Delta c$$

increases in both survival probability and cost differentials (consistent with the vertical differentiation literature, e.g., Shaked and Sutton, 1982).

Time-to-settlement choice at $t = -2$. Next, we characterize the equilibrium in the time-to-settlement stage of the game, given the Bertrand competition solutions at the price-setting stage. Intermediaries choose time-to-settlement to maximize profits, given equilibrium-path prices at $t = -1$.

From equation (12) and Lemma 1, the equilibrium prices yield the following demand functions:

$$D_L = \frac{1}{3}\frac{\Delta c}{\Delta s}, \text{ and} \tag{14}$$

$$D_H = 1 - \frac{1}{3}\frac{\Delta c}{\Delta s}. \tag{15}$$

It follows that the profits of the two intermediaries are

$$\pi_L = \underbrace{\left(\frac{1}{3}\Delta c\right)}_{\text{Mark-up}} \times \underbrace{\left(\frac{1}{3}\frac{\Delta c}{\Delta s}\right)}_{\text{Market share}}, \tag{16}$$

$$\pi_H = \underbrace{\left(\Delta s - \frac{1}{3}\Delta c\right)}_{\text{Mark-up}} \times \underbrace{\left(1 - \frac{1}{3}\frac{\Delta c}{\Delta s}\right)}_{\text{Market share}}, \tag{17}$$

where both Δc and Δs depend on times-to-settlement T_L and T_H.

We observe that both mark-ups and relative market shares of the two intermediaries depend crucially on the cost-to-quality ratio $\Delta c / \Delta s$. Generally,

$$\frac{\Delta c}{\Delta s} = 1 + \frac{\lambda}{\delta} - \lambda \left(T_L + T_H\right), \tag{18}$$

decreases in both T_L and T_H (at linear rate λ). The result follows from the convexity of Δc (illustrated in Figure 5). In particular, Δc increases at a slower rate in T_L for high values of T_L, and decreases at a slower rate in T_H for low values of T_H.

To illustrate how equilibrium times-to-settlement are set, Figure 6 plots the best response function of each intermediary at $t = -2$ to the competitor's time-to-settlement.

[insert Figure 6 here]

The best-response functions are upward sloping: intermediary j optimally responds with a lower time-to-settlement if intermediary $-j$ also decides to settle trades faster. The positive slopes of the reaction functions follow from the properties of the cost-to-quality ratio $\Delta c / \Delta s$ given in equation (18). As T_L increases, $\Delta c / \Delta s$ decreases. All else equal, intermediary H is able to capture a higher market share. Consequently, H can afford to differentiate less aggressively and increases T_H to reduce her marginal cost. Similarly, an increase in T_H leads to a drop in $\Delta c / \Delta s$. All else equal, intermediary L captures a lower market share. Consequently, L needs to differentiate more aggressively from her competitor and increase T_L.

Proposition 2. (Equilibrium, flexible settlement) *The pure strategy sub-game perfect Nash equilibria of the trading game, if time-to-settlement is flexible, are as follows:*

(i) For $\delta \leq \bar{\delta} \equiv \frac{4}{5}\lambda$*, there are two pure-strategy symmetric equilibria of* delayed-settlement *type. The pair of equilibrium price and time-to-settlement contracts set by the two intermediaries are*

$$(p_L^\star, T_L^\star) = \left(v\left[\frac{1}{2} + \frac{17}{64}\frac{\delta}{\lambda} - \frac{1}{4}\frac{\lambda}{\delta}\right], \frac{1}{2\delta} + \frac{1}{8\lambda}\right), \tag{19}$$

$$(p_H^\star, T_H^\star) = \left(v\left[\frac{1}{2} + \frac{89}{64}\frac{\delta}{\lambda} - \frac{1}{4}\frac{\lambda}{\delta}\right], \frac{1}{2\delta} - \frac{5}{8\lambda}\right). \tag{20}$$

The marginal buyer has valuation parameter $\bar{\theta} = \frac{3}{2}$*. All buyers with valuation parameter* $\theta_i \leq \bar{\theta}$ *choose contract* (p_L, T_L) *and all buyers with valuation parameter* $\theta_i > \bar{\theta}$ *choose contract* (p_H, T_H)*. Intermediaries are indifferent between offering the low- or high-quality contract.*

Since intermediaries are indifferent between offering the high- or low-quality contract, there also exists a continuum of mixed-strategy equilibria: The first intermediary at the market chooses a contract at random, and the second intermediary at the market chooses the other contract.

(ii) For $\delta > \bar{\delta} \equiv \frac{4}{5}\lambda$*, the unique equilibrium is of* immediate-settlement *type. The pair of equilibrium price and time-to-settlement contracts set by the two intermediaries are*

$$(p_L^\star, T_L^\star) = \left(\frac{1}{27}v\left[19 - 4\frac{\delta}{\lambda} - 4\frac{\lambda}{\delta}\right], \frac{\delta+\lambda}{3\delta\lambda}\right), \tag{21}$$

$$(p_H^\star, T_H^\star) = \left(\frac{1}{27}v\left[32 + 7\frac{\delta}{\lambda} - 2\frac{\lambda}{\delta}\right], 0\right). \tag{22}$$

The marginal buyer has valuation parameter $\bar{\theta} = \frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta}$*. All buyers with valuation parameter* $\theta_i \leq \bar{\theta}$ *choose contract* (p_L, T_L) *and all buyers with valuation parameter* $\theta_i > \bar{\theta}$ *choose contract* (p_H, T_H)*. The first intermediary at the market chooses to offer the high-quality contract* (p_H, T_H)*.*

Proposition 2 characterizes the equilibrium of the two-stage game. First, we observe that $T_L = T_H$ is not an equilibrium outcome. If the two intermediaries offer the same time-to-settlement they would set prices at marginal cost in the next period. Therefore, both intermediaries earn zero profit. Differentiation in time-to-settlement allows both intermediaries to earn non-negative profits.

The type of the equilibrium depends on the level of the default rate δ. It is important to understand how intermediaries' best-responses functions change in δ. The cost-to-quality ratio $\Delta c/\Delta s$ decreases in default rate δ. This is because the quality difference adjusts faster than the marginal cost difference (as the latter is also driven by the search rate). For a given T_L, an increase in δ makes intermediary H better off: the quality difference improvement exceeds the change in marginal costs. As a result, she differentiates more aggressively and quotes a lower T_H. Conversely, for a given T_H, intermediary L is worse off if δ increases: She is less aggressive and quotes a lower T_L. Figure 6 illustrates how reaction functions (and, consequently, equilibrium times-to-settlement) shift if the default rate increases.

Figure 7 plots the competitive equilibrium times-to-settlement for the two intermediaries, as a function of the default rate.

[insert Figure 7 here]

For a low enough default rate ($\delta \leq \bar{\delta}$), both intermediaries offer delayed time-to-settlement, have equal market shares, and earn equal rents. We refer to this scenario as the *delayed-settlement* equilibrium. If the default rate exceeds the threshold, the high-quality intermediary H offers immediate settlement, whereas the low-quality intermediary L offers delayed settlement – an *immediate-settlement* equilibrium emerges. For any default rate that exceeds the threshold, intermediary H has a higher market share and earns a larger profit than intermediary L.

Corollary 2 and Figure 8 characterize equilibrium demands for the two intermediaries with flexible time-to-settlement.

Corollary 2. *The equilibrium demands for the two intermediaries are:*

(i) If $\delta \leq \bar{\delta} \equiv \frac{4}{5}\lambda$*, then* $D_L^\star = D_H^\star = \frac{1}{2}$.

(ii) If $\delta > \bar{\delta} \equiv \frac{4}{5}\lambda$*, then*

$$D_L^\star = \frac{2}{9} + \frac{2}{9}\frac{\lambda}{\delta} \text{ and } D_H^\star = \frac{7}{9} - \frac{2}{9}\frac{\lambda}{\delta}. \tag{23}$$

In the *delayed-settlement* equilibrium, both intermediaries have equal market shares, i.e., half of buyers choose each contract. As the default rate δ increases, the scope for specialization widens, and both intermediaries charge higher mark-ups. The high-quality intermediary H does not offer immediate settlement: for low enough default rate, more buyers would prefer a low-quality, cheap trade to an expensive trade with immediate settlement. In the *immediate-settlement* equilibrium, however, the high-quality intermediary obtains superior market share, since intermediary L endogenously has a lower marginal cost advantage for high δ: She is forced to close the quality gap as the default rate increases. A salient feature of Figure 8 is that a larger fraction of buyers settle trades immediately in the competitive equilibrium than in the optimal scenario. Further, immediate settlement of trades occurs in equilibrium for a lower default rate (i.e., $\delta = \frac{4}{5}\lambda$) than the optimal case (i.e., $\delta = \lambda$). Competition between intermediaries leads to an over-proliferation of immediate settlement.

[insert Figure 8 here]

Figure 9 and Corollary 3 describe equilibrium profits for the two intermediaries with flexible time-to-settlement.

[insert Figure 9 here]

Corollary 3. *In the* delayed-settlement *equilibrium, profits earned by the intermediaries are*

$$\pi_L^\star = \pi_H^\star = \frac{3v\delta}{16\lambda} > 0. \tag{24}$$

In the immediate-settlement *equilibrium, profits earned by the intermediaries are*

$$\pi_L^\star = \frac{4v(\delta+\lambda)^3}{243\delta^2\lambda}, \tag{25}$$

$$\pi_H^\star = \frac{v(7\delta-2\lambda)^2(\delta+\lambda)}{243\delta^2\lambda} > \pi_L^\star. \tag{26}$$

A high default rate offers a "latent" advantage to the high-quality intermediary. If the default rate is below the threshold, then both intermediaries improve quality (i.e., reduce T) in lock-step. The quality and marginal cost differentials change at the same rate. Profits increase to the larger scope for differentiation, which allows intermediaries to quote a higher mark-up. If default rate exceeds the threshold $\bar{\delta}$, then intermediary H offers the maximum contract quality: she cannot reduce time-to-settlement following subsequent changes in counterparty risk. If the default rate δ increases further, intermediary L needs to improve quality to prevent losing market share. Consequently, the quality gap closes as δ increases beyond the threshold. However, the marginal cost advantage of intermediary L drops at a faster rate than the quality gap. Therefore, intermediary L cannot decrease time-to-settlement T_L without reducing her own mark-up. For a default rate above the threshold, the latent advantage is materialized: the high-quality intermediary profit increases in δ, whereas the low-quality intermediary's profits decreases in default rate δ.

An important implication of Corollary 3 is that, at least for $\delta < \bar{\delta}$, both intermediaries are better off for a higher default rate. Since higher counterparty risk implies higher potential for specialization, we postulate that flexible time-to-settlement would have a negative impact on risk-management incentives for intermediaries (i.e., if intermediaries control the level of δ).

4.2 Fixed time-to-settlement

In this Section, we focus on a market design where the exchange decides on time-to-settlement at $t = -2$.

With fixed time-to-settlement set by the exchange, intermediaries cannot differentiate counterparty risk levels. At $t = 0$, the buyer's choice between the two intermediaries is solely determined by price: that is, each buyer chooses the intermediary quoting the lowest price, irrespective of their private valuation. Consequently, Bertrand price competition emerges at $t = -1$ and intermediaries quote a price equal to their marginal cost. Therefore, intermediaries earn zero expected profit and buyers capture the full gains from trade.

At $t = -2$, the exchange chooses an unique time-to-settlement $T^{\star\star}$ that maximizes the expected trade surplus on all trades, that is

$$\mathbb{E}\text{TradeSurplus}\,(T) = \int_1^2 v(1-\delta T)\,[\theta_i - (1-\lambda T)]\,\mathrm{d}\theta_i \tag{27}$$

Equivalently, $T^{\star\star}$ maximizes trade surplus for the median-valuation buyer (i.e., $\theta_i = \frac{3}{2}$):

$$T^{\star\star} = \arg\max_T v(1 - \delta T)\left(\lambda T + \frac{1}{2}\right). \tag{28}$$

Proposition 3 formally characterizes the equilibrium with a fixed time-to-settlement.

Proposition 3. (Equilibrium, fixed settlement) *The unique sub-game perfect Nash equilibria of the trading game, if time-to-settlement is fixed by the exchange, is as follows:*

(i) At $t = -2$, the exchange sets the unique settlement time

$$T^{\star\star} = \frac{1}{2\delta} - \frac{1}{4\lambda} > 0. \tag{29}$$

(ii) The two intermediaries offer identical price and time-to-settlement contracts at $t = -1$, that yield zero expected profit for the intermediaries:

$$(p^{\star\star}, T^{\star\star}) = \left(\frac{1}{16}v\left[5\frac{\delta}{\lambda} - 4\frac{\lambda}{\delta} + 8\right], \frac{1}{2\delta} - \frac{1}{4\lambda}\right). \tag{30}$$

(iii) At $t = 0$, buyers are indifferent between the two intermediaries and choose a contract at random. Intermediaries have equal expected demands.

5 Welfare analysis

This section compares welfare under the two market designs in Sections 4.1 and 4.2, i.e., an OTC market with flexible and fixed time-to-settlement. Since sellers have zero utility in all equilibria, for each market design we measure welfare as the trade surplus between intermediary and buyer.

Optimal T benchmark. A natural welfare benchmark is the trade surplus under the optimal time-to-settlement $T_i^\star$ defined in Proposition 1, where time-to-settlement is a function of **B**'s private value θ_i. It follows that

$$\text{Welfare}_{\text{Optimal}} \equiv \mathbb{E}\text{TradeSurplus}\left(T_i^\star\right) = \int_1^2 v(1-\delta T_i^\star)\left[\theta_i - (1-\lambda T_i^\star)\right] \mathrm{d}\theta_i. \tag{31}$$

From Proposition 1, buyers with low private values (i.e., $\theta_i < 1 + \lambda/\delta$) are better off with delayed settlement $T_i^\star > 0$, whereas buyers with high private values (i.e., $\theta_i \geq 1 + \lambda/\delta$) are better off with immediate settlement:

$$\begin{aligned}\text{Welfare}_{\text{Optimal}} = &\underbrace{\int_1^{1+\frac{\lambda}{\delta}} v\left(1 - \frac{\lambda - \delta\left(\theta_i - 1\right)}{2\lambda}\right)\left[\theta_i - \left(1 - \frac{\lambda - \delta\left(\theta_i - 1\right)}{2\delta}\right)\right] \mathrm{d}\theta_i}_{\text{Delayed settlement}} \\ &+ \underbrace{\max\left\{\int_{1+\frac{\lambda}{\delta}}^2 v\left(\theta_i - 1\right)\mathrm{d}\theta_i, 0\right\}}_{\text{Immediate settlement}}.\end{aligned} \tag{32}$$

If $\lambda > \delta$, then all buyers choose delayed settlement, and the second integral term in equation (32) is equal to zero. Conversely, if $\lambda < \delta$, that is if the default rate is high enough, at least some betters are better off with delayed settlement. It follows that

$$\text{Welfare}_{\text{Optimal}} = \begin{cases} \frac{1}{12}\left(6 + \frac{\lambda^2}{\delta^2}\right), & \text{if } \frac{\lambda}{\delta} \leq 1; \\ \frac{1}{12}\left(3 + 3\frac{\lambda}{\delta} + \frac{\delta}{\lambda}\right), & \text{if } \frac{\lambda}{\delta} > 1. \end{cases} \tag{33}$$

Flexible time-to-settlement. Welfare under a market design with flexible time-to-settlement is determined by trade surplus unde the equilibrium contracts and buyers' choices described in Proposition 2, that is

$$\text{Welfare}_{\text{Flexible T}} = \underbrace{\int_1^{\bar{\theta}} v\left(1 - \delta T_L^\star\right)\left[\theta_i - \left(1 - \lambda T_L^\star\right)\right] \mathrm{d}\theta_i}_{\text{Trades between buyers and } \mathbf{I}_L} + \underbrace{\int_{\bar{\theta}}^2 v\left(1 - \delta T_H^\star\right)\left[\theta_i - \left(1 - \lambda T_H^\star\right)\right] \mathrm{d}\theta_i}_{\text{Trades between buyers and } \mathbf{I}_H}. \tag{34}$$

Buyers with low private values ($\theta_i \leq \bar{\theta}$) choose the low-price, high counterparty-risk contract (p_L, T_L), whereas buyers with high private values ($\theta_i > \bar{\theta}$) choose the high-price, low counterparty-risk contract (p_H, T_H). From equation (34) and Proposition 2, it follows that the welfare function depends on whether the *delayed-* or *immediate-settlement* equilibrium emerges.

$$\text{Welfare}_{\text{Flexible T}} = \begin{cases} \frac{1}{64}\left(\frac{\delta}{\lambda} + 16\frac{\lambda}{\delta} + 16\right), & \text{if } \delta \leq \frac{4}{5}\lambda \\ \frac{1}{486\delta^2\lambda}\left(20\lambda^3 + 24\delta\lambda^2 + 231\delta^2\lambda - 16\delta^3\right), & \text{if } \delta > \frac{4}{5}\lambda. \end{cases} \tag{35}$$

Fixed time-to-settlement. Welfare under a market design with fixed time-to-settlement is determined by trade surplus under the equilibrium contracts and buyers' choices described in Proposition 3. In particular, all buyers choose equivalent contracts: the time-to-settlement is set by the exchange and both intermediaries quote prices equal to their marginal costs. It follows that

$$\begin{aligned} \text{Welfare}_{\text{Fixed T}} &= \int_1^2 v\left(1 - \delta T^{\star\star}\right)\left[\theta_i - \left(1 - \lambda T^{\star\star}\right)\right] \mathrm{d}\theta_i \\ &= \frac{1}{16\delta\lambda}\left(\delta + 2\lambda\right)^2 \end{aligned} \tag{36}$$

Proposition 4. (Welfare) *Welfare under fixed time-to-settlement is higher than welfare under flexible time-to-settlement.*

Proposition 4 compares welfare under the two market designs. It follows that market quality, as measured by the trade surplus, improves if time-to-settlement is set by the exchange. If intermediaries have the option to choose time-to-settlement, they will engage in rent-seeking behaviour and offer contracts of varying quality. Intermediaries are better off in a market with flexible time-to-settlement, but buyers are at the same time worse off. Consequently, welfare is overall lower: Intermediaries capture a higher share of a smaller trade surplus.

[insert Figure 10 here]

Figure 10 illustrates this effect. It plots welfare under the two market design choices, and the benchmark welfare, as a function of default rate δ. Not surprisingly, all welfare functions decrease in default rate since the likelihood of a trade (and, therefore, of the trade surplus being realized) is lower. Neither flexible nor fixed time-to-settlement welfare is equivalent to the benchmark welfare. However, a fixed time-to-settlement market always welfare-dominates the flexible time-to-settlement market.

6 Conclusions

To the best of our knowledge, this paper provides the first insight into the consequences of changing the rules for trade settlement on financial markets. The current settlement process featuring several days of delay between the trade and settlement seems at odds with the fast-paced markets of today. Both market participants and financial regulators agree on this.

The use of a new and potent decentralized ledger technology, such as Blockchain, can allow for trades to be settled immediately. Even more importantly, the Blockchain technology can offer the flexibility for counterparties to fine-tune time-to-settlement on a trade-by-trade or asset-by-asset basis, thus not necessarily imposing immediate settlement for all trades. We build a theoretical model to understand and evaluate the benefits and costs of these different settlement options.

We emphasize three insights emerging from our results. First, the immediate settlement is not necessarily a panacea for market quality. For a subset of trades it is excessive: Immediate settlement over-emphasizes the counterparty risk at too large a cost in liquidity terms, thus leading to sub-optimal liquidity. Secondly, allowing for flexible time-to-settlement in quote-driven markets results in poor risk management incentives as traders' rents increase in default risk. Intermediaries use the endogenous time-to-settlement to relax price competition by offering different price-"quality" menus, where contract quality is proxied by the level of exposure to counterparty risk. Finally, the market design where exchanges decide on the time-to-settlement for all trades in a particular security is preferable to the market design where traders choose the length of the settlement cycle themselves. The exchange-set settlement cycle improves welfare by discouraging rent-seeking behaviour of intermediaries. In setting the settlement rules, exchanges should incorporate information on counterparty risk and search frictions, potentially deciding on the time-to-settlement in a dynamic way as a function of market conditions.

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A Notation summary

Model parameters and their interpretation.

Parameter	Definition
v	Common value of the asset.
δ	Default rate for intermediaries.
λ	Seller search rate for intermediaries.
θ_i	Private-to-common value ratio for buyer i.
T	Time-to-settlement for the buyer-intermediary trade.

B Proofs

Proposition 1

Proof. The optimal time-to-settlement maximizes the trade surplus between buyer $\mathbf{B}_i$ and intermediary $\mathbf{I}$. It follows that

$$T_i^{\star} = \arg\max_{T} v\left(1 - \delta T\right)\left[\theta_i - \left(1 - \lambda T\right)\right], \tag{B.1}$$

subject to the constraint that the time-to-settlement is non-negative, i.e., $T \geq 0$.

The first-order condition is:

$$\frac{\partial \text{TradeSurplus}_i}{\partial T} = 0 \Longrightarrow v\left[1 - \delta\left(\theta_i - 1 + 2\lambda T\right)\right] = 0. \tag{B.2}$$

We solve equation (B.2) for T and we obtain:

$$\widetilde{T}_i^{\star} = \frac{\lambda - \delta\left(\theta_i - 1\right)}{2\delta\lambda}. \tag{B.3}$$

If $\widetilde{T}_i^{\star} < 0$, then from equation (B.2) it follows that $\frac{\partial \text{TradeSurplus}_i}{\partial T} < 0$ for all $T > 0$ and therefore the trade surplus decreases in T for all positive times-to-settlement. It follows that the trade surplus is maximum for $T_i = 0$. Consequently, the optimal time to settlement is

$$T_i^{\star} = \max\left\{\widetilde{T}_i^{\star}, 0\right\}. \tag{B.4}$$

To prove that the optimal time-to-settlement is implemented by a Nash bargaining protocol, let η and $1 - \eta$ be the bargaining powers of the buyer and the intermediary, respectively. The buyer and the intermediary set the price $p^\star$ and time-to-settlement T to maximize the Nash product

$$p^\star = \arg\max_p \left[(1-\delta T)\,\theta_i v - p\right]^\eta \left[p - (1-\delta T)\,(1-\lambda T)\,v\right]^{1-\eta} \tag{B.5}$$

From the first order condition with respect to price, it follows that

$$p^\star = v\,(1-\delta T)\left[\theta\,(1-\eta) + \eta\,(1-\lambda T)\right]. \tag{B.6}$$

The buyer's utility at the equilibrium price $p^\star$ is a fraction η of the total trade surplus, i.e.,

$$U_{\mathbf{B}_i} = v\,(1-\delta T)\,\eta\,(\theta_i - (1-\lambda T)). \tag{B.7}$$

Similarly, the intermediary's utility at the equilibrium price $p^\star$ is a fraction $1-\eta$ of the total trade surplus, i.e.,

$$U_{\mathbf{I}} = v\,(1-\delta T)\,(1-\eta)\,(\theta_i - (1-\lambda T)). \tag{B.8}$$

The sum of buyer's and intermediary's utility, evaluated at the bargaining price, is equivalent to the total trading surplus. That is, the price is simply a transfer between the counterparties and does not impact the total gains from trade: The time-to-settlement that maximizes the trade surplus is the same as in equation (B.4). This concludes the proof. □

Corollary 1

Proof. The partial derivative of $T_i^\star$ with respect to λ is

$$\frac{\partial T_i^\star}{\partial \lambda} = \frac{\theta_i - 1}{2\lambda^2} > 0. \tag{B.9}$$

Since the partial derivative of $T_i^\star$ with respect to λ is positive, the optimal time-to-settlement $T_i^\star$ increases in the search rate λ.

The partial derivative of $T_i^\star$ with respect to δ is

$$\frac{\partial T_i^\star}{\partial \delta} = -\frac{1}{2\delta^2} < 0. \tag{B.10}$$

Since the partial derivative of $T_i^\star$ with respect to δ is negative, the optimal time-to-settlement $T_i^\star$ decreases in the default rate δ.

The partial derivative of $T_i^\star$ with respect to θ_i is

$$\frac{\partial T_i^\star}{\partial \theta_i} = -\frac{1}{2\theta_i} < 0. \tag{B.11}$$

Since the partial derivative of $T_i^\star$ with respect to θ_i is negative, the optimal time-to-settlement $T_i^\star$ decreases in the buyer's private value θ_i. □

Lemma 1

Proof. From equation (12), the two intermediaries choose prices to maximize

$$\pi_L = (p_L - c_L)\left(\frac{p_H - p_L}{s_H - s_L} - 1\right) \text{ and} \quad \text{(B.12)}$$
$$\pi_H = (p_H - c_H)\left(2 - \frac{p_H - p_L}{s_H - s_L}\right).$$

The system formed by the two first order conditions, that is, $\frac{\partial \pi_j}{\partial p_j} = 0$, $j \in \{L, H\}$ is given by

$$\frac{1}{\Delta s}\left(c_L + p_H - \Delta s - 2p_L\right) = 0 \text{ and} \quad \text{(B.13)}$$
$$\frac{1}{\Delta s}\left(c_H + p_L + 2\Delta s - 2p_H\right) = 0.$$

We solve system (B.13) for p_L and p_H and obtain

$$p_L^\star = c_L + \frac{1}{3}\Delta c, \quad \text{(B.14)}$$
$$p_H^\star = c_H - \frac{1}{3}\Delta c + \Delta s > p_L^\star,$$

which concludes the proof. □

Proposition 2

Proof. At $t = -2$, intermediaries choose times-to-settlement to maximize expected profits knowing that at $t = -1$ prices are set as in Lemma 1. From Lemma 1, equations (2) and (12), and the definitions of c_j and s_j, it follows that intermediary profits are

$$\pi_L = \frac{v(T_L - T_H)(\lambda - \delta(\lambda T_H + \lambda T_L - 1))^2}{9\delta} \text{ and} \quad \text{(B.15)}$$
$$\pi_H = \frac{v(T_L - T_H)(\lambda - \delta(\lambda T_H + \lambda T_L + 2))^2}{9\delta}.$$

The corresponding first-order conditions are:

$$\frac{\partial \pi_L}{\partial T_L} = \frac{v(\delta + \lambda + \delta\lambda T_H - 3\delta\lambda T_L)(\delta(\lambda T_H + \lambda T_L - 1) - \lambda)}{9\delta} = 0 \text{ and} \qquad \text{(B.16)}$$
$$\frac{\partial \pi_H}{\partial T_H} = \frac{v(\lambda - \delta(3\lambda T_H - \lambda T_L + 2))(\delta(\lambda T_H + \lambda T_L + 2) - \lambda)}{9\delta} = 0.$$

We solve system (B.16) and obtain that profits are maximized for

$$T_L^\star = \frac{1}{2\delta} + \frac{1}{8\lambda} \text{ and } T_H^\star = \frac{1}{2\delta} - \frac{5}{8\lambda}. \qquad \text{(B.17)}$$

We note that the first-order condition system (B.16) has two other solutions,

$$(T_L, T_H) = \left\{ \left(\frac{1}{2\delta} + \frac{5}{4\lambda}, \frac{1}{2\delta} - \frac{1}{4\lambda} \right), \left(\frac{1}{2\delta} - \frac{1}{4\lambda}, \frac{1}{2\delta} - \frac{7}{4\lambda} \right) \right\},$$

yielding zero demand for exactly one intermediary. These solutions are not an equilibrium, as they both correspond to a saddle point – namely the Hessian matrix of the profit functions,

$$H = \begin{pmatrix} \frac{2}{9} v\lambda(\delta(T_H\lambda + 3T_L\lambda - 2) - 2\lambda) & -\frac{2}{9}(T_H - T_L)v\delta\lambda^2 \\ -\frac{2}{9}(T_H - T_L)v\delta\lambda^2 & -\frac{2}{9}v\lambda(\delta(3T_H\lambda + T_L\lambda + 4) - 2\lambda) \end{pmatrix},$$

is indefinite. Profits are jointly maximized (that is, H is negative definite) only for the solution in equation (B.17).

It immediately follows from equation (B.17) that $T_L^\star > 0$. Further, if $\delta \leq \frac{4}{5}\lambda$, also $T_H^\star > 0$. Therefore, $T_L^\star$ and $T_H^\star$ as defined in equation (B.17) are the unique equilibrium settlement times. Assumption 1 guarantees that all probabilities are well defined at the equilibrium times. From equation (B.15), both intermediary profits are strictly positive if and only if $T_L > T_H$. Therefore, since times-to-settlement are common knowledge and are set sequentially at $t = -2$, intermediaries never set $T_L = T_H$ in equilibrium.

From Lemma 1 and equation (B.17), the equilibrium prices for $\delta \leq \frac{4}{5}\lambda$ are:

$$p_L^\star = v\left[\frac{1}{2} + \frac{17}{64}\frac{\delta}{\lambda} - \frac{1}{4}\frac{\lambda}{\delta}\right] \text{ and } p_H^\star = v\left[\frac{1}{2} + \frac{89}{64}\frac{\delta}{\lambda} - \frac{1}{4}\frac{\lambda}{\delta}\right]. \qquad \text{(B.18)}$$

Finally, since the marginal buyer has valuation $\bar{\theta} = \frac{p_H - p_L}{\delta(T_L - T_H)}$, from equations (B.17) and (B.18) it follows that for $\delta \leq \frac{4}{5}\lambda$, $\bar{\theta} = \frac{3}{2}$. Buyers with private valuation parameters $\theta_i \in \left[1, \frac{3}{2}\right]$ choose contract $(p_L^\star, T_L^\star)$, whereas buyers with private valuation parameters $\theta_i \in \left(\frac{3}{2}, 2\right]$ choose contract $(p_H^\star, T_H^\star)$.

From Corollary 3, for $\delta \leq \frac{4}{5}\lambda$ intermediaries earn equal profits. Therefore, the first **I** at the market is indifferent between $T_L^\star$ and $T_H^\star$. Two equilibrium in pure strategies emerge, corresponding to the cases where the first intermediary chooses the low- or the high-quality contract. Further, there is a continuum of mixed-strategy equilibria indexed by ϕ where the first intermediary at the market chooses the high-quality contract with probability $\phi \in (0, 1)$. Times-to-settlement, prices, and profits are the same in all such equilibria.

For $\delta > \frac{4}{5}\lambda$, system (B.16) has one negative solution, i.e., $T_H^\star < 0$. Since times-to-settlement cannot be negative, the high-quality intermediary has to set $T_H^\star = 0$, that is immediate settlement. The low-quality intermediary maximizes her profit under this constraint. We find that, for $\delta > \frac{4}{5}\lambda$,

$$T_L^\star = \frac{\delta + \lambda}{3\delta\lambda} \text{ and } T_H^\star = 0. \tag{B.19}$$

Assumption 1 guarantees that all probabilities are well defined at the equilibrium times.

From Lemma 1 and equation (B.19), the equilibrium prices for $\delta > \frac{4}{5}\lambda$ are:

$$p_L^\star = \frac{1}{27} v \left[19 - 4\frac{\delta}{\lambda} - 4\frac{\lambda}{\delta}\right] \text{ and } p_H^\star = \frac{1}{27} v \left[32 + 7\frac{\delta}{\lambda} - 2\frac{\lambda}{\delta}\right]. \tag{B.20}$$

Again, since the marginal buyer has valuation $\bar{\theta} = \frac{p_H - p_L}{\delta(T_L - T_H)}$, from equations (B.19) and (B.20) it follows that for $\delta > \frac{4}{5}\lambda$, $\bar{\theta} = \frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta} < \frac{3}{2}$. Buyers with private valuation parameters $\theta_i \in \left[1, \frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta}\right]$ choose contract $(p_L^\star, T_L^\star)$, whereas buyers with private valuation parameters $\theta_i \in \left(\frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta}, 2\right]$ choose contract $(p_H^\star, T_H^\star)$.

From Corollary 3, for $\delta > \frac{4}{5}\lambda$ intermediary H earns higher profit than intermediary L. Therefore, the first **I** at the market chooses $T_H^\star$. □

Corollary 2

Proof. If $\delta \leq \bar{\delta} \equiv \frac{4}{5}\lambda$, from equations (12) and Proposition 2, it follows that equilibrium demands are

$$\begin{aligned} D_L(p_L^\star, p_H^\star) &= \bar{\theta} - 1 = \frac{3}{2} - 1 = \frac{1}{2}, \text{ and} \\ D_H(p_L^\star, p_H^\star) &= 2 - \bar{\theta} = 2 - \frac{3}{2} = \frac{1}{2}. \end{aligned} \tag{B.21}$$

If $\delta > \bar{\delta} \equiv \frac{4}{5}\lambda$, from equations (12) and Proposition 2, it follows that equilibrium demands are

$$\begin{aligned} D_L(p_L^\star, p_H^\star) &= \bar{\theta} - 1 = \frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta} - 1 = \frac{2}{9} + \frac{2}{9}\frac{\lambda}{\delta}, \text{ and} \\ D_H(p_L^\star, p_H^\star) &= 2 - \left(\frac{11}{9} + \frac{2}{9}\frac{\lambda}{\delta}\right) = \frac{7}{9} - \frac{2}{9}\frac{\lambda}{\delta}. \end{aligned} \tag{B.22}$$

Under Assumption 1, all equilibrium demands are positive. This concludes the proof. □

Corollary 3

Proof. The profit values follow immediately from plugging in equilibrium times-to-settlement from equations (B.17) and (B.19), respectively, in equation system (B.15).

Finally, we need to show that for $\delta > \frac{4}{5}\lambda$,

$$\pi_H^\star > \pi_L^\star \Longleftrightarrow \frac{v(7\delta - 2\lambda)^2(\delta + \lambda)}{243\delta^2\lambda} > \frac{4v(\delta + \lambda)^3}{243\delta^2\lambda}. \tag{B.23}$$

Equation (B.23) is equivalent to showing

$$(7\delta - 2\lambda)^2 - 4(\delta + \lambda)^2 > 0 \Longleftrightarrow 9\delta(5\delta - 4\lambda) > 0, \tag{B.24}$$

which is true for $\delta > \frac{4}{5}\lambda$. This concludes the proof. □

Proposition 3

Proof. If time-to-settlement is fixed ($T^{\star\star}$), then at $t = 0$, buyers choose the contract with the lowest price. Consequently, at $t = -1$, intermediaries compete à la Bertrand in prices and set prices equal to their marginal cost:

$$p_1 = p_2 = (1 - \delta T^{\star\star})(1 - \lambda T^{\star\star}). \tag{B.25}$$

Since both intermediaries have equal marginal costs, buyers are indifferent between the two contracts. Further, since both intermediaries quote a zero mark-up, neither intermediary earn a positive profit in expectation.

The time-to-settlement $T^{\star\star}$ is uniquely set by the exchange at $t = -2$ to maximize expected trade surplus on all trades, that is

$$T^{\star\star} = \arg\max_T \int_1^2 v(1 - \delta T)\left[\theta_i - (1 - \lambda T)\right] \mathrm{d}\theta_i. \tag{B.26}$$

Equivalently, after computing the integral, $T^{\star\star}$ maximizes trade surplus for the trader with the median valuation, $\theta_i = \frac{3}{2}$:

$$T^{\star\star} = \arg\max_T v(1 - \delta T)\left(\lambda T + \frac{1}{2}\right). \tag{B.27}$$

It follows immediately that $T^{\star\star} = \frac{1}{2\delta} - \frac{1}{4\lambda}$. Since, from Assumption 1, $\delta \leq 2\lambda$, it further follows that $T^{\star\star} \geq 0$. Equilibrium price is, from equations (B.25) and (B.27),

$$p^{\star\star} = \frac{1}{16} v \left(5\frac{\delta}{\lambda} - 4\frac{\lambda}{\delta} + 8 \right), \tag{B.28}$$

which completes the proof. □

Proposition 4

Proof. From equation (35) and (36), it follows that for $\delta \leq \frac{4}{5}\lambda$,

$$\text{Welfare}_{\text{Fixed T}} - \text{Welfare}_{\text{Flexible T}} = \frac{3\delta}{64\lambda} > 0. \tag{B.29}$$

For $\delta > \frac{4}{5}\lambda$, it follows that

$$\text{Welfare}_{\text{Fixed T}} - \text{Welfare}_{\text{Flexible T}} = \frac{371\delta^3 - 876\delta^2\lambda + 780\delta\lambda^2 - 160\lambda^3}{3888\delta^2\lambda}. \tag{B.30}$$

The denominator of equation (B.30) is larger than zero. It remains to show that for $\delta > \frac{4}{5}\lambda$,

$$f(\delta, \lambda) \equiv 371\delta^3 - 876\delta^2\lambda + 780\delta\lambda^2 - 160\lambda^3 > 0. \tag{B.31}$$

Let $x = \frac{\delta}{\lambda}$. It follows that

$$f(\delta, \lambda) = \lambda^3 \left(371x^3 - 876x^2 + 780x - 160 \right) > 0. \tag{B.32}$$

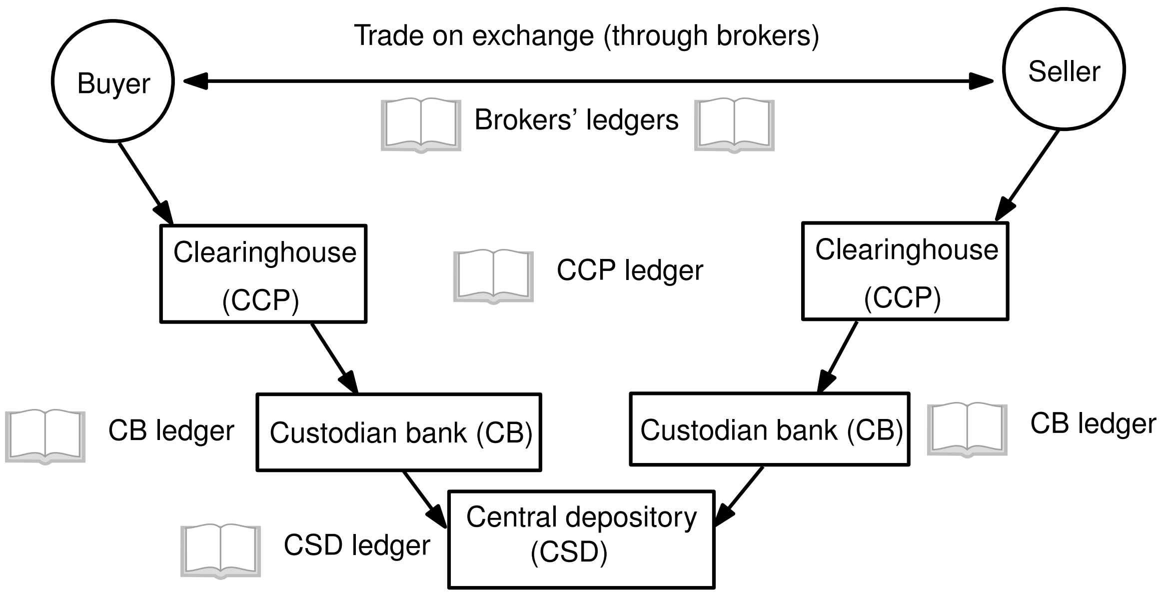
The third-degree polynomial in x from equation (B.32) has two imaginary solutions, $x_{2,3} = \dfrac{1}{53}\left(55 \pm 9i\sqrt{15}\right)$ and one real solution, that is $x_1 = \dfrac{2}{7}$. It follows that $f(\delta, \lambda) > 0$ for $x > \dfrac{2}{7}$. This is true since

$$x = \frac{\delta}{\lambda} > \frac{4}{5} > \frac{2}{7},$$

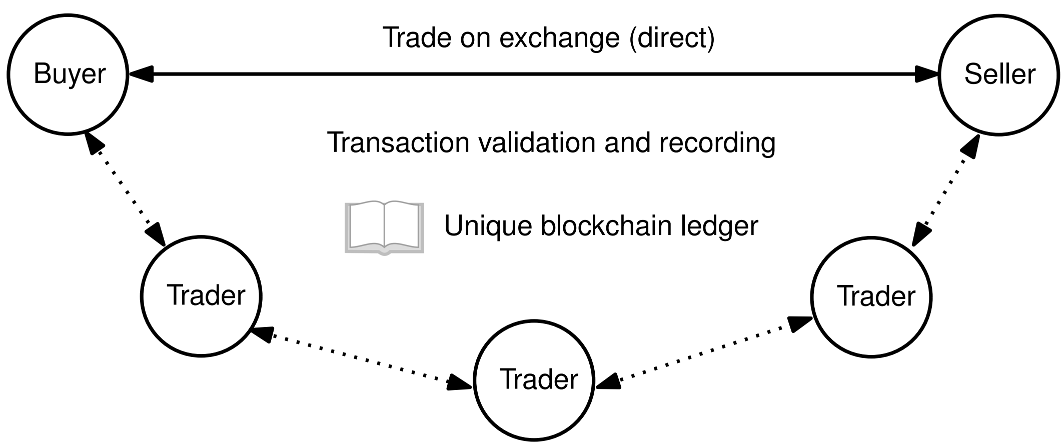
which concludes the proof. □

Figure 1: **Structure of the settlement chain**

This figure illustrates the settlement chain for both the existing market infrastructure and a Blockchain-driven market infrastructure, starting from a single trade. It highlights the intermediaries on the settlement chain as well as each individual recording of the transaction in a private or public ledger. Sources: Accenture (2015) and Collomb and Sok (2016).



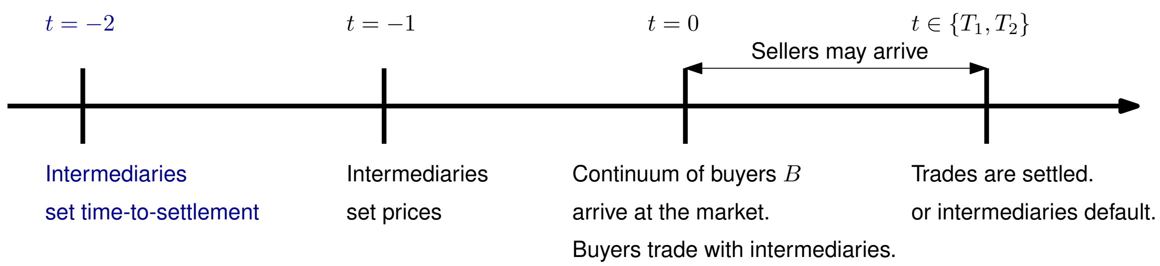
(a) Traditional settlement chain



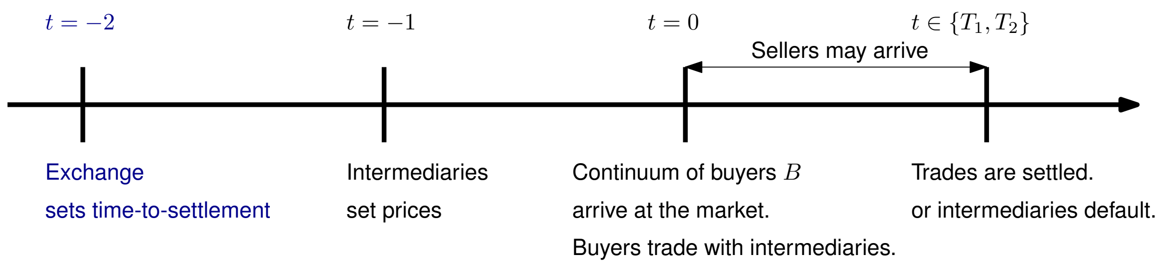
(b) Blockchain settlement chain

Figure 2: **Model timing**

This figure illustrates the model timing. Panels (a) and (b) are identical except for the decision at $t = -2$. In Panel (a), time-to-settlement is set by intermediaries and can vary across trades. In contrast, in Panel (b), time-to-settlement is set by the exchange and does not vary across trades.



(a) Intermediaries set time-to-settlement



(b) Exchange sets time-to-settlement

Figure 3: **Trading surplus**

This figure illustrates the trading surplus for a given transaction under blockchain settlement as a function of time-to-settlement. The private value of the buyer (θ) is fixed. The solid blue line corresponds to a low default rate δ, for which delayed settlement is optimal. The dashed green line corresponds to a high default rate δ, for which immediate settlement is optimal. Parameter values: $v = 2.5$, $\theta = 2$, $\lambda = 0.12$, and the default rates are $\delta = 0.08$ (solid blue line), $\delta = 0.12$ (dashed green line).

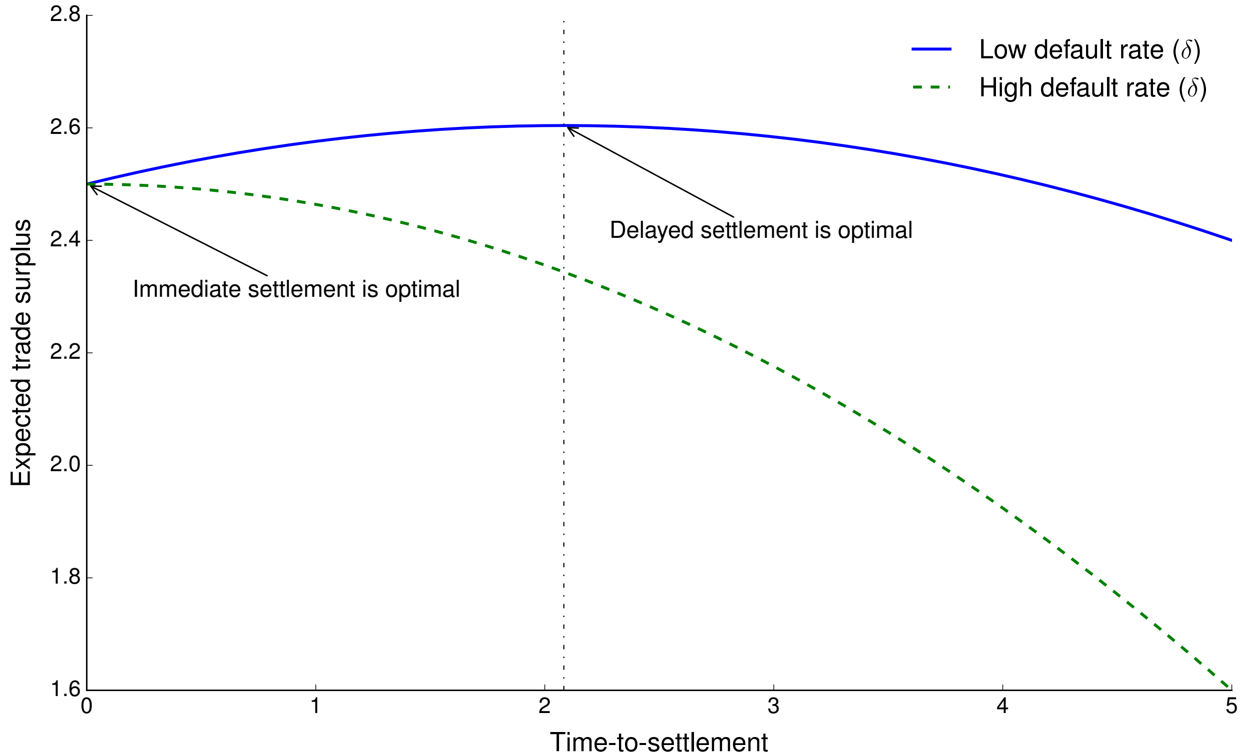
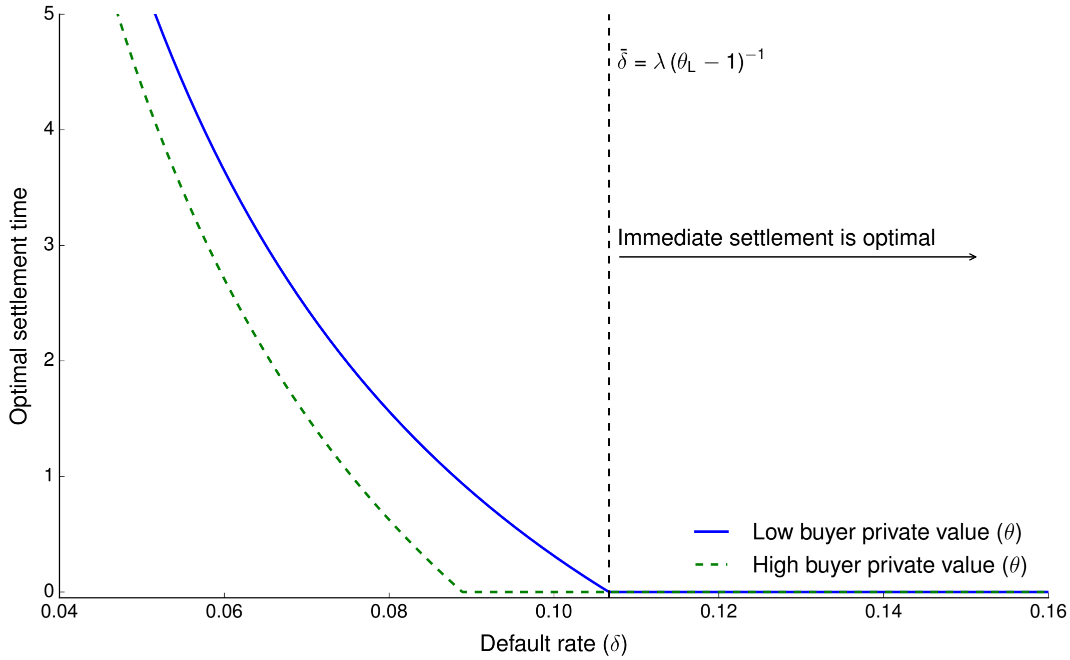
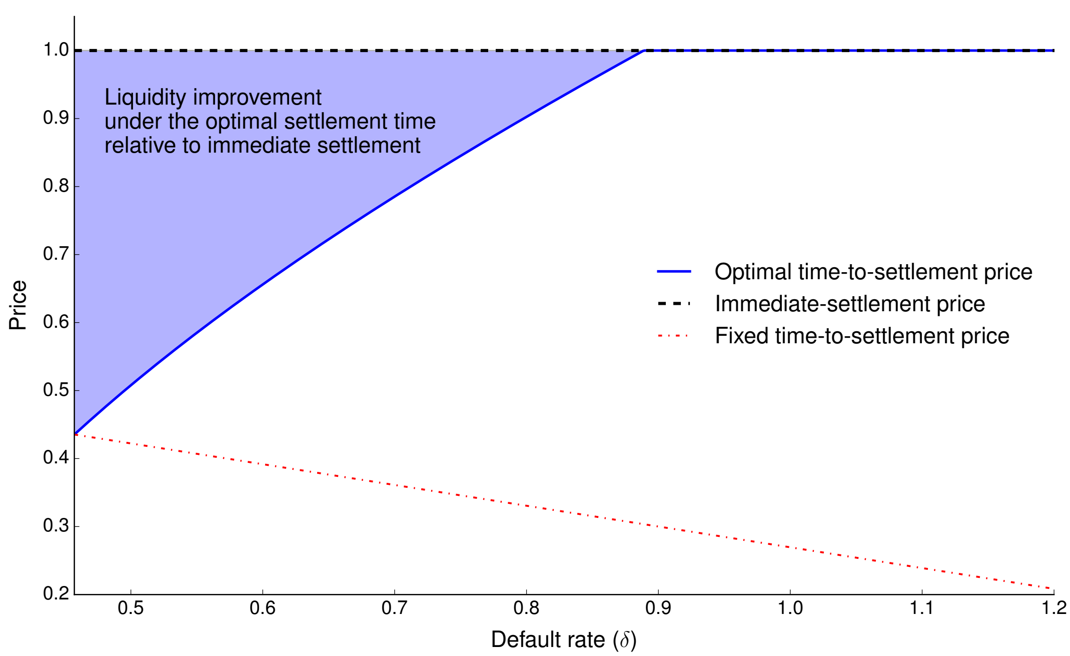


Figure 4: **Optimal time-to-settlement and corresponding price**

This figure illustrates the optimal time-to-settlement (top panel) and the trade price corresponding to optimal T (bottom panel) and as a function of the default rate δ. The private value of the buyer (θ) is deterministic. In the bottom panel, the price corresponding to the optimal T is benchmarked against the immediate-settlement price and a fixed time-to-settlement price. Parameter values: $v = 1$, $\theta = 1$ (Panel (b)), $\lambda = 0.8$, and $\delta = 0.03$. In Panel (a), $\theta_H = 1.9$ and $\theta_L = 1.75$.



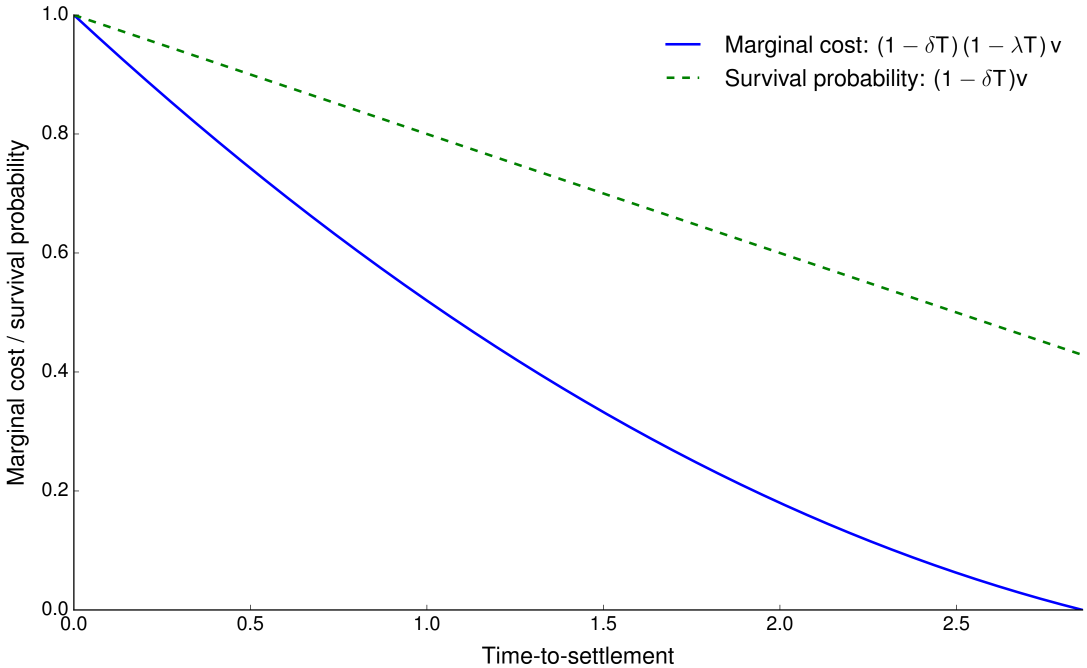
(a) Optimal time-to-settlement



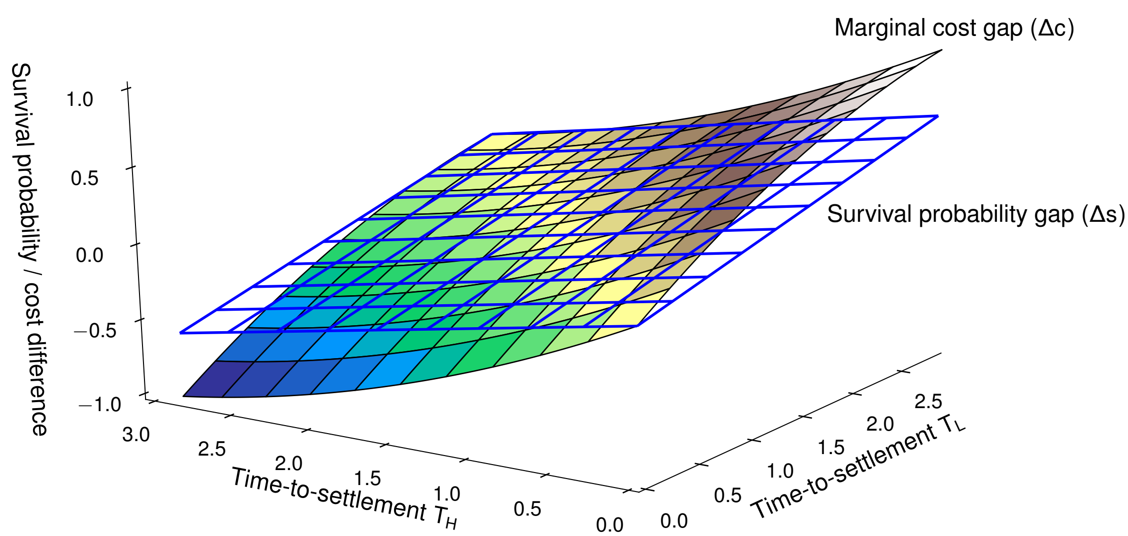
(b) Trade price corresponding to $T_i^\star$

Figure 5: **Survival probability and marginal cost**

This figure plots survival probability (i.e., $(1-\delta T)\,v$) and marginal cost – that is the expected payment $(1-\delta T)\,(1-\lambda T)\,v$ – as a function of settlement time. The top panel illustrates the univariate approach for a single intermediary. The bottom panel plots the survival probability and marginal cost *gaps* across intermediaries as a function of both quoted times to settlement. Parameter values: $v=1$, $\lambda=0.35$, and $\delta=0.2$.

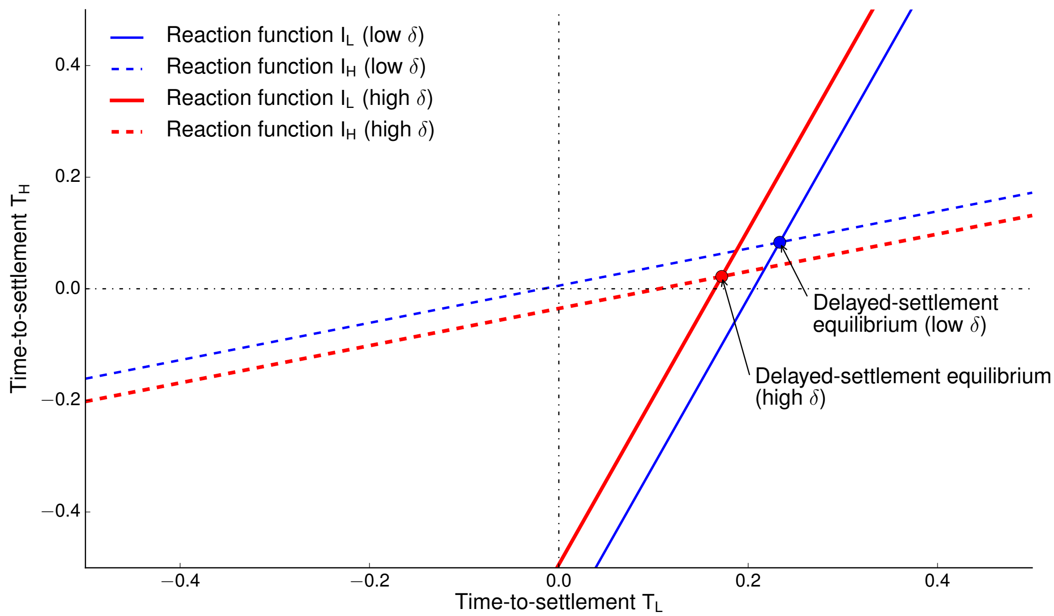


(a) Univariate case: One intermediary

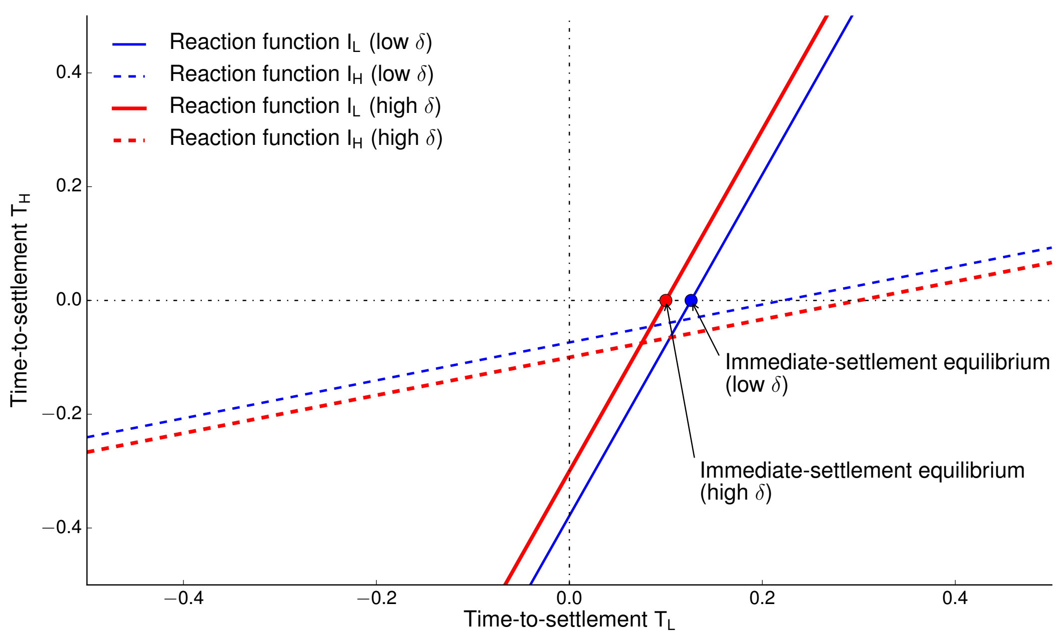


(b) Bivariate case: Two intermediaries

Figure 6: **Reaction functions and intermediary specialization**
The figure illustrates the best response of each intermediary at $t = -2$ to the competitor's time-to-settlement. The equilibrium times-to-settlement emerge at the interesection of the two reaction functions. The top panel illustrates the *delayed-settlement* equilibrium, whereas the bottom panel illustrates the *immediate-settlement* equilibrium. Reaction functions are plotted for both a low default rate δ (blue, thin lines) and a high default rate (red, thick lines) to illustrate how equilibrium times-to-settlement depend on the default rate. Parameter values: $v = 1$, $\lambda = 5$. In Panel (a), $\delta_L = 2.4$ and $\delta_H = 3.4$. In Panel (b), $\delta_L = 5.6$ and $\delta_H = 10$.



(a) Delayed-settlement equilibrium



(b) Immediate-settlement equilibrium

Figure 7: **Times-to-settlement in the competitive equilibrium**
This figure illustrates the competitive equilibrium times-to-settlement for the two intermediaries, as a function of the default rate δ. Parameter values: $v = 1$, $\lambda = 5$.

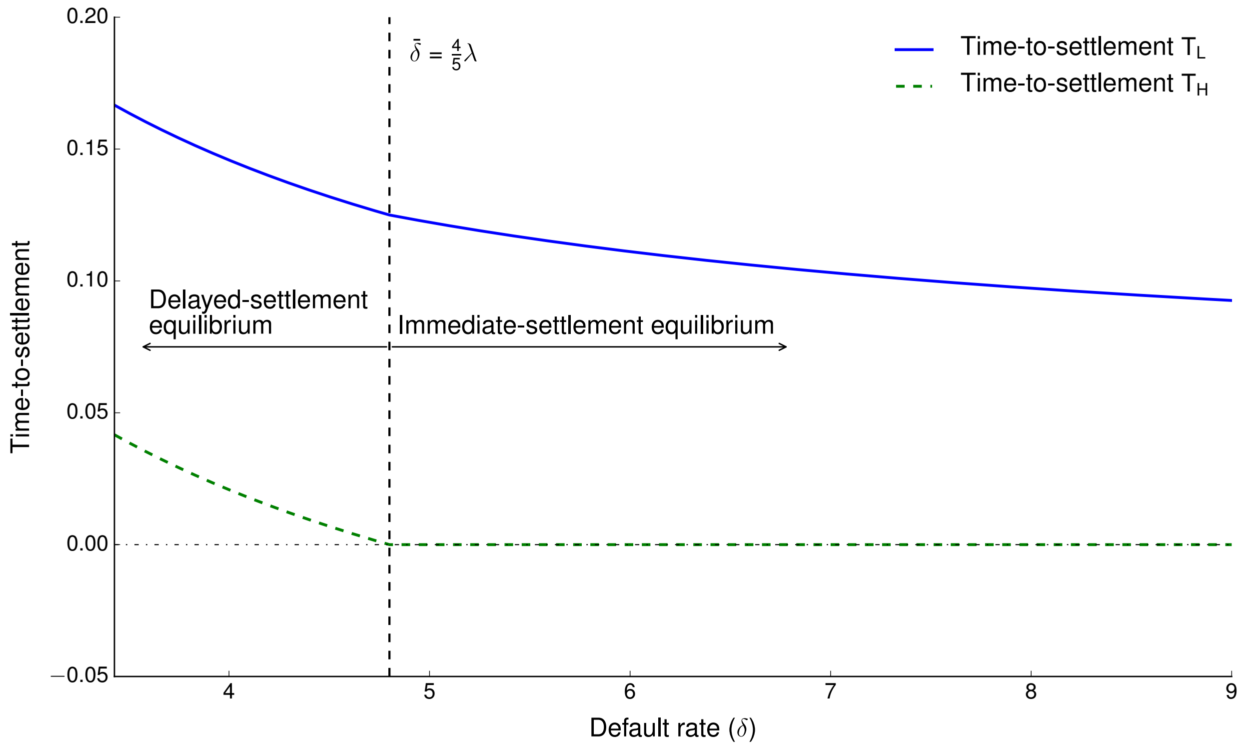
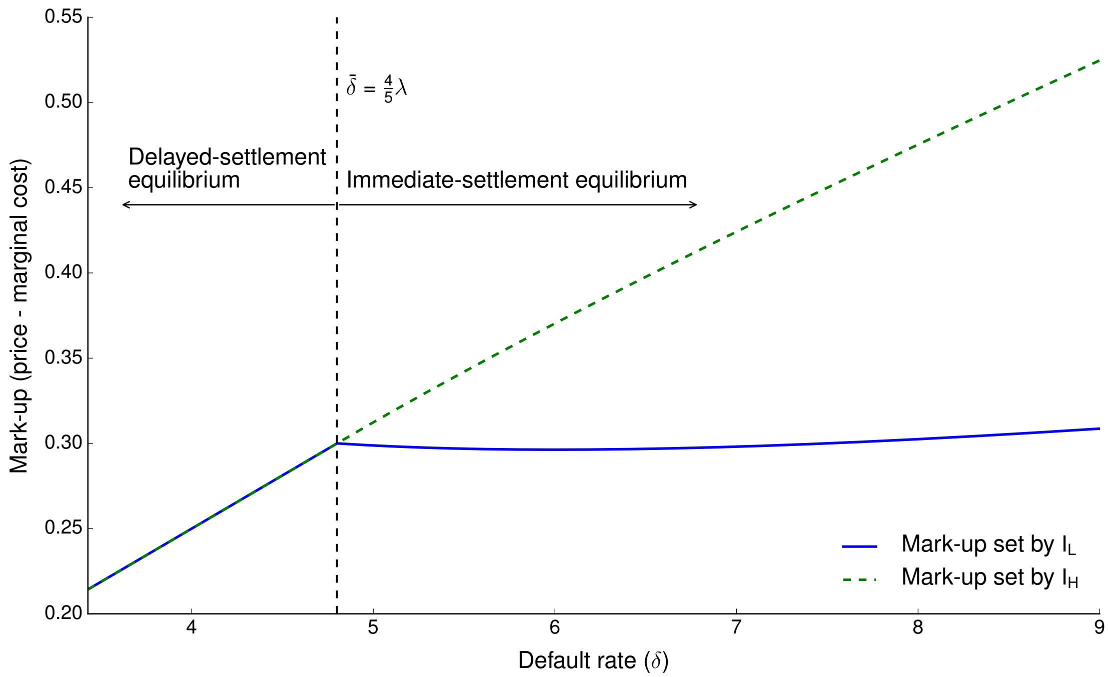
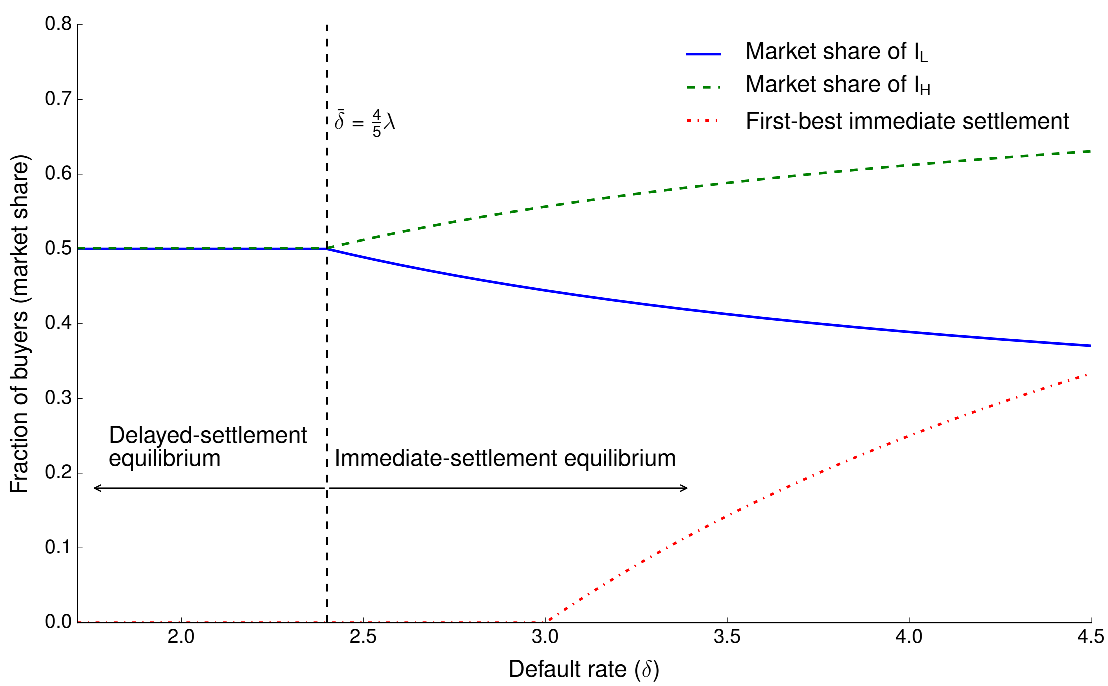


Figure 8: **Mark-ups and market shares in the competitive equilibrium**
This figure illustrates, for each intermediary, the equilibrium mark-up (i.e., the price requested minus the marginal cost, or expected payment on settlement) and the equilibrium market share (i.e., the fraction of buyers served) as a function of the default rate δ. Parameter values: $v = 1$, $\lambda = 5$.



(a) Mark-up



(b) Market share

Figure 9: **Intermediary profits in the competitive equilibrium**
This figure illustrates, for each intermediary, the equilibrium expected profits in the competitive equilibrium as a function of the default rate δ. The profits are equal for $\delta < \bar{\delta}$ (the delayed-settlement equilibrium) and increase in the default rate δ. The high-quality intermediary I_H earns higher profits for $\delta > \bar{\delta}$, that is in the immediate-settlement equilibrium. Parameter values: $v = 1$, $\lambda = 5$.

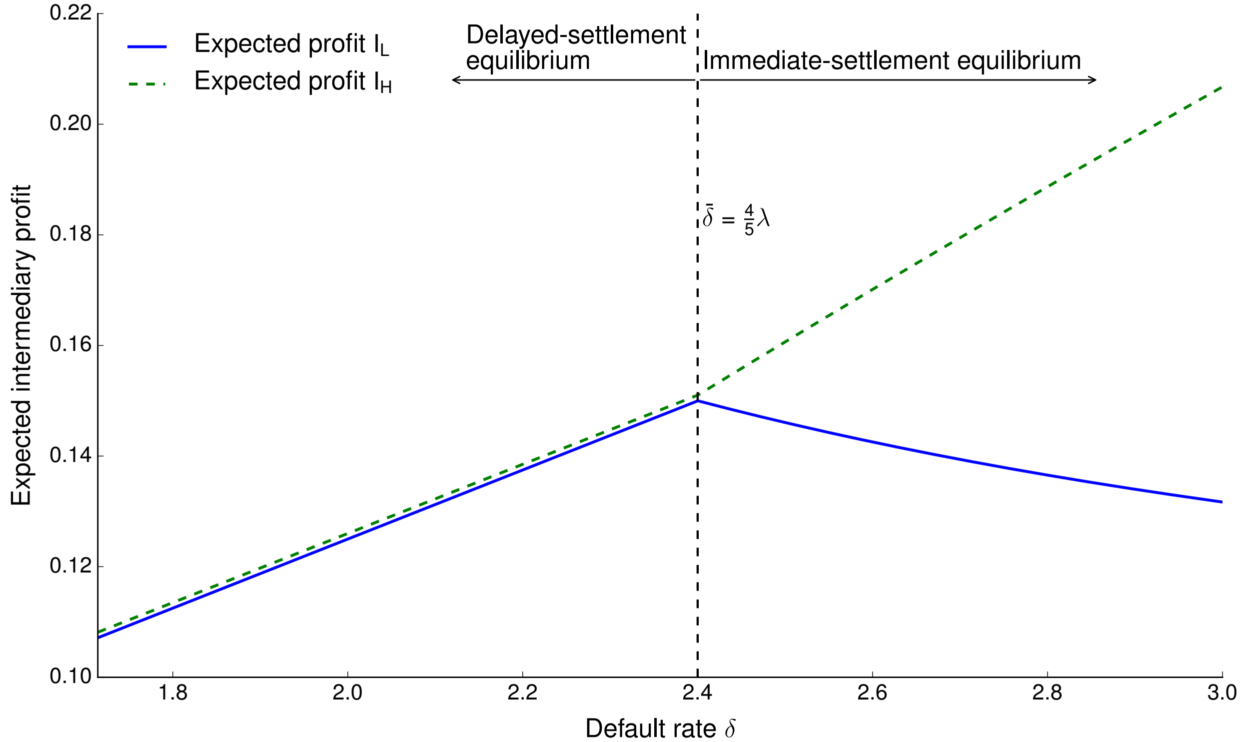


Figure 10: **Welfare analysis.**
This figure plots expected welfare as a function of the default rate δ. Welfare decreases in default rate, as counterparty risk is larger. The red dotted line illustrates the benchmark welfare with optimal time-to-settlment. The green dashed line corresponds to welfare in the case the settlement-time is set by the exchange at $t = -2$, unique for all trades. The solid blue line corresponds to welfare in the market design with flexible time-to-settlement. Parameter values: $v = 1$, $\lambda = 5$.