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Raising rival's costs in the securities settlement industry ☆

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Abstract

The competition between a central securities depository (CSD) and a custodian bank is analyzed in a Stackelberg model. Investor banks decide whether to use the services of the CSD or of the custodian bank, depending on the prices and their preferences for their inhomogeneous services. Since the custodian bank uses services provided by the CSD as input, the CSD can raise its rival's costs. The CSD's equilibrium market share is higher than socially optimal, unless the CSD is not allowed to charge negative prices. This result has important policy implications that are related to a discussion currently taking place in the securities settlement industry.

JEL classification: G10; G20; L14

Keywords: Securities settlement; Network competition; Raising rival's cost

1. Introduction

Every financial market transaction in which securities are traded involves settlement, i.e. the transfer of the securities from the seller to the buyer, and the related payment from the buyer to the seller. Before settlement can take place, each trading party needs to choose a settlement service provider that carries out asset transfers on behalf of the respective party. The different settlement service providers compete with each other for customers. In this paper, we model

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the competition between two potentially very different settlement service providers, a central securities depository (CSD) and a custodian bank.

Today, a physical transfer of securities certificates or cash between the seller and the buyer hardly takes place anymore. Instead, assets are transferred electronically by account entries. To facilitate the electronic transfer of securities, most industrialized countries have established a CSD. CSDs are central store houses for securities. If an issuer wants to issue securities in a given country, he usually deposits the entire issue with the national CSD.[1] An investor who owns securities deposited in the CSD must hold them either on a securities account directly with the CSD; or on a securities account with an intermediary that has a securities account with the CSD.[2] For each securities issue, the amount of securities deposited in the CSD must, by construction, equal the amount of securities in accounts with the CSD. Furthermore, the amount of securities that some entity A holds in accounts with other entities (intermediaries or the CSD) must equal the amount of securities owned by A plus the amount of securities in securities accounts of other entities with A.

This "double booking principle" determines the booking procedure required for the transfer of securities from the seller to the buyer, i.e. the securities settlement process. If for example the seller and the buyer have securities accounts with the same entity (the CSD or an intermediary), then the transfer is settled simply by debiting the seller's and crediting the buyer's account (internal settlement). Figure 1 may help to illustrate this process. In the figure, an arrow from one institution to another indicates that the former has a securities account with the latter. Investor Bank 2 and Investor Bank 3 both have a securities account with Custodian Bank, an intermediary. A transfer of securities from Investor Bank 2 to Investor Bank 3 simply requires that Investor Bank 2's account is debited and Investor Bank 3's account is credited.

If now the seller has an account with the CSD and the buyer has an account with an intermediary that has an account with the CSD, then the seller's account with the CSD has to be debited and the intermediary's account with the CSD and the buyer's account with the intermediary have to be credited. I.e. in this case, three securities accounts are involved. If, in Fig. 1, Investor Bank 1 sells to Investor Bank 2, then Investor Bank 1's account with the CSD is debited, Custodian Bank's account with the CSD is credited and Investor Bank 2's account with Custodian Bank is credited.

An entity that holds securities in accounts with other entities mainly on behalf of (small or institutional) investors or on its own behalf is called an *investor bank* throughout this paper. Institutions that hold securities in accounts with other institutions mainly on behalf of investor banks are called *custodian banks*. I.e. custodian banks act as intermediaries between investor banks and CSDs.

In the past ten to fifteen years, custodian banking has become increasingly important.[3] Technological progress in information technology and an increasing globalization contributed to a rapidly growing complexity of financial markets. Many CSDs for example abolished communication by fax and started to require participants to use computer-based communication technology. Many especially smaller investor banks decided not to invest into expensive technologies and responded to these developments by outsourcing activities to other banks. Some big banks became custodian banks specialized in the securities custody and settlement business.

[1] Today, the securities are usually deposited electronically in the CSD, not in form of physical paper certificates.

[2] Or on a securities account with an intermediary that has a securities account with another intermediary that has a securities account with the CSD, etc.

[3] See for example ECSDA (2002, p. 15ff).

Investor banks now have the choice either to have securities accounts directly with the CSD or with a custodian bank. I.e. the CSD and the custodian bank compete with each other for investor banks.

The competition between the CSD and the custodian banks has been somewhat limited in many cases as custodian banks offer services beyond what the CSD can offer. For example, custodian banks grant cash credit to investor banks while CSDs are typically prohibited from granting credit. Thus, custodian banks and CSDs do not offer homogeneous services. In particular foreign investor banks often find it difficult to use the national CSD directly and use a custodian bank instead while domestic investor banks may have stronger preferences for using the national CSD.[4]

In some European countries however, the national CSD merged with one of the two so-called ICSDs (international central securities depository). These ICSDs, Clearstream Banking Luxembourg (CBL) and Euroclear Bank of Belgium, are settlement service providers with a range of services at offer that is similar to those of custodian banks. In 2002, CBL merged with Clearstream Banking Frankfurt (CBF), the German CSD. In 2001 and 2002, Euroclear Bank bought the French CSD Sicovam (now Euroclear France), the Dutch CSD Necigef (now Euroclear Netherlands) and the UK CSD CrestCo. Due to these mergers, the respective CSD (through an ICSD) can now offer services to investor banks that are similar to those offered by the custodian banks. The competition between the national CSD and the custodian banks in Germany, France, the Netherlands and the UK, in particular for foreign investors, has been getting stronger accordingly and the custodian banks might have lost ground.

The mergers of CSDs with ICSDs have triggered a debate in Europe of the economic consequences of such mergers. Naturally, custodian banks argue that CSDs and ICSDs should not have merged. In their argumentation, they refer to a special feature of the competition between CSDs and custodian banks: in order to settle securities stored in a CSD, custodian banks use services provided by the CSD as input, but not vice versa. If both the seller and the buyer in a securities transaction have an account with the custodian bank, the custodian bank can settle the transaction internally as described above without routing it to the CSD. However, if an investor bank that has a securities account with a custodian bank trades with another investor bank that has an account with the CSD (or with another custodian bank), then internalizations of settlement within the custodian bank is not possible. The transaction is settled through the custodian bank's account with the CSD as described above and the custodian bank has to pay a price to the CSD for having its securities account with the CSD credited or debited. I.e. the CSD can raise the costs of the custodian bank by increasing the price the custodian bank has to pay to the CSD as the CSD has a monopoly as central depository. Custodian banks argue that this can lead to a socially sub-optimal distortion in favor of the CSD, in particular if the CSD—after merging with an ICSD—offers services that are similar to those of the custodian banks.[5]

In this paper, we present a simple model describing the competition between a CSD and a custodian bank. We assume that there is only one CSD, one custodian bank and a continuum of investor banks. The CSD moves first. It sets a price q_C for opening a securities account with the CSD and another price p_C for debiting or crediting this account, i.e. for the settlement of a securities transaction in this account. The custodian bank moves second. It also sets a price q_A

[4] For example, CSDs typically settle the cash leg of securities transactions in the national central bank. Thus, direct participation in the national CSD requires access to the national central bank which is often restricted for foreign investor banks.

[5] See for example BNP Paribas Securities Services (2002), Citigroup (2003) and Fair & Clear Group (2003).

for opening and another price p_A for debiting or crediting a securities account with the custodian bank, taking into account the prices set by the CSD. Next, each investor bank opens an account with either the CSD or the custodian bank. Finally, banks are randomly matched to trade with each other and the transactions are settled through accounts with the CSD and the custodian bank. Note that we assume that the CSD is not able to price discriminate directly by setting one settlement price $p_{C,1}$ to be paid by investor banks and another settlement price $p_{C,2}$ to be paid by the custodian bank. This assumption can be justified because in reality, competition authorities would probably not allow this kind of direct price discrimination.

We assume that the CSD (as well as the custodian bank) is a for-profit institution. This is of course crucial for our main results. In reality, CSDs are usually private entities. Only a few (usually small) CSDs are still operated by central banks or other public entities. CSDs that are private entities are often subsidiaries of listed companies and the for-profit assumption might appear reasonable (in Europe for examples the CSDs of Germany and Italy). The same holds for CBL, i.e. one of the two ICSDs. Other CSDs argue to be user-owned and user-oriented rather than for-profit (for example the Euroclear CSDs including the ICSD Euroclear Bank). However, in particular custodian banks often argue that the user-orientation of these institutions existed only on paper while they were in fact very much profit-oriented.

We show that the CSD can raise the costs of the custodian bank in a very subtle way. Compare the custodian bank with an investor bank that has opened an account with the CSD. Since both have only one securities account with the CSD, both have to pay to the CSD the price q_C. But the number of transactions settled on an investor bank's account with the CSD is low compared to the number of transactions settled on a custodian bank's account with the CSD unless the custodian bank can by chance internalize the settlement of almost all transactions of its customers. Thus, the relative relevance of the price p_C compared to the price q_C is higher for the custodian bank than for the investor bank. If the CSD raises p_C and simultaneously reduces q_C, the overall costs for investor banks for using the service of the CSD may remain unchanged. However, the overall costs for the custodian bank for using the services of the CSD rise. Thus, with this strategy, the CSD can raise its rival's costs without losing investor banks as customers. To the contrary, the custodian bank has to raise its own prices to cover the additional costs it has to pay to the CSD and thus looses investor banks as customers to the CSD. As can be expected from the reasoning above, we show that in equilibrium the market share of the CSD is higher than the market share of the custodian bank though we assume that the CSD and the custodian bank face the same exogenous cost and demand parameters (symmetry).

Most importantly, we compare the equilibrium market shares with the socially optimal market shares. We show that the CSD's market share is higher than socially optimal if the CSD can charge a negative account price q_C. A negative price q_C can be interpreted as the CSD providing valuable additional services free-of-charge to all those investor banks that open a securities account with the CSD, for example market information services. Allowing for a negative account price is therefore economically meaningful. Moreover, we find that in our model, allowing the CSD to charge a negative account price has the same effect as allowing the CSD to directly price discriminate, i.e. to set one settlement price $p_{C,1}$ to be paid by investor banks and another settlement price $p_{C,2}$ to be paid by the custodian bank. Thus, if the CSD can charge a negative account price, then a regulatory intervention that prohibits the CSD to directly price discriminate has no impact on the allocation whatsoever.

If the CSD cannot charge a negative price q_C, then it is limited in applying its strategy to raise its rival's costs. In equilibrium, corner solutions occur with $q_C = 0$. In these cases, the market share of the CSD can be higher than, equal to or lower than the social optimum.

In any case, a social optimum is reached if relatively many investor banks concentrate in either the CSD or the custodian bank. The reason is the presence of network externalities. The CSD and the custodian bank are two different settlement networks. Settling transactions across the two networks is socially expensive. It is better to pool to a certain extent many investor banks in one of the two networks, for example in the CSD.

Our results have important policy implications that are related to the discussion that currently takes place in the market as outlined above. In our model, it is true that the CSD can exploit its monopoly position as a central depository by raising the custodian bank's costs to gain a higher market share. The equilibrium market share of the CSD is higher than socially optimal, unless the CSD cannot freely cross-subsidize different services by charging negative prices. These results support to a large extent the view of the custodian banks in the current debate.

Our model is obviously closely related to the theoretical literature on network industries. This literature can be separated into two branches. The first branch analyzes industries like the electricity or gas industry with only one network provider (the owner of the cable or pipeline network, the so-called upstream firm). Firms (the downstream firms) specialized in supplying consumers with the commodity conveyed through the network (electricity or gas) need to buy access to the network from the network provider.[6] The network provider itself may also offer the commodity to consumers. In this case, it is both an input supplier for and a direct competitor of the other firms at the market.[7] In this respect, the competition between the network provider and other suppliers of the commodity resembles the competition between a CSD and custodian banks. However, in the gas industry for example, a supplier of gas has to use the more services of the provider of the network the more consumers the supplier can attract. But the more investor banks a custodian bank can attract, the more likely is the case that the buyer and the seller of a securities transaction both have an account with this custodian bank so that the custodian bank can internalize the settlement without routing it through its account with the CSD. In the extreme case that all buyers and sellers of securities have an account with the same custodian bank, the custodian bank can internalize the settlement of all transactions and no settlement is routed through its account with the CSD.

The second branch of literature on network industries looks at competition between networks.[8] The most prominent example is the competition between two mobile phone networks. Consumers have the choice between both networks. If a customer of one network wants to call a customer of another network, the call has to be routed through a link between the two networks. This situation obviously resembles the competition between a CSD and a custodian bank. However, while the competition between mobile phone networks is symmetric, the competition between the CSD and the custodian bank is asymmetric insofar as only the custodian bank has an account with the CSD, but not vice versa.

Note that the CSD price discriminates in our model by applying a two-part tariff comprising an access price q_C plus a per-transaction price p_C. Thus, we look at a special case of nonlinear pricing. Nonlinear pricing has been discussed extensively in the academic literature. A comprehensive analysis is provided in Wilson (1993). More important, nonlinear pricing as a tool to price discriminate, so-called second degree price discrimination, has been analyzed as well. An overview can be found in Stole (2005). This literature has focused on the competition between

[6] This literature focuses mainly on access price regulation. See for example Armstrong et al. (1996), Laffont and Tirole (1994) and Vickers (1995).

[7] Rey and Tirole (2003) for an overview of vertical foreclosure.

[8] See Laffont et al. (1996a, 1996b).

second degree price discriminating firms that are not vertically related to each other. Following the second branch of literature on network industries mentioned above, Dessein (2003) discusses nonlinear pricing by competing networks. In his paper, networks charge nonlinear tariffs to final customers and not to the competitor. We are not aware of any academic papers in which an upstream monopolistic firm charges a nonlinear tariff also to competing downstream firms.

There is a growing academic literature on the securities settlement industry. Our model is closest related to Rochet (2005) who explicitly introduces his model as a variant of ours. This author looks at an industry with a CSD, a custodian bank and an ICSD.[9] He compares the case that the CSD and the ICSD are independently operated with the case that the CSD and the ICSD have merged. He concludes that the welfare effect of the merger are ambiguous. In contrast to our paper, it is assumed that custodian banks cannot internalize settlement but all settlement takes place in the CSD. Network effects are therefore not present. Rochet (2005) is to our knowledge the only other paper that analyzes the competition between custodian banks and CSDs from an academic perspective.

Kauko (2002, 2003) concentrates on the competition between two CSDs. These papers appear to be more in line with the above described second branch of literature on network industries. Koeppl and Monnet (2004) and Tapking and Yang (2004) analyze mergers of CSDs and thus discuss issues related to financial market integration. Other academic papers on securities settlement are empirical and deal mainly with the costs of domestic versus cross-border settlement, for example Lannoo and Levin (2001), Schmiedel et al. (2002) and Van Cayseele and Wuyts (2005).

The paper is organized as follows: The assumptions of the model are described in Section 2. In Section 3, we derive the social welfare optimum. The payoff functions of the players are described in Section 4.1. In Sections 4.2, 4.3 and 4.4, we analyze the equilibrium behavior of the players, and Section 4.5 discusses implications for welfare. Section 5.1 is devoted to an alternative version of our model in which the CSD and the custodian bank set their prices simultaneously. We show that the simultaneous move game has no equilibrium in pure strategies. This result can be seen as a good justification of our assumption that the CSD moves first. Finally, Section 5.2 briefly discusses the case that the custodian bank rather than the CSD moves first. We show that in this case, the CSD and the custodian bank reach the same market share. This shows that the custodian bank cannot reach a market share that is higher than that of the CSD even if the custodian bank moves first. It might therefore be reasonable to attribute the relatively high market share that the CSD can reach in our model more to the fact that the CSD can raise the custodian bank's costs than to the CSD's first mover advantage.

2. The model

In this section, we describe the assumptions of our model. We assume that there is one CSD, one custodian bank A and a continuum $[0, 1]$ of investor banks. Figure 1 depicts the structure of our model. An investor bank can maintain a securities account either with the CSD, or with the custodian bank, which in turn must have an account with the CSD. Decisions are taken in three stages.

(1) The CSD moves first. It sets a price q_C that each bank has to pay if it wants to open a securities account with the CSD and a price p_C that it has to pay when a securities transaction is settled in its account with the CSD. As mentioned in the introduction, we do not allow for direct

[9] He calls the custodian bank "Custodian Bank 2" and the ICSD "Custodian Bank 1".

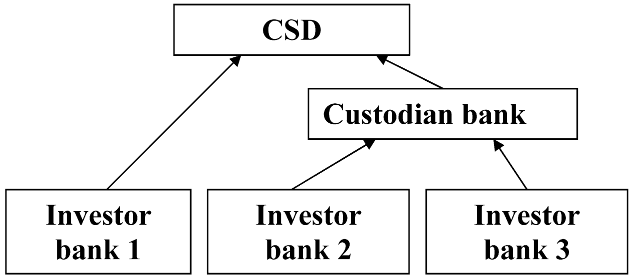

Fig. 1. The structure of settlement relationships.

price discrimination, i.e. the CSD is not allowed to charge investor banks a settlement price $p_{C,1}$ and to charge the custodian bank another settlement price $p_{C,2} \neq p_{C,1}$. We believe this assumption to be quite realistic, as competition authorities are unlikely to allow price discrimination of this kind. The CSD's marginal costs of maintaining an account for a bank are c_a. When securities are transferred from one account with the CSD to another account with the CSD, then the CSD has marginal costs of $2c_s$ (one account has to be debited, the other has to be credited).

(2) Custodian bank A moves second. It sets a price q_A an investor bank has to pay if it wants to open a securities account with the custodian bank and a price p_A an investor bank has to pay when a securities transaction is settled in its account with the custodian bank. The custodian bank's marginal costs of maintaining an account for a bank are $\tilde{c}_a$. When securities are transferred from one account with the custodian bank to another account with the custodian bank, the custodian bank has costs of $2\tilde{c}_s$ (again, one account has to be debited, the other has to be credited). In most parts of this paper, we will assume $\tilde{c}_a = c_a$ and $\tilde{c}_s = c_s$. We assume that custodians charge the same price for its services, irrespective of whether internalization of settlement is possible or not. This seems to correspond best to the real world, where large custodians tend to charge the same fee in both cases.

(3) The investor banks move next. Each of these banks has to open a securities account with either the CSD or the custodian bank. Besides the differences in prices, the quality of the services of the CSD on the one hand and the custodian bank on the other hand matters. This is reflected in our model by the assumption that bank $i \in [0, 1]$ has additional costs $c(\frac{1}{2} - i)$, $c > 0$, when choosing to open an account with the custodian bank. Thus, if the prices of the CSD and the custodian bank were equal ($q_C = q_A$ and $p_C = p_A$), then all banks in $[0, \frac{1}{2}[$ would go to the custodian bank and all banks in $]\frac{1}{2}, 1]$ would go to the CSD. This assumption implies that on average the quality or nature of the services provided by the CSD and by the custodian bank is equally high. The parameter c determines the degree of homogeneity of the services provided by the CSD and the custodian bank. If c is low, then these services are relatively homogeneous. With a view to the discussion in the introduction, the case of a "low" c could be interpreted as the case of competition between a custodian bank and a CSD that has merged with an ICSD, while a "high" c could represent the case of competition between a custodian bank and a CSD that has not merged with an ICSD. Denote by k the proportion of investor banks with an account with the CSD, i.e. $1 - k$ is the proportion of investor banks with an account with the custodian bank.

After the investor banks have made their decision, a security is issued into the CSD. We assume that each investor bank has a 50% chance to receive the security at the primary market, where investor banks are drawn independently. As a result, one-half of all investor banks buy one unit of the security on the primary market. To be more precise, we assume that a number α is drawn randomly, representing the proportion of investor banks with an account with the CSD that receive one unit of the security at the primary market, $0 \leqslant \alpha \leqslant 1$. Thus, αk banks with an account with the CSD and $\frac{1}{2} - \alpha k$ banks with an account with the custodian bank receive a security at the primary market, where $\frac{1}{2} - \alpha k \leqslant 1 - k$. As only one-half of all investor banks buy the security at the primary market, additional restrictions are $0 \leqslant \alpha k \leqslant \frac{1}{2}$ and $0 \leqslant \frac{1}{2} - \alpha k \leqslant \frac{1}{2}$ so that

$$\alpha \in \left[\max\left\{0, 1 - \frac{1}{2k}\right]; \min\left\{1, \frac{1}{2k}\right\}\right] \tag{1}$$

where α is uniformly distributed over this interval.

Each investor bank that bought the security at the primary market has to sell its unit. All other investor banks buy one unit of the security at the secondary market. We assume that those banks with an account with the custodian bank simply give their sell or buy order to the custodian bank. The custodian bank acts as a broker and executes the orders of its customer banks. To save on fees, it internalizes as many trades as possible. Whether there is a net transfer of securities from the CSD to the custodian bank or vice versa depends on the realization of α: If $\alpha \leqslant \frac{1}{2}$, that is, less than half of the banks with an account with the CSD wish to sell the security, then αk securities are sold from customers of the CSD to other customers of the CSD (internal settlement), $(1 - 2\alpha)k$ securities are sold from customers of the custodian bank to those of the CSD, while $\frac{1}{2} - k + \alpha k$ securities are sold from customers of the custodian bank to other customers of the custodian (again, internal settlement takes place). Similarly, for $\alpha \geqslant \frac{1}{2}$, $(1 - \alpha)k$ trades are settled within the CSD, $k - 2(1 - \alpha)k = 2\alpha k - k$ trades are settled across the two institutions, while $\frac{1}{2} - \alpha k$ securities are sold from customers of the custodian bank to customers of the custodian bank.

Note that in our model, we assume that each investor bank has one primary market and one secondary market transaction to settle. In reality however, primary market settlement accounts for only a very small part of overall settlement activities. To adjust our model, the single secondary market transaction of each investor bank is to be interpreted as representing a large number of such transactions compared to which the number of primary market transactions is negligible. Thus, we assume that all costs related to primary market settlement can be neglected. Investor banks do not have to pay for the settlement of primary market transactions, i.e. the prices p_C and p_A only refer to secondary market settlement. Consequently, we neglect the costs of primary market settlement that would be borne by the CSD and the custodian bank, i.e. c_s and $\tilde{c}_s$ refer only to secondary market settlement, too.

It is essential to clearly understand how secondary market trades are settled. Take for example the case that an investor bank with an account with the CSD sells to another investor bank that also has an account with the CSD. In this case, the account of the former is debited and the account of the latter is credited. The CSD incurs marginal costs of $2c_s$ and both banks pay p_C as price for the settlement to the CSD. If instead a bank with an account with the CSD sells to another bank with an account with the custodian bank, the transaction has to be settled across the two settlement service providers. The account of the seller with the CSD is debited and the (so-called omnibus) account of the custodian bank with the CSD and the account of the buyer with the custodian bank are both credited. Here, the CSD faces marginal costs $2c_s$ and the custodian bank $\tilde{c}_s$. The seller and the custodian bank both pay p_C to the CSD and the buyer pays p_A to the custodian bank.

3. Social welfare

In this section, we derive the social welfare optimum, i.e. the socially optimal allocation of investor banks to the two settlement service providers. There are two types of costs whose sum should be minimized: first, the direct cost of settlement, and second, the 'preference cost' that arises for investor banks from settling at the custodian bank.

Let us turn to the settlement cost first. Each investor bank has to open one account, either with the CSD or with the custodian. This implies social costs incurred at the CSD of kc_a and social costs incurred at the custodian bank of $(1-k)\tilde{c}_a$. Also, because investor banks either send or receive the security exactly once, their accounts have to be either debited once or credited once. This implies social costs incurred at the CSD of kc_s and social costs incurred at the custodian bank of $(1-k)\tilde{c}_s$. Furthermore, if $\alpha \leqslant \frac{1}{2}$, a proportion of $(1-2\alpha)k$ transactions has to be settled through the custodian bank's account with the CSD, i.e. this account has to be credited $(1-2\alpha)k$ times. The social costs for this settlement across the two settlement service providers are $(1-2\alpha)kc_s$ (incurred at the CSD). Analogously, if $\alpha \geqslant \frac{1}{2}$, a proportion of $(2\alpha-1)k$ transactions has to be settled on the custodian bank's account with a CSD, i.e. this account has to be debited $(2\alpha-1)k$ times. The social costs are $(2\alpha-1)kc_s$ (again incurred at the CSD).

Second, the preference costs incurred at the investor banks are $\int_k^1 c(\frac{1}{2}-i)\,\mathrm{d}i$. Taking both together, the social costs of settlement for given α and k are

$$S = \begin{cases} k(c_a+c_s)+(1-k)(\tilde{c}_a+\tilde{c}_s)+(1-2\alpha)kc_s+\int_k^1 c\left(\frac{1}{2}-i\right)\mathrm{d}i, & \text{for } \alpha \leqslant \frac{1}{2}, \\ k(c_a+c_s)+(1-k)(\tilde{c}_a+\tilde{c}_s)+(2\alpha-1)kc_s+\int_k^1 c\left(\frac{1}{2}-i\right)\mathrm{d}i, & \text{for } \alpha > \frac{1}{2}. \end{cases}$$

Taking expectations with respect to α we find

Lemma 1. *The expected social cost of welfare is given by*

$$E(S) = \begin{cases} \widetilde{S}+\frac{1}{2}kc_s & \text{for } k \leqslant \frac{1}{2}, \\ \widetilde{S}+\frac{1}{2}(1-k)c_s & \text{for } k > \frac{1}{2} \end{cases} \tag{2}$$

where $\widetilde{S} \equiv k(c_a+c_s)+(1-k)(\tilde{c}_a+\tilde{c}_s)-\frac{1}{2}ck(1-k)$.

Here, the second term $\frac{1}{2}kc_s$ (respectively $\frac{1}{2}(1-k)c_s$) represents the expected social costs of settling transactions across the two service providers, i.e. on the account of the custodian bank with the CSD. This term is decreasing as k moves away from its midpoint $\frac{1}{2}$. The reason is that settlement across institutions is costly. If many investor banks are concentrated in either the CSD or in the custodian bank (in other words, k is close to either 1 or 0), then most trades can be settled internally and these costs are avoided. The term can be interpreted as network externalities that arise from concentrating securities accounts in one institution.

To derive the socially optimal k, $E(S)$ has to be minimized with respect to k and subject to $0 \leqslant k \leqslant 1$. In Appendix A, we prove

Proposition 2. *To avoid corner solutions, assume $c \geqslant c_s$. The socially optimal market share of the CSD k is given by $k = k_{opt}$ with*

$$k_{opt} \begin{cases} = \max\left\{\frac{c-c_s}{2c} + \frac{\tilde{c}_a+\tilde{c}_s-c_a-c_s}{c}, 0\right\} & \text{if } \tilde{c}_a + \tilde{c}_s < c_a + c_s, \\ \in \left\{\frac{c-c_s}{2c}, \frac{c+c_s}{2c}\right\} & \text{if } \tilde{c}_a + \tilde{c}_s = c_a + c_s, \\ = \min\left\{\frac{c+c_s}{2c} + \frac{\tilde{c}_a+\tilde{c}_s-c_a-c_s}{c}, 1\right\} & \text{if } \tilde{c}_a + \tilde{c}_s > c_a + c_s. \end{cases}$$

Looking at the middle case first, if the CSD and the custodian bank have the same cost structure ($\tilde{c}_a + \tilde{c}_s = c_a + c_s$), then there are two socially optimal allocations, namely

$$k_{opt}^1 = \frac{c - c_s}{2c} < 1/2 \quad \text{and} \quad k_{opt}^2 = \frac{c + c_s}{2c} > 1/2.$$

Both are symmetric in the sense that they have the same distance from $k = 1/2$. To understand the meaning of these solutions, let us focus on the extreme case where $c_s = 0$. In this case, settlement across institutions is not socially costly, so the only relevant cost parameter that a social planner would care about are the investor banks' preferences, whose settlement costs are minimized for $k = \frac{1}{2}$. In this case, it is optimal that any investor bank $i \in [0, \frac{1}{2}[$ goes to the custodian bank and any investor bank $i \in]\frac{1}{2}, 1]$ goes to the CSD.

If c_s increases, it is more and more important to avoid settlement across the two service providers, i.e. to pool many investor banks in one service provider. By doing so, network externalities can be exploited. If c_s is sufficiently high and c sufficiently low, it is optimal that all investor banks have accounts with the same institution ($k = 0$ or $k = 1$) so that settlement across service providers does not take place at all. In other words, the social planner has to balance the costs of forcing investor banks to settle with the institution that is not their preferred one (as measured by c) against the cost of settling across institutions c_s. Note that as long as the cost structure is equal for both institutions, it is irrelevant for the social optimum at which institution more settlement takes place, i.e. whether $k < \frac{1}{2}$ or $k > \frac{1}{2}$.

Proposition 2 also tells us that when the cost structures differ for the CSD and the custodian bank so that $\tilde{c}_a + \tilde{c}_s \neq c_a + c_s$, there is a correcting term in the definition of k_{opt} that implies that the number of customers settling at the more costly institution should be further reduced. Notice that in this case, there is no multiplicity of equilibria: if the custodian bank has a more efficient cost structure, then the optimal allocation predicts that $k_{opt} < \frac{1}{2}$ while the opposite is true if the CSD is more efficient.

From now on, we focus on the case $\tilde{c}_a + \tilde{c}_s = c_a + c_s$ to reduce the mathematical complexity of the analysis. Also, to avoid corner solutions with $k_{opt}^1 = 0$ and $k_{opt}^2 = 1$, we assume for the rest of the paper $c \geqslant c_s$.

4. The equilibrium

4.1. The payoff functions

We now present the payoff functions of the players for given k and prices p_A, q_A, p_C and q_C. The payoff function of some investor bank $i \in [0, 1]$ is simply

$$\pi_i = \begin{cases} -\left[q_A + p_A + c\left(\frac{1}{2} - i\right)\right] & \text{if } i \text{ is customer of the custodian bank,} \\ -[q_C + p_C] & \text{if } i \text{ is customer of the CSD.} \end{cases}$$

Now consider the custodian bank. For each investor bank that maintains an account with it and uses it to make one transaction, the custodian bank receives $q_A + p_A$, but incurs settlement costs of $c_a + c_s$. Moreover, for those $k - 2\alpha$ (respectively $2\alpha - k$) transactions where the receiver (the sender) is customer of the CSD, the custodian bank needs to pay a fee p_C to the CSD for settlement. All other trades are settled internally. The profit of the custodian bank is thus given by

$$\pi_A = \begin{cases} (1-k)(q_A - c_a + p_A - c_s) - (1-2\alpha)kp_C & \text{for } \alpha < \frac{1}{2}, \\ (1-k)(q_A - c_a + p_A - c_s) - (2\alpha - 1)kp_C & \text{for } \alpha > \frac{1}{2}. \end{cases}$$

Taking expectations with respect to α (see proof of Lemma 1), we obtain the custodian bank's payoff function

$$E[\pi_A] = \begin{cases} (1-k)(q_A - c_a + p_A - c_s) - \frac{1}{2}kp_C & \text{for } k \leqslant \frac{1}{2}, \\ (1-k)(q_A - c_a + p_A - c_s) - \frac{1}{2}(1-k)p_C & \text{for } k \geqslant \frac{1}{2}. \end{cases} \tag{3}$$

Again, $\frac{1}{2}k$ is the expected number of trades to be settled through the custodian bank's account with the CSD if $k \leqslant \frac{1}{2}$ (and $\frac{1}{2}(1-k)$ if $k \geqslant \frac{1}{2}$). Obviously, it peaks at $k = 1/2$, that is, when just one half of all investor banks have an account with either institution. In the other extreme, for $k = 0$, all trades can be settled internally on accounts with the custodian bank. Similarly, if $k = 1$, all banks maintain an account with the CSD, so the custodian bank settles no trades.

Finally, consider the CSD. Similar considerations as above lead to the CSD's profit

$$\pi_C = \begin{cases} k(q_C - c_a + p_C - c_s) + (1-2\alpha)k(p_C - c_s) & \text{for } \alpha < \frac{1}{2}, \\ k(q_C - c_a + p_C - c_s) + (2\alpha - 1)k(p_C - c_s) & \text{for } \alpha > \frac{1}{2}. \end{cases}$$

Taking expectations with respect to α gives the CSD's payoff function

$$E[\pi_C] = \begin{cases} k(q_C - c_a + p_C - c_s) + \frac{1}{2}k(p_C - c_s) & \text{for } k \leqslant \frac{1}{2}, \\ k(q_C - c_a + p_C - c_s) + \frac{1}{2}(1-k)(p_C - c_s) & \text{for } k \geqslant \frac{1}{2}. \end{cases} \tag{4}$$

4.2. *The decision of the investor banks*

We solve the model backwards and start with stage (3). Here, each bank $i \in [0, 1]$ has to decide which service provider it wants to have an account with, given the prices q_c, p_C, q_A, p_A. Bank i is indifferent if and only if

$$\begin{aligned} & q_C + p_C = c\left(\frac{1}{2} - i\right) + q_A + p_A \\ \iff \quad & i = \frac{1}{2} + \frac{q_A + p_A - q_C - p_C}{c}. \end{aligned}$$

Thus, the proportion of banks with an account with the CSD is

$$k = \begin{cases} 0 & \text{if } q_A + p_A - q_C - p_C < -\frac{1}{2}c, \\ \frac{1}{2} + \frac{q_A + p_A - q_C - p_C}{c} & \text{if } -\frac{1}{2}c \leqslant q_A + p_A - q_C - p_C \leqslant \frac{1}{2}c, \\ 1 & \text{otherwise.} \end{cases} \tag{5}$$

From now on, we assume that corner solutions with $k = 0$ or $k = 1$ will not occur in equilibrium.

If $q_A + p_A = q_C + p_C$, we of course have $k = \frac{1}{2}$. If the CSD and the custodian bank charge different prices, i.e. $q_A + p_A >$ (or $<$)$q_C + p_C$, we have $k > (<)\frac{1}{2}$ so that more investor banks settle at the institution with lower prices. Finally, notice the impact of the investors' cost c of having to settle at a different institution than the preferred one: If c increases, then k moves closer to $\frac{1}{2}$ since it gets more expensive for banks in $[0, \frac{1}{2}[$ and less expensive for banks in $]\frac{1}{2}, 1]$ to use the custodian bank. Thus, k is decreasing (increasing) in c if $q_A + p_A > (<) q_C + p_C$.

4.3. The decision of the custodian bank

Because investor banks make only one transaction each, the payoff function of the custodian bank is simply a function of $q_A + p_A$. Thus, to derive the best response correspondence of the custodian bank on given prices q_C and p_C, $E[\pi_A]$ is to be maximized with respect to $q_A + p_A$ only (not with respect to q_A and p_A) and subject to Eq. (5), $q_A + p_A \geqslant 0$ and $0 \leqslant k \leqslant 1$. In Appendix A, we prove

Proposition 3 *(Best response correspondence of the custodian bank). An interior solution to the custodian bank's problem exists if and only if* $2q_C + p_C \geqslant 2(c_a + c_s) - c$ *and* $2q_C + 3p_C \leqslant 3c + 2(c_a + c_s)$

$$q_A + p_A \begin{cases} = X & \text{if } q_C + p_C > \hat{c}, \\ \in \{X, Y\} & \text{if } q_C + p_C = \hat{c}, \\ = Y & \text{if } q_C + p_C < \hat{c} \end{cases}$$

where $\hat{c} \equiv \frac{1}{2}c + c_a + c_s$, $X \equiv \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$, *and* $Y \equiv \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C$.

If either $2q_C + p_C < 2(c_a + c_s) - c$, *or* $2q_C + 3p_C > 3c + 2(c_a + c_s)$, *then we obtain a corner solution in which either* $k = 0$ *or* $k = 1$.

The case treated in the proposition represents an interior solution where $0 < k < 1$. Here, there exist two possible optimal responses by the custodian bank: if the prices set by the CSD are rather high, the custodian bank is able to attract customers by choosing rather low prices $q_A + p_A = X$. If the CSD sets low prices, on the other hand, the custodian bank knows that it will not be able to attract a large mass of depositors and chooses high prices $q_A + p_A = Y$. The other omitted cases represent corner solutions in which either $k = 0$ or $k = 1$. However, as we will see later on, only the interior solution is relevant in equilibrium.

Furthermore, it is important to note that in $q_C + p_C = \frac{1}{2}c + (c_a + c_s)$ the best response correspondence is discontinuous (at least if $p_C > 0$). The custodian bank is indifferent between $q_A + p_A = X$ ($k = \frac{1}{2} - \frac{p_C}{4c} < \frac{1}{2}$) and $q_A + p_A = Y$ ($k = \frac{1}{2} + \frac{p_C}{4c} > \frac{1}{2}$). This is due to the fact that the custodian bank's payoff function $E[\pi_A]$ is not quasi-concave in $q_A + p_A$. For this reason, there is no equilibrium in the simultaneous move game (i.e. in the setup in which the CSD and the custodian bank choose their prices simultaneously, see Section 5.1).

4.4. The decision of the CSD

The CSD moves first so that it maximizes $E[\pi_C]$ with respect to q_C and p_C taking into account both $q_A + p_A$ as given in Proposition 3 and k as derived in Section 4.2. We distinguish two cases, the case that the CSD cannot charge negative prices ($q_C \geqslant 0$ and $p_C \geqslant 0$) and the case that it can charge negative prices. A negative price q_C reflects a situation in which the CSD charges a very low account fee and at the same time provides to each of its customers valuable free-of-charge services like the provision of market information.[10]

Moreover, we argue that allowing the CSD to charge a negative price $q_C < 0$ is the same as allowing the CSD to directly price discriminate by setting one settlement price $p_{C,1}$ to be paid by investor banks and another settlement price $p_{C,2}$ to be paid by the custodian bank. This is easy to see. The investor banks always consider only the sum of the account price and the settlement price, i.e. $p_{C,1} + q_C$ in case of direct price discrimination and $p_C + q_C$ otherwise, but not the two prices separately. The custodian bank considers only the settlement price, i.e. $p_{C,2}$ or p_C, but not the account price q_C, because the account price is negligible compared to the price per transaction (the custodian settles many trades with the CSD). In the case of direct price discrimination, the CSD can choose any combination of $p_{C,1} + q_C$ and $p_{C,2}$. In the case that direct price discrimination is not allowed, but a negative price $q_C < 0$, it can choose any combination of $p_C + q_C$ and p_C. If the CSD would like to set a very high price p_C, but a very low $p_C + q_C$, it can do so by choosing a negative q_C. Thus, allowing for a negative account price offers the same strategic opportunities to the CSD as allowing for direct price discrimination.

We show in the appendix that the maximization leads to the following proposition:

Proposition 4 *(Equilibrium).* (a) *Suppose that the CSD cannot charge negative prices, i.e. $q_C \geqslant 0$ and $p_C \geqslant 0$. Then the following holds*:

(1) *If $c_a \leqslant c - \frac{1}{2}c_s$, then the CSD chooses $q_C = 0$ and $p_C = \frac{1}{2}c + c_a + c_s$. In this case, the prices of the custodian bank are given by any q_A–p_A combination satisfying $q_A + p_A = \frac{5}{8}c + \frac{5}{4}(c_a + c_s)$, $q_A \geqslant 0$ and $p_A \geqslant 0$. We have*

$$k = \frac{\frac{5}{8}c + \frac{1}{4}(c_a + c_s)}{c} \equiv k_1.$$

(2) *If $c_a \geqslant c - \frac{1}{2}c_s$, then the CSD chooses $p_C = \frac{3}{2}c + \frac{1}{2}c_s$ and $q_C = c_a + \frac{1}{2}c_s - c$. In this case, the prices of the custodian bank are given by any q_A–p_A combination satisfying $q_A + p_A = \frac{7}{8}c + c_a + \frac{9}{8}c_s$, $q_A \geqslant 0$ and $p_A \geqslant 0$, and we have*

$$k = \frac{\frac{7}{8}c + \frac{1}{8}c_s}{c} \equiv k_2.$$

(b) *Now suppose that the CSD can charge negative prices. Then the CSD chooses $p_C = \frac{3}{2}c + \frac{1}{2}c_s$ and $q_C = c_a + \frac{1}{2}c_s - c$, the prices of the custodian bank are given by any q_A–p_A combination satisfying $q_A + p_A = \frac{7}{8}c + c_a + \frac{9}{8}c_s$, $q_A \geqslant 0$ and $p_A \geqslant 0$ and $k = k_2$.*

From Proposition 4, we can draw some remarkable conclusions. In the first place, we see that $q_C + p_C < q_A + p_A$ so that investor banks always face lower prices when settling at the CSD than if they settled with the custodian bank. As a result, $k > 1/2$, i.e. the CSD is able to attract

[10] For example suppose that the CSD, for legal or operational reasons, has to provide a fixed set of information to each of its customers. Assume that the benefit for the customer from receiving the information is b while the costs for the CSD to provide the information is d. The parameters b and d are assumed to be exogenous. We can now define $q_C = \hat{q}_C - b$ and $c_a = \hat{c}_a - b + d$. Here, $\hat{q}_C \geqslant 0$ is the (monetary) account fee to be paid by each CSD customer. And $\hat{c}_a$ are the costs of the CSD for maintaining a customer account net of the additional costs d. This re-interpretation of q_C and c_a would not change the mathematical characteristics of our model accept that we can now allow q_C to be as low as $-b$. If we assume b to be sufficiently high, than we assume that the CSD can set any negative price q_C in the relevant range.

more customers than the custodian bank although we have assumed symmetry in marginal costs ($\tilde{c}_a = c_a$ and $\tilde{c}_s = c_s$) and in the quality of the settlement services of the two service providers.

The main reason is that the CSD can raise the costs of the custodian bank without raising the costs of its other customers in the following way[11]: The CSD can increase p_C and simultaneously decrease q_C by the same amount. The costs of investor banks with the CSD remain unchanged since these banks have one account with the CSD and want to have only one trade settled. However, the costs of the custodian bank increase since it has also only one account, but many trades settled through its account with the CSD. The resulting higher costs for the custodian bank normally force it to increase its prices so that it loses customers to the CSD. If c_a is low and the CSD restricted to choose a price $q_C \geqslant 0$ (case (1) in the proposition), then in equilibrium we have $q_C = 0$, i.e. corner solutions occur. In other words, the CSD applies the above described strategy of raising-rival's-costs as far as possible. If q_C may be negative, corner solutions never occur. Note that in both cases, $k > 1/2$ even if $c \to \infty$. This is because if c approaches infinity, the prices of both service providers do the same.

Generally, the price set by the CSD is increasing in its costs parameters (c_a and c_s). Moreover, prices are increasing in c: the more costly it is for investor banks to switch between service providers (i.e. the higher c), the higher the CSD can set prices without having to fear that many customers move to the custodian bank.

If c_a is high and c low (case (2) in the proposition), we find $q_C > 0$, i.e. the CSD has less incentives to raise the cost of the custodian bank. The reason appears to be the following: If c is low and $q_C + p_C$ is only slightly lower than $q_A + p_A$, it is attractive to choose the CSD even for those investor banks that are located close to the bottom of the interval [0, 1]. In this case, it is sufficient for the CSD to raise the costs of the custodian bank only little.

Notice that k is decreasing in c.[12] This makes sense given that we have $k > 1/2$ in equilibrium (recall the results of Section 4.2). If c increases, banks in $[0, \frac{1}{2}[$ increasingly prefer to go to the custodian bank and banks in $]\frac{1}{2}, 1]$ increasingly prefer to go to the CSD, provided prices remain unchanged. Consequently, if $k > 1/2$ and c increases, then the CSD will lose customers. Finally, k is increasing in c_a and c_s, i.e. technological progress leads to a lower k, thus to more custodian banking.

4.5. *Welfare assessment*

We now compare the equilibrium with the results of our welfare analysis (Proposition 2). As discussed in Section 3, there are two welfare maximizers, namely $k^1_{opt} = \frac{1}{2}\frac{c-c_s}{c} < 1/2$ and $k^2_{opt} = \frac{1}{2}\frac{c+c_s}{c} > 1/2$. Since both equilibrium solutions k_1 and k_2 are above 1/2, it is obvious that in equilibrium we have

$$k > k^1_{opt}.$$

Since $c \geqslant c_s$, we also have $k_2 \geqslant k^2_{opt}$. This apparently implies

Proposition 5. *If the CSD is able to charge a negative price $q_C < 0$, then the CSD's market share in equilibrium is always higher than socially optimal.*

[11] Another reason is the first mover advantage of the CSD, see Section 5.2.

[12] k is a continuous function of c. However, if the CSD cannot charge a negative account price, then k is not differentiable in $c_a = c - \frac{1}{2}c_s$.

Network externalities imply that a relatively high market share of the CSD, i.e. one that is greater than $1/2$, would be socially optimal. However, the CSD raises its rival's costs even beyond what is socially optimal. This result reflects the fact that the CSD and a social planner care differently about the costs arising from consumer preferences and network externalities. In particular, comparing the functional form for social welfare (2) and the CSD's profit function (4), we see that the CSD is less concerned than the planner about the cost arising from settlement across institutions. Still, these costs (which are borne by the custodian bank) are relevant for social welfare.

However, if we assume that the CSD cannot charge negative prices, we also have to compare k_1 and k_{opt}^2. Indeed, it is easy to check that

$$k_1 \leqslant k_{opt}^2 \quad \Leftrightarrow \quad c_a \leqslant c_s - \frac{1}{2}c. \tag{6}$$

In other words, if the CSD cannot charge negative prices, then the market share chosen by the CSD in equilibrium is smaller than the (highest) social optimum k_{opt}^2 if and only if $c_a \leqslant \min\{c - \frac{1}{2}c_s, c_s - \frac{1}{2}c\} = c_s - \frac{1}{2}c$. This is illustrated in Fig. 2, which displays all relevant conditions in the (c_a/c_s)-graph. As we only consider parameter values for which $c \geqslant c_s$, the relevant area is the one on the left of the dotted line. The dashed line separates the regions for which the different equilibria are obtained in equilibrium: k_1 results for low values of c_a, while k_2 is obtained for parameter combinations above the dashed line. The solid line separates the region for which the market share of the CSD is higher than k_{opt}^2 (area above the solid line) from the region where it is lower than k_{opt}^2 (area below the solid line).

To get an understanding of our results illustrated in Fig. 2, consider a decline of c_a. First note that this has no impact on the social optimum k_{opt}^2 as the social costs for the maintenance of accounts do not depend on the market shares. Now consider point A first. Here, we are above the

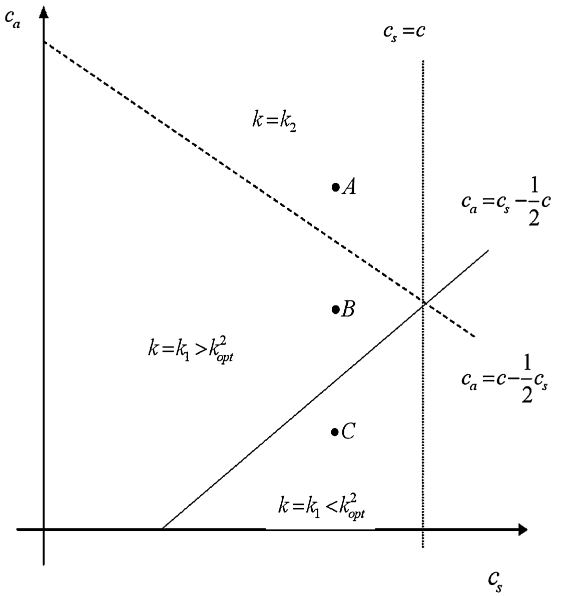

Fig. 2. The figure refers to the case that the CSD cannot charge a negative account price. The equilibrium value of k is lower than the socially optimal one below the solid line.

dashed line so that $k = k_2 > k^2_{opt}$. If now c_a goes down a bit, then p_C remains unchanged and q_C and $q_A + p_A$ decrease at the same pace so that the CSD's market share k remains unchanged. The CSD is adjusting its raising-rival's-costs strategy to the changing cost parameter c_a.

When we reach the dashed line, we are at $q_C = 0$ and q_C cannot decline further. Thus if, c_a now declines further down to point B and below, then the CSD is unable to further adjust its raising-rival's-costs strategy. The CSD starts losing market share. However, as long as we are above the solid line, we still have $k = k_1 > k^2_{opt}$. As soon as we reach the solid line, we get $k = k_1 = k^2_{opt}$. The social optimum k^2_{opt} has now caught up with the equilibrium market share. If c_a decreases further (for example down to point C), we enter the region below the solid line. The CSD is still losing market share and we finally get $k = k_1 < k^2_{opt}$.

5. Model variations

We now briefly discuss two model variations. In Section 5.1, we show that the simultaneous move game has no equilibrium in pure strategies. In Section 5.2, we show that the CSD's equilibrium market share is $k = \frac{1}{2}$ if the custodian bank rather than the CSD moves first. We assume throughout that the CSD cannot charge negative prices.

5.1. The simultaneous move game

In this section, we show that our model would have no equilibrium in pure strategies if we were assuming that the CSD and the custodian bank set their prices simultaneously. Firstly note as mentioned earlier that the payoff function $E[\pi_A]$ of the custodian bank is not quasi concave in $q_A + p_A$. For given prices q_C and p_C of the CSD, $E[\pi_A]$ has a local maximum with $q_A + p_A$ somewhere between $q_C + p_C - \frac{1}{2}c$ and $q_C + p_C$ and another local maximum with $q_A + p_A$ somewhere between $q_C + p_C$ and $q_C + p_C + \frac{1}{2}c$. Thus, the sufficient conditions for the existence of a Nash equilibrium are not satisfied. However, that does not necessarily imply that there is no Nash equilibrium.

To show that there is indeed no Nash equilibrium, we have to derive the best response function of the CSD which is given by

Proposition 6. *The best response function of the CSD is*

$$p_C \begin{cases} \in [0, q_A + p_A - \frac{1}{2}c] & \text{if } \frac{5}{2}c + 2c_a + c_s \leqslant q_A + p_A, \\ = \frac{3}{4}c + \frac{1}{2}(q_A + p_A) + c_a + \frac{1}{2}c_s & \text{if } \frac{3}{2}c + 2c_a + c_s \leqslant q_A + p_A \leqslant \frac{5}{2}c + 2c_a + c_s, \\ = q_A + p_A & \text{if } \frac{1}{2}c + \frac{2}{3}c_a + c_s \leqslant q_A + p_A \leqslant \frac{3}{2}c + 2c_a + c_s, \\ = \frac{1}{4}c + \frac{1}{2}(q_A + p_A) + \frac{1}{3}c_a + \frac{1}{2}c_s & \text{if } \frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{1}{2}c + \frac{2}{3}c_a + c_s, \\ \in [0, \frac{1}{2}c + q_A + p_A] & \text{if } q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c; \end{cases}$$

$$q_C \begin{cases} = q_A + p_A - \frac{1}{2}c - p_C & \text{if } \frac{5}{2}c + 2c_a + c_s \leqslant q_A + p_A, \\ = 0 & \text{if } \frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{5}{2}c + 2c_a + c_s, \\ = q_A + p_A + \frac{1}{2}c - p_C & \text{if } q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c. \end{cases}$$

We see from this proposition that in the simultaneous move game the CSD still has clear incentives to set $q_C = 0$ and p_C relatively high to raise the custodian bank's costs without raising the overall costs of the investor banks. Furthermore, note that p_C is increasing in $q_A + p_A$

and continuous in $q_A + p_A$, while the custodian banks best response correspondence $q_A + p_A$ is discontinuous according to Proposition 3. As mentioned before, this is the reason why the simultaneous move game has no equilibrium as stated in

Proposition 7. *If the CSD and the custodian bank set their prices simultaneously, then there is no equilibrium in pure strategies.*

With numeric examples, it is easy to show that in a diagram with $q_A + p_A$ on the horizontal and p_C on the vertical axis, the best response of the custodian bank runs right of the best response of the CSD as long as $p_C < \frac{1}{2}c + c_a + c_s$ (and $q_C = 0$). For $p_C > \frac{1}{2}c + c_a + c_s$ (and $q_C = 0$) however, it runs left of the CSD's best response. I.e. it jumps from the right to the left of the CSD's best response in $p_C = \frac{1}{2}c + c_a + c_s$. For that reason, there is no interception of the two best responses and no equilibrium in pure strategies.

5.2. The custodian bank moves first

We finally look at the case that not the CSD, but the custodian bank sets its prices first. In Appendix A, we show

Proposition 8. *If the custodian bank moves first, then the equilibrium is given by $q_A + p_A = \frac{3}{2}c + 2c_a + c_s$, $q_C = 0$, $p_C = q_A + p_A$, $k = \frac{1}{2}$.*

Given that the CSD offers input services to the custodian bank and not vice versa, it might be more realistic to assume that the CSD rather than the custodian bank moves first. But still, analyzing the opposite case is interesting as it shows that the custodian bank cannot reach a market share that is higher than that of the CSD even if the custodian bank moves first. It might therefore be reasonable to attribute the relatively high market share of the CSD in our model described in Section 4.4 more to the fact that the CSD can raise the custodian bank's costs than to the CSD's first mover advantage. Note that the CSD always applies its strategy of raising rival's costs to the greatest extent possible (i.e. $q_C = 0$), if the custodian bank moves first.

6. Concluding remarks

We have discussed a simple model of the competition between a CSD and a custodian bank. It has been shown that the CSD is able to exploit its monopoly position as central depository by raising the custodian bank's costs to attract more investor banks as customers. We have shown that the market share of the CSD in equilibrium is higher than socially optimal if the CSD can charge a negative account price. A negative account price means that the CSD provides to each customer bank additional services free of charge such as access to market information. We argue that charging a negative price is equivalent to allowing the CSD to directly price discriminate between investor banks and the custodian bank. If the CSD cannot charge a negative account price, then the CSD's market share may be lower than socially optimal (lower than the highest social optimum).

Our analysis appears to be relevant in two ways. Firstly, it contributes to the current discussion between market participants, especially ICSDs and custodian banks, on whether and how competition in the securities settlement industry is distorted. Our results support to a large extent the view of the custodian banks in this debate. Secondly, our analysis is theoretically relevant in that it considers a case of asymmetric network competition which has not been analyzed yet.

Extensions of the model could go into different directions. Firstly, one may want to analyze our model with the assumption that the CSD can charge a progressive settlement price, i.e. the more trades a customer of the CSD wants to have settled through accounts with the CSD, the higher the price per settlement this customer has to pay. Since the custodian bank is the customer of the CSD with the highest number of trades to be settled through accounts with the CSD, this would clearly adversely effect the custodian bank and give the CSD power to raise its rival's cost even higher.

Secondly, it might be interesting to assume that there are more than one custodian banks so that there is competition between several custodian banks (and the CSD). There may be two different modeling strategies in this respect:

(1) It could be assumed that the services of all custodian banks are perfect substitutes for all investor banks. It is likely that in this case, due to network externalities, only one of the custodian banks can in fact attract customers, but this custodian bank has to charge low prices to deter potential competitors so that it makes possibly only zero profits. The CSD may need to charge also lower prices as the prices of its competitor are low, but it can still raise its rival's costs and may still be able to attract more than half of all investor banks. In this setting, the welfare results of Section 3 still hold. But whether the CSD's market share will always be higher than k^2_{opt} will have to be verified.

(2) It could instead be assumed that the different custodian banks offer imperfect substitutes. For example, n custodian banks and the CSD could be located on the same Hotelling line [0, 1] as the investor banks and each investor bank's additional costs of using one of these $n + 1$ service providers equal its distance to the respective service provider. This setting would of course alter the analysis of Section 3. Furthermore, it may have a strong influence on the number of transactions that can be internalized.

Both modeling strategies however appear very difficult to pursue and therefore have to be left to further research.

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Appendix A

Proof of Lemma 1. In determining the expected social costs, we need to take into account constraint (1). Let us first assume that $k \leqslant \frac{1}{2}$, i.e. α is uniformly distributed over [0, 1]. In this case, we have

$$E(S) = \widetilde{S} + \int_0^{\frac{1}{2}} (1 - 2\alpha)kc_s \,\mathrm{d}\alpha + \int_{\frac{1}{2}}^1 (2\alpha - 1)kc_s \,\mathrm{d}\alpha$$

$$= \widetilde{S} + \frac{1}{2}kc_s.$$

Now assume that $k \geqslant \frac{1}{2}$, thus α is uniformly distributed over $[1-\frac{1}{2k}; \frac{1}{2k}]$ with density $\frac{k}{1-k}$. In this case, we get

$$E(S) = \widetilde{S} + \int_{1-\frac{1}{2k}}^{\frac{1}{2}} (1-2\alpha)kc_s \frac{k}{1-k}\,\mathrm{d}\alpha + \int_{\frac{1}{2}}^{\frac{1}{2k}} (2\alpha-1)kc_s \frac{k}{1-k}\,\mathrm{d}\alpha$$
$$= \widetilde{S} + \frac{1}{2}(1-k)c_s.$$

Lemma 1 follows. □

Proof of Proposition 2. Let $E[S^u] = k(c_a+c_s) + (1-k)(\tilde{c}_a+\tilde{c}_s) + \frac{1}{2}kc_s - \frac{1}{2}ck(1-k)$ be the upper branch of $E[S]$. This is a convex function in k with a minimum in

$$k = \frac{c-c_s}{2c} + \frac{\tilde{c}_a+\tilde{c}_s-c_a-c_s}{c} \equiv k_U$$

with

$$E\big[S^u\big]^* = \tilde{c}_a + \tilde{c}_s - \frac{1}{2}\frac{[\frac{1}{2}c+\tilde{c}_a+\tilde{c}_s-c_a-\frac{3}{2}c_s]^2}{c}.$$

Let $E[S^L] = k(c_a+c_s) + (1-k)(\tilde{c}_a+\tilde{c}_s) + \frac{1}{2}(1-k)c_s - \frac{1}{2}ck(1-k)$. This is also a convex function in k with a minimum in

$$k = \frac{c+c_s}{2c} + \frac{\tilde{c}_a+\tilde{c}_s-c_a-c_s}{c} \equiv k_L$$

with

$$E\big[S^L\big]^* = \tilde{c}_a + \tilde{c}_s + \frac{1}{2}c_s - \frac{1}{2}\frac{[\frac{1}{2}c+\tilde{c}_a+\tilde{c}_s-c_a-\frac{1}{2}c_s]^2}{c}.$$

It is easy to show that

$$E\big[S^u\big]^* \geqslant E\big[S^L\big]^*$$
$$\Leftrightarrow \quad \tilde{c}_a+\tilde{c}_s \geqslant c_a+c_s.$$

Assume $c_a+c_s \leqslant \tilde{c}_a+\tilde{c}_s$. In this case, we have $E[S^u]^* \geqslant E[S^L]^*$ and $k_U \leqslant \frac{1}{2}$, i.e. $k_{opt} = k_U$. Assume instead $\tilde{c}_a+\tilde{c}_s \leqslant c_a+c_s$. In this case, we have $E[S^u]^* \leqslant E[S^L]^*$ and $\frac{1}{2} \leqslant k_L$, i.e. $k_{opt} = k_L$. This completes the proof of the proposition. □

Proof of Proposition 3. We prove a bit more than what is stated in Proposition 3 as this is needed for the proof of Proposition 4. We prove

Lemma 9. (i) *If* $2q_C + p_C \geqslant 2(c_a+c_s) - c$ *and* $2q_C + 3p_C \leqslant 3c + 2(c_a+c_s)$, *then*

$$q_A + p_A \begin{cases} = X & \text{if } q_C+p_C > \hat{c}, \\ \in \{X, Y\} & \text{if } q_C+p_C = \hat{c}, \\ = Y & \text{if } q_C+p_C < \hat{c}; \end{cases}$$

(ii) *If* $2q_C + p_C < 2(c_a + c_s) - c$, *then*

$$q_A + p_A \begin{cases} = V & \text{if } 2q_C + 3p_C > 3c + 2(c_a + c_s) \text{ and } q_C + p_C > \hat{c}, \\ \in \{V, W\} & \text{if } 2q_C + 3p_C > 3c + 2(c_a + c_s) \text{ and } q_C + p_C = \hat{c}, \\ = W & \text{otherwise}; \end{cases}$$

(iii) *If* $2q_C + 3p_C > 3c + 2(c_a + c_s)$, *then*

$$q_A + p_A \begin{cases} = W & \text{if } 2q_C + p_C < 2(c_a + c_s) - c \text{ and } q_C + p_C < \hat{c}, \\ \in \{V, W\} & \text{if } 2q_C + p_C < 2(c_a + c_s) - c \text{ and } q_C + p_C = \hat{c}, \\ = V & \text{otherwise} \end{cases}$$

with $\hat{c} \equiv \frac{1}{2}c + c_a + c_s$, X *and* Y *defined as in Proposition 3,* $V \equiv q_C + p_C - \frac{1}{2}c$ *and* $W \equiv q_C + p_C + \frac{1}{2}c$.

Apparently, part (i) coincides with Proposition 3. To prove the lemma, we have to maximize $E[\pi_A]$ as given in Eq. (3) with respect to $q_A + p_A$ for given prices q_C and p_C and subject to $q_A + p_A \geqslant 0$ and $0 \leqslant k \leqslant 1$, where k is given by Eq. (5).

Let $E[\pi_A^U] = (1-k)(q_A - c_a + p_A - c_s) - \frac{1}{2}kp_C$ be the upper branch of $E[\pi_A]$. In a first step, we maximize $E[\pi_A^U]$ subject to $q_A + p_A \geqslant 0$ and $0 \leqslant k \leqslant \frac{1}{2}$. We easily get the following maximizer and maximum:

$$q_A + p_A = \begin{cases} q_C + p_C & \text{if } q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c, \\ \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C & \text{if } c_a + c_s + \frac{1}{2}c \\ & \quad \leqslant q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c, \\ q_C + p_C - \frac{1}{2}c & \text{if } q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c \end{cases}$$

and

$$E[\pi_A^U]^* = \begin{cases} \frac{1}{2}q_C + \frac{1}{4}p_C - \frac{1}{2}(c_a + c_s) \equiv E_1 & \text{if } q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c, \\ \frac{[\frac{1}{4}c - \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C]^2}{c} - \frac{1}{2}p_C \equiv E_2 & \text{if } c_a + c_s + \frac{1}{2}c \leqslant q_C + \frac{3}{2}p_C \\ & \quad \leqslant c_a + c_s + \frac{3}{2}c, \\ q_C + p_C - \frac{1}{2}c - (c_a + c_s) \equiv E_3 & \text{if } q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c. \end{cases}$$

Let $E[\pi_A^L] = (1-k)(q_A - c_a + p_A - c_s) - \frac{1}{2}(1-k)p_C$ be the lower branch of $E[\pi_A]$. We maximize $E[\pi_A^L]$ subject to $q_A + p_A \geqslant 0$ and $\frac{1}{2} \leqslant k \leqslant 1$. Again we easily get the maximizer and maximum:

$$q_A + p_A = \begin{cases} q_C + p_C + \frac{1}{2}c & \text{if } q_C + \frac{1}{2}p_C < c_a + c_s - \frac{1}{2}c, \\ \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C & \text{if } c_a + c_s - \frac{1}{2}c \leqslant q_C + \frac{1}{2}p_C \\ & \quad \leqslant c_a + c_s + \frac{1}{2}c, \\ q_C + p_C & \text{if } q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c \end{cases}$$

and

$$E[\pi_A^U]^* = \begin{cases} 0 \equiv E_4 & \text{if } q_C + \frac{1}{2}p_C < c_a + c_s - \frac{1}{2}c, \\ \frac{[\frac{1}{4}c - \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C]^2}{c} \equiv E_5 & \text{if } c_a + c_s - \frac{1}{2}c \leqslant q_C + \frac{1}{2}p_C \\ & \quad \leqslant c_a + c_s + \frac{1}{2}c, \\ \frac{1}{2}q_C + \frac{1}{4}p_C - \frac{1}{2}(c_a + c_s) \equiv E_6 & \text{if } q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c. \end{cases}$$

We now have to consider the following nine sets of mutually exclusive constellations.

A) $q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c$ and $q_C + \frac{1}{2}p_C < c_a + c_s - \frac{1}{2}c$. It follows immediately that $q_C + p_C < c_a + c_s$, i.e. $E_1 < 0 = E_4$. The best response is thus given by $q_A + p_A = q_C + p_C + \frac{1}{2}c$.

B) $q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c$ and $c_a + c_s - \frac{1}{2}c \leqslant q_C + \frac{1}{2}p_C \leqslant c_a + c_s + \frac{1}{2}c$. Because $E_5 = \frac{1}{c}[\frac{1}{4}c + E_1]^2$, we know that $E_5 \leqslant E_1 \Leftrightarrow [E_1 - \frac{1}{4}c]^2 \leqslant 0$. This is only possible if $E_1 = \frac{1}{4}c$, i.e. $q_C + \frac{1}{2}p_C = c_a + c_s + \frac{1}{2}c$ which is in contradiction to $q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c$. The best response is thus given by $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C$.

C) $q_C + \frac{3}{2}p_C < c_a + c_s + \frac{1}{2}c$ and $q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c$. This case is not possible.

D) $c_a + c_s + \frac{1}{2}c \leqslant q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c$ and $q_C + \frac{1}{2}p_C < c_a + c_s - \frac{1}{2}c$. First note that this implies that $\frac{1}{4}c - \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C \geqslant 0$ so that E_2 is decreasing in $(c_a + c_s)$. We now have to consider two sub-cases: (i) $2c \geqslant p_C$. Since $c_a + c_s > q_C + \frac{1}{2}p_C + \frac{1}{2}c$, we get $E_2 < \frac{1}{2}p_C[\frac{1}{2c}p_C - 1] \leqslant 0$ as we consider $2c \geqslant p_C$. (ii) $2c < p_C$. Since $c_a + c_s \geqslant q_C + \frac{3}{2}p_C - \frac{3}{2}c$, we get $E_2 \leqslant c - \frac{1}{2}p_C < 0$ as we now consider $2c < p_C$. I.e. we have $E_2 < E_4$ and the best response is $q_A + p_A = q_C + p_C + \frac{1}{2}c$.

E) $c_a + c_s + \frac{1}{2}c \leqslant q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c$ and $c_a + c_s - \frac{1}{2}c \leqslant q_C + \frac{1}{2}p_C \leqslant c_a + c_s + \frac{1}{2}c$. It is easy to see that $E_2 \geqslant E_5 \Leftrightarrow q_C + p_C \geqslant \frac{1}{2}c + c_a + c_s$. The best response is therefore $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$ if $q_C + p_C \geqslant \frac{1}{2}c + c_a + c_s$ and $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C$ if $q_C + p_C \leqslant \frac{1}{2}c + c_a + c_s$.

F) $c_a + c_s + \frac{1}{2}c \leqslant q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c$ and $q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c$. Because $E_2 = \frac{1}{c}[\frac{1}{4}c + \frac{1}{2}p_C + E_6]^2 - \frac{1}{2}p_C$, we know that $E_2 \leqslant E_6 \Leftrightarrow [\frac{1}{4}c - E_6 - \frac{1}{2}p_C]^2 \leqslant 0$. This is only possible if $E_6 = \frac{1}{4}c - \frac{1}{2}p_C$, i.e. $q_C + \frac{3}{2}p_C = c_a + c_s + \frac{1}{2}c$ which is in contradiction to $q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c$. Thus we get $E_2 > E_6$ and $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$ as the best response.

G) $q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c$ and $q_C + \frac{1}{2}p_C < c_a + c_s - \frac{1}{2}c$. Here we have $E_3 \geqslant E_4 \Leftrightarrow q_C + p_C \geqslant \frac{1}{2}c + c_a + c_s$. The best response is therefore $q_A + p_A = q_C + p_C - \frac{1}{2}c$ if $q_C + p_C \geqslant \frac{1}{2}c + c_a + c_s$ and $q_A + p_A = q_C + p_C + \frac{1}{2}c$ if $q_C + p_C \leqslant \frac{1}{2}c + c_a + c_s$.

H) $q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c$ and $c_a + c_s - \frac{1}{2}c \leqslant q_C + \frac{1}{2}p_C \leqslant c_a + c_s + \frac{1}{2}c$. First note that this implies that $\Psi \equiv \frac{1}{4}c - \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C \geqslant 0$. Moreover, we have $\Psi \geqslant c \Leftrightarrow q_C + \frac{1}{2}p_C \geqslant c_a + c_s + \frac{3}{2}c$. As $q_C + \frac{1}{2}p_C \geqslant c_a + c_s + \frac{3}{2}c$ is in contradiction to $q_C + \frac{1}{2}p_C \leqslant c_a + c_s + \frac{1}{2}c$, we now know that $\Psi < c$. With this and as $E_5 = \frac{\Psi^2}{c}$, we get $E_5 < \Psi$. Since $\Psi \geqslant E_3 \Leftrightarrow q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c$ and as $q_C + \frac{3}{2}p_C \leqslant c_a + c_s + \frac{3}{2}c$ is in contradiction to above, we conclude that $E_3 > E_5$ and get as the best response $q_A + p_A = q_C + p_C - \frac{1}{2}c$.

I) $q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c$ and $q_C + \frac{1}{2}p_C > c_a + c_s + \frac{1}{2}c$. Since $E_3 \leqslant E_6 \Leftrightarrow q_C + \frac{3}{2}p_C \leqslant c_a + c_s + c$ which is in contradiction to $q_C + \frac{3}{2}p_C > c_a + c_s + \frac{3}{2}c$, we get $E_3 > E_6$ and $q_A + p_A = q_C + p_C - \frac{1}{2}c$ as the best response.

It is easy to verify that these results finalize the proof. □

Proof of Proposition 4. We concentrate on the case $q_C \geqslant 0$ and $p_C \geqslant 0$. The case of unrestricted prices follows straightforward. Following Lemma 9, we have to discuss four mutually exclusive cases.

(I) To begin with, we determine the best the CSD can do under the restrictions $q_C \geqslant 0$, $p_C \geqslant 0$, $2q_C + p_C \geqslant 2(c_a + c_s) - c$, $2q_C + 3p_C \leqslant 3c + 2(c_a + c_s)$, $q_C + p_C \leqslant \hat{c}$. Here, the custodian bank chooses according to Lemma 9 $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{3}{4}p_C$ so that $k =$

$\frac{1}{c}[\frac{3}{4}c+\frac{1}{2}(c_a+c_s)-\frac{1}{2}q_C-\frac{1}{4}p_C]\geqslant\frac{1}{2}$. Thus, we have to solve

$$\begin{aligned}
&\operatorname{Max} E[\pi_C]=k(q_C-c_a+p_C-c_s)+\frac{1}{2}(1-k)(p_C-c_s)\\
&\text{s.t.}\quad q_C\geqslant 0,\ p_C\geqslant 0,\ q_C+p_C\leqslant c_a+c_s+\frac{1}{2}c,\\
&2q_C+p_C\geqslant 2(c_a+c_s)-c,\ 2q_C+3p_C\leqslant 2(c_a+c_s)+3c.
\end{aligned}$$

We proceed as follows: We ignore the last two constraints and then show that the solution of the reduced problem satisfies the last two constraints, i.e. these constraints are not binding. Using the Kuhn–Tucker theorem, it is easy to show that the solution of the reduced problem is the following:

(i) If $c\geqslant c_a+\frac{1}{2}c_s$, then $q_C=0$ and $p_C=\frac{1}{2}c+c_a+c_s$. In this case, we have $2q_C+p_C<2(c_a+c_s)-c\Leftrightarrow\frac{1}{2}c+c<c_a+\frac{1}{2}c_s+\frac{1}{2}c_s$ and $2q_C+3p_C>2(c_a+c_s)+3c\Leftrightarrow\frac{1}{2}c+c<c_a+\frac{1}{2}c_s+\frac{1}{2}c_s$ which is in contradiction to $c\geqslant c_a+\frac{1}{2}c_s$ and $c\geqslant c_s$ so that the solution satisfies the constraints $2q_C+p_C\geqslant 2(c_a+c_s)-c$ and $2q_C+3p_C\leqslant 2(c_a+c_s)+3c$. Furthermore, we get $q_A+p_A=\frac{5}{8}c+\frac{5}{4}(c_a+c_s)$, $k=\frac{1}{c}[\frac{5}{8}c+\frac{1}{4}(c_a+c_s)]$ and $E[\pi_C]=\frac{1}{c}[\frac{5}{8}c+\frac{1}{4}(c_a+c_s)][\frac{1}{4}c-\frac{1}{2}c_a]+\frac{1}{4}c+\frac{1}{2}c_a\equiv E_{\mathrm{I(i)}}$.

(ii) If $c\leqslant c_a+\frac{1}{2}c_s$, then $q_C=c_a+\frac{1}{2}c_s-c$ and $p_C=\frac{3}{2}c+\frac{1}{2}c_s$. In this case, we have $2q_C+p_C<2(c_a+c_s)-c\Leftrightarrow c<c_s$ and $2q_C+3p_C>2(c_a+c_s)+3c\Leftrightarrow c<c_s$ which is in contradiction to $c\geqslant c_s$ so that the solution satisfies the constraints $2q_C+p_C\geqslant 2(c_a+c_s)-c$ and $2q_C+3p_C\leqslant 2(c_a+c_s)+3c$. Furthermore, we get $q_A+p_A=\frac{7}{8}c+c_a+\frac{9}{8}c_s$, $k=\frac{1}{c}[\frac{7}{8}c+\frac{1}{8}c_s]$ and $E[\pi_C]=\frac{1}{2c}[\frac{1}{4}c-\frac{1}{4}c_s]^2+\frac{1}{2}c\equiv E_{\mathrm{I(ii)}}$.

(II) Now we show that the best the CSD can do under the restrictions $q_C\geqslant 0$, $p_C\geqslant 0$, $2q_C+p_C\geqslant 2(c_a+c_s)-c$, $2q_C+3p_C\leqslant 3c+2(c_a+c_s)$, $q_C+p_C\geqslant\hat{c}$ would make the CSD worse off. Here, the custodian bank chooses according to Lemma 9 $q_A+p_A=\frac{1}{4}c+\frac{1}{2}(c_a+c_s)+\frac{1}{2}q_C+\frac{1}{4}p_C$ so that $k=\frac{1}{c}[\frac{3}{4}c+\frac{1}{2}(c_a+c_s)-\frac{1}{2}q_C-\frac{3}{4}p_C]\leqslant\frac{1}{2}$ and

$$E[\pi_C]=\frac{1}{c}\left[\frac{3}{4}c+\frac{1}{2}(c_a+c_s)-\frac{1}{2}\left(q_C+\frac{3}{2}p_C\right)\right]\left[q_C+\frac{3}{2}p_C-c_a-\frac{3}{2}c_s\right].$$

We ignore the constraints and maximize $E[\pi_C]$ with respect to $q_C+\frac{3}{2}p_C$. It is very easy to check that the maximum is given by $E[\pi_C]=\frac{1}{2c}[\frac{3}{4}c-\frac{1}{4}c_s]^2\equiv E_{\mathrm{II}}$. It is clear that the maximum under the constraints of (II) cannot be higher than E_{II}. Thus, we only have to compare

(α) E_{II} with $E_{\mathrm{I(i)}}$ under $c\geqslant c_a+\frac{1}{2}c_s$. It is easy to see that $E_{\mathrm{II}}\geqslant E_{\mathrm{I(i)}}\Leftrightarrow c[c+2c_a+2c_s]\leqslant[c_a+\frac{1}{2}c_s]^2$ which is in contradiction to $c\geqslant c_a+\frac{1}{2}c_s$ so that $E_{\mathrm{II}}<E_{\mathrm{I(i)}}$.

(β) E_{II} with $E_{\mathrm{I(ii)}}$ under $c\leqslant c_a+\frac{1}{2}c_s$. It is easy to see that $E_{\mathrm{II}}\geqslant E_{\mathrm{I(ii)}}\Leftrightarrow c+\frac{1}{2}c_s\leqslant 0$ so that $E_{\mathrm{II}}<E_{\mathrm{I(ii)}}$.

(III) Now we show that the best the CSD can do under the restrictions that $q_A+p_A=V$ would make the CSD worse off compared to the maximum derived under (I). If $q_A+p_A=V$, then $E[\pi_C]=0\equiv E_{\mathrm{III}}$. Thus we have to compare

(α) $E_{\mathrm{III}}=0$ with $E_{\mathrm{I(i)}}$ under $c\geqslant c_a+\frac{1}{2}c_s$. As long as $\frac{1}{4}c-\frac{1}{2}c_a\geqslant 0$, we have $E_{\mathrm{I(i)}}>0$, i.e. $E_{\mathrm{III}}<E_{\mathrm{I(i)}}$. If $\frac{1}{4}c-\frac{1}{2}c_a<0$, then $E_{\mathrm{I(i)}}\geqslant\frac{1}{4}c-\frac{1}{2}c_a+\frac{1}{4}c+\frac{1}{2}c_a>0$. Thus, we again have $E_{\mathrm{III}}<E_{\mathrm{I(i)}}$.

(β) E_{III} with $E_{\mathrm{I(ii)}}$ under $c\leqslant c_a+\frac{1}{2}c_s$. Since we obviously have $E_{\mathrm{I(ii)}}>0$, we immediately get $E_{\mathrm{III}}<E_{\mathrm{I(ii)}}$.

(IV) Finally, we show that the best the CSD can do under the restrictions that $q_A + p_A = W$ would make the CSD worse off compared to the maximum derived under (I). If $q_A + p_A = W$, then $E[\pi_C] = q_C + p_C - c_a - c_s$.

(α) $c \geqslant c_a + \frac{1}{2}c_s$. According to Lemma 9, we have $q_A + p_A = W$ only if $2q_C + p_C < 2(c_a + c_s) - c$. Thus, the CSD cannot do better under $q_A + p_A = W$ than what it gets when it maximizes $q_C + p_C - c_a - c_s$ subject to $q_C \geqslant 0$, $p_C \geqslant 0$, $2q_C + p_C < 2(c_a + c_s) - c$, i.e. when it chooses $q_C = 0$, $p_C = 2(c_a + c_s) - c$ so that $E[\pi_C] = c_a + c_s - c \equiv E_{\mathrm{IV}(\alpha)}$. (a) If $\frac{1}{4}c - \frac{1}{2}c_a > 0$, we have $E_{\mathrm{I(i)}} > \frac{1}{2}[\frac{1}{4}c - \frac{1}{2}c_a] + \frac{1}{4}c + \frac{1}{2}c_a$. With $c \geqslant c_a + \frac{1}{2}c_s$ we easily get $\frac{1}{2}[\frac{1}{4}c - \frac{1}{2}c_a] + \frac{1}{4}c + \frac{1}{2}c_a < E_{\mathrm{IV}(\alpha)} \Rightarrow c < c_s$. This is in contradiction to our assumption $c \geqslant c_s$. (b) If $\frac{1}{4}c - \frac{1}{2}c_a = 0$, we have $E_{\mathrm{I(i)}} = \frac{1}{2}c$ and $E_{\mathrm{IV}(\alpha)} = c_s - \frac{1}{2}c$ so that $E_{\mathrm{I(i)}} > E_{\mathrm{IV}(\alpha)}$ as long as $c > c_s$. For $c = c_s$, the cases (I) and (IV)(α) are equivalent and do not need to be distinguished. (c) If $\frac{1}{4}c - \frac{1}{2}c_a < 0$, we have $E_{\mathrm{I(i)}} > \frac{1}{2}c$ and $E_{\mathrm{IV}(\alpha)} \leqslant \frac{1}{2}c$ so that again $E_{\mathrm{I(i)}} > E_{\mathrm{IV}(\alpha)}$.

(β) $c \leqslant c_a + \frac{1}{2}c_s$. According to Lemma 9, we have $q_A + p_A = W$ only in the following two cases: (a) $2q_C + p_C < 2(c_a + c_s) - c$ and $2q_C + 3p_C \leqslant 3c + 2(c_a + c_s)$. This implies $q_C + p_C < c_a + c_s + \frac{1}{2}c$, i.e. $E[\pi_C] < \frac{1}{2}c \leqslant E_{\mathrm{I(ii)}}$. (b) $2q_C + 3p_C > 3c + 2(c_a + c_s)$, $2q_C + p_C < 2(c_a + c_s) - c$ and $q_C + p_C \leqslant c_a + c_s + \frac{1}{2}c$. Again, this implies $E[\pi_C] < \frac{1}{2}c \leqslant E_{\mathrm{I(ii)}}$. □

Proof of Proposition 6. For given prices $q_A + p_A$, we have to maximize $E[\pi_C]$ as given in Eq. (4) with respect to q_C and p_C subject to $q_C \geqslant 0$, $p_C \geqslant 0$ and $0 \leqslant k \leqslant 1$, where k is given by Eq. (5).

Let $E[\pi_C^L] = k(q_C - c_a + p_C - c_s) + \frac{1}{2}(1-k)(p_C - c_s)$ be the lower branch of $E[\pi_C]$. In a first step, we maximize $E[\pi_C^L]$ subject to $q_C \geqslant 0$, $p_C \geqslant 0$ and $\frac{1}{2} \leqslant k \leqslant 1$. We get the following maximizer and maximum:

$$p_C \begin{cases} = q_A + p_A & \text{if } q_A + p_A < 2c_a + c_s + \frac{3}{2}c, \\ = \frac{3}{4}c + c_a + \frac{1}{2}c_s + \frac{1}{2}(q_A + p_A) & \text{if } 2c_a + c_s + \frac{3}{2}c \leqslant q_A + p_A \leqslant 2c_a + c_s + \frac{5}{2}c, \\ \in [0, q_A + p_A - \frac{1}{2}c] & \text{if } q_A + p_A > 2c_a + c_s + \frac{5}{2}c, \end{cases}$$

$$q_C \begin{cases} = 0 & \text{if } q_A + p_A < 2c_a + c_s + \frac{5}{2}c, \\ = q_A + p_A - \frac{1}{2}c - p_C & \text{if } q_A + p_A \geqslant 2c_a + c_s + \frac{5}{2}c \end{cases}$$

and

$$E[\pi_C^L]^* = \begin{cases} \frac{3}{4}(q_A + p_A) - \frac{1}{2}c_a - \frac{3}{4}c_s \equiv \widetilde{E}_1 & \text{if } q_A + p_A < 2c_a + c_s + \frac{3}{2}c, \\ \frac{1}{2}\frac{[\frac{3}{4}c + \frac{1}{2}(q_A + p_A) - c_a - \frac{1}{2}c_s]^2}{c} + c_a \equiv \widetilde{E}_2 & \text{if } 2c_a + c_s + \frac{3}{2}c \leqslant q_A + p_A \\ & \qquad \leqslant 2c_a + c_s + \frac{5}{2}c, \\ q_A + p_A - \frac{1}{2}c - c_a - c_s \equiv \widetilde{E}_3 & \text{if } q_A + p_A > 2c_a + c_s + \frac{5}{2}c. \end{cases}$$

Let $E[\pi_C^U] = k(q_C - c_a + p_C - c_s) + \frac{1}{2}k(p_C - c_s)$ be the upper branch of $E[\pi_C]$. We maximize $E[\pi_C^U]$ subject to $q_C \geqslant 0$, $p_C \geqslant 0$ and $0 \leqslant k \leqslant \frac{1}{2}$. We get the following maximizer and maximum:

$$p_C \begin{cases} = q_A + p_A & \text{if } q_A + p_A > \frac{2}{3}c_a + c_s + \frac{1}{2}c, \\ = \frac{1}{4}c + \frac{1}{3}c_a + \frac{1}{2}c_s + \frac{1}{2}(q_A + p_A) & \text{if } \frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{2}{3}c_a + c_s + \frac{1}{2}c, \\ \in [0, q_A + p_A + \frac{1}{2}c] & \text{if } q_A + p_A < \frac{2}{3}c_a + c_s - \frac{1}{2}c; \end{cases}$$

$$q_C \begin{cases} = 0 & \text{if } q_A + p_A \geqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c, \\ = q_A + p_A + \frac{1}{2}c - p_C & \text{if } q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c \end{cases}$$

and

$$E[\pi_C^U]^* = \begin{cases} \frac{3}{4}(q_A + p_A) - \frac{1}{2}c_a - \frac{3}{4}c_s \equiv \widetilde{E}_4 & \text{if } q_A + p_A > \frac{2}{3}c_a + c_s + \frac{1}{2}c, \\ \frac{3}{2}\frac{[\frac{1}{4}c + \frac{1}{2}(q_A+p_A) - \frac{1}{3}c_a - \frac{1}{2}c_s]^2}{c} \equiv \widetilde{E}_5 & \text{if } \frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \\ & \quad \leqslant \frac{2}{3}c_a + c_s + \frac{1}{2}c, \\ 0 \equiv \widetilde{E}_6 & \text{if } q_A + p_A < \frac{2}{3}c_a + c_s - \frac{1}{2}c. \end{cases}$$

We now have to consider the following five mutually exclusive cases:

A) $q_A + p_A > 2c_a + c_s + \frac{5}{2}c$. We easily find that $\widetilde{E}_3 > \widetilde{E}_4$, i.e. the best response is $p_C \in [0, q_A + p_A - \frac{1}{2}c]$, $q_C = q_A + p_A - \frac{1}{2}c - p_C$.

B) $2c_a + c_s + \frac{3}{2}c \leqslant q_A + p_A \leqslant 2c_a + c_s + \frac{5}{2}c$. Here we have $\widetilde{E}_2 > \widetilde{E}_4$, i.e. $p_C = \frac{3}{4}c + c_a + \frac{1}{2}c_s + \frac{1}{2}(q_A + p_A)$, $q_C = 0$.

C) $\frac{2}{3}c_a + c_s + \frac{1}{2}c \leqslant q_A + p_A \leqslant 2c_a + c_s + \frac{3}{2}c$. Here we have $\widetilde{E}_1 = \widetilde{E}_4$, i.e. $p_C = q_A + p_A$, $q_C = 0$.

D) $\frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{2}{3}c_a + c_s + \frac{1}{2}c$. Here we have $\widetilde{E}_1 < \widetilde{E}_5$, i.e. $p_C = \frac{1}{4}c + \frac{1}{3}c_a + \frac{1}{2}c_s + \frac{1}{2}(q_A + p_A)$, $q_C = 0$.

E) $q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c$. Here we have $\widetilde{E}_1 < \widetilde{E}_6$, i.e. $p_C \in [0, q_A + p_A + \frac{1}{2}c]$, $q_C = q_A + p_A + \frac{1}{2}c - p_C$.

This finalizes the proof. □

Proof of Proposition 7. To prove this proposition, one would need to consider 20 (mutually exclusive) cases. Since the proof is simple, but tedious, we discuss only the first two cases:

(1) $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$ and $q_C + p_C = q_A + p_A - \frac{1}{2}c$. This implies $q_C + p_C + \frac{1}{2}c = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$, i.e. $2q_C + 3p_C = 2(c_a + c_s) - c$. Since $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$ requires $2q_C + p_C \geqslant 2(c_a + c_s) - c$, this is only possible if $p_C = 0$, i.e. $q_C = c_a + c_s - \frac{1}{2}c$. Since $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$ also requires $q_C + p_C \geqslant \frac{1}{2}c + c_a + c_s$, this is not possible.

(2) $q_A + p_A = \frac{1}{4}c + \frac{1}{2}(c_a + c_s) + \frac{1}{2}q_C + \frac{1}{4}p_C$, $q_C = 0$ and $p_C = \frac{3}{4}c + \frac{1}{2}(q_A + p_A) + c_a + \frac{1}{2}c_s$. This implies $q_A + p_A = \frac{1}{2}c + \frac{6}{7}c_a + \frac{5}{7}c_s$. This is not possible since $q_C = 0$ and $p_C = \frac{3}{4}c + \frac{1}{2}(q_A + p_A) + c_a + \frac{1}{2}c_s$ requires $q_A + p_A \geqslant 2c_a + c_s + \frac{3}{2}c$. □

Proof of Proposition 8. This proof refers to Eq. (3) and Proposition 6. We have to consider five mutually exclusive cases.

(I) To begin with, we determine the best the custodian bank can do under the restrictions $q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c$. Here, the CSD chooses according to Proposition 4 $q_C + p_C = q_A + p_A + \frac{1}{2}c$ so that $k = 0$. Thus, we have to maximize $E[\pi_A] = q_A + p_A - c_a - c_s$ subject to $q_A \geqslant 0$, $p_A \geqslant 0$, $q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c$. It is obvious that the solution is $q_A + p_A = \frac{2}{3}c_a + c_s - \frac{1}{2}c$ with a maximum payoff for the custodian bank of $E[\pi_A] = -\frac{1}{3}c_a - \frac{1}{2}c < 0$. Thus, there is no equilibrium with $q_A + p_A \leqslant \frac{2}{3}c_a + c_s - \frac{1}{2}c$.

(II) We now determine the best the custodian bank can do under the restrictions $\frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{1}{2}c + \frac{2}{3}c_a + c_s$. Here, the CSD chooses according to Proposition 6 $q_C = 0$,

$p_C = \frac{1}{4}c + \frac{1}{2}(q_A + p_A) + \frac{1}{3}c_a + \frac{1}{2}c_s$. This implies $k \leqslant \frac{1}{2}$ as is easy to see. Thus, we have to solve

$$\text{Max } E[\pi_A] = (1-k)(q_A + p_A - c_a - c_s) - \frac{1}{2}kp_C$$
$$\text{s.t.} \quad q_A \geqslant 0,\ p_A \geqslant 0,\ \frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{1}{2}c + \frac{2}{3}c_a + c_s.$$

We first ignore the constraints and maximize $E[\pi_A]$. This gives us $q_A + p_A = \frac{1}{2}c + \frac{2}{3}c_a + \frac{4}{5}c_s$. Note that this fulfills the above constraints as $c > c_s$. Thus, the best the custodian bank can do under the restrictions $\frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{1}{2}c + \frac{2}{3}c_a + c_s$ is to choose $q_A + p_A = \frac{1}{2}c + \frac{2}{3}c_a + \frac{4}{5}c_s$. This gives

$$E[\pi_A] = \frac{1}{8}c - \frac{1}{3}c_a - \frac{1}{4}c_s + \frac{1}{40c}c_s^2 \equiv E_{\mathrm{A}}^{\mathrm{II}}$$

(III) We now determine the best the custodian bank can do under the restrictions $\frac{1}{2}c + \frac{2}{3}c_a + c_s \leqslant q_A + p_A \leqslant \frac{3}{2}c + 2c_a + c_s$. Here, the CSD chooses according to Proposition 6 $q_C = 0$, $p_C = q_A + p_A$ so that $k = \frac{1}{2}$. Thus, we have to solve

$$\text{Max } E[\pi_A] = \frac{1}{2}(q_A + p_A - c_a - c_s) - \frac{1}{4}(q_A + p_A)$$
$$\text{s.t.} \quad q_A \geqslant 0,\ p_A \geqslant 0,\ \frac{1}{2}c + \frac{2}{3}c_a + c_s \leqslant q_A + p_A \leqslant \frac{3}{2}c + 2c_a + c_s.$$

It is obvious that the solution is $q_A + p_A = \frac{3}{2}c + 2c_a + c_s$ with a maximum payoff for the custodian bank of $E[\pi_A] = \frac{3}{8}c - \frac{1}{4}c_s \equiv E_{\mathrm{A}}^{\mathrm{III}} > E_{\mathrm{A}}^{\mathrm{II}}$ (as $c > c_s$).

(IV) We now determine the best the custodian bank can do under the restrictions $\frac{3}{2}c + 2c_a + c_s \leqslant q_A + p_A \leqslant \frac{5}{2}c + 2c_a + c_s$. Here, the CSD chooses according to Proposition 6 $q_C = 0$, $p_C = \frac{3}{4}c + \frac{1}{2}(q_A + p_A) + c_a + \frac{1}{2}c_s$. This implies $k \geqslant \frac{1}{2}$ so that we have to solve

$$\text{Max } E[\pi_A] = (1-k)(q_A + p_A - c_a - c_s) - \frac{1}{2}(1-k)p_C$$
$$\text{s.t.} \quad q_A \geqslant 0,\ p_A \geqslant 0,\ \frac{3}{2}c + 2c_a + c_s \leqslant q_A + p_A \leqslant \frac{5}{2}c + 2c_a + c_s.$$

We first ignore the constraints and maximize $E[\pi_A]$. This gives $q_A + p_A = 2c_a + 2c_s - \frac{1}{2}c$. Note that this never fulfills the above constraint $\frac{3}{2}c + 2c_a + c_s \leqslant q_A + p_A$ as $c > c_s$. Thus, the best the custodian bank can do under the restrictions $\frac{2}{3}c_a + c_s - \frac{1}{2}c \leqslant q_A + p_A \leqslant \frac{1}{2}c + \frac{2}{3}c_a + c_s$ is to choose a corner solution $q_A + p_A = \frac{3}{2}c + 2c_a + c_s$. This gives $k = \frac{1}{2}$ and $E[\pi_A] = \frac{3}{8}c - \frac{1}{4}c_s = E_{\mathrm{A}}^{\mathrm{III}}$.

(V) We finally determine the best the custodian bank can do under the restrictions $\frac{5}{2}c + 2c_a + c_s \leqslant q_A + p_A$. Here, the CSD chooses according to Proposition 6 $q_C + p_C = q_A + p_A - \frac{1}{2}c$ so that $k = 1$. Thus, we get $E[\pi_A] = 0$.

It follows that the equilibrium is given by $q_A + p_A = \frac{3}{2}c + 2c_a + c_s$, $q_C = 0$, $p_C = q_A + p_A$, $k = \frac{1}{2}$. □

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