From Disclosure to Transparency:

Essays on Firms' Voluntary Disclosure in a Transforming Environment

Inaugural Dissertation
to Obtain the Academic Degree of a Doctor
in Business Administration at the University of Mannheim

submitted by
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Day of oral examination: 22.06.2023

This cumulative thesis is based on three articles, one of which have been published and two as preprint.

- Article I

  Gao Fritz, Q. (2023). Disclosure of greenhouse gas emissions. Preprint at https://ssrn.com/abstract=4559222.

- Article II

  Gao Fritz, Q. (2023). Label to match - Firms' signaling decisions when not everyone cares. Preprint at https://doi.org/10.31235/osf.io/ay8rq.

- Article III

  Franke, B., Gao Fritz, Q., & Stenzel, A. (2023). The (limited) power of blockchain networks for information provision. Management Science. Advance online publication. https://doi.org/10.1287/mnsc.2023.4718.

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List of Abbreviations

CDP Carbon Disclosure Project

CDSB Climate Disclosure Standards Board

CSR Corporate Social Responsibility

CSRD Corporate Sustainability Reporting Directive

ERP Enterprise Resource Planning

ESG Environmental, Social and Governance

EU European Union

GHG Greenhouse Gas

LHS Left-hand-side

NGO Non-Governmental Organisation

RHS Right-hand-side

SEC Securities and Exchange Commission

U.S. United States

1 Introduction

"The idea that the future is unpredictable is undermined every day by the ease with which the past is explained."

– Daniel Kahneman

Participants in economic transactions, especially transactions involving (ex-ante) unobservable product quality,[1] are often asymmetrically informed. Parties possessing essential information could maximize their outcomes at the expense of others. However, less-informed parties may anticipate such intentions and react accordingly. Akerlof (1970) illustrates the potentially detrimental effect of asymmetric information in analyzing the used car market. In the market, only sellers can observe the quality of their cars. Assume that buyers and sellers agree on the car's value, had they all known the quality. Uninformed buyers first rationally set the price corresponding to the average quality (value) of the cars on the market. Second, sellers with above-average quality cars will leave the market to avoid selling their products below the "actual" value. Next, buyers correctly anticipate such behavior and adjust the price downwards. Eventually, all but the worst quality cars are driven out of the market. This illustration highlights the significance of informed parties having incentives to overcome information asymmetry.

[1] Such transactions appear in many markets, like the used car market introduced in later text. Chapter 3 introduces product markets in which some consumer-preferred product attributes, like the GHG emission level or labor working conditions during production, cannot be observed even after the purchase. Another prominent example of these markets is the financial market. For example, entrepreneurs have private information about the project they seek for finance, or borrowers know their collateral better than the lenders.

Apply the same argument in the corporation context. If information asymmetry persists, firms may only sell their products, services, or shares of the firm at the lowest price. It is thus beneficial for firms to develop mechanisms to solve such an informational problem. Whereas firms can take observable actions as signals to convey relevant information to other parties,[2] they can also communicate their private information by disclosure.[3]

To illustrate how firms' voluntary disclosure may occur, consider firms aiming to finance projects whose quality is highly variable. Like the used car example, only firms privately observe the value of the technology. Without information transfer, the capital market might collapse like the used car market (Leland and Pyle, 1977). However, if firms can credibly[4] reveal this information, firms with above-average quality projects have the strongest incentive to do so. They now distinguish themselves from firms with lower-quality projects through disclosure instead of dropping out of the market. Buyers set up the price according to the disclosed quality. If disclosure cost is negligible, all but the worst quality cars disclose their private information without positive disclosure regulation. This line of argument represents the simplified concept of the unraveling principle (see Viscusi, 1978; Grossman and Hart, 1980; Grossman, 1981; Milgrom, 1981).

As compelling as the intuition behind the unraveling principle is, the result only holds when the disclosure context is strongly restricted.[5] Restrictions include but are not limited to settings in which disclosure is costless, firms receive private information with certainty, and both firms' objectives and receivers' reactions are homogeneous.

[2]Examples of these actions are providing product warranties (Grossman, 1981; Lutz, 1989), setting up pricing strategies (Milgrom and Roberts, 1986), choosing different debt levels (see, for example in Macho-Stadler and Pérez-Castrillo, 2001)

[3]Lang and Lundholm (1993, 2000) document that firms tend to increase their voluntary disclosure before equity offering. A similar pattern can be observed in firms' non-financial information disclosure (see, for example, Dhaliwal et al., 2011).

[4]Viscusi (1978) assumes that the disclosure can be perfectly verified by third parties. Hughes (1986) uses a contingent contract with a penalty for fraudulent disclosure to ensure truthfulness.

[5]Forsythe et al. (1989) and King and Wallin (1991) use laboratory markets to test the robustness of full disclosure prediction and show that in a simple seller-buyer setting, unraveling may be attained when disclosures are credible. The latter further indicates that the information credibility does not only include telling the truth but the whole truth.

Furthermore, the disclosure must be truthful.[6] In reality, firms' disclosure environment mostly does not hold on to such restrictions. The presence of different reporting incentives, multiple information receivers with conflicting objectives, or the existence of multiple signals, both within and outside the firm, complicate the disclosure decision process. At the same time, concerns may arise with respect to the disclosure credibility (see, e.g., Pownall and Waymire, 1989; Rogers and Stocken, 2005; Guan et al., 2020). These factors further interact with one another and jointly feature the disclosure environment.

Moreover, the above-described disclosure environment is not static but evolving over time. Dye (1985) and Jung and Kwon (1988) indicate that firms' probability of obtaining private information increases as time elapses. Fischer and Verrecchia (2000) further show that managers' incentives may vary at different points in time depending on the manager's time horizon and compensation contract, etc. Beyond the firm-specific context, transformations in the environment in which firms operate influence firms' disclosure decision-making process. For instance, several studies investigate the interaction between firms' voluntary disclosure and mandatory disclosure (see, for example, Einhorn, 2005; Bagnoli and Watts, 2007; Zhang, 2012). The results imply that disclosure regulation changes may also change firms' voluntary disclosure decisions (e.g., Gordon et al., 2006; Kim and Park, 2009). It is thus imperative to identify features of the evolving environment to reach optimal disclosure strategies.

Over the last decades, firms have been facing a prodigious transformation in their disclosure environment. One significant societal movement is the increased attention to firms' social impact. According to the Deloitte Millennial Survey (2016), 87% of the survey attendees believe that the goal of a business should be more than just its financial performance. This shift enlarges the criteria used to assess firm value and creates demand for non-financial information (see Amel-Zadeh and Serafeim, 2018; Christensen et al., 2021).

[6] For a thorough review of the restrictions, see, e.g., Beyer et al. (2010) and Dye (2017b).

Another important environmental transformation relates to technology development. Over the last two decades, the enormous expansion of the internet and the accompanying information-collecting and dissemination technologies have dramatically changed the dynamics of information supply and demand. Empirical research documents firms' usage of internet financial reporting and investigates its determinants and effects (e.g., Beattie and Pratt, 2003; Kelton and Yang, 2008; Trabelsi et al., 2008). Studies further show how the landscape of firms' disclosure has been transformed (e.g., Saxton, 2012; Blankespoor et al., 2014; Blankespoor, 2018). However, such developments may not only enlarge firms' set of potential disclosure channels but also fundamentally change the trade-offs that the firms face when making disclosure decisions. Wagenhofer (2007) shows that easy access to information with lower costs may encourage firms to disclose additional, however less precise, information. In addition, more timely interaction between firms and information receivers may change the initial disclosure decisions (Bagnoli and Watts, 2021).

In this thesis, I focus on a setting in which firms possess private information relevant to one or more information receivers' decision-making and can decide whether and how to disclose such information. The main objective is to investigate firms' disclosure decisions incorporating the evolving societal and technological development. Overall, the thesis examines how much and what quality of information enters the public domain in a transforming environment. Specifically, I answer the following questions. Are firms always willing to provide private information voluntarily when facing increasing information demand? How does imperfect information verification influence such disclosure decisions? Furthermore, how does the latest technological development influence information provision?

The most apparent reason to hold managers back from disclosing their private information is the cost related to such disclosure. Jovanovic (1982) and Verrecchia (1983) consider that firms' disclosure gives rise to a fixed non-proprietary cost related to the preparation and dissemination of the information. This cost allows the worst-performing firms to obscure the incentive of nondisclosure. Full disclosure does not arise. Instead, separating occurs from the top. Only firms with sufficiently good news incur this cost and disclose.[7]

Later research further enriches the disclosure environment by giving the disclosure cost a context. One widely held view is that the information the firm possesses is proprietary. Disclosing the information may allow other strategic players to use it to their advantage and reduce the firm's future cash flows. Such strategic players can be competitors (e.g., Darrough, 1993; Dontoh, 1989) but can also be suppliers (Li and Zhang, 2008; Mittendorf et al., 2013), labor unions, or government parties (see empirical support, such as Chung et al., 2016; Hilary, 2006).

Furthermore, the co-existence of information receivers who react differently to the disclosure leads to the rise of partial disclosure equilibria. Different reactions may come from different receivers, such as capital market and product market (Darrough and Stoughton, 1990; Wagenhofer, 1990; Feltham and Xie, 1992; Suijs, 2005) or suppliers and competitors (e.g., Arya et al., 2019; Li and Zhang, 2008). At the same time, each of these groups of information receivers might not react homogeneously to corporate disclosure. Fishman and Hagerty (2003) show how the presence of sophisticated and unsophisticated consumers influences firms' voluntary disclosure incentives. Furthermore, uncertain reactions from one type of information receivers may also result from different levels of private information that receivers possess (e.g., Dutta and Trueman, 2002; Dye, 1998; Suijs, 2007; Thakor, 2015).

Information receivers may react differently when multiple signals are relevant in determining firms' value. Arya et al. (2010) consider a setting in which competitors represent the only addressee of disclosure. However, firm value is determined by the performance of two segments. Although unraveling occurs on the firm level (aggre-

[7] The similar effect occurs if we consider that firms may not have private information (Dye, 1985; Jung and Kwon, 1988). Poorly performing firms now are able to pool with the firms that do not receive private information.

gated), full disclosure is prevented in the sense that firms are not willing to disclose both of their signals relating to the individual segments. Other researchers consider interactions among multiple signals and analyze the impact on disclosure decisions (see, for example, Hayes and Lundholm, 1996; Einhorn, 2005; Pae, 2005; Guttman et al., 2014; Cheynel and Levine, 2020). Whereas Hayes and Lundholm (1996), Pae (2005), and Guttman et al. (2014) consider firms receive multiple signals relevant to the firm value and may selectively disclose some of these signals, Einhorn (2005) and Cheynel and Levine (2020) show that other information sources (like firms' mandatory disclosure or information gathered by third parties) influence firms' voluntary disclosure decisions.

The first part of this thesis responds to the disclosure environment transformation regarding the increased demand for firms' non-financial information. The model in Chapter 2 extends the multiple audiences setting into the non-financial information context. More specifically, it considers how different information receivers may influence firms' greenhouse gas (GHG) emission disclosure decisions. This disclosure decision further interacts with firms' financial information signal. It thus also connects to the literature examining the interaction among multiple signals.

The situation gets even more complicated when we zoom in and put the signal being disclosed under the microscope. There exist two dimensions of concerns over disclosure. Firms may intentionally bias the signal they privately observe. In addition, one could also question the informativeness of the signal itself.[8]

Once the truthful disclosure assumption is lifted, unraveling result may no longer stand.[9] A large body of literature focuses on the incentives and the magnitude of bias imposed by managers and the impact of the bias. Two streams of literature fall into this category.

[8]Liang and Zhang (2006) define these two types of concerns over information quality as incentive uncertainty and inherent uncertainty.

[9]Korn and Schiller (2003) show that even if one assumes truthful disclosure in equilibrium, partial disclosure equilibria may be supported once misreporting is part of an off-equilibrium path.

First, cheap talk models consider that disclosure does not incur a direct cost and information is not verifiable. Crawford and Sobel (1982) show that full revelation is impossible when the information sender's and receiver's interests are not fully aligned. To the extreme, when their interests are too misaligned, "babbling equilibrium" occurs, and no information is transmitted. However, above mentioned disclosure frictions, such as the existence of different information receivers and the interaction with other relevant signals, ensure incomplete but still informative disclosure (e.g., Farrell and Gibbons, 1989; Newman and Sansing, 1993; Gigler, 1994; Stocken, 2000; Evans and Sridhar, 2002; Goltsman and Pavlov, 2011; Bertomeu and Marinovic, 2016). For example, Farrell and Gibbons (1989) and Gigler (1994) show that the presence of multiple information receivers with conflicting interests may discipline communication. In addition, competing communication channels can also ensure the informativeness of unverified disclosure (Bertomeu and Marinovic, 2016).

The second stream of literature relating to disclosure bias considers that disclosure manipulation is costly. Here, firms can misreport their signals but only at some cost. Whereas a large body of literature considers costly manipulation under a mandatory disclosure regime (e.g., Fischer and Verrecchia, 2000; Dye and Sridhar, 2004; Ewert and Wagenhofer, 2005; Beyer, 2009; Yu, 2017),[10] several studies incorporate it in the voluntary disclosure setting (e.g., Korn, 2004; Beyer and Guttman, 2012; Einhorn and Ziv, 2012; Heinle and Verrecchia, 2016; Versano and Trueman, 2017). Both Beyer and Guttman (2012) and Einhorn and Ziv (2012) consider a setting where managers decide to disclose or withhold their private information and further misreport if they choose to disclose. Whereas Einhorn and Ziv (2012) show that the decision concerning releasing or withholding information is not influenced by later misreporting possibility, Beyer and Guttman (2012) add an investment decision into the model and focus on the interdependences between managers' decisions.

[10] Moreover, auditing literature largely considers the strategic interaction between managers and auditors to see how auditors can improve disclosure credibility. However, most of these studies also rest in mandatory disclosure settings (see Ye, 2021, for a comprehensive review).

Other than focusing on a potential bias in the disclosure, several studies turn their attention to the informativeness of disclosure. Informativeness is the "representational faithfulness with which the ...(signals)... reflect their economic circumstances" (Stocken et al., 2013, p. 263). There are two commonly used ways to model such disclosure quality. One option is to model a signal's quality via its precision measured as the inverse of its variance (see, for example, Verrecchia, 1990; Kirschenheiter, 1997; Hughes and Pae, 2004; Einhorn, 2005; Gao, 2010; Cheynel and Levine, 2020). Alternatively, one can model the informativeness of the signal as the probability of full revelation of a firm's value (see, for example, Liang and Zhang, 2006; Bertomeu and Magee, 2011; Zhang, 2012; Gao and Liang, 2013; Edmans et al., 2016).

Verrecchia (1990) considers the impact of information quality on the disclosure threshold. Withholding more precise information is more detrimental to the firm. Richarson (2001) models the disclosure cost as a function of the information quality and concludes that more precise information does not necessarily lead to more disclosure. Dye (2017a) analyzes a similar setting in which a seller receives private information regarding the asset's value with uncertainty. She may be held liable for damages if she fails to disclose her private information to buyers. The more probable the seller is caught withholding her information, the less often she discloses.

The aforementioned papers take informativeness as an exogenously given parameter and investigate its impact on firms' voluntary disclosure decisions. Other research assumes that firms can autonomously choose the level of informativeness inherent in their disclosure (e.g., Titman and Trueman, 1986; Penno, 1996, 1997; Hughes and Pae, 2004; Edmans et al., 2016). Titman and Trueman (1986) incorporate this choice by letting firms hire different qualities of auditors and investment bankers, which in turn determines the quality of information transmitted to investors. The more favorable the firm's private information is, the higher the quality of information transferred. Contrary to this result, Penno (1996) predicts that management chooses high precision when the prospects are poor. The critical difference is that the author assumes that firms commit to a precision level prior to observing their private information. Hughes and Pae (2004) consider that the firm's information acquisition decision determines the information precision. It intertwines with voluntary disclosure such that under nondisclosure, investors cannot differentiate whether the firm has the information and chooses not to disclose it or the firm does not possess such information.

Moreover, several papers take a positive approach and investigate how an economy-wide disclosure quality can be established (see, for example, Dye and Sridhar, 2008; Bertomeu and Magee, 2011, 2015a; Bertomeu et al., 2019). Bertomeu and Magee (2011) assume that the majority of the firms vote for the reporting quality, i.e., the probability with which firm type is disclosed.

The second part of the thesis consists of Chapter 3 and Chapter 4 and focuses on the firms' non-financial information quality. The contribution of this part is twofold. In Chapter 3, I consider firms may only be able to disclose some of their non-financial information through a third-party (certifier). The imperfect certification thus determines firms' disclosure quality. I investigate how such imperfect certification affects firms' disclosure decisions. As a novelty, I combine the signaling game with a matching game. Whereas the second project in the thesis considers informativeness as exogenously given, the third model in Chapter 4 examines how an endogenously determined informativeness may influence firms' disclosure decisions. It explores the implication of recent technology development - blockchain to serve as a disclosure mechanism. More importantly, it examines how the new technology application may influence the information quality entering the public domain.

The remaining structure of the thesis is as follows: Chapter 2 begins by considering firms' disclosure behavior concerning their greenhouse gas emissions. Over the last decades, increasing awareness of climate change has brought transparency of firms' environment-related performance into the spotlight. Consequently, firms started to voluntarily disclose relevant information, including their greenhouse gas (GHG) emissions. However, anecdotal evidence shows the insufficiencies in firms' GHG emission disclosure (Alliance for Corporate Transparency, 2020) despite the surging demand. The U.S. Securities and Exchange Commission (SEC) recently proposed to mandate such disclosure (Securities and Exchange Commission, 2022). In the meantime, in the latest Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2022), the EU Commission extends the sustainability reporting requirements to all large companies and all listed companies. Both regulatory changes indicate that firms' voluntary disclosure fails to meet society's requirements, at least to a certain extent. I initiate the project to understand why unraveling does not occur regarding firms' GHG emission information.

On the one hand, disclosing GHG emission intensity levels assists investors, customers, and other stakeholders in evaluating firms' environmental performance. On the other hand, firms' emissions are associated with their operational activities. Revealing such information may thus unveil proprietary information regarding production and operation to competitors (Breuer et al., 2022; Ott et al., 2017). High-emission firms may gain a competitive advantage by disclosing their private information to competitors. But they also face potential adverse societal reactions, e.g., reduced product demand due to customers' dislikes. The model presented in Chapter 2 captures the trade-offs firms need to take when facing multiple information receivers with conflicting interests. In doing so, it investigates firms' incentives to disclose or withhold their GHG emission information.

The results show the potential existence of nondisclosure, full disclosure, and partial disclosure equilibria. However, full disclosure equilibrium never prevails. Moreover, a partial disclosure equilibrium in which only low-emission firms talk occurs when the adverse effect (demand reduction) of emissions is strong enough. On the contrary, a partial disclosure equilibrium where only high-emission firms disclose occurs only when the emissions' adverse effect is weak.

Beyond disclosing the emission status quo, society cares even more about whether and how firms are taking action to combat climate change. The model incorporates firms' abatement actions to understand how an emission reduction decision is made and how it also influences firms' disclosure decisions. Intuitively, firms are willing to reduce emissions only when the benefits outweigh the reduction costs. I show that mandating firms that would otherwise keep silent about their emission intensity levels may adversely affect some firms' emission reduction incentives.

Chapter 2 examines a setting in which firms' private signal is perfect, and disclosure must be truthful. I justify the truthful assumption by considering the increased level of verification mechanisms and high reputation loss on the firm level. Next, I relax this assumption in Chapter 3 and focus on non-financial information disclosure on the product level.

Information asymmetry is pronounced when individual consumers cannot verify private information easily, even after consumption. This is often the case when we talk about products' sustainable characteristics, such as information on their carbon footprint, the usage (or non-usage) of organic components, or the working conditions during production. Under such conditions, voluntary disclosure, or self-labeling in this context, may be deemed as cheap talk.[11] One prominent way to establish disclosure credibility is to use third-party certifications (e.g., Kirchhoff, 2000; Crespi and Marette, 2005; Baksi and Bose, 2007).[12] The second project in the thesis, "Dress up for the audience - Firms' signaling decisions when not all recipients care", investigates how imperfect certification may influence firms' disclosure behavior.

Another important characteristic of these hidden attributes is that not all consumers care or equally care about them. While some consumers are more aware and concerned with such attributes and ready to pay a price premium for products that meet their

[11] Government organizations often provide guidelines for such self-labeling. For example, the European Union provides guidelines for firms' environmental claims (see European Commission, 2021, 4.1.1). However, the monitoring effort is minimal (Kirchhoff, 2000).

[12] In the financial reporting domain, the role of certification, especially certification provided by auditors, in ensuring disclosure credibility is well recognized (see, for example, Minnis, 2011; Kausar et al., 2016).

needs (see, for example, Bjørner et al., 2004; Casadesus-Masanell et al., 2009; Carrington et al., 2021), others may not (e.g., De Pelsmacker et al., 2005; Rokka and Uusitalo, 2008; Hilger et al., 2019). Prior literature mostly considers homogenous suppliers with vertical product differentiation. They compete in a market in which consumers are either homogenous or uniformly distributed regarding their attitude towards the relevant product quality (e.g., De and Nabar, 1991; Ibanez and Grolleau, 2008; Mason, 2011; Bottega and De Freitas, 2019).

In my model, the product market consists of socially conscious and non-conscious consumers depending on their willingness to pay. In addition, competing firms may have different sizes. By combining a signaling game with a matching problem, I am able to investigate the impact of different shares of socially conscious consumers and different firm sizes on firms' decisions in seeking certification.

The model identifies equilibrium conditions under which different types of firms decide to seek certification. Third-party certifier quality negatively affects low-quality firms' incentive to seek certification. Notably, more socially conscious buyers attract a higher number of firms to label themselves, thus increasing the occurrence of equilibria in which either only high-quality or both types of firms seek certification. However, an increase in the share of conscious buyers does not monotonically reduce the occurrence of non-certification pooling equilibrium. Interestingly, once more than half of the consumers are conscious, further share expansion makes this pooling equilibrium more likely to occur. The matching schemes determine the impact of asymmetric firm size.

Whereas Chapter 3 focuses on the impact of an exogenously given assurance level, Chapter 4 investigates how late technological development, specifically blockchain applications, may serve as a disclosure mechanism and, more importantly, endogenously determine disclosure informativeness.

Over the last decades, the demand for real-time accounting has been on the surge. Technological development of the internet and Enterprise Resource Planning (ERP) system has enabled firms to provide real-time information. However, to ensure the credibility of such information, auditors (either under mandatory requirements or voluntary delegation) need to change their procedures from "mainly outcome-related to continuous, process-related audits" (Wagenhofer, 2007, p.117) (see also Alles et al., 2000). In comparison, the peer-to-peer network structure of blockchains provides an opportunity to autonomously deliver real-time information with an endogenously determined level of assurance.

However, before promoting such mechanisms, we must determine blockchains' ability in information provision. On the one hand, this ability depends on the firm-specific data profile. On the other hand, blockchain technology needs to exploit all the data in the network to provide a certain level of assurance. Thus the ability in information provision also depends on the number of firms adopting this technology. Incorporating these two fundamental features, we provide a theoretical model in which heterogeneous firms choose between adopting a blockchain or relying on traditional institutions to inform the capital market.

The results show that blockchains can improve the information environment through two channels. First, firms' adoption decisions may serve as a credible value signal. Second, the application analyzes all participating firms' data and uncovers firm value. However, we also characterize an equilibrium in which neither of the two channels realizes its potential, and information provision declines not only for individual firms but also in aggregate. This result highlights situations to which regulators and accounting professionals should pay particular attention.

Chapter 5 concludes the dissertation. The results from the three chapters are of interest to several parties. First, they assist investors and other stakeholders in evaluating firm value based on the firms' disclosure strategies. Second, this dissertation contributes theoretical insights for society on how to nudge firms to act in a certain way. Moreover, the findings also shed some light on constructing more efficient regulations. The discussed models can help regulators to assess the potential impact of different regulatory approaches on different firms. More importantly, they help regulators and other stakeholders to predict which firms are more likely to lobby against a regulation proposal or exercise discretions once the regulation comes into force.

2 Disclosure of greenhouse gas emissions[1]

2.1 Introduction

The U.S. Securities and Exchange Commission (SEC) recently proposed requiring U.S.-listed companies to disclose climate-related information including firms' greenhouse gas (GHG) emissions. Similarly, in the latest Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2022), the European Commission extends the sustainability reporting requirements to all large companies and all listed companies. To better evaluate the potential effects and the efficacy of such mandates, we first need to identify which firms will be influenced by the regulations the most, i.e., which are the non-disclosers under the voluntary disclosure regime. Furthermore, it is critical to understand whether and how the disclosure mandate will influence firms' GHG emissions. I propose an analytical model to investigate firms' emission investments and disclosure decisions.

[1]I thank Dirk Simons, Georg Schneider (GEABA discussant), Sebastian Kronenberger, Elisabeth Plietzsch, Felix Niggemann, Ulrich Schäfer, Jack Stecher and seminar participants at the University of Graz, University of Mannheim, University of Manchester and the SKEMA Business School for their helpful comments and suggestions. I further appreciate participants' comments at the 2022 Annual Meeting of the German Academic Association for Business Research (VHB), the 2022 EAA Annual Meeting in Bergen, and the 2021 TRR266 Annual Meeting. I also gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (Project-ID 403041268 -TRR 266) and the financial support of the J.P. Stiegler foundation.

Over the last decades, we have observed increased demand from different stakeholders for firms' environmental, social, and governance (ESG) information. Among others, customers and consumers utilize such information to make their purchase decisions (see, for example, PwC, 2021; Darendeli et al., 2022). In response to such demand, many firms have (gradually) voluntarily disclosed their GHG emissions through various channels, including providing relevant information to data providers, such as the Carbon Disclosure Project (CDP). Besides the actual emission levels, firms may also report plans or actions for emission reductions (e.g., Ramadorai and Zeni, 2022).[2] However, we also observe missing information or even missing disclosure from many others. An assessment report from the Alliance of Corporate Transparency shows that around two-thirds of Europe's largest companies mandated to disclose relevant non-financial information according to the European Commission (2014) fail to provide all pertinent information about GHG emissions.[3] Such a shortage can even be observed in high-impact industries, such as the energy sector (Alliance for Corporate Transparency, 2020).[4]

One may presume that firms that do not voluntarily provide such information must be poor performers since high-level emissions face various stakeholders' adverse reactions (e.g., Branco and Rodrigues, 2006; Sharfman and Fernando, 2008; Jouvenot and Krueger, 2020). For instance, consumers and corporate customers seem to shy away from high-emission suppliers (e.g., Casadesus-Masanell et al., 2009; Achtnicht, 2012; Mishal et al., 2017; Darendeli et al., 2022). It is thus natural to assume that firms with low emission levels would use disclosure to distinguish themselves. In a similar vein, some empirical studies find that more environmentally friendly, e.g., emitting less emissions, are more probable to be disclosed (e.g., Clarkson et al., 2008; Harris, 2019).

[2]Nevertheless, as Comello et al. (2021) noted, even within several large firms, some of these pledges do not include detailed progress reports, thus providing minimal information.

[3]Missing data includes not only the actual emission levels but also policies committed to mitigating the environmental impact.

[4]A similar result is shown by a review provided by the Climate Disclosure Standards Board (CDSB). It reviewed the 2019 climate-related disclosures of Europe's 50 largest listed companies. The results show that although all of them provide somewhat GHG emission information, only half of them provide all integral parts (see https://www.cdsb.net/eu-non-financial-reporting-directive/1047/78-europe's-largest-companies-falling-short-adequately).

However, there also exists evidence showing the opposite. Cho and Patten (2007) and Luo (2019) document that firms with poorer environmental performance, i.e., higher emissions, provide more disclosure. Anecdotal evidence also exhibits some reluctances to disclose from low-emission firms. It is suggested that emissions may reveal firms' proprietary information (see, for example, Ott et al., 2017; Breuer et al., 2022).

By incorporating these features of firms' emission information, I propose a model to investigate firms' emission disclosure and abatement decisions. To be more specific, I answer the question, are firms that voluntarily disclose their GHG emissions cleaner? Moreover, will mandating emission disclosure improve firms' environmental performance?

In the game, two firms engage in a Cournot competition and aim to maximize the period-end profits. Customers may dislike emissions associated with the products. As a result, disclosing such information may influence customer demand for the products. Both firms can conduct investments to reduce their emission intensities[5] and alleviate the negative impact on the demand.

Furthermore, firms' initial emission intensity level also reveals proprietary information about their productions (see, for example, Cropper and Oates, 1992; Färe et al., 2007; Oehmke and Opp, 2023). Emissions can be viewed as a proxy showing how the firm uses the environment in the production process (Copeland and Taylor, 2004; Färe et al., 2007; Tang et al., 2015). For relatively similar production technologies, it is often assumed that a clean policy associated with lower GHG emissions is linked with higher costs to produce the same goods. Following the consideration, I employ a production function assuming that a dirty environmental policy leads to a high input-output ratio and, at the same time, a high emission intensity level. Including the production function in the model further allows interaction between financial and non-financial information.

[5]Throughout the analysis, I interchange the terms "investment decisions" and "abatement activities".

I take two steps in the equilibrium analysis to isolate the disclosure driving forces and the investment decision-making process. In the baseline model, I neglect the investment decision (emission abatement possibility) and focus on firms' disclosure decisions regarding their initial emission intensity levels. Emission intensity disclosure first resolves information uncertainty. More importantly, it creates contradictory effects on the firm's profit due to the co-existence of the competitor and customers. I show conditions supporting nondisclosure and full disclosure equilibria. However, full disclosure equilibrium never prevails. Moreover, different partial disclosure equilibria may occur depending on the customers' dislike level. Nondisclosure is not an unambiguous signal of bad environmental performance.

In the general model, firms may actively decide to invest in an emission abatement project. I show that both the firm's and the competitor's abatement levels influence the firm's production decisions. Once an abatement activity is conducted, the firm prefers to disclose it.

Furthermore, disclosing a positive abatement level is not simply supplementary to the initial emission intensity level disclosure. Instead, it increases firms' incentive to reveal their high emission intensity levels and decreases their incentive to disclose their low emission intensity levels. As a result, when firms make emission-abatement investment decisions, they also need to consider the subsequent disclosure strategies.

I further reach an important regulation implication: mandating firms to disclose their initial emission intensity levels may adversely influence some firms' abatement decisions. Moreover, even when disclosure mandates encourage some firms to abate emission more, the overall impact on firms' total emissions is unclear.

This study contributes to a large and still growing body of literature considering different environmental, social, and governance (ESG) activities. Most theoretical studies in this area focus on firms' corporate social responsibility (CSR) activities (investments) and do not consider information asymmetry (e.g., Heinkel et al., 2001; Friedman and Heinle, 2016; Bagnoli and Watts, 2017; Albuquerque et al., 2019; Wu et al., 2020;

De Angelis et al., 2022). My study shows the importance of firms' disclosure strategies in investigating CSR investment decisions. Exceptions considering firms' disclosure decisions include Li et al. (1997), Sinclair-Desgagne and Gozlan (2003), Friedman et al. (2021), and Xue (2023). Whereas Sinclair-Desgagne and Gozlan (2003) and Xue (2023) focus on information precision, this paper investigates specifically firms' emission disclosure behavior. In my model, firms may choose to disclose, partially disclose, or withhold emission-relevant information. This setup is descriptive concerning the disclosure status quo (see, for example, Alliance for Corporate Transparency, 2020). In addition, Sinclair-Desgagne and Gozlan (2003) consider information to be the exogenously determined environmental risk. In comparison, I allow firms to reduce their emissions. By doing so, the model also brings insight into the firms' sustainable investment decisions.

Friedman et al. (2021) consider different aspects of firms' ESG actions and emphasize the salience of greenwashing. In contrast, I focus on the firms' emission disclosure strategies. Such focus allows the model to provide some testable empirical predictions. Several empirical studies investigate the determinants of the voluntary disclosure decision about the firm's CSR information (e.g., Clarkson et al., 2008; Cho and Patten, 2007; Ott et al., 2017; Harris, 2019; Luo, 2019). The results, however, are mixed. This model provides an opportunity to accommodate both observations.

I also contribute to the ongoing discussion of mandating firms' ESG information disclosure (see, for example, Bolton et al., 2021; Christensen et al., 2021; Christensen, 2022; Fiechter et al., 2022). Regarding the overall effect of emission disclosure regulations, both Downar et al. (2021) and Tomar (2023) document emission reductions following disclosure regulations. However, Yang et al. (2021) identify strategic actions taken by firms subject to the regulation. Bauckloh et al. (2023) show that although firms decrease their emission intensity level, their absolute emissions are not influenced by the mandate. My model results speak directly to the underlying mechanism.

This study also belongs to the large body of disclosure theory research. Studies in this area have long started to consider multiple information recipients. Examples like Darrough and Stoughton (1990), Wagenhofer (1990), and Gigler (1994) consider that both the product market and capital market are observing the information, or Arya et al. (2010) investigate the case in which firms are competing with multiple competitors in a multisegment product market. Following these arguments, both the competitor and customers in my model utilize firms' emission information in their decision-making process. In addition, I include a production function in the product-market setting. This inclusion further allows the interaction between GHG emissions and the firm's financial performance. Such interaction also puts us into the literature stream investigating interactions among multiple signals (e.g., Einhorn, 2005; Bagnoli and Watts, 2007; Guttman et al., 2014). Furthermore, the model contributes to the literature investigating the impact of firms' disclosure and/or disclosure regulations on corporate investment (see, for example, Kanodia and Sapra, 2016; Guttman and Meng, 2021).

This paper proceeds as follows. I describe the model setup and the key assumptions in Section 2.2. Section 2.3.1 contains the analysis of the baseline model, in which I omit the abatement possibility. In Section 2.3.2, the generalized setting allows firms to reduce their emission levels prior to disclosure and investigates how it affects the disclosure decisions. Section 2.4 discusses the regulation implication, and Section 2.5 concludes.

2.2 Model setup

I consider a single-period game in which two firms engage in Cournot competition. Subscripts i and j are used to denote each firm with $i, j \in \{1, 2\}$ and $i \neq j$. Two distinct features are incorporated into the model. First, I explicitly include a production function in the product-market setting. Such inclusion allows interactions between financial and non-financial information. Second, customers in the market may dislike emissions associated with the products.

Firms' GHG emissions are associated with their production process. For firms possessing similar production technologies, applying a cleaner policy requires the firm to deploy more resources, such as capital and labor, to monitor and reduce emissions. As a result, on the one hand, a cleaner policy generates a lower level of GHG emissions during production. On the other hand, for the same level of outputs, the firm with a cleaner policy has a higher input level. The following production function represents the interdependence between the firm's production performance and its environmental policy:[6]

$$q_i = a_i \cdot x_i, \tag{2.1}$$

where q_i and x_i denote firm i's output and input quantities, respectively. x_i is provided at a marginal cost $c_i \in [\underline{c}, \bar{c}]$, which is exogenous given and known to all. a_i indicates the given environmental policy's input-output ratio. This ratio can be measured by the firm's initial emission intensity level. For simplicity, let a_i also represent this intensity level.[7] I assume independence between the input cost and the firm's initial emission intensity level.

I develop the model details and assumptions with the timeline illustrated in Figure 2.1. The model's main notations are summarized in Table A.1 in Appendix A.1.

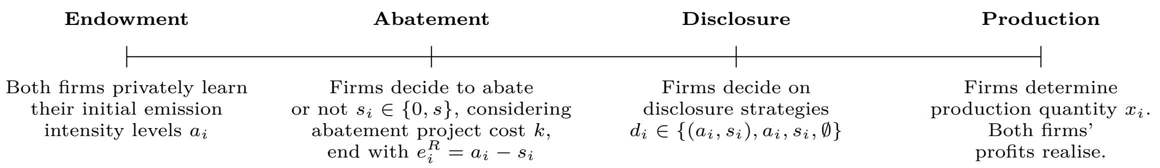
Endowment stage

At this stage, both firms privately observe their own initial emission intensity levels, i.e., the benchmark input-output ratio a_i, drawn from a continuous distribution with

[6] There are two ways to introduce emissions into production models, either as inputs or as outputs (Färe et al., 2007). The production function used in this model treats emissions as input and captures how firms exploit or even abuse the environment in the production process (see also Cropper and Oates, 1992; Keilbach, 1995; Landier and Lovo, 2020; Landier et al., 2022).

[7] The equality is not an essential requirement of the model. Any one-to-one mapping relationship can be employed, as long as it allows the firm's initial emission intensity level to be used to deduce the firm's environmental policy.

Figure 2.1: Timeline of events



p.d.f. $f(.)$, c.d.f. $F(.)$ and support $A = [1, \bar{a}]$. The mean of the distribution is denoted μ.

Abatement stage

After privately and perfectly observing their initial emission intensity level a_i, both firms can decide whether or not to conduct an investment project to abate their emissions. Such an investment project can be purchasing emission offset credits, transforming the production line to be more energy efficient, or applying some emission capture technology.

Conducting such activity can reduce the emission intensity level by s. I restrict the abatement level $s \in (0, 1]$, such that the emission intensity level always remains non-negative.[8] The investment decision is thus binary and denoted $s_i \in \{0, s\}$.[9] The chosen level is unobservable to outsiders. Investing in such a project requires the firm to bear a lump sum cost k. Examples of the cost are a capital investment in new machinery, purchasing price for carbon credits, etc. We thus have $C_i(s_i) \in \{0, k\}$.

Abatement activity is set up so that the production process is not affected. They only reduce the overall emissions to a residual level. In the following, I abuse the notion s_i and use it to indicate the firm i's abatement level at the same time. The residual emission intensity level is thus $e_i^R = a_i - s_i$.

[8]Although some companies, such as Microsoft, have set their goals of becoming not just carbon neutral but carbon negative, they are not the majority. In addition, it is still unclear whether a negative emission will trigger customers to consume more products than they would, should emission is not considered.

[9]In Appendix A.5, I relax the binary setting and consider a continuous abatement level together with variable abatement cost. The main results do not change qualitatively.

Disclosure stage

Until this stage, firms privately observe their own initial emission intensity levels and the abatement levels. Before making production decisions, both firms can decide to disclose both, one of, or even none of the two signals. We have $d_i \in \{(a_i, s_i), a_i, s_i, \emptyset\}$.

I assume that disclosed information is credible[10] and that there is no direct cost associated with disclosure. Upon observing the firm's disclosure strategy, both the competitor and customers update their beliefs. Note that they use the information to derive two values: $E[a_i|d_i]$ and $E[e_i^R|d_i]$ (equivalently $E[s_i|d_i]$).

Production stage

Following Vives (1984) and Singh and Vives (1984), I consider a continuum of customers with the same utility function that is separable and linear in the product. One additional feature here is that the product's emission intensity level decreases the customers' utilities from consumption (Michel and Rotillon, 1995; Elhadj and Tarola, 2015). I express this utility of a representative consumer from consuming q_1 and q_2 quantity of products from both firms as follows:[11]

$$U(q_1, q_2) = (b - \beta \cdot e_1^R)q_1 + (b - \beta \cdot e_2^R)q_2 - \frac{1}{2}(q_1^2 + 2\gamma q_1 q_2 + q_2^2), \tag{2.2}$$

where b is a positive constant that captures the size of the market. Variable $\beta \geq 0$ measures the customers' average dislikes over emissions, and $\gamma \in (0, 1]$ denotes the degree of substitution between the products from both firms.

The representative consumer chooses the quantities of each product to maximize her preference $U(q_1, q_2) - \sum_{i=1}^{2} p_i q_i$. This leads us to the following standard linear (inverse) demand function:

$$p_i = b - \beta \cdot e_i^R - q_i - \gamma q_j, \quad \forall (i, j) \quad i \neq j \tag{2.3}$$

[10]This assumption can be justified by the increased level of verification mechanisms as well as the potential loss in case of lying.

[11]When disclosure decision is included, e_i^R in (2.2) is replaced by $\mathrm{E}[e_i^R|d_i]$. This follows in (2.3) and (2.4).

At the production stage, both firms determine their input quantities for the production and aim to maximize the period end profit (π_i), which is the product market profit (π_i^P) reduced by the abatement cost $C_i(s_i)$. We can express it as follows:

$$\begin{aligned}\pi_i &= \pi_i^P - C_i(s_i)\\ &= p_i \cdot q_i - x_i \cdot c_i - C_i(s_i)\\ &= (b - \beta \cdot e_i^R - a_i \cdot x_i - \gamma \cdot q_j) \cdot a_i \cdot x_i - x_i \cdot c_i - C_i(s_i) \qquad (2.4)\end{aligned}$$

To ensure a positive input quantity even under the "least favorable condition", we assume that $b > \beta\mu + \frac{2\bar{c}-\gamma\underline{c}}{\mu(2-\gamma)}$.[12]

I apply the concept of **Perfect Bayesian Equilibrium** for the analysis.

2.3 Equilibrium analysis

To isolate the drivers for firms' disclosure decisions and the impact of firms' abatement activities, I solve the problem in two steps. In the baseline model, I omit the emission abatement possibility.

2.3.1 Baseline setting - abatement is omitted

Since we do not consider the abatement activities, disclosure strategies here are restricted to either disclosing or withholding the initial emission intensity level, $d_i^b \in \{a_i, \emptyset\}$.[13] I define the nondisclosure set as N^b, $N^b \subseteq A$. That is to say, when $a_i \in N^b$, $d_i = \emptyset$.

After observing firms' disclosure decisions, both the competitor and customers update their beliefs and reach either $E[a_i|d_i^b = a_i] = a_i$ or $E[a_i|d_i^b = \emptyset]$. The latter follows

[12] The derivation can be found in Appendix A.2.

[13] Superscription b indicates the baseline model. Superscription s in later sections indicates the general model in which a positive abatement is considered.

Bayes' rule. The firms then make their production decisions accordingly. The firms' objective here is to maximize their product market profits:

$$\max_{d_i^b, x_i^b} E[\pi_i] = \max_{d_i^b, x_i^b} E[\pi_i^P] \tag{2.5}$$

Production decisions

Use backward induction to solve the game. We first determine each firm's production level.

Given the disclosure strategy d_i^b, firm i determines its input quantity x_i^b such that:

$$x_i^{b*} \in \arg\max_{x_i^b} E[\pi_i^P | d_i], \tag{2.6}$$

where

$$\begin{aligned} \mathrm{E}[\pi_i^P | d_i] &= q_i \cdot \mathrm{E}[p_i | d_i] - c_i \cdot x_i^b \\ &= (b - \beta \mathrm{E}[a_i | d_i^b] - a_i x_i^b - \gamma \mathrm{E}[q_j | d_j]^{b \cdot Conj}) \cdot a_i x_i^b - c_i x_i^b \end{aligned} \tag{2.7}$$

We can derive the Nash Equilibrium input quantity for firm $i, j \in \{1, 2\}$ in Lemma 2.1:

Lemma 2.1 *For firm i with a_i, without abatement activities, the optimal input quantity following given disclosure decisions d_i & d_j is:*

$$\begin{aligned} x_i^{b*} = &\frac{a_i \mathrm{E}[a_j|d_j]\Big[2(b - \beta \mathrm{E}[a_i|d_i]) - \gamma(b - \beta \mathrm{E}[a_j|d_j])\Big] - 2\mathrm{E}[a_j|d_j]c_i + \gamma a_i c_j}{(4a_i - \gamma^2 \mathrm{E}[a_i|d_i]) a_i \mathrm{E}[a_j|d_j]} \\ &- \frac{a_i \mathrm{E}[a_j|d_j]\Big[2\gamma \mathrm{Cov}[a_j, x_j|d_j] - \gamma^2 \mathrm{Cov}[a_i, x_i|d_i]\Big]}{(4a_i - \gamma^2 \mathrm{E}[a_i|d_i]) a_i \mathrm{E}[a_j|d_j]} \end{aligned} \tag{2.8}$$

Proof. See Appendix A.3.1. □

The equilibrium product market profit satisfies $\pi_i^{P*} = (x_i^{b*})^2 \cdot a_i^2$.[14]

[14]Proof see (A.21).

Lemma 2.1 shows that firm i's optimal input quantity (x_i^{b*}) increases with the decrease of the firm's own cost level (c_i) and the increase of the competitor's cost level (c_j). These factors also have the same directional impact on the equilibrium profit. Intuitively, higher production costs undermine the firm's competitive advantage, and lead to a lower firm profit. On the contrary, a higher competitor's production cost is conducive to the firm and results in higher firm profit.

In comparison, the impact of both the firm's initial emission level (a_i) and the competitor's (a_j) on the firm's profit is not monotone. Let's assume that no information asymmetry exists, i.e., the emission information is perfectly known by all, $E[a_i|d_i] = a_i$ and $E[a_j|d_j] = a_j$. A higher firm's own emission level leads to a higher production profit when the customers' dislike of high emissions is low enough ($\beta < c_i/a_i^2$).[15] Once β exceeds the threshold, a higher emission intensity level oppositely leads to lower firm profit. Two aspects need to be pointed out. First, high emission intensity level creates a competitive advantage. However, it also has a negative impact on the firm's profit by reducing product demand. The impact of the emission level on firms' production quantities thus depends on the level of customers' dislike. Second, the threshold for customers' dislike level is determined by the relationship between the firm's input cost c_i and its initial emission intensity level. It is because a high emission level can increase the firm's profit by saving production costs. The larger the input cost, the higher the positive effect of high emission level on the profit, and the higher the threshold for β. The competitor's emission intensity level has exactly the opposite effect on the firm's profit. A higher competitor's emission level leads to lower firm profit when the customers' dislike level is low enough. The threshold here is c_j/a_j^2, which corresponds to the relative impact of the competitor's emission level on the competition.

The results show that the firm's emission disclosure is not a standalone decision. The firm's financial information—the marginal input cost $c_{i/j}$ in the model—plays an important role in shaping the emission disclosure decision-making.

[15] The results' derivation can be found in Appendix A.2.

Disclosure decisions

Now we turn to firms' emission disclosure decisions.

We know that $\pi_i^{P*} = x_i^{*2} \cdot a_i^2$. Under the restriction that $x_i \geq 0$, maximizing the expected product market profit is thus equivalent to maximizing the expected input quantity. That is to say, for firm i with the initial emission intensity level a_i:

$$\arg\max_{d_i^b} E[\pi_i^P | d_i^b] = \{d_i | E[x_i^b | d_i^b] \geq E[x_i^b | d_i^{b'}], \forall d_i^{b'}\}. \tag{2.9}$$

At this stage, firm i privately learns its initial emission intensity level a_i. However, it still holds the prior belief about the competitor's level. That is to say, $E[E[a_j|d_j]] = E[a_j] = \mu$. I further use "$\widehat{\ }$" to denote the posterior belief following a given disclosure strategy. Inserting these into the (expected) optimal input quantity (2.8) in Lemma 2.1, we get:

$$E[x_i^{b*}|d_i] = \frac{2a_i\mu(b - \gamma H - \beta\widehat{a}_i) - \gamma a_i\mu(b - \beta\mu) - 2\mu c_i + \gamma a_i c_j + a_i\mu\gamma^2 \mathrm{Cov}[a_i, x_i|d_i]}{(4a_i - \gamma^2\widehat{a}_i)a_i\mu}, \tag{2.10}$$

where H denotes the ex-ante covariance between a_j and x_j, $j \in \{1, 2\}$ (see (A.22)):

$$\begin{aligned} H &= \mathrm{E}[\mathrm{E}[\mathrm{Cov}[a_j, x_j^*|d_j]]] = \mathrm{E}[\mathrm{Cov}[a_j, x_j^*]] \\ &= \frac{\mu[2b - \gamma(b - \beta\mu)] + \gamma c_j}{(4-\gamma^2)\mu} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}] - \frac{2c_i}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i^2}] \\ &= \underbrace{\frac{\mu[2-\gamma]b + \gamma c_j}{(4-\gamma^2)\mu} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}] - \frac{2c_i}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i^2}]}_{K} + \frac{\gamma\beta\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}]. \end{aligned}$$

Equation (2.10) highlights the key drivers of the firm's disclosure decision. Above all, disclosing the initial emission intensity resolves information uncertainty. This is because $\mathrm{Cov}[a_i, x_i|d_i = a_i] = 0$. However, depending on the distribution function, $\mathrm{Cov}[a_i, x_i]$ may take a positive or negative value.

More importantly, the disclosure decision creates contradictory effects on the input quantity due to different information recipients. By disclosing its emission level, a high-emission firm may intimidate the competitor and earns a high product market profit. This corresponds to the positive effect of being perceived as a high-emission firm in (2.10)'s denominator. However, being perceived as a dirty firm also leads to a potential demand reduction. Hence the negative effect in the numerator. Firms thus trade off the competition effect and the demand effect and make their disclosure decisions. When the benefits outweigh the loss, firms with high emission levels disclose their private information. Firms with lower emission levels take the exact opposite consideration.

I denote the posterior belief of the firm's emission intensity level upon observing nondisclosure a_p.[16] In the baseline model, firms compare the expected input quantity following disclosing and non-disclosing a_i and make their disclosure decisions. These input quantities are:

$$E[x_i^{b*}|d_i^b = a_i] = \frac{2a_i\mu(b - \gamma H - \beta a_i) - \gamma a_i\mu(b - \beta\mu) - 2\mu c_i + \gamma a_i c_j}{(4a_i - \gamma^2 a_i)a_i\mu} \tag{2.11}$$

$$E[x_i^{b*}|d_i^b = \emptyset] = \frac{2a_i\mu(b - \gamma H - \beta a_p^b) - \gamma a_i\mu(b - \beta\mu) - 2\mu c_i + \gamma a_i c_j + a_i\mu\gamma^2\mathrm{Cov}[a_i, x_i|\emptyset]}{(4a_i - \gamma^2 a_p^b)a_i\mu} \tag{2.12}$$

Restrict the attention to symmetric equilibria. We face three types of disclosure strategies : (i)a nondisclosure equilibrium where firms never disclose their emission intensity level a_i ($N^b = A$); (ii) a full disclosure equilibrium where firms always disclose their emission intensity level ($N^b = \emptyset$); and (iii) a partial disclosure equilibrium where firms only disclose their emission intensity levels when the level belongs to a subset of the support ($N^b \subset A$). I first characterize the non- and full disclosure equilibria.

[16]The posterior belief follows Bayes' rule whenever is possible. Given full disclosure, I assume the off-path belief to be $a_p^b = E[a_i|d_i^b = \emptyset] = \mu$ and $\mathrm{Cov}[a_i, x_i|d_i^b\emptyset] = H$.

Proposition 2.1 *Nondisclosure equilibrium ($N^b = A$) exists if and only if the following condition holds:*

$$\max\{\beta^b_{thres}|a_i \in (\mu, \bar{a}]\} \leq \beta \leq \min\{\beta^b_{thres}|a_i \in [1, \mu)\}$$

Moreover, nondisclosure equilibrium can only occur when $H > 0$.
On the contrary, full disclosure equilibrium ($N^b = \emptyset$) exists if and only if the following condition holds:

$$\max\{\beta^b_{thres}|a_i \in [1, \mu)\} \leq \beta \leq \min\{\beta^b_{thres}|a_i \in (\mu, \bar{a}]\}$$

And it can only occur when $H < 0$.
β^b_{thres} is defined as:

$$\beta^b_{thres} = \frac{\gamma^2\Big((b\mu(2-\gamma) - 2\mu\gamma K + \gamma c_j)a_i - 2\mu c_i - \frac{(4-\gamma^2)\mu K a_i^2}{a_i - \mu}\Big)}{\mu a_i\Big(8a_i - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2}\text{Cov}[a_i, \frac{1}{a_i}] + \frac{\gamma^3 a_i \mu}{a_i - \mu}\text{Cov}[a_i, \frac{1}{a_i}]\Big)}$$

Proof. See Appendix A.3.2. □

The mechanism here corresponds to the three effects the emission information has. When β is either very weak or very strong, either the competition effect or the demand effect dominates. Under this condition, the very clean or the very dirty firms have strong incentives to disclose or withhold their emission intensity level. Non- or full disclosure equilibria thus cannot occur.

More importantly, nondisclosure equilibrium cannot occur when the ex-ante covariance between a_i and x_i is negative. This is because disclosing the emission intensity level always affects the input quantity positively by reducing the negative covariance impact. Take $a_i = \mu$ as the example. Without considering the information uncertainty, it is indifferent between not disclosing and deviating from the nondisclosure equilibrium. However, it strictly prefers to disclose since disclosing reduces the negative effect of information uncertainty. On the contrary, when the ex-ante covariance is positive, full disclosure equilibrium cannot be supported even if we relax the off-path belief.

Next, I characterize the partial disclosure equilibrium in Proposition 2.2.

Proposition 2.2 *A partial disclosure equilibrium is characterized by the following nondisclosure set:*

$$N^b = [1, \bar{a}] \cup \Big([a_1^b, a_2^b] \cap [a_3^b, \infty) \Big), \quad N^b \subset A = [1, \bar{a}],$$

in which $a_i = a_1^b$, $a_i = a_2^b$, $a_i = a_3^b$ *solves the following equation with* $a_1^b \leq a_2^b \leq a_3^b$*:*

$$(a_i - a_p^b)(a_i - a_l^b)(a_i - a_h^b) = -\frac{(4-\gamma^2)\gamma^2 \mathrm{Cov}[a_i, x_i|\emptyset]}{8\beta} \cdot a_i^2. \tag{2.13}$$

Further

$$a_p^b = \mathrm{E}[a_i | a_i \in N^b], \tag{2.14}$$

$$\begin{aligned} \mathrm{Cov}[a_i, x_i | a_i \in N^b] = & \frac{\mu[2b - \gamma(b - \beta\mu)] + \gamma c_j}{(4-\gamma^2)\mu} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i} | a_i \in N^b] \\ & - \frac{2c_i}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i^2} | a_i \in N^b]. \end{aligned} \tag{2.15}$$

and

$$a_l^b = \frac{L - \sqrt{L - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}, \tag{2.16}$$

$$a_h^b = \frac{L + \sqrt{L - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}. \tag{2.17}$$

$$L = \gamma^2 \Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j \Big)$$

Proof. See Appendix A.3.2. □

We further illustrate the necessary conditions supporting partial disclosure equilibrium in Corollary 2.1.

Corollary 2.1 *A partial disclosure equilibrium in which firms only disclose low emission intensity levels occurs when the customers' dislike level is strong enough:*

$$\beta > \beta_3^b \tag{2.18}$$

On the contrary, a partial disclosure equilibrium in which firms only disclose high emission intensity levels occurs when the customers' dislike level is low enough:

$$\beta < \beta_4^b \tag{2.19}$$

When the customers' dislike level is intermediary, we may observe mediocre firms disclose or withhold their information.

β_3^b *and* β_4^b *are characterized by*

$$\beta_3^b = \frac{\gamma^2[(2-\gamma)\mu b - 2\gamma\mu K - 2\mu c_i + \gamma c_j]}{\mu(8 - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{2.20}$$

$$\beta_4^b = \frac{\gamma^2[(2-\gamma)\bar{a}\mu b - 2\gamma\bar{a}\mu K - 2\mu c_i + \gamma\bar{a} c_j]}{\bar{a}\mu(8\bar{a} - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{2.21}$$

Proof. See Appendix A.3.2 for a detailed elaboration of necessary conditions supporting any potential partial disclosure equilibrium. □

The intuition behind Corollary 2.1 again speaks to the disclosure's contradictory effect due to the two information recipients. When the customer's dislike level is low enough, the competition effect dominates. An equilibrium in which firms are only willing to talk when their emission intensity levels are high can only be supported here. On the contrary, the demand effect dominates when β is strong enough. Only then a partial disclosure equilibrium in which firms only reveal low emission intensity levels can be supported.

Moreover, when β is of intermediate level, we may face mediocre firms disclosing or withholding their information. Overall, nondisclosure is not an unambiguous bad signal regarding firms' environmental performance.

Corollary 2.2 *Full disclosure equilibrium never prevails.*

Proof. Following Proposition 2.1, full disclosure equilibrium only occurs when the ex-ante covariance is negative ($H < 0$). Multiplicity arise since partial disclosure equilibrium may occur under the condition. Consequently, there are always firms prefer non-disclosure since $\mathrm{E}[x_i^{b*}|d_i = \emptyset] > \mathrm{E}[x_i^{b*}|d_i = a_i]$. □

The implication from Corollary 2.2 responds to the current insufficient emission disclosure status quo.

2.3.2 General case

After isolating the firms' disclosure determinants, we now incorporate the firms' abatement activities into the consideration. The firm's objective function is now extended as follows:

$$\begin{aligned}\max_{s_i,d_i,x_i} E[\pi_i] &= \max_{s_i,d_i,x_i} E[\pi_i^P] - C_i(s_i) \\ &= \max_{s_i,d_i,x_i} (b - \beta E[e_i^R|d_i] - a_i x_i - \gamma E[q_j|d_j]^{Conj}) \cdot a_i x_i - c_i x_i - C_i(s_i) \quad (2.22)\end{aligned}$$

We again use backward induction to determine firms' decisions.

Production decisions

Compared to the baseline model, abatement activity allows the firm to alleviate customers' dislikes and thus influences the firm's production decision. Given abatement decision s_i and disclosure strategy d_i, firms make the production decision to maximize their profit, which is equivalent to choosing the input quantity to maximize the expected product market profit since now the abatement cost is sunk.

$$x_i \in \arg\max E[\pi_i^P | s_i, d_i] \tag{2.23}$$

I still use "$\widehat{\ }$" to indicate the posterior belief. Solving the maximization problem leads to the equilibrium input quantity:

$$\begin{aligned} x_i^* =& \frac{2a_i\widehat{a_j}\Big[b-\beta(\widehat{a_i}-\widehat{s_i})\Big]-\gamma a_i\widehat{a_j}\Big[b-\beta(\widehat{a_j}-\widehat{s_j})\Big]-2\widehat{a_j}c_i+\gamma a_i c_j}{(4a_i-\gamma^2\widehat{a_i})a_i\widehat{a_j}} \\ &-\frac{a_i\widehat{a_j}\Big[2\gamma \text{Cov}[a_j,x_j|d_j]-\gamma^2\text{Cov}[a_i,x_i|d_i]\Big]}{(4a_i-\gamma^2\widehat{a_i})a_i\widehat{a_j}} \end{aligned} \tag{2.24}$$

It still follows that $\pi^{P*} = x_i^{*2} a_i^2$.

Both the firm's and the competitor's abatement activities affect the firm's production decisions. Specifically, the increase in the perceived firm's abatement level ($\widehat{s_i}$) and the decrease in the expected competitor's abatement level ($\widehat{s_j}$) increase the firm's input quantity and, consequently, the firm's product market profit. This is consistent with the empirical evidence showing that peers' emission performance and disclosure have an impact on firms' real decisions (Tomar, 2023).

Disclosure decisions

We now move to the disclosure stage. Following the same line of argument in the baseline model, the choice of disclosure strategy is again to maximize the expected input quantity since, at this stage, the abatement cost is sunk. We again have $\text{E}[a_j] = E[\widehat{a_j}] = \mu$, and $\text{E}[\text{E}[\text{Cov}[a_j, x_j^*|d_j]]] = \text{E}[\text{Cov}[a_j, x_j^*]] = H$. Thus, the expected input quantity following a given disclosure strategy d_i is:

$$\text{E}[x_i|d_i] = \frac{2a_i\mu\Big[b-\gamma H-\beta(\widehat{a_i}-\widehat{s_i})\Big]-\gamma a_i\mu\Big[b-\beta(\mu-\widehat{s_j})\Big]-2\mu c_i+\gamma a_i c_j+a_i\mu\gamma^2\text{Cov}[a_i,x_i|d_i]}{(4a_i-\gamma^2\widehat{a_i})a_i\mu} \tag{2.25}$$

Clearly, we have $\frac{\partial \mathrm{E}[x_i|d_i]}{\partial \widehat{s_i}} > 0$. That is to say, the firm's expected abatement level is positively correlated with its expected input quantity, it is intuitive to arrive at the following observation:

Observation 2.1 *For firms with positive abatement levels, without considering the impact on the perceived initial emission intensity level, it is always preferable to disclose such information.*

This leads to a direct result: for firms with a positive abatement level ($s_i > 0$), disclosure strategy $\{a_i, s_i\}$ strictly dominates $\{a_i\}$. However, one question remains: will firms' abatement disclosure only be supplementary to the disclosure of the initial emission intensity level? Namely, will firms stay with the disclosure strategy determined in the baseline model and disclose positive abatement activities in addition? To answer this question, we again need to compare the expected optimal input quantity following different disclosure strategies.

We differentiate two cases: (1) no emission abatement is executed by firm i at stage 2; (2) firm i has initiated the emission reduction project and reduces the emission intensity level by s.

In case (1), since no abatement activity is conducted, firms again can only decide to disclose or withhold the initial emission intensity level. The analysis then fully coincides with the baseline model analysis.

In case (2), following Observation 2.1, at the disclosure stage, firms choose between fully disclosing the emission-related information ($d_i = (a_i, s_i)$) or withholding the initial emission intensity level ($d_i = s_i$). We have $\widehat{s_i} = s_i = s$. I refer to nondisclosure in this case as not disclosing the firm's emission intensity level and define the nondisclosure set as N^s, $N^s \subseteq A$. We thus have, when $a_i \in N^s$, $d_i = s_i$. When $a_i \in (A \setminus N^s)$, $d_i = (a_i, s_i)$.

We again face the same structure of potential disclosure equilibria characterized in Proposition 2.1 and Proposition 2.2.[17] Firms' positive abatement level changes the β conditions that support different disclosure equilibria.

Overall, positive abatement increases high-emission firms' incentive to disclose their emission intensity levels. This is because positive abatement activity mitigates the negative impact of high emissions on product demand, such that high-emission firms can better exploit the competitive advantages. On the contrary, positive abatement decreases low-emission firms' incentive to disclose.

Such effects consequently influence the occurrence of partial disclosure equilibria, which is summarized in Corollary 2.3:

Corollary 2.3 *A positive abatement level decreases the necessary β condition supporting the partial disclosure equilibrium in which only low emission firms disclose; increases the possibility of partial disclosure equilibrium in which only high emission firms disclose to occur.*

Proof. See Appendix A.4.1. □

Abatement decisions

Lastly, we turn to the firms' abatement decisions. Clearly, firms decide to reduce their emission intensity level once the benefit from such reduction exceeds the cost. However, while the abatement cost is fixed, benefits construction is not straightforward. Whereas positive abatement increases the firm's input quantity and, consequently, its profit, it also changes firms' disclosure behavior. The comparison between conducting the abatement activity and not thus needs to include the subsequent (equilibrium) disclosure decisions.

From the disclosure strategy analysis, we can conclude that information recipients can always correctly infer firms' abatement level based on firms' disclosure strategies.

[17] See Appendix A.4.1 for a detailed elaboration on disclosure equilibria and the necessary β conditions.

I thus use $x_i(\widehat{a}_i, s_i, \mathrm{Cov}[a_i, x_i|d_i^*])$ to indicate the optimal input quantity following the given abatement decision and equilibrium disclosure strategy. That is to say

$$
\begin{aligned}
& x_i(\widehat{a}_i, s_i, \mathrm{Cov}[a_i, x_i|d_i^*]) \\
=& E[x_i|s_i, d_i^*] \\
=& \frac{2a_i\mu\Big[b-\gamma H-\beta(\widehat{a}_i-s_i)\Big]-\gamma a_i\mu\Big[b-\beta(\mu-\widehat{s}_j)\Big]-2\mu c_i+\gamma a_i c_j+a_i\gamma^2\mu\mathrm{Cov}[a_i,x_i|d_i^*]}{(4a_i-\gamma^2\widehat{a}_i)a_i\mu}
\end{aligned}
\tag{2.26}
$$

Consider firms' disclosure strategies with or without abatement activities. We may face the following four scenarios:

- Firm i does not disclose its initial emission intensity level with or without abatement activity ($a_i \in N^s \cup N^b$). The firm thus compares the following two profits to make the abatement decision:

$$E[\pi|s_i = s] = a_i^2 \cdot x_i^2(a_p^s, s, \mathrm{Cov}[a_i, x_i|N^s]) - k$$

vs.

$$E[\pi|s_i = 0] = a_i^2 \cdot x_i^2(a_p^b, 0, \mathrm{Cov}[a_i, x_i|N^b])$$

The firm only undertakes the abatement project when the cost is below threshold k_1, where

$$k_1 = a_i^2 \cdot \Big(x_i^2(a_p^s, s, \mathrm{Cov}[a_i, x_i|N^s]) - x_i^2(a_p^b, 0, \mathrm{Cov}[a_i, x_i|N^b])\Big) \tag{2.27}$$

- Firm i always discloses its initial emission intensity level ($a_i \in (A\backslash N^s)\cup(A\backslash N^b)$). The abatement cost threshold for the firm is thus:

$$
\begin{aligned}
k_2 &= a_i^2 \cdot \Big(x_i^2(a_i, s, 0) - x_i^2(a_i, 0, 0)\Big) \\
&= a_i^2 \frac{4\beta s\Big[2a_i\mu\Big(b-\gamma H-\beta a_i\Big)-\gamma a_i\mu\Big(b-\beta(\mu-\widehat{s}_j)\Big)-2\mu c_i+\gamma a_i c_j+a_i\mu\beta s\Big]}{(4a_i-\gamma^2 a_i)^2 a_i\mu}
\end{aligned}
\tag{2.28}
$$

- Firm i chooses not to disclose when it decided to reduce the emission by s, but discloses a_i had it not conducted the abatement ($a_i \in N^s \cup (A \setminus N^b)$). The comparison of profits with or without abatement leads to the following abatement cost threshold:

$$k_3 = a_i^2 \cdot \Big(x_i^2(a_p^s, s, \mathrm{Cov}[a_i, x_i|N^s]) - x_i^2(a_i, 0, 0)\Big) \tag{2.29}$$

- Firm i chooses to disclose when it decided to reduce the emission by s, and not to disclose when abatement is not conducted ($a_i \in (A \setminus N^s) \cup N^b$). We then have the following abatement cost threshold:

$$k_4 = a_i^2 \cdot \Big(x_i^2(a_i, s, 0) - x_i^2(a_p^b, 0, \mathrm{Cov}[a_i, x_i|N^b])\Big) \tag{2.30}$$

To elaborate it further, consider that nondisclosure equilibrium occurs both with or without abatement activities. Firm i always withholds its emission intensity level. In both cases, $a_p = \mu$, and $\mathrm{Cov}[a_i, x_i|N] = H$. The firm thus compares the following two profits to make the abatement decision:

$$E[\pi|s_i = s, d_i = \emptyset] = a_i^2 \cdot x_i^2(\mu, s, H) - k$$

vs.

$$E[\pi|s_i = 0, d_i = \emptyset,] = a_i^2 \cdot x_i^2(\mu, 0, H).$$

It only undertakes the abatement project when the cost is below threshold k_5, where

$$\begin{aligned} k_5 &= a_i^2 \cdot \Big(x_i^2(\mu, s, H) - x_i^2(\mu, 0, H)\Big) \\ &= a_i^2 \frac{4\beta s\Big[2a_i\mu\Big(b - \gamma H - \beta\mu\Big) - \gamma a_i\mu\Big(b - \beta(\mu - \widehat{s_j})\Big) - 2\mu c_i + \gamma a_i c_j + a_i\gamma^2\mu H + a_i\mu\beta s\Big]}{(4a_i - \gamma^2\mu)^2 a_i\mu}. \end{aligned} \tag{2.31}$$

Clearly, the firm's prospective disclosure strategy plays a vital role in shaping its abatement decision. Forcing firms that would otherwise keep silent to reveal their emission intensity level thus may influence their abatement activities.

2.4 Implication on regulations

As the model identifies, despite the increased demand for the firms' GHG emission information, we still observe a relatively low level of information provision. In response to such unbalanced information demand and supply, regulators like the SEC and the EU Commission are setting up new regulations requiring more firm disclosure. Furthermore, the EU Commission aims to encourage firms to behave more sustainably through increased transparency.

Concerning information provision, we need to bear the following points in mind. The practice in the EU after the promulgation of the Non-financial Reporting Directive (European Commission, 2014) shows that, due to the complexity of emission scopes,[18] horizon, and measurement issues (Comello et al., 2021), disclosure regulations in this area may remain symbolic (Haji et al., 2022). Moreover, the model shows that firms with positive abatement activities prefer to disclose such information. Disclosure mandates regarding firms' actions in reducing their GHG emissions thus may not be necessary.

Impact on abatement incentives

Beyond forcing firms to provide stakeholders with sufficient information, disclosure regulations may also influence firms' investment decisions. Downar et al. (2021) and

[18]The Greenhouse Gas Protocol distinguishes between three different sources of emissions: Scope 1 are the direct GHG emissions, which "occur from sources that are owned or controlled by the company"; Scope 2 are electricity indirect GHG emissions. They "come from the generation of purchased electricity consumed by the company". Scope 3 emissions are caused by "the activities of the company, but occur from sources not owned or controlled by the company" (GHG-Protocol, 2015, p.25).

Tomar (2023) document increases in emission reductions following the disclosure mandate. However, my model provides evidence of a potentially adverse effect on firms' abatement considerations that may not be captured by empirical evidence.

Assume that the implemented regulation effectively forces firms to disclose their initial emission intensity level. When firms decide on their abatement strategies, they compare the expected profits with or without abatement, whereas emission intensity levels are always disclosed. It means firms with any a_i use k_2 (2.28) as the abatement cost threshold, i.e.,

$$k^{md} = k_2 \tag{2.32}$$

To better illustrate regulatory impacts on firms' abatement incentives. I consider an example in which a_i is uniformly distributed between 1 and $\bar{a}$. For the given parameters, nondisclosure equilibrium occurs with or without abatement activity. I demonstrate the abatement cost thresholds under the voluntary and mandatory disclosure regime in Figure 2.2.

In this numerical example, for firms with low emission intensity levels, the abatement cost threshold under the mandatory disclosure regime (dashed line) is lower than the one under the voluntary disclosure regime (solid line). As a result, firms with relatively low initial emission intensity levels are less likely to conduct abatement activities.

This result can be generalized in the following proposition.

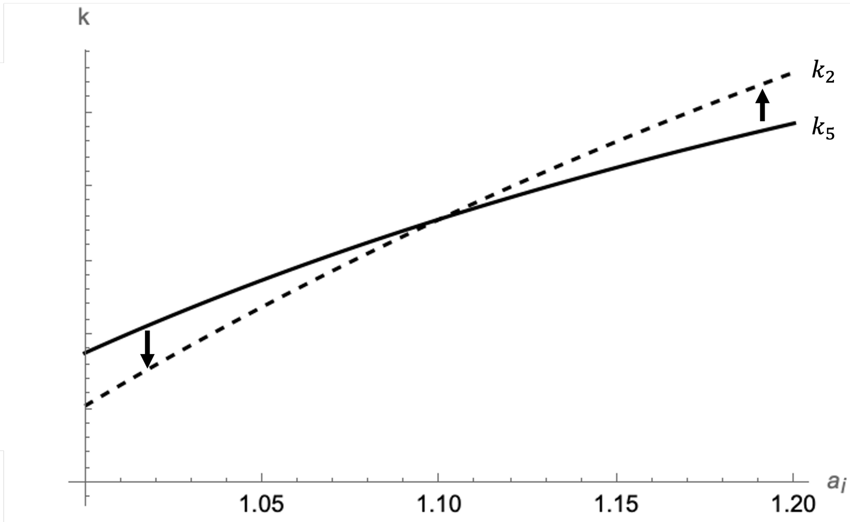
Proposition 2.3 *When nondisclosure equilibrium occurs in the voluntary disclosure regime, forcing firms to reveal their emission intensity level negatively influences some firms' abatement incentives.*

Proof. We have $k_5(a_i = \mu) > k_2(a_i = \mu)$. This directly follows Proposition 2.1 since nondisclosure equilibrium occurs only when $H > 0$. Both functions (k_2 and k_5) are continuous. We thus have

$$\exists a_i \in [1, \bar{a}] \quad \text{such that} \quad k^{md} = k_2 < k_5.$$

Figure 2.2: Disclosure regulation impact

The solid line indicates the abatement cost thresholds under voluntary disclosure regime (k_5), whereas the dashed line shows the abatement cost thresholds when firms are mandated to disclose their emission intensity level (k_2).
The parameter values are: $b = 30$, $\gamma = 1$, $\mu = 1.1$, $c_i = 10$, $c_j = 4$, $\beta = 2$ and $s = 0.0002$.



□

Such a negative impact does not restrict to the nondisclosure equilibrium case. In the case of partial disclosure equilibrium, mandating firms to reveal their emission intensity level may negatively influence some firms' abatement incentives since $k^{md} = k_2 < k_3$ holds always.

Impact on production quantities

Due to the impact on firms' abatement incentives, how the disclosure mandates may influence firms' production quantities is not straightforward. As a direct effect, forcing non-disclosers to talk leads to lower production quantities because these firms prefer not to voluntarily disclose their emission intensity level.

At the same time, the indirect effect caused by the affected abatement levels also needs to be considered. As Figure 2.2 shows, disclosure mandates may discourage abatement incentives from low-emission non-disclosers. This further decreases their production quantities. However, for firms with higher emissions levels, forcing them to reveal their emission intensity level encourages them to abate more. The increased abatement level alleviates the emission's adverse effect on product demand and leads to a higher production level. The overall effect of disclosure mandates on these firms then depends on the abatement level s.

Impact on total emissions

The potential effect of disclosure mandates on firms' total emissions is even less clear. Whereas low-emission firms abate less, they now also produce less. It is thus unclear at first sight how these firms' total emission levels may change. By contrast, high-emission non-disclosers reduce a higher level of emission intensities. However, they may now be able to produce more, which may even lead to a higher level of total emissions. This corresponds to what Bauckloh et al. (2023) document. I demonstrate this effect in Appendix A.5 by considering continuous abatement levels.

2.5 Interim conclusion

I propose a model investigating firms' GHG emission disclosure and investment decisions. Similar to firms' financial information, there are different recipients of non-financial information, in this case, GHG emissions. Firms evaluate the contradictory effects on the competitor and the customers from the emission-related information and make the disclosure decision. Furthermore, the benefit of conducting investment projects to abate emissions depends on the perceived emission intensity level. Strikingly, disclosure regulations may adversely affect firms' emission abatement incentives. The underlying mechanism may be generalized to other environmental-related topics, such as water consumption, biodiversity, etc.

The model results may deliver some testable hypotheses regarding cross-sectional disclosure patterns and provide insights for regulators. To see the generalizability of such implications, I further discuss the robustness of the model. First, model results do not change qualitatively if we consider price competition instead of quantity competition. With Bertrand competition, a higher emission intensity level always allows the firm to set up a lower price. However, disclosing such information still creates contradictory effects on its profit. We thus still have the potential existence of different disclosure equilibria. Furthermore, the potential adverse effect of disclosure regulations persists.

Second, the capital market, especially green investors in the capital market, are also important players in forming firms' emission-related investment and disclosure decisions. Green investors may incorporate climate externalities into asset pricing, either due to altruism (Friedman and Heinle, 2016) or due to firms' potential exposure to climate transition risks (such as changes in consumer preference) (De Angelis et al., 2022). Incorporating the capital market from this perspective again retains the main results of the model.

However, the model also subjects to limitations. First, the model may not apply to competition between firms using different technologies. Second, the disclosure mandate impact is abstract from considering the attention raised by disclosure regulations or the additional capital market incentives for abatement activities, such as shareholder engagement. These would be of interest to future research.

In addition, several extensions may be considered. The first one is to include a carbon tax in the model. The imposing of a carbon tax generates an additional cost for high-emission firms. It thus relaxes the independence assumption between the marginal input cost and the emission level.

A further extension is to add the information endowment uncertainty into the model. Ott et al. (2017) postulate that interested firms might keep silent simply because they do not have such information. Anecdotal evidence also shows that the most missing information is the Scope 3 GHG emissions. Since it requires firms to get information from both upstream and downstream of the supply chain, one can argue that firms observe this information imperfectly. If we assume exogenously given information endowment probability, following Dye (1985) and Jung and Kwon (1988), we expect nondisclosure (or partial disclosure) to appear more often. However, studying when discretional information acquisition decisions determine the endowment probability would be interesting.

3 Dress up for the audience - Firms' signaling decisions when not all recipients care[1]

3.1 Introduction

Over the last decades, concerns over sustainability, especially environmental concerns, have become substantial in all types of markets. An increasing number of consumers seek more sustainable and environmentally friendly products, such as jeans whose production does not exploit child labor or services with a smaller carbon footprint (see, for example, Zadek et al., 1998; Steering Committee of the State-of-Knowledge Assessment of Standards and Certification, 2012). Moreover, these consumers are also ready to pay a price premium for products that meet their needs (e.g., Bjørner et al., 2004; De Pelsmacker et al., 2005; Casadesus-Masanell et al., 2009). In this article, I call them socially conscious consumers or conscious consumers and investigate firms' signaling decisions to attract these consumers.

[1] I wish to thank Dirk Simons, Yasmin Hoffmann for their helpful comments and suggestions. I also gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (Project-ID 403041268 -TRR 266).

The preferences of socially conscious consumers for environmentally friendly products and the preferences of firms for conscious consumers due to the price premium align the purchasing process with the search and matching problem.[2]

Ideally, conscious consumers identify the products that meet their requirements and pay higher prices accordingly. However, most of these products' attributes share the same feature as credence goods.[3] Namely, their verification by individual consumers is either infeasible or too expensive, even after purchase or consumption. Hence, without additional assurance mechanisms, assessing the truthfulness of a firm's claim is nearly impossible. Given that these attributes cannot be credibly conveyed, products superior in these attributes are driven out (Akerlof, 1970).

One mechanism for firms to alleviate such market inefficiency is to engage an independent certifier who verifies qualities and issues a "label" once the product quality meets a given standard (see, for example, Kirchhoff, 2000; Crespi and Marette, 2005; Baksi and Bose, 2007; Bonroy and Constantatos, 2015). By doing so, "green" firms, firms with products that meet or exceed conscious consumers' requirements, may distinguish themselves from "brown" ones.[4] Viscusi (1978) shows that given perfect certification, the quality certification process unravels from the top.

[2]The beginning of the matching literature goes back to the path-breaking article by Gale and Shapley (1962). In the model, a number of men and women seek to get married in accordance with their preferences. The authors investigate whether there is a "stable" way to match men and women such that no unmatched pair can do better by matching each other. Later literature applies the matching game in many areas, such as the school choice problem (Balinski and Sönmez, 1999), kidney problem (Roth et al., 2007), but also in economics, such as housing allocation (Hylland and Zeckhauser, 1979) and trading problems (Deb et al., 2016).

[3]The concept of credence goods was first introduced by Darby and Karni (1973). They differentiate three types of qualities associated with a particular purchase. "(S)earch qualities which are known before purchase, experience qualities which are known costlessly only after purchase, and credence qualities which are expensive to judge even after purchase" (Darby and Karni, 1973, p. 69). Two types of credence qualities are considered later on in the literature. First, customers may not observe certain characteristics ex-ante, but they may observe the utility of what they acquire (see, for example, Dulleck and Kerschbamer, 2006; Dulleck et al., 2011). Examples of such type are car repairing or health care services. Second, there also exist goods for which the relevant qualities are expensive to assess even after purchase (e.g., Feddersen and Gilligan, 2001; Baksi and Bose, 2007). Many products' sustainable attributes fall into this category, for example, whether the products are produced by firms exploiting child labor or the product's carbon footprint. This thesis focuses on the second type of credence goods.

[4]Such certification agencies can be government agencies (like the U.S. Food and Drug Administration) or private firms or NGOs, such as Fairtrade or Climate Bonds initiatives.

Although many studies assume perfect third-party certification (see, for example, Baksi and Bose, 2007; Bonroy and Constantatos, 2008; Fischer and Lyon, 2014), it is realistic to assume that certifications may contain errors. Models holding the latter assumption often consider homogeneous firms and consumers and investigate firms' certification decisions (see, for example, De and Nabar, 1991; Mason, 2011; Fischer and Lyon, 2014).[5] De and Nabar (1991) assume that homogenous consumers can observe both the firms' decisions to seek certification and also the results, i.e. the labels the firms get. They then find that no separating equilibrium exists. Relaxing this assumption, Mason (2011) identifies that green firms use certification as a costly signal to differentiate themselves when certification cost is sufficiently high. The lower the certification cost, the higher the likelihood that brown firms are willing to take the chance and seek certification.

However, not all consumers behave the same or are willing to trade off quality with prices (Guide and Li, 2010; Genc and De Giovanni, 2021). Moreover, firms competing in the market are not necessarily comparable in size. Assume a grocery shop offers mangos from two different brands. The two brands could belong to two multinational food trading companies. However, one could also come from a small plantation in Brazil. Similarly, consumers may choose sports shoes from two different brands. Such competition may arise between Nike and Addidas. But it could also be between Nike and a smaller and specialized competitor, such as Veja.[6] In this paper, I explore how these two features influence firms' signaling decisions.

To capture the procedure through which conscious consumers try to identify green products, I combine a signaling game with a matching problem in this paper. In the model, two firms provide either green or brown products to a market populated by both socially conscious and unconscious consumers. Both firms may seek certification and try to label their products as green. A matching scheme is in place to allocate

[5] Others assume consumers with continuously distributed interest in the products' quality (e.g., Ibanez and Grolleau, 2008; Bottega and De Freitas, 2019; Fischer and Lyon, 2019).

[6] Throughout the paper, I use these two examples to illustrate the setting.

the products to the consumers. I investigate firms' signaling decisions - decisions in seeking certification. By constructing such a model, I answer two key questions. First, how may different shares of conscious consumers influence the firms' incentives to seek certification? Second, what if the firms in the market are of different sizes (different products quantities provided to the market in the game)?

I consider two types of matching schemes in the model, random or quasi-ranking. A random matching scheme (see Roth and Vate, 1990; Pais, 2008) allocates randomly consumers with the same preference to the products with the same label status. Again, consider two mango brands in the grocery shop. Assume that both brands are (un)labeled as low carbon footprint. The same type of consumers will most probably treat the (un)labeled mangos equally and purchase them randomly. A quasi-ranking matching scheme (see Gale and Shapley, 1962; Abdulkadiroğlu and Sönmez, 2003; Fox, 2010) allocates consumers with the same preference to the products with the same label status according to their ranking order. Now consider sports shoes from two different brands. Again, both are labeled or unlabeled as having a low carbon footprint. Instead of choosing one pair of shoes randomly, consumers may rank these two brands and make the purchase accordingly.

I start the analysis by considering that both firms are symmetric regarding their sizes - the quantities of products they provide. Similar to prior literature (see Dosi and Moretto, 2001; Mason, 2011; Fischer and Lyon, 2014), products provided by both firms may only differ in one attribute, being either green or brown. In addition, only part of the consumers, the socially conscious ones, care about this attribute. Firms may engage a third-party certifier with a cost to label their products as green. I further assume that green products will always get labeled once they seek certification. Brown products may be identified with an exogenously given probability.

The results echo many signaling games' results (e.g., Hughes and Schwartz, 1988; Bagnoli and Watts, 2017). The level of certification costs determines the occurrence of (i) a separating equilibrium where different product types choose different certification strategies; (ii) a partial pooling equilibrium in which both green and brown products choose to certificate, products may be partially distinguished due to the imperfect certification technology; and (iii) a pooling equilibrium where both types choose not to certificate. Increasing the certification quality decreases the brown firms' incentive to seek certification.

More importantly, more socially conscious consumers increase the probability that the separating and partial pooling equilibria occur. On the contrary, the effect is less straightforward for the pooling equilibrium. When conscious consumers are less than half of the consumers' pool, increase in their shares decreases the pooling equilibrium occurrence. However, when conscious consumers make up more than half of the consumers' pool, further share expansion makes the pooling equilibrium more probable to occur. The reason is twofold. On the one hand, the increase in conscious consumers unambiguously increases the pooling price for both firm types. On the other hand, such growth does not change green firms' benefits from deviating (separating from brown ones).

I then consider the case in which two firms are of different sizes. Here the matching scheme matters. Under a random matching scheme, the asymmetric size negatively influences the occurrence of all three equilibria. The larger the size difference, the larger the negative impact on equilibrium occurrence. In comparison, if the quasi-ranking matching scheme is in place, the equilibrium conditions do not change when there are only small number of socially conscious consumers. On the contrary, once the number exceeds the quantity the smaller firm provides, the equilibrium condition becomes tighter. Moreover, the larger the firm-size difference, the larger the negative impact on the equilibrium occurrence. These results are equal for the effect of the share of conscious consumers.

This paper proceeds as follows. Section 3.2 describes the setup of the model and introduces the key assumptions. Section 3.3 contains the equilibrium analysis, where

I first consider symmetric firms and proceed with asymmetric ones next. Section 3.4 discusses implication discussions and potential extensions.

3.2 Model setup

I incorporate a matching problem into a signaling game to capture the procedure that both firms and consumers try to find the best match with each other.

In the model, a green credence market is populated with a set of consumers, $i \in N = \{1, \ldots, n\}$. Two firms, $j \in F = \{1, 2\}$, are providing products in this market. An allocation of products (matching) is denoted by $\{x_{i,j} : \forall i \in N \ \& \ j \in F\}$ with the restriction that each consumer buys exactly one unit of product.

$$\sum_{j \in F} x_{i,j} = 1 \quad \forall i \in N \tag{3.1}$$

The quantity of products from each firm is m_j, with $\sum_j m_j = n$. Both firms' products are otherwise equivalent except for one attribute being either green or brown, i.e., $\theta_j \in \{g, b\}$, where θ can be considered as the firm/product type.[7] The production of green products entails an additional cost e.[8] Ex-ante, the probability that any product is green equals p, i.e.

$$Pr(\theta_j = g) = p.$$

Both firms perfectly observe their own products' attributes.

Only a subset of consumers cares about this attribute and prefers the green product. I denote this subset of socially conscious consumers by $A = \{1, \ldots, a\}$, where $a \in \mathbb{Z} : 1 \leq a \leq n$. For simplicity, I assume that consumers of the same type, either socially conscious consumers ($i \in A$) or unconscious consumers ($i \in N \setminus A$), assign the same

[7] In the following, I use the terms product type and firm type, green products and green firms, or brown products and brown firms, interchangable.

[8] In the static setting, this cost is sunk. Thus, it neither influences the matching process nor the firms' signaling decision-making.

value for the same product type. The value consumer i grants a product from firm j is denoted by $v_{i,j}$. Since all products are equal except the attribute θ_j. We can conclude

$$v_{i,j} = v_{i,\theta_j}. \tag{3.2}$$

If socially conscious consumers perfectly learn the product's attributes, they are willing to assign a green product a higher value. We normalize values to $v_{A,b} = 1$ for brown products and $v_{A,g} = \beta > 1$ for green products. Consequently, $\beta - 1$ also measures, on average, how much these conscious consumers are willing to pay extra for this attribute.

On the contrary, consumers that do not care about the product attribute equal value to all products, i.e., $v_{N \setminus A,j} = 1$. For simplicity, I assume that the value set up by the consumers–willingness to pay–is also the price received by the firm.[9] The overall revenue firm j gets is then

$$s_j = \sum_{i \in N} x_{i,j} \cdot E[v_{i,j}] \tag{3.3}$$

In the first-best scenario, conscious consumers identify green products and pay accordingly. However, the products have the feature of a credence good. That is to say, the actual product attribute, g or b, cannot be easily observed or verified by individual consumers, even after purchase and consumption. Because of the extra "willingness-to-pay" from conscious consumers, both firm types are willing to appear green. Consequently, any voluntary disclosure as such type [10] is deemed as cheap talk and transmits no additional information.[11] Without any further mechanism, consumers can only treat the products equally and value them based on their prior beliefs. No real matching is in place.

[9]This simplification is associated with the setting that individual consumers have an inelastic demand for one unit of green (see also Fischer and Lyon, 2014).

[10]Such voluntary disclosure is considered self-labeling or even greenwashing (Delmas and Burbano, 2011; Dumitrescu et al., 2022).

[11]In the model, we consider that false labeling causes no direct cost to the firm. Consequently, self-labeling without certification will be considered by the consumers as cheap talk and granted no additional value (Crawford and Sobel, 1982).

To alleviate the information asymmetry, firms can seek certification and get labeled as green products. I use $d_j \in \{0, 1\}$ to indicate the decision of firm j to seek certification ($d_j = 1$) or not ($d_j = 0$). A (non-strategic) third party provides such a certification, through issuing a label, with a fixed fee c ($c > 0$) and a limited level of assurance. That is to say, while the green type will be labeled (l) with certainty, brown products may be identified (unlabeled, i.e., ul) with an exogenously given probability λ. Eventually, the consumers observe the products being labeled or not, i.e., $r_j \in \{l, ul\}$.

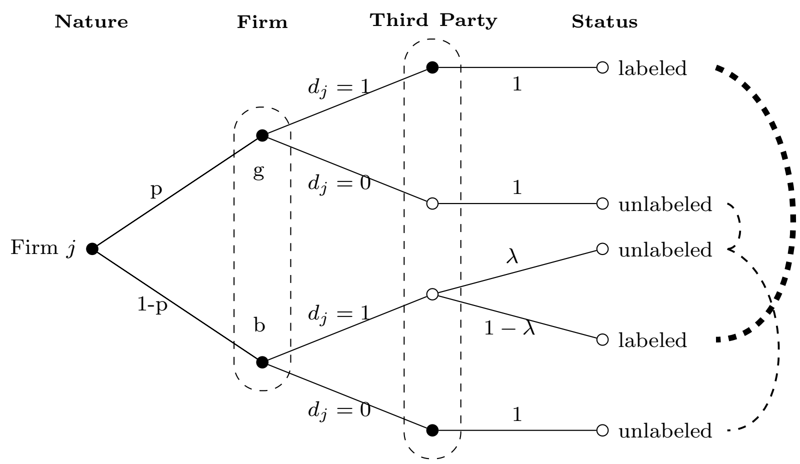
$$Pr(r_j = l|\theta_j = g, d_j = 1) = 1$$

$$Pr(r_j = l|\theta_j = b, d_j = 1) = 1 - \lambda$$

Figure 3.1 depicts the relationship between product type and product's label:

Figure 3.1: Game tree depicting product attributes and label status

The dotted circles and dotted lines indicate the consumers' information set.



I summarize the notations throughout the analysis in Table B.1 in Appendix B.1.

Equilibrium concept

Upon observing whether or not the products have labels r_j, consumers update their beliefs of the probability that products from firm j are green, i.e., $Pr(\theta_j = g|r_j)$. They then form the expected value as follows:

$$\begin{aligned} E[v_{i,j}|r_j] &= E[v_{i,\theta_j}|r_j] \\ &= v_{i,g} \cdot Pr(\theta_j = g|r_j) + v_{i,b} \cdot (1 - Pr(\theta_j = g|r_j)) \\ &= \begin{cases} 1 + Pr(\theta_j = g|r_j) \cdot (\beta - 1), & \forall i \in A \\ 1, & \forall i \in N \setminus A \end{cases} \end{aligned} \tag{3.4}$$

The two firms' signaling policies d_j and a product allocation scheme $\{x_{i,j}\}$ constitute an equilibrium if:

1. Firm j chooses d_j to maximize its expected profit π_j:

$$d_j(\theta_j) \in \arg\max_{d_j} E[\pi_j|d_j], \tag{3.5}$$

   where

$$\begin{aligned} E[\pi_j|d_j] &= E[s_j|d_j] - c \cdot d_j{}^{12} \\ &= \sum_{i \in N} E[x_{i,j}|d_j] \cdot E[v_{i,j}|d_j] - c \cdot d_j. \end{aligned} \tag{3.6}$$

   And

$$E[v_{i,j}|d_j] = E[v_{i,j}|r_j = l] \cdot Pr(r_j = l|\theta_j, d_j) + E[v_{i,j}|r_j = ul] \cdot Pr(r_j = ul|\theta_j, d_j) \tag{3.7}$$

2. The production allocation $\{x_{i,j}\}$ is stable and subjects to

$$\sum_{j \in F} x_{i,j} = 1 \quad \forall i \in N \tag{3.8}$$

$$\sum_{i \in N} x_{i,j} = m_j \quad \forall j \in F \tag{3.9}$$

$$x_{i,j} \geq 0 \quad \forall i \in N \quad \text{and} \quad j \in F. \tag{3.10}$$

3. consumers' posterior belief follows Bayes' rule whenever possible.

3.3 Equilibrium analysis

3.3.1 A stable matching

The matching problem in this model is assigning exactly one unit of product to each consumer. A matching is stable if no unmatched pair can find it better by matching each other (see Gale and Shapley, 1962; Abdulkadiroglu and Sönmez, 2013).[13] Following Gale and Shapley (1962), we can apply the deferred acceptance algorithm as follows to get a stable matching:

Step 1. Both firms first offer their products to conscious consumers. These consumers evaluate the products' value based on the equilibrium condition and labels. They then purchase the products with the higher expected value first.[14]

Step 2. If these consumers still have remaining purchasing capacity, they turn to the rest of the products.

Step 3. All the left products will be assigned to the unconscious consumers.

Remark 3.1 *We derive a stable matching by applying the deferred acceptance algorithm.*

Proof. It is easy to show that this matching is not blocked by any pair (i, j). Since conscious consumers get to pick first, they will not find it better to match with other products. □

[13]To illustrate an unstable matching, I use a simplified mango example. Assume that there are only one "green" mango and one "brown" mango on the market. Also, there are only one socially conscious consumer and one unconscious. A matching scheme that assigns the "brown" mango to the socially conscious consumer and the "green" mango to the unconscious consumer is unstable. This is because one unmatched pair, "green" mango and the conscious consumer, finds it better by matching with each other.

[14]Note that we do not restrict the divisibility of the products. In the case that the number of higher valued products is smaller than the number of conscious consumers, we may assume that each buyer can only buy an equal share of the products (less than one unit), such that the matching is not blocked by $i \in A$.

In expectation of this matching scheme, firms make their signaling decisions. In the following equilibrium analysis the main focus lies on the firms' signaling strategies. I look for symmetric Perfect Bayesian Equilibria, i.e., equilibria in which the same firm type (θ) plays the same strategy.[15] We thus denote a candidate strategy profile by $\{d(g), d(b)\}$. Similarly, s_θ and π_θ indicate the revenue and profit of a firm with type θ. It is easy to derive that firms with green products have higher incentives to seek certification.[16] Consequently, a strategy profile that firms with brown products seek certification, whereas green ones do not cannot be an equilibrium. I summarize the main results in Table 3.1.

Strategies	Type g chooses certification $d(g) = 1$	Type g chooses no certification $d(g) = 0$
Type b chooses certification $d(b) = 1$	Partial pooling equilibrium	No equilibrium
Type b chooses no certification $d(b) = 0$	Separating equilibrium	Pooling equilibrium

Table 3.1: Potential equilibrium candidates

3.3.2 Symmetric firms

I start the analysis by considering two equal-sized firms. That is to say $m_1 = m_2 = \frac{n}{2}$. Here, firms with the same product type play the same signaling strategy. Each type chooses either certification or not. I sketch the pure strategy equilibrium results below.

[15] Theoretically, we have four firm types' signaling strategies $\{d_1(\theta_1 = g), d_1(\theta_1 = b), d_2(\theta_2 = g), d_2(\theta_2 = b)\}$ under consideration, which leads to sixteen strategy profiles for further analysis. It is easy to show that strategy profiles in which firms of the same type play different strategies cannot constitute an equilibrium (see a detailed elaboration in Appendix B.2).

[16] This is always the case even if the certification process is not perfect for green products, but with a higher probability of granting the label than for brown products.

Separating equilibrium ($\{d(g) = 1, d(b) = 0\}$)

We first determine the conditions that a separating equilibrium will obtain. In equilibrium, green firms choose certification, and brown firms choose no certification. Given such equilibrium behavior, consumers will have the following update:

$$Pr(\theta_j = g | r_j = l) = 1, \tag{3.11}$$

and

$$Pr(\theta_j = g | r_j = ul) = 0, \tag{3.12}$$

Inserting them into (3.4) leads to:

$$E[v_{A,j} | r_j = l] = \beta \quad \& \quad E[v_{A,j} | r_j = ul] = 1.$$

Following the matching algorithm described in Section 3.3.1, conscious consumers choose to buy labeled products first if they appear on the market. However, this matching process complicates the firms' payoffs.

Consider that firm j's product is green. We start with the on-path payoffs' analysis. Seeking certification leads to the following (see (3.7)):

$$\begin{aligned} E[v_{i,j} | d_j = 1] &= E[v_{i,j} | r_j = l] \cdot Pr(r_j = l | \theta_j = g, d_j = 1) + E[v_{i,j} | r_j = ul] \cdot Pr(r_j = ul | \theta_j = g, d_j = 1) \\ &= E[v_{i,j} | r_j = l] \\ &= v_{i,g} \cdot Pr(\theta_j = g | r_j = l) \\ &= v_{i,g} \end{aligned} \tag{3.13}$$

Namely, in the separating equilibrium, green firms are identified perfectly.

Ex-ante, firm j expects that with probability p firm $\neg j$ also has green products. In this case, both firms choose to certify their products. There are thus n labeled products on the market. Following the stable product allocation scheme[17] described above, $a/2$ units of firm j's products are purchased by conscious consumers, and unconscious ones buy the rest. Namely, when $\theta_j = g$, with probability p, it expects:

$$\sum_{i \in A} x_{i,j} = \frac{a}{2}$$

$$\sum_{i \in N \setminus A} x_{i,j} = \frac{m}{2} - \frac{a}{2}$$

However, with probability $1 - p$, firm $\neg j$ has brown products and chooses not to label them. Under this scenario, only $n/2$ products (from firm 1) are labeled. Thus $\min\{a, n/2\}$ units of firm j's products are purchased by conscious consumers.

Insert (3.13) and the expected product allocation into firms' profit function (3.6). We get the payoff for the green firm staying on the equilibrium path as follows:

$$\begin{aligned}
\pi_g &= E[s_j | d_j = 1] - c \\
&= \sum_{i \in N} E[x_{i,j} | d_j] \cdot E[v_{i,j} | d_j]) - c \\
&= \sum_{i \in N} E[x_{i,j} | d_j] \cdot v_{i,g} - c \\
&= \sum_{i \in A} E[x_{i,j} | d_j] \cdot v_{A,g} + \sum_{i \in N \setminus A} E[x_{i,j} | d_j] \cdot v_{N \setminus A,g} - c \\
&= -c + p[\frac{a}{2} \cdot \beta + (\frac{n}{2} - \frac{a}{2}) \cdot 1] + (1-p)[\min\{a, \frac{n}{2}\} \cdot \beta + \max\{\frac{n}{2} - a, 0\} \cdot 1] \quad (3.14)
\end{aligned}$$

The payoffs indicate that in the separating equilibrium, green firms get identified perfectly. The payoffs thus only depend on the competitor's type and the number of socially conscious consumers.

Now consider the products from firm j are brown, $\theta_j = b$. The firm chooses not to label the products ($d_1 = 0$). The payoff is now more straightforward since all consumers

[17] I leave the detailed description of the two matching schemes to Section 3.3.3, since the later analysis shows that matching schemes do not create a difference when two firms' product quantities are the same.

will pay the minimum for each unit:

$$\pi_b = \frac{n}{2}. \tag{3.15}$$

We now consider the deviation incentives for both firm types. I use superscription ^{d} to indicate the case of deviation. If the green firm decides not to label the products, it also gets

$$\pi_g^d = \frac{n}{2}. \tag{3.16}$$

The deviation consideration needs to cover more scenarios for the brown firm. It may or may not get the label when it decides to seek certification, with probability $1-\lambda$ and λ, respectively. When the products are not labeled (with probability λ), the firm always earns $n/2$. On the contrary, with probability $1-\lambda$, the firm gets its $n/2$ units of product all labeled and receives the payoffs like the green firm (see (3.14)). We thus get the brown firm's payoff when it deviates from the equilibrium path:

$$\begin{aligned}\pi_b^d = &-c + \lambda \cdot \frac{n}{2}\\ &+ (1-\lambda)\Big(p[\frac{a}{2}\cdot\beta + (\frac{n}{2}-\frac{a}{2})\cdot 1] + (1-p)[\min\{a,\frac{n}{2}\}\cdot\beta + \max\{\frac{n}{2}-a,0\}\cdot 1]\Big)\end{aligned} \tag{3.17}$$

Comparing (3.14) with (3.16) and (3.15) with (3.17), we can derive conditions supporting the separating equilibrium:

$$\begin{aligned}(1-\lambda)\Big(p[\frac{a}{2}\cdot\beta + (\frac{n}{2}-\frac{a}{2})\cdot 1] + (1-p)[\min\{a,\frac{n}{2}\}\cdot\beta + \max\{\frac{n}{2}-a,0\}\cdot 1] - \frac{n}{2}\Big)\\ \le c \le \\ p[\frac{a}{2}\cdot\beta + (\frac{n}{2}-\frac{a}{2})\cdot 1] + (1-p)[\min\{a,\frac{n}{2}\}\cdot\beta + \max\{\frac{n}{2}-a,0\}\cdot 1] - \frac{n}{2}\end{aligned} \tag{3.18}$$

Following the same procedure as above, I go through the partial pooling equilibrium and pooling equilibrium in Appendix B.3. The equilibrium conditions are summarized in Proposition 3.1.

Proposition 3.1 *The following pure strategy profiles can be supported in equilibrium.*

- *A partial pooling equilibrium in which both firm types decide to seek certification is supported when* $c \leq c_1$*;*
- *A separating equilibrium in which green firms certify their products while brown ones do not exists only if* $c_2 \leq c \leq c_3$*;*
- *A pooling equilibrium in which both types decide not to seek certification is supported when* $c > c_4$*,*

where,

when $a \leq \frac{n}{2}$

$$\begin{cases} c_1 = (1-\lambda)(\beta-1)[\frac{p}{p+(1-p)(1-\lambda)} - \frac{p}{2}]a \\ c_2 = (1-\lambda)(\beta-1)[1-\frac{p}{2}]a \\ c_3 = c_4 = (\beta-1)[1-\frac{p}{2}]a \end{cases} \tag{3.19}$$

when $a > \frac{n}{2}$

$$\begin{cases} c_1 = (1-\lambda)(\beta-1)[\frac{p}{2}\cdot a + (1-p)\cdot\frac{n}{2}\cdot\frac{p}{p+(1-p)(1-\lambda)}\lambda] \\ c_2 = (1-\lambda)(\beta-1)[\frac{p}{2}\cdot a + (1-p)\cdot\frac{n}{2}] \\ c_3 = (\beta-1)[\frac{p}{2}\cdot a + (1-p)\cdot\frac{n}{2}] \\ c_4 = (\beta-1)[p\cdot(\frac{n}{2}-\frac{a}{2}) + (1-p)\cdot\frac{n}{2}] = (\beta-1)[\frac{n}{2}-\frac{p}{2}\cdot a] \end{cases} \tag{3.20}$$

Proof. See above and Appendix B.3. □

Clearly, green firms are willing to take the certification as a costly signal when the level of certification costs is sufficiently high. Brown firms try to take the chance of pooling when the costs are low enough. Note that $c_1 < c_2 < c_3$. However, for $a \leq \frac{n}{2}$, the pooling equilibrium now overlaps with the separating equilibrium ($c_4 < c_3$). Under such a condition, both types of firms prefer the pooling equilibrium so that consumers do not get additional information.

We first consider the impact of certification quality on firms' incentives to seek certification.

Corollary 3.1 *Ceteris paribus, the increase in the quality of third-party certification (λ) decreases the occurrence of the partial pooling equilibrium and increases the occurrence of the separating equilibrium. This quality, however, does not influence the pooling equilibrium condition.*

Proof. It is easy to show that $\forall a \in [1, n]$, there are $\partial c_1/\partial\lambda < 0$, $\partial c_2/\partial\lambda < 0$, $\partial c_3/\partial\lambda = 0$, and $\partial c_4/\partial\lambda = 0$. □

The intuition is straightforward. Increasing the certification quality means decreasing the possibility that brown products getting labeled. This accordingly decreases the incentives for brown firms seeking certification.

Furthermore, we can derive the impact of different shares of conscious consumers on the equilibria occurrence. We summarize the effects in Corollary 3.2.

Corollary 3.2 *When no consumers care about the product attribute (a=0), firms have no incentive to seek certification with a positive cost. More importantly, ceteris paribus, the increase in the number of conscious consumers (increasing a) increases the occurrence of separating equilibrium and partial pooling equilibrium. When $a \leq \frac{n}{2}$, such an increase also decreases the occurrence of pooling equilibrium. However, when $a > \frac{n}{2}$, an increase in the number of conscious consumers increases the occurrence of pooling equilibrium.*

Proof. It is easy to show that $\forall a \in [1, n]$, there are $\partial c_1/\partial a > 0$ and $\partial(c_3 - c_2)/\partial a > 0$. However, for $a \leq \frac{n}{2}$, $\partial c_4/\partial a > 0$. For $a > \frac{n}{2}$, $\partial c_4/\partial a < 0$ □

The result is mostly intuitive. The increase in the share of conscious consumers increases the payoffs of being a green firm in general. As a result, more conscious consumers increase the green firms' incentives to separate and the brown firms' incentives to pool. Intuitively, it leads to more occurrences of the separating and partial pooling equilibria. However, the effect is less straightforward for the pooling equilibrium. When conscious consumers are less than half of the consumers' pool, the higher share of them leads to lower occurrence of the pooling equilibrium. However, if more than half of the consumers are already socially conscious, further share expansion makes the pooling equilibrium more probable to occur. While the increase in conscious consumers unambiguously increases the pooling price for all firm types, such an increase generates no additional benefits for green firms to deviate.

3.3.3 Asymmetric firms

I now consider asymmetric firms in the market. Without loss of generality, we assume that $m_1 < \frac{n}{2} < m_2$.

Different matching schemes

Within the concept of stable matching, two different ways of production allocation may appear. Conscious consumers may

- treat all products with the same status (labeled or unlabeled) equally and purchase the preferred products randomly.
- Or, instead of such a random pick, conscious consumers may treat the products from each firm as quasi-ranked. That is to say, they denote these products by $f_j^1, \dots, f_j^{m_j}$ (see Abdulkadiroglu and Sönmez, 2013) and make their purchase in that order.

As illustrated in Section 3.1, we see that different types of products fit different matching schemes, like a random matching scheme for mangos and a quasi-ranking scheme for sports shoes.

Note that when the two firms are symmetric, namely having the same units of products, both allocation schemes lead to the same result. However, when the two firms are asymmetric, different allocation schemes make a difference.

To see the difference, we can use one example. Let's assume that $m_1 = n/4$, $m_2 = 3n/4$ and $a = 3n/5$. Consider that we are in the partial pooling equilibrium. If both firms' products are labeled,[18] the two different ways of matching will lead to different units of products from firm j being purchased by conscious consumers. Specifically,

- under the *random selection allocation*, firm 1 will sell $3n/20$ units of the product to conscious consumers, while firm 2 will sell $9n/20$ units. The units sold to conscious consumers are proportionate to the firms' own sizes.
- On the contrary, under the *quasi-ranking allocation*, conscious consumers rank the products from the two firms as follows:

  $$f_1^1, f_1^2, \ldots, f_1^{m_1}$$

  $$f_2^1, f_2^2, \ldots, f_2^{m_1}, f_2^{m_1+1}, \ldots, f_j^{m_2}$$

  Furthermore, since products from both firms are labeled, consumers are indifferent between f_1^x and f_2^x. They then make their acquisition based on such ranking. Consequently, firm 1 sells all its $n/4$ units to conscious consumers, and firm 2 sells $7n/20$ units.

I then analyze how such asymmetry firm sizes accompanied by different matching schemes may impact firms' signaling strategies. As indicated in Appendix B.2, I still focus on profiles in which the same firm type plays the same strategy. This allows us to focus on the impact of asymmetric firm size under different matching schemes.

[18]Ex-ante probability equals to $[1 - (1 - p)(1 - \lambda)]^2$.

Random selection matching scheme

Under this matching mechanism, the firms' payoffs are proportionate to the firm's size (the firm's product quantity). The symmetry case discussed in Section 3.3.2 can be seen as a special case here. We now need to consider deviation incentives from more firm types with asymmetric firms. Since the equilibrium condition always takes the most stringent requirement, intuitively, we observe the less probable occurrence of all three equilibria. Furthermore, the more significant the size difference is (smaller m_1 and larger m_2), the less likely all three equilibria occur. A full characterization of the three equilibria and the thresholds discussion can be found in Appendix B.4.

Quasi-ranking matching scheme

Under the quasi-ranking matching scheme, the firms' payoffs are no longer proportionate to the firm's product quantity. Comparing the equilibria conditions with those considering symmetric firms in Proposition 3.1, we can see that the equilibrium condition remains the same for a low number of socially conscious consumers ($a < m_1$). Conversely, once the number exceeds the quantity provided by firm 1, the equilibrium condition becomes tighter. The larger the size difference ($m_2 - m_1$) is, the more significant the negative impact on the equilibrium occurrence. Interestingly, the more conscious consumers there are, the larger this negative impact. A full characterization of the three equilibria and the thresholds discussion can be found in Appendix B.4.

3.4 Interim conclusion

In this article, I incorporate a matching problem into a signaling game to capture the procedure through which products with different attributes and consumers with different interests try to find the best match. In addition to the results that the certification costs determine the occurrence of different equilibria, I also assess the impact of different shares of conscious consumers and different firm sizes on the equilibria conditions.

Discussion and implication

The model considers only two firms. However, the results, especially those considering the impact of asymmetric firm sizes, can easily be carried over to a multi-firm setting.

The analysis suggests that different product markets may present different signaling equilibria even when the certification cost and quality are comparable. First, different shares of conscious consumers may cause such differences. For a relatively low level of certification cost, a partial pooling equilibrium in which both firm types seek certification is more probable to occur in the market with more conscious consumers.

Second, different equilibria occurring in different product markets may also be caused by how the allocation schemes differ. Again for a relatively low level of certification cost, in markets where the brand name is not essential, more significant firm size differences may lead to a less probable occurrence of partial pooling equilibrium.

Potential extension

Lastly, it is appropriate to address some limitations and possible extensions of the analysis. The biggest caveat is that the model is static. Both firms are determined to have either green or brown products with a given probability. In reality, one should expect firms to evaluate the share of conscious consumers and the additional cost of providing green products and decide on products' attributes accordingly.

Moreover, the model focuses on pure strategy equilibrium. Considering the full set of equilibrium candidates may bring more insight into different industries labeling practices. Lastly, the certification agency acts as non-strategic player, and its quality is exogenously given. By combining insights from the auditing theory literature, we can consider the agency as a strategic player and allow the certification costs and the quality correlated.

4 The (limited) Power of Blockchain Networks for Information Provision[1]

4.1 Introduction

Recent innovations in computer science have fueled the belief that new technologies will improve information provision and eliminate the need for third-party intermediaries. A prime example is blockchain technology that originated as the distributed ledger technology behind the cryptocurrency Bitcoin. Blockchains are peer-to-peer networks designed to keep records of participating parties and can be programmed to analyze or validate data automatically. This functionality offers far-reaching potential, especially in accounting and finance.[2] Policymakers are increasingly active in promoting and

[1]This chapter is based on joint work with Benedikt Franke and André Stenzel and published in the Management Science (forthcoming). We thank Christian Laux (EAA discussant), Dirk Simons, Anton Sobolev and seminar participants at the University of Bonn, Skema Business School, the University of Graz, and the University of Mannheim for their helpful comments and suggestions. We further appreciate participants' comments at the 2019 AAA Annual Meeting in San Francisco, the 2020 Annual Meeting of German Academic Association for Business Research (VHB) in Frankfurt, and the 2021 EAA Virtual Annual Meeting. I gratefully acknowledge funding from the Deutsche Forschungsgemeinschaft (Project-ID 403041268 -TRR 266). Dr. Stenzel gratefully acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via CRC TR 224 (Project C03) during his prior employment at the University of Mannheim.

[2]See, for example, Dai and Vasarhelyi (2017); Yermack (2017); Cao et al. (2019); Cong and He (2019); Pimentel and Boulianne (2020); Cong et al. (2021).

creating a regulatory basis for blockchain applications.[3] However, the technology's economic impact is still largely unknown. This paper offers new insights by analyzing the potential and limits of corporate blockchain applications for information provision. We model blockchain technology as a disclosure regime of endogenous strength that leverages participating firms' data to generate information while ensuring the necessary data privacy. A central result of our analysis is that such blockchain applications can lead to a deterioration of information provision not only for individual firms but also for the economy in aggregate.

Firms' data carry valuable information about their behavior, profitability, or economic value, that the capital market would like to access for decision-making. However, it is usually not optimal for firms to disclose granular data voluntarily, e.g., due to proprietary disclosure cost (e.g., D'Souza et al., 2010; Ebert et al., 2017). There are also limits to the amount of information and detail required in mandatory disclosures because it can distort investment incentives or create tensions between managers and shareholders (e.g., Berger and Hann, 2007; Arya et al., 2013; Schneider and Scholze, 2015; Jayaraman and Wu, 2019). Traditionally, this has resulted in firms providing aggregate disclosures and investors relying on third-party intermediaries, such as auditors, analysts, or rating agencies, to generate and verify disclosures.

Corporate blockchain applications are set to rival these intermediaries by offering alternative means of creating and disseminating credible disclosures. Most applications rely on private blockchains utilizing the distributed ledger technology to digitize services as code and deliver them via technical and operational layers.[4] While numerous incarnations exist, all share the core capability of generating information by utilizing participating firms' data (Cong and He, 2019). Essentially, the private blockchains keep participating firms' data without exposing individual records—which is crucial in the corporate context—and host applications that analyze the linked data

[3] In the United States, the 117th Congress has seen 35 bills in 2021 that focused on cryptocurrencies, blockchain technology, or central bank digital currencies (Brett, 2021).

[4] For a more detailed discussion of the corporate setting and the use of the distributed ledger technology, see Section 4.2.

autonomously, e.g., by cross-referencing records or predictive analyses (e.g., Yermack, 2017; Narang et al., 2019; Bakos et al., 2021).[5] The outcome is usually shared via public-facing services in the form of predefined aggregate metrics, such as scores or ratings. Conceptually, blockchain technology enables a transition from a situation in which informativeness and credibility of disclosures derives from third parties, to one in which it derives directly from the network that holds the data.

Whether the transition from a third-party to a blockchain-based system improves information provision critically depends on firms' adoption decisions because blockchain's information capabilities rest on connecting and analyzing previously isolated data sources. Adoption incentives are inherently firm-specific. They ultimately depend on a firm's desire to provide information, and the extent to which other firms' data are informative about a given firm. Each firm's adoption decision also imposes an externality on the other firms in the economy, making the overall information provision the result of a complex coordination game.

Consider a blockchain application, such as GumboNet ESG, that uses firms' operational data to generate metrics for environmental, social, and governance (ESG) disclosures. ESG reporting is still largely voluntary, but will likely become mandatory soon (see the recently proposed disclosure mandate by the Securities and Exchange Commission, see SEC 2022). Such an area is promising for blockchain applications because it relies on access to sensitive data from various parties, such as buyers, suppliers, or logistics, requires a high level of assurance, and traditional institutions are not yet well-entrenched (see, e.g., Simnett et al., 2009; Pflugrath et al., 2011; Casey and Grenier, 2015; Caglio et al., 2020; Christensen et al., 2021). Informational externalities arise because ESG-related data regularly carry information on other firms' ESG performances. For instance, a firm's emission data can inform about other firms' emissions either directly, e.g., suppliers contribute to producers' overall emissions under

[5]Public blockchains, such as Bitcoin and Ethereum, offer limited privacy that may result in deanonymization of users. Cryptographic means, such as zero-knowledge proofs, offer a privacy-increasing analysis, even on public blockchains.

the widely-used Greenhouse Gas (GHG) Protocol, or indirectly, by serving as reference points. As such, the more firms contribute data to the blockchain, the more complete the picture of firms' performance becomes.

An environmentally friendly firm striving to signal its type should be more likely to adopt the blockchain application when it expects more firms to contribute data. However, whether the adoption actually improves the firm's ability to signal its type also depends on its fit with the other firms' data, i.e., how much their data are predictive of its environmental friendliness. While the data on the blockchain may be more indicative of one firm's environmental friendliness, it may be less indicative of another firm's. For example, other firms' data are arguably more likely to reveal information about the firm when they share similar business models or technologies.[6] Moreover, each firm's adoption decision itself can serve as a signal. Depending on the pool of expected adopters, forgoing traditional third-party services can reveal information about a firm's type.

To study the impact of blockchain technology on information provision, we introduce a model that captures the essential features driving firms' adoption decisions in a disclosure setting. Heterogeneous firms simultaneously decide whether to rely on an exogenous disclosure regime—the traditional institutions—or adopt a disclosure regime with endogenous and firm-specific strength—the blockchain application. Each firm is characterized by a privately known two-dimensional type that consists of its value, which can be high or low, and its fit for being analyzed by the blockchain, which can be good or bad. Firms select the disclosure regime that maximizes their expected market valuation. Naturally, high-value firms seek information provision to separate from low-value firms, and low-value firms attempt to hide and pool with high-value firms (as in, e.g., Verrecchia, 1983; Dye, 1985; Jung and Kwon, 1988).

[6] Applications, such as Maple Finance, Bloom, or LedgerScore, allow investors to retrieve credit scores based on firms' background information without exposing financial data. Similarly, the scores' informativeness weakly increases in coverage and depends on whether the other firms' records are actually predictive for a firm's future creditworthiness.

Firms trade off between the blockchain application that assesses participating firms' data and traditional intermediaries. The blockchain publicly disseminates an aggregate signal containing either a firm's actual value or no information. The probability that a firm's value is revealed—synonymous with the signal's informativeness—increases both in how many firms adopt the blockchain—its reach into the economy—and the fit with the firm's data profile. Traditional institutions reveal a firm's value with an exogenous probability shared by all firms, representing the average capabilities of all non-blockchain institutions. This approach implicitly incorporates a comparative advantage of traditional institutions in assessing data that are inherently challenging to analyze for the blockchain. Both systems come at a fixed cost, and the blockchain application can be costlier or cheaper than traditional institutions.

We begin our analysis by studying a baseline setting in which the information generation by traditional institutions is muted and blockchain adoption is costly. This setting allows us to cleanly identify two channels through which the technology can provide information. First, firms' adoption decisions may signal their value types. When adoption costs are sufficiently high, only high-value firms join the blockchain in equilibrium, and market participants perfectly learn all firms' values. Second, the blockchain's distributed ledger capabilities may generate information about participating firms. If adoption costs are sufficiently low, some low-value firms join the high-value firms in the blockchain. While the signal from observing firms' adoption decisions becomes less informative, more firms contributing data to the network improves its ability to generate information.

In the generalized setting, we let the relative informativeness of the blockchain and traditional institutions depend on firms' equilibrium actions entirely. Traditional institutions provide information about non-adopting firms, and may be costlier or cheaper than the blockchain application. While both information provision channels from the baseline setting carry over, the key takeaway is the emergence of a novel equilibrium in which a mix of high-value and low-value firms is present both inside and outside the blockchain. In this equilibrium, neither the signaling nor the actual information generation channel work to their full potential. While blockchain technology can improve the information environment, we provide sharp conditions for when this potential is not realized. Specifically, average mispricing in the economy may increase due to the emergence of blockchain technology and information provision deteriorate not only for individual firms but also in aggregate. Importantly, the adverse outcome results from a blockchain-induced coordination game and not blockchain being an inherently bad technology to generate information. Information provision may deteriorate in equilibrium, even when blockchain technology is in principle beneficial and would improve the information environment under (mandated) full adoption.

The adverse mixed-adoption equilibrium is a warning sign offering broader implications for policymakers and capital market participants. For instance, economies with intermediate traditional institutions are more likely to suffer from a decrease in information provision, unless the institutions are sufficiently strong to rule out the mixed-adoption equilibrium. Moreover, the emergence of blockchain technology results in a complex coordination game in which heterogeneity in firms' fit makes a lack of coordination more likely. The heterogeneity not only impedes the blockchain's capabilities to analyze a given firm's data but also weakens the signaling value of firms' endogenous adoption decisions. Policymakers should therefore monitor potential adopters and provide incentives to keep heterogeneity low, e.g., in the form of monetary incentives or regulatory relief. However, there is no simple immediate regulatory solution. For example, mandating blockchain adoption for all firms, in the spirit of requiring audited financial statements from public firms, is not unambiguously optimal concerning overall welfare. While this would eliminate the coordination problem, mandating adoption entails direct costs for all firms, and may additionally harm the information environment when there is a sufficient proportion of firms for which the blockchain is an inherently bad technology.

Related literature

Our study contributes to the literature on emerging technologies in accounting and finance, and specifically on the informational aspects of blockchain technology. Most studies concentrate on the technical feasibility (e.g., Vukolić, 2015; Christidis and Devetsikiotis, 2016; Du et al., 2017) and discuss potential benefits and obstacles associated with specific applications (e.g., Yermack, 2017; Wang and Kogan, 2018; Abadi and Brunnermeier, 2022; Chod et al., 2020; Cao et al., 2020). Dai and Vasarhelyi (2017) emphasize that the blockchain could enable a real-time, verifiable, and transparent accounting ecosystem by enabling timely examinations of potential errors via automatic verification of transactions using data from other participants. The blockchain in our model explicitly features these peer-to-peer capabilities while also ensuring the data privacy necessary in the corporate context (e.g., Narang et al., 2019; Bakos et al., 2021).

A growing list of studies explores the economic implications of blockchain adoption with a focus on cryptocurrencies and smart contracts (e.g., Fanning and Centers, 2016; Cong and He, 2019; Cong et al., 2021; Easley et al., 2019; Lumineau et al., 2021; Chod and Lyandres, 2022). Most closely related to our study are Cao et al. (2019), who focus on auditors integrating blockchain into their audit technology. They examine the effects of auditors' adoption and analyze audit market competition, audit quality, and client misstatements. In their setting, an outside party, such as a regulator, may have to "select" an equilibrium to ensure lower misstatements, audit effort, and regulatory costs. We complement their work by studying firms' adoptions in a disclosure setting and providing policy implications for when blockchain is either a rival or a substitute for traditional institutions.

By considering firms' adoption decisions and the endogenous strength of blockchain, our model relates to positive accounting theory studying the development of accounting-related institutions (Dye and Sridhar, 2008; Bertomeu and Magee, 2011, 2015a,b; Chen and Yang, 2022). The endogenous nature of the blockchain's strength also differentiates us from other blockchain-related studies, such as Chod et al. (2020), that focus on the benefits of blockchain-enabled supply chain transparency. Our model further speaks to the research concerning firms' ex-ante commitment to a disclosure regime (e.g., Ferreira et al., 2012; Hermalin and Weisbach, 2012; Heinle and Verrecchia, 2016; Edmans et al., 2016). For example, Heinle and Verrecchia (2016) consider homogeneous firms that can commit to a disclosure regime but ex-post have some discretion about the information being revealed. In contrast, we consider heterogeneous firms that can commit to a disclosure regime—the blockchain—characterized by an endogenous probability of revealing a firm's value.

Lastly, our paper relates to the broad literature on multi-sided markets and network effects going back to Katz and Shapiro (1985) (see Rochet and Tirole, 2006; Farrell and Klemperer, 2007, for overviews). Specifically, the blockchain in our model operates as a platform and firms' adoption decisions impose externalities on other participating firms. However, our model differs from existing studies by abstracting from a (product market) game on the platform and instead focusing on complex network effects that are inherent to blockchain applications in a disclosure context. The complexity originates from two sources. First, a heterogeneous fit with the technology implies differences in the extent to which firms benefit from other firms joining the blockchain. Studies with this type of explicit heterogeneity are comparatively scarce, with the notable exception of Weyl (2010) and recent work by Jeitschko and Tremblay (2020). Second, other firms' adoption decisions not only affect the informativeness of the blockchain, but also the pooling price of non-identified firms, with the informativeness and pooling price impacting other firms differentially.

The paper proceeds as follows. Section 4.2 illustrates the common corporate blockchain architecture and the economic setting. Section 4.3 introduces the model setup and key assumptions. Section 4.4 contains the analysis of the key mechanisms and the general model. Section 4.5 discusses additional considerations and the robustness of our model. Section 4.6 concludes.

4.2 Background

We next introduce the basic architecture of corporate blockchains hosting existing applications, such as GumboNet ESG, IBM Food Trust, GuildOne, or Bloom, and highlight the key factors determining their capabilities to generate information.[7]

Most people associate the word "blockchain" with public blockchains like Bitcoin and Ethereum. These decentralized networks are permissionless and rely on an associated cryptocurrency, e.g., bitcoin or ether, to incentivize participants (miners) to maintain the network. Permissionless networks prosper when numerous mistrusting parties interact and cannot or do not want to rely on a third party to maintain the ledger. However, this feature of public blockchains also induces scalability and privacy issues, making them largely unfit for corporate use (e.g., Fanning and Centers, 2016; Yermack, 2017; Bakos and Halaburda, 2021; Chen et al., 2021).[8]

Corporate blockchains are predominantly private and permissioned blockchains tailored to address corporate-specific needs, such as data privacy, versatility, and governance control. Private blockchains do require a third party to maintain the network but in return provide confidentiality of participants and data at scale—data can only be read by explicitly permissioned users. Third parties that host private blockchains rely on trust in a traditional sense, e.g., based on reputation and contractual enforcement outside the ecosystem, but may not control the data (e.g., Chen et al., 2021; Bakos et al., 2021).[9] Importantly, the consensus generating process and data integrity

[7]GumboNet ESG automates ESG reporting following a pre-defined standard. IBM Food Trust creates food safety and freshness data according to the latest FDA regulations. GuildOne prevents provides information about exploration, extraction, and production in the oil and gas industry. Bloom is a privacy-preserving credit-scoring system.

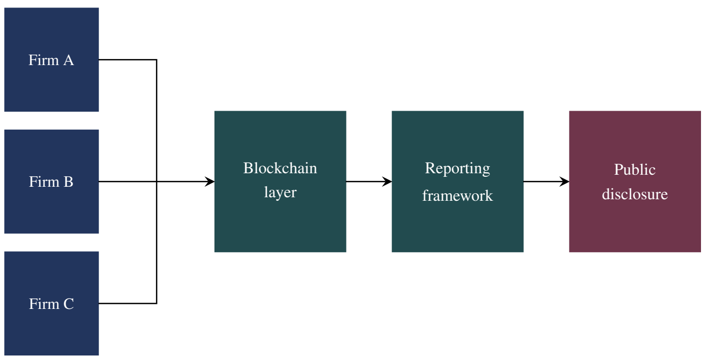
[8]For instance, Ethereum switched to a proof-of-stake architecture in 2022 to increase security and energy efficiency, and to introduce better scaling solutions compared to its previous proof-of-work architecture.

[9]For example, Hyperledger, R3, or the Enterprise Ethereum Alliance with their solutions Fabric, Corda and Enterprise Ethereum have earned considerable recognition as hosts. These consortia have numerous members spanning across industries using their solutions. For instance, Hyperledger currently lists 168 members, including Accenture, Bosch, FedEx, IBM, Oracle, Visa, or Walmart.

is still ensured by the blockchain's decentralized architecture.[10] Although corporate blockchains lack the maintenance component of their public counterparts, they embrace the advantage of increased data coordination across shared ledgers. Before, each firm's stored its ledger separately and third parties needed to reconcile them largely without having direct access to other firms' data.

Figure 4.1 illustrates the design behind most corporate blockchain applications to date. Private blockchains host participating firms' data and run protocols to analyze the data autonomously. Data records are put into blocks, added to the chain in chronological order, and stored in a privacy-preserving way. The blockchain layer analyzes the submitted data and establishes a consensus in the form of a predefined state or metric that is later disclosed via public-facing services. For example, Data Gumbo, the provider of the private blockchain-backed network GumboNet, hosts GumboNet ESG that gathers data from firms' operations and transactions to run calculations and generate metrics for ESG reporting. The application integrates with Topl's Blockchain-as-a-Service platform to publish results on their public blockchain (Data Gumbo, 2021).

Figure 4.1: Illustration of a blockchain disclosure application

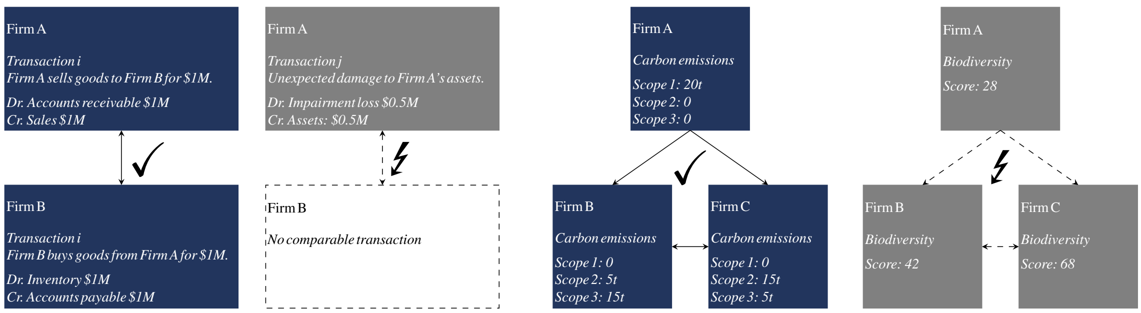


The distributed ledger architecture allows private blockchains to deliver services traditionally provided by third-party intermediaries via technical layers. Consider a blockchain application that provides income statement information based on firms'

[10]Bakos and Halaburda (2021) also show that blockchain operators with a minimal level of trust and well-designed permissioned blockchains can offer both high operational efficiency and high transaction security.

reporting data.[11] Figure 4.2 (a) depicts a common sales transaction and an asset impairment. The seller claims $1M in its accounts receivable. The blockchain layer can establish a consensus by directly verifying $1M in the buyer's accounts payable.[12] In contrast, an asset impairment is more idiosyncratic in nature, making it inherently more difficult to establish a consensus based on other firms' data. Simply put, a firm recording an asset impairment may not result in another firm recording a similar impairment. The blockchain can revert to historical data to derive an estimate. Nevertheless, the consensus is likely less reliable and informative than the one for the cash transaction. A third party may even be more capable of deriving a reliable estimate as it could physically inspect the asset, use non-digital peer-firm information, or rely on tacit knowledge. These aspects are not unique to mandatory financial reporting, but extend to other types of disclosure.

Figure 4.2: Illustration of blockchain information generation



(a) Financial data **(b)** Non-financial data

Figure 4.2 (b) depicts data relevant for ESG disclosures. Blockchain applications are promising in such an area because disclosures rely on data from various parties along firms' value chain and require a high level of assurance. Moreover, traditional institutions are not yet as well entrenched, e.g., compared to the financial reporting

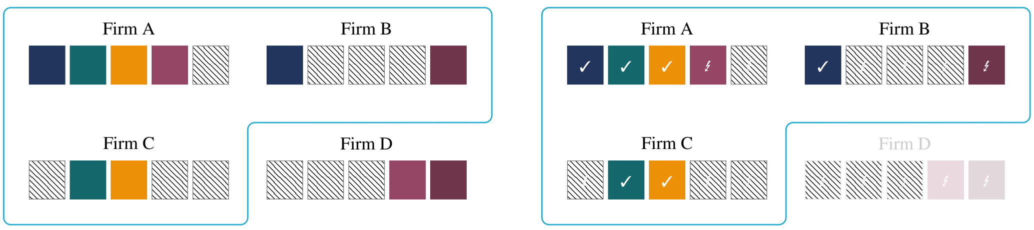
[11] Accounting academics and professionals have proposed to refine double-entry bookkeeping into a triple-entry system to incorporate blockchain technology (e.g., Grigg, 2005; Kiviat, 2015; Dai and Vasarhelyi, 2017; Carlin, 2019; Cai, 2021). The third entry is a digital representation of firms' own accounting records on the blockchain.

[12] Note that the buyer has little incentive to collude in such a transaction because it implies that the buyer overstates the purchase and the seller shows a lower net income to stretch sales. Such collusion costs also imply that information provided by the counterparty can even be more reliable than the seller would provide alone (Cao et al., 2019).

context, meaning that firms likely face a decision to either adopt a new technology or rely on traditional institutions to inform outsiders.[13] Various solutions are available on blockchain networks, such as GumboNet, IBM's Responsible Sourcing Blockchain Network, Kaleido, or Hyperledger Fabric.

Suppose Firm A is an energy producer. It reports its emissions under Scope 1 following the GHG protocol.[14] Firms B and C consume the energy and report indirect emissions under Scope 2. Both firms also interact and report the other firm's emissions under Scope 3. Distributed ledger applications thrive in such a setting. Firm A's direct emissions serve a reference point for the other firms' indirect emissions, and Firm B's indirect emissions serve as a reference point for Firm C's emissions, and vice versa. However, similar to above, other sustainability metrics, such as a firms' impact on local biodiversity, are more challenging. Because blockchains rely on analyzing firms' data on the shared ledgers, its ability to generate information hinges on the informativeness of other firms' data. As a firm's impact on biodiversity depends on unique features, such as its location or technology, other firms' data may not be as indicative. The higher a firm's proportion of challenging data entries of this kind, the less likely the application can generate reliable information.

Figure 4.3: Illustration of blockchain information provision layer



(a) Network data structure **(b)** Network data status

[13]The most prominent players representing traditional third-party institutions in this context are ESG data providers, such as Bloomberg, Refinitiv, Sustainalytics, or MSCI ESG Research, the big-three rating agencies, the big-four auditors, or assurance providers.

[14]Scope 1 emissions are direct emissions from firm-controlled resources. Scope 2 emissions are indirect emissions from purchased energy. Scope 3 emissions are the remaining indirect emissions along the value chain (GHG-Protocol, 2015).

The previous examples implicitly assumed that all firms contribute data. However, the blockchain's access to the data depends on firms' adoption decisions. Intuitively, the more firms join the blockchain, the more complete the digital picture of the transaction space becomes. Figure 4.3 depicts an economy of four firms, with all but Firm D contributing data. The solid blocks represent data entries that the blockchain can analyze using other firms' data. In contrast, the lined blocks represent data entries for which other firms' data are not informative.

The blockchain is most likely to generate a reliable signal for Firm A, with four out of five entries being in principle analyzable. The other firms have a lower potential, with two out of five analyzable entries. Considering that Firm D does not contribute data, the blockchain cannot inform about Firm D and, in addition, is limited in its ability to inform about the other firms because some relevant data—that of Firm D—is inaccessible. The blockchain is still most likely to inform about Firm A in this scenario, with the signal being based on three out of five entries. However, the other firms exhibit varying degrees of informativeness. Firm C remains at two, whereas Firms B and D drop to one and zero out of five analyzable entries, respectively.

The above highlights that information provision is inherently firm-specific—depending on each firm's data profile and fit with the distributed ledger technology—and endogenous—driven by firms' adoption decisions. Moreover, each firm's adoption imposes an externality on other firms, making the overall information provision the result of a complex coordination game. We next introduce an analytical model that explicitly captures these inherent features driving information provision, and use ESG disclosure applications to illustrate our results when appropriate.

4.3 Model

Firm types

We consider an economy populated by a mass of firms, which we normalize to one. Each firm i has a privately known type (v^i, f^i) that consists of its value $v^i \in \{l, h\}$ and its fit for being analyzed by the blockchain $f^i \in \{b, g\}$. For notational convenience, the type is denoted by $\theta^i \in \Theta \equiv \{hg, hb, lb, lg\}$, e.g., hg is shorthand for (h, g). We use v_θ as the firm value of type θ, e.g., $v_{hg} = v_{hb} = h$, and similarly f_θ as the fit of type θ, e.g., $f_{hb} = f_{lb} = b$. We normalize values to $l = 0$ for low-value firms and $h = 1$ for high-value firms.

Each firm's fit captures blockchain's differential ability to analyze a given set of data entries. In light of environmental disclosure, a firm exhibits a good fit when its environmental friendliness depends on carbon emissions that are in principle analyzable by the blockchain. In contrast, a firm exhibits a bad fit when its environmental friendliness to some degree also depends on bio diversity that is more challenging for the blockchain. For firms with a good fit, we set the share of analyzable entries to $g = 1$. For firms with a bad fit, the share of in principle analyzable entries is $b = \beta \in (0, 1)$. The proportion of type $\theta \in \Theta$ in the economy is denoted by $\sigma_\theta \in (0, 1)$. We impose no restrictions on σ_θ so that any correlation between the two dimensions of firms' types is possible. Figure 4.4 summarizes the distribution of the firm types.

Figure 4.4: Distribution of firm types

		Fit		
		good	bad	
Firm value	high	σ_{hg}	σ_{hb}	σ_h
	low	σ_{lg}	σ_{lb}	σ_l
		σ_g	σ_b	

Firm incentives

Firms' values are relevant for the capital market, and each firm aims to maximize its market valuation.[15] We denote the price an investor is willing to pay for a share in firm i by p^i and normalize the amount of shares to 1. Although a firm cannot credibly inform the market about its value, information can be transmitted via one of two regimes. Firms simultaneously choose to either contribute data to a corporate blockchain application or rely on traditional third-party institutions.[16] We let $D^i \in \{0, 1\}$ indicate the decision of firm i to enter the blockchain ($D^i = 1$) or not ($D^i = 0$). Both regimes are costly, with respective costs $C_B \in \mathbb{R}_+$ for the blockchain and $C_T \in \mathbb{R}_+$ for traditional institutions. The cost difference is denoted $C \equiv C_B - C_T \in \mathbb{R}$. Investors observe all firms' adoption decisions and a firm-specific message generated by either the blockchain or the traditional institutions. The adoption decision is synonymous with committing to one of two disclosure regimes, where one—the blockchain—has an endogenous and firm-specific quality, and the commitment itself may carry information. As such, when deciding about adopting a blockchain application, such as GumboNet ESG, a firm has to trade off the assurance by traditional institutions against disclosure that endogenously depends on the amount and composition of adopting firms.

Information provision

To capture this tradeoff, we formalize information provision via a message m^i that is generated for each firm. The message may either reveal a firm's value, $m^i = v^i$, or be uninformative, $m^i = \emptyset$. The probability of revealing a firm's value represents the informativeness of the respective disclosure regime. As such, information generation resembles disclosure models in which the capital market prices firms according to their

[15]We take this objective as given. It is easy to provide a micro foundation, e.g., by having firms require additional capital that is raised via an equity issuance.

[16]Absent type-specific coordination opportunities, both simultaneous and sequential decision-making require each atomistic firm to form beliefs about all firms' equilibrium actions, irrespective of the sequence in which they would act in the sequential game. We therefore restrict attention to simultaneous play to facilitate the formal exposition.

disclosed value or according to a pooling price following no disclosure (see e.g., Dye, 1985; Wagenhofer, 1990; Bertomeu et al., 2021).[17]

Inside the blockchain, the information generated about each firm depends on its fit and the amount of data accessible to the blockchain. The blockchain reveals a firm's type with a firm-specific probability η^i, which increases in the fit f^i and the (equilibrium) reach of the blockchain ρ. For expositional purposes, we assume that all firms contribute equally to the blockchain's efficacy irrespective of their fit so that the reach is equal to the equilibrium mass of firms adopting the blockchain, $\int \mathbb{1}_{D^i=1} di$.[18] Formally, we consider $Pr\{m^i = v^i | D^i = 1\} = \eta^i = \rho \cdot f^i$. For example, if only hg-type firms and hb-type firms adopt, an hg-firm's type is revealed with probability $f_{hg} \cdot \rho = 1 \cdot (\sigma_{hg} + \sigma_{hb}) = \sigma_h$, whereas an hb-firm's type is revealed with probability $f_{hb} \cdot \rho = \beta \cdot \sigma_h$.[19] Outside the blockchain, information provision is independent of a firm's data profile. Traditional institutions provide a credible signal about a firm's type with exogenous probability $Pr\{m^i = v^i | D^i = 0\} = \gamma \in [0, 1)$. This allows traditional institutions to enjoy a comparative advantage in evaluating data entries that are inherently challenging for blockchain's shared ledger architecture.[20]

Investor beliefs and pricing

Investors observe a firm's adoption decision along with the generated message, but not firms' fit or value. They update their beliefs about firms' values following Bayes' Rule and price them according to their posteriors. We denote the pooling prices inside

[17]The reduced-form characterization of signal informativeness is similar to prior literature on disclosure regime or information system commitment, see, e.g., Bertomeu and Magee (2011); Gao and Liang (2013); Edmans et al. (2016).

[18]We discuss heterogeneity in the contribution to the blockchain in Section 4.5. Results are robust to bad-fit firms exerting an externality on good-fit firms by contributing less to the blockchain's reach, and to firms strategically falsifying data entries to lower the blockchain's efficacy.

[19] We abstract from explicitly collusive behavior. It is unlikely to occur if incentives are misaligned, e.g., because a high sales price in a purchase of goods benefits the seller but harms the buyer. If incentives are aligned, e.g., because one firm pockets cash payments in exchange, the blockchain can use all participating firms' data, including that of firms not taking part in a given transaction, to identify fraudulent transactions and raise red flags.

[20]Consider the extreme case with $\beta = 0$. Irrespective of the equilibrium reach, traditional institutions always outperform the blockchain for bad-fit firms.

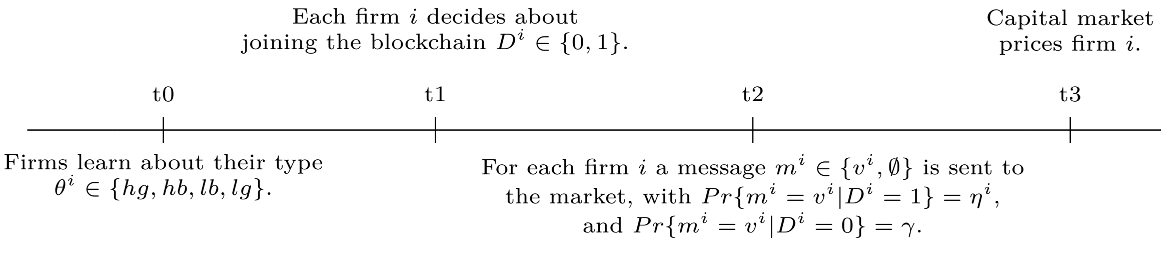
and outside the blockchain (equal to the posterior beliefs) following an uninformative message by p^I and p^O, i.e., $p^I = Pr\{v^i = 1 | D^i = 1 \wedge m^i = \emptyset\}$ and $p^O = Pr\{v^i = 1 | D^i = 0 \wedge m^i = \emptyset\}$. Formally, this gives for the price p^i paid by investors of firm i:

$$p^i(D^i, m^i) = \begin{cases} v^i & \text{if} \quad m^i = v^i \\ p^I & \text{if} \quad m^i = \emptyset \wedge D^i = 1 \\ p^O & \text{if} \quad m^i = \emptyset \wedge D^i = 0. \end{cases} \tag{4.1}$$

Timing of the game

At the beginning of the game, each firm i privately learns its type $\theta^i \in \{hg, hb, lb, lg\}$; all firms then simultaneously decide whether to join the blockchain ($D^i = 1$) or not ($D^i = 0$). For each firm, a message m^i is generated and made available to the capital market. Subsequently, the market uses all available information, i.e., (i) whether firm i entered the blockchain, (ii) the firm-specific message m^i, and (iii) the total mass of adopting firms, to price each firm according to the posterior belief that it is of high value. Figure 4.5 summarizes the timing.

Figure 4.5: Timeline of events



Equilibrium concept

We look for symmetric Perfect Bayesian Equilibria, i.e., equilibria in which all firms of type θ play the same strategy. We denote a *candidate strategy profile* by $\{q_{hg}, q_{hb}, q_{lb}, q_{lg}\}$, where q_θ refers to the probability that a firm of type θ joins the blockchain, i.e.,

$q_\theta = Pr\{D_\theta = 1\}$. Throughout the analysis, we focus our discussion on pure strategy equilibria and characterize all mixed-strategy equilibria in the Appendix.[21]

In any equilibrium in which there is a positive mass of firms both inside and outside the blockchain, i.e., where $0 < \sum_\theta q_\theta < 4$, the pooling prices p^I and p^O are determined by Bayes' Rule.

$$p^I = \frac{\sum_\theta (1-\eta_\theta)\cdot\sigma_\theta\cdot q_\theta\cdot v_\theta}{\sum_\theta (1-\eta_\theta)\cdot\sigma_\theta\cdot q_\theta} = \frac{\sum_\theta (1-\rho f_\theta)\cdot\sigma_\theta\cdot q_\theta\cdot v_\theta}{\sum_\theta (1-\rho f_\theta)\cdot\sigma_\theta\cdot q_\theta}, \tag{4.2}$$

$$p^O = \frac{\sum_\theta (1-\gamma)\cdot\sigma_\theta\cdot(1-q_\theta)\cdot v_\theta}{\sum_\theta (1-\gamma)\cdot\sigma_\theta\cdot(1-q_\theta)} = \frac{\sum_\theta \sigma_\theta\cdot(1-D_\theta)\cdot v_\theta}{\sum_\theta \sigma_\theta\cdot(1-D_\theta)}. \tag{4.3}$$

Note that the outside pooling price p^O is independent of γ as the probability of being identified is identical across firm types. If all firms join (do not join), the price outside (inside) the blockchain is determined by off-path beliefs.[22]

As each individual firm is atomistic, its decision whether to join the blockchain does not affect these pooling prices. This implies that firms of the same type face the same type-specific expected prices p^I_θ when joining, and p^O_θ when not joining as

$$p^I_\theta = E[p^i|\theta^i = \theta \wedge D^i = 1] = \eta_\theta \cdot v_\theta + (1-\eta_\theta)\cdot p^I, \tag{4.4}$$

$$p^O_\theta = E[p^i|\theta^i = \theta \wedge D^i = 0] = \gamma \cdot v_\theta + (1-\gamma)\cdot p^O, \tag{4.5}$$

where η_θ, p^I, and p^O are determined by all other firms' equilibrium decisions.

Adoption decisions

The expected prices p^I_θ and p^O_θ drive firms' adoption decisions—firm i joins whenever the benefits Δ^i exceed the cost C. Importantly, Δ^i is identical for all firms of the same

[21] Mixed strategy equilibria predominantly "fill in the gap" between pure strategy equilibria, adding little economic meaning to our main message.

[22] To characterize the full set of sustainable equilibria, it is hence natural to adopt the most pessimistic off-path beliefs, i.e., $p^I = 0$ ($p^O = 0$), to provide the strongest incentives against possible deviations.

type, $\Delta^i = \Delta_{\theta^i} = p^I_{\theta^i} - p^O_{\theta^i}$. Formally,

$$D^i = D_{\theta^i} = \begin{cases} 1 & \text{if} \quad \Delta_{\theta^i} > C \\ q^i \in [0,1] & \text{if} \quad \Delta_{\theta^i} = C \\ 0 & \text{if} \quad \Delta_{\theta^i} < C \end{cases}, \tag{4.6}$$

where the Δ_θ satisfy

$$\begin{aligned} \Delta_{hg} &= \rho - \gamma + (1-\rho)p^I - (1-\gamma)p^O \\ \Delta_{hb} &= \rho\beta - \gamma + (1-\rho\beta)p^I - (1-\gamma)p^O \end{aligned} \quad \text{and} \quad \begin{aligned} \Delta_{lb} &= (1-\rho\beta)p^I - (1-\gamma)p^O \\ \Delta_{lg} &= (1-\rho)p^I - (1-\gamma)p^O. \end{aligned} \tag{4.7}$$

The Δ_θ exhibit natural comparative statics, i.e., weakly increase (decrease) in the inside (outside) pooling price. For high-value firms, Δ_θ is increasing in ρ and decreasing in γ, while the reverse is true for low-value firms.

Ordering of firms' incentives

Before turning to the analysis of potential equilibria, it is helpful to assess the relative incentives of different types to adopt the blockchain. This implies—under certain conditions—an ordering in types' adoption incentives that restricts the set of potential equilibria. Naturally, high-value firms seek to be identified whereas low-value firms strive to avoid detection. In addition, hg-type firms for whom the blockchain provides a better fit have weakly higher incentives to join the blockchain than hb-type firms, while the reverse is true between lg-type and lb-type firms. These relations follow because the blockchain's ability to generate information about a firm increases in the firm-specific fit. Formally, this is captured by Lemma 4.1.

Lemma 4.1 *hg-type firms benefit weakly more from joining the blockchain than hb-type firms, while lg-type firms benefit weakly less than lb-type firms:*

$$\Delta_{hg} \geq \Delta_{hb} \text{ and } \Delta_{lg} \leq \Delta_{lb}. \tag{4.8}$$

Proof. Proof of Lemma 4.1. See Appendix C.2. □

Pairs of high-value and low-value firms of the same fit—for given strategies of all other firms—have the same probability of being identified inside and outside the blockchain, respectively. However, high-value types enjoy a valuation of 1 when identified, whereas low-value types receive a valuation of 0. The relative attractiveness of the blockchain is thus driven by the relative degree of information generation. We obtain

$$\Delta_{hg} - \Delta_{lg} = \rho - \gamma \tag{4.9}$$

$$\Delta_{hb} - \Delta_{lb} = \rho\beta - \gamma. \tag{4.10}$$

The ordering of adoption incentives between the pairs depends on the strength of traditional institutions γ and in particular the blockchain's equilibrium reach ρ. This exemplifies the complementarity in firms' adoption decisions via the endogenous determination of the blockchain's reach.

We also need to consider the relative incentives to join the blockchain between *hg*-types and *lb*-types, and *hb*-types and *lg*-types, respectively. These incentives depend not only on the primitives β and γ along with the endogenously determined reach ρ, but also on the endogenous pooling price p^I.

$$\Delta_{hg} - \Delta_{lb} = \rho - \gamma - (1-\beta)\rho p^I \tag{4.11}$$

$$\Delta_{hb} - \Delta_{lg} = \rho\beta - \gamma + (1-\beta)\rho p^I. \tag{4.12}$$

The pairwise comparisons provide the basis for the subsequent equilibrium analysis in which we exploit the implied ordering regarding firms' adoption incentives.

4.4 Analysis

The complementarity of firms' decisions naturally gives rise to potential equilibrium multiplicity. As the two actions—adopting and not adopting the blockchain—are both taken by a positive mass of firms in all but two potential equilibria (full adoption and full non-adoption), standard equilibrium refinements that restrict off-path beliefs cannot overcome this multiplicity.[23] Throughout the analysis, we therefore focus on the likelihood of equilibria obtained by considering comparative statics that affect the size of the parameter space supporting the respective equilibria.

4.4.1 Baseline setting

We start our analysis by investigating a baseline setting in which information provision by traditional institutions is muted, i.e., $\gamma = 0$, and the blockchain is relatively costly, i.e., $C > 0$. This allows us to carve out the key mechanisms driving firms' adoption decisions and the resulting information provision to capital market participants.

Because outside information provision is muted, information provision inside the blockchain is strictly stronger whenever a positive mass of firms adopts. As a consequence, high-value firms that seek to signal their type always face stronger adoption incentives than low-value firms of the same fit. Together with Lemma 4.1, this implies the following ordering of adoption incentives.

Lemma 4.2 (Ordering baseline) *When information provision by traditional institutions is muted, i.e., for $\gamma = 0$, the benefits for type θ of joining the blockchain, Δ_θ, satisfy*

$$\Delta_{hg} \geq \Delta_{hb} \geq \Delta_{lb} \geq \Delta_{lg}. \tag{4.13}$$

If a positive mass of firms joins the blockchain, i.e., $\rho > 0$, (i) $\Delta_{hb} > \Delta_{lb}$, (ii) $\Delta_{hg} > \Delta_{hb}$ as long as $p^I < 1$, and (iii) $\Delta_{lb} > \Delta_{lg}$ as long as $p^I > 0$.

[23] We discuss the application of the Intuitive Criterion in detail in Appendix C.12.

Proof. Proof of Lemma 4.2. Follows from the preceding discussion and Lemma 4.1 with (4.9) and (4.10). □

Together with the implications for ρ and p^I from considering a given candidate profile, we obtain Lemma 4.3 that characterizes the reduced set of pure-strategy equilibrium candidates.[24]

Lemma 4.3 (Equilibrium candidates baseline) *The following pure-strategy profiles are potential equilibria:*

$$\{1,1,1,0\}\,,\,\{1,1,0,0\}\,,\,\{1,0,0,0\}\,,\,\{0,1,0,0\}\,,\,\{0,0,0,0\}. \tag{4.14}$$

Proof. Proof of Lemma 4.3. See Appendix C.3. □

Proposition 4.1 provides conditions on C such that these candidates are supported in equilibrium.[25]

Proposition 4.1 (Equilibria baseline) *The following pure strategy profiles can be supported in equilibrium for $\gamma = 0$ depending on the cost $C \geq 0$ of adopting the blockchain technology.*

(i) For $C \in \left[\underline{C}, \bar{C}\right]$, $\{1,1,1,0\}$ can be supported.

(ii) For $C \in \left[1 - \beta\left(\sigma_{hb} + \sigma_{hg}\right), 1\right]$, $\{1,1,0,0\}$, can be supported.

(iii) There exists a unique $C^{\{1,0,0,0\}} \in \left(1 - \left(\sigma_{hg} + \sigma_{hb}\right), 1\right)$ such that $\{1,0,0,0\}$ can be supported, and a unique $C^{\{0,1,0,0\}} \in \left(1 - \left(\sigma_{hg} + \sigma_{hb}\right), 1\right)$ such that $\{0,1,0,0\}$ can be supported.

[24] For example, whenever a positive fraction of lb-types joins, i.e., $q_{lb} \in (0,1)$, it must be the case that $\Delta_{lb} = C$ so that lb-types are indifferent. If this holds in equilibrium, we also have $\rho > 0$ and hence $\Delta_{hg} \geq \Delta_{hb} > \Delta_{lb} = C$, i.e., all high-value types strictly prefer to join the blockchain.

[25] Note that the equilibria in which only hg-types or hb-types join, respectively, are only sustainable when C satisfies a knife-edge condition. In contrast, the other pure-strategy equilibria {1,1,1,0} and {1,1,0,0} are sustainable for a range of costs C, with {1,1,1,0} being sustainable for a disjoint and lower cost range than {1,1,0,0}. We also characterize the emerging mixed-strategy equilibria in Appendix C.4.

(iv) For $C > 0$, $\{0, 0, 0, 0\}$ *can be supported.*

$\underline{C}$ *and* $\bar{C}$ *are characterized by*

$$\underline{C} = \sigma_{lg} \frac{\sigma_{lg}\sigma_{hg} + (1 - \beta(1 - \sigma_{lg}))\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1 - \beta(1 - \sigma_{lg}))(\sigma_{hb} + \sigma_{lb})} \quad (4.15)$$

$$\bar{C} = (1 - \beta(1 - \sigma_{lg})) \frac{\sigma_{lg}\sigma_{hg} + (1 - \beta(1 - \sigma_{lg}))\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1 - \beta(1 - \sigma_{lg}))(\sigma_{hb} + \sigma_{lb})} \quad (4.16)$$

Proof. Proof of Proposition 4.1. See Appendix C.4. □

Proposition 4.1 highlights the two information provision channels through which the capital market can learn about firms' value types. First, the adoption decisions themselves may reveal information about firms' values—depending on each firm's equilibrium action, the adoption decision may even be perfectly informative. Second, the capital market may learn about participating firms' values via an informative message generated by the blockchain.[26]

Despite firms facing identical adoption costs, joining the blockchain may serve as a credible signal of firm value because benefits—the expected payoffs from joining—differ across firm types. Even perfect separation is possible once adoption costs become sufficiently high. In the context of environmental disclosure, only environmentally friendly firms would be willing to bear the costs of adopting a blockchain-based application to inform investors, whereas non-environmentally friendly firms would not adopt. The blockchain essentially becomes a "money-burning" signaling device. However, as common in these settings, environmentally friendly firms may be adversely affected by the availability of the blockchain application. In particular, the gains from being correctly

[26] Due to the one-period nature of our model, both information provision channels have equal weight. Allowing for multiple periods with potentially changing firm values would render the adoption signal weaker than the blockchain's ongoing information provision. Nonetheless, both two channels remain relevant in such a setting.

perceived as environmentally friendly relative to the situation in which the blockchain application is not available may be more than offset by the costs.[27]

Because environmentally friendly firms have incentives to adopt blockchain applications to separate, non-environmentally friendly firms may also want to adopt to not be singled out.[28] However, adopting the application and contributing data to the blockchain not only entails direct costs but also increases the blockchain's reach, improving its ability to reveal firms' value types. In equilibrium, non-environmentally friendly firms balance these considerations. For intermediate costs, only low-value, bad-fit firms—non-environmentally friendly firms with biodiversity issues driving their bad environmental performance—join the environmentally friendly firms in the blockchain. The risk of being identified is sufficiently low and the expected benefits from being pooled with environmentally friendly firms compensate for the direct adoption cost. In contrast, low-value, good-fit firms—non-environmentally friendly firms with carbon emissions driving their bad environmental performance—do not expect a sufficient compensation. With more firms contributing data to the blockchain, the application can provide a largely informative message about participating firms' values, especially when their data is easier to analyze.

4.4.2 Generalized setting

We next lift the restriction muting outside information generation, i.e., we allow for $\gamma \in [0,1)$, and consider the blockchain to be cheaper or costlier than traditional institutions, i.e., $C \in \mathbb{R}$.

In contrast to the baseline setting, the blockchain may now provide less information than traditional institutions which affects type-specific adoption incentives and results

[27]For $C \to 1$, the $\{1,1,0,0\}$-equilibrium exists and features $p^I_\theta - C \to 0$ for $\theta \in \{hg, hb\}$. If the blockchain were unavailable, these two types would enjoy a strictly positive p^O_θ. Nonetheless, high-value firms strictly prefer to adopt the blockchain in this equilibrium as they earn $1-C$ instead of 0, which is the pooling price outside the blockchain.

[28]The only exceptions are the equilibrium in which all firms rely on traditional institutions, $\{0,0,0,0\}$, and the knife-edge equilibria in which one of the high-value types joins, while the other relies on traditional institutions.

in novel tradeoffs. Consider the baseline setting with intermediate adoption cost such that, in equilibrium, some low-value firms join the high-value firms in the blockchain. The pooling price for unidentified firms using the blockchain application is strictly below 1. Firms outside the blockchain are expected to be low-value firms, resulting in an outside pooling price of 0. However, for the same adoption cost, this is no longer an equilibrium in the generalized setting for sufficiently strong traditional institutions. For γ close to 1, high-value firms have strict incentives to remain with the traditional institutions because they expect them to generate more information than the emerging blockchain. Their expected payoffs approach their true value despite the capital market perceiving them to be of low value following an uninformative message. This highlights that the equilibria in the generalized setting will depend on both the adoption cost C and the strength of traditional institutions γ.

Figure 4.6: Illustration of pure-strategy equilibria

This figure illustrates the pure-strategy equilibria in the generalized setting. The lined and dark-gray areas depict equilibria in which high-value and low-value firms join the blockchain whereas the light-gray areas depict fully separating equilibria. For ease of exposition, we omit equilibria in which no firm adopts, all firms adopt, and equilibria relying on knife-edge conditions.

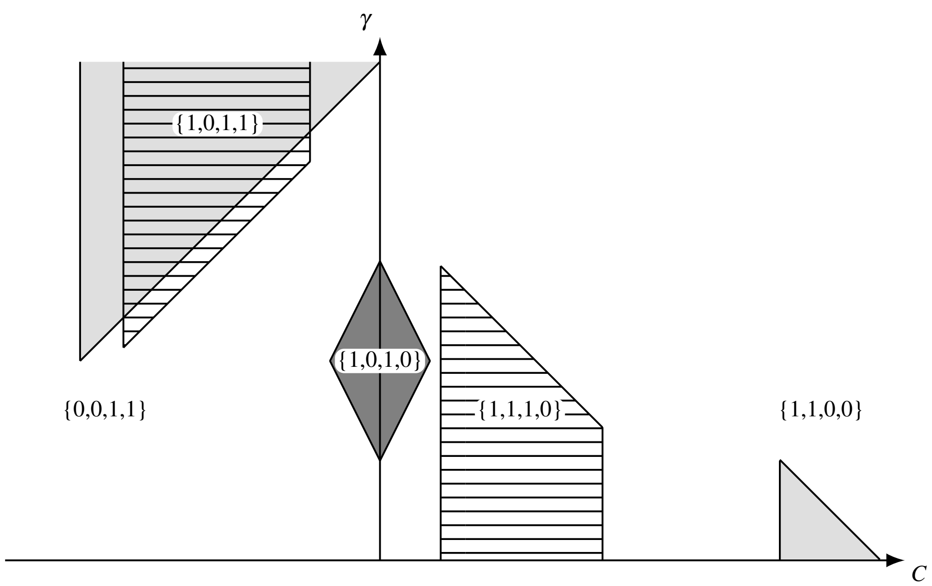


Figure 4.6 depicts the pure-strategy equilibria for combinations of the relative adoption cost C and the strength of traditional institutions γ, omitting equilibria in which no firm adopts, all firms adopt, and equilibria relying on knife-edge conditions. The full

characterization of all equilibria is in Appendix C.5.[29] Information provision still occurs via the two channels identified in the baseline setting. However, while the adoption decision may carry information, it no longer always serves as a credible signal of high value. Instead, the reliance on traditional institutions can indicate a high value when the blockchain is cheaper. Moreover, firms now have to consider the relative strength of the two information systems, with the blockchain's informativeness depending on the mass and composition of adopting firms.

The light-gray areas represent separating equilibria in which firms separate according to their value types via the adoption decisions. If traditional institutions are sufficiently weak (sufficiently low γ), high-value firms seek other means of signaling. For example, for sufficiently high adoption costs ($C >> 0$), environmentally friendly firms would again adopt and incur the high adoption costs to separate from non-environmentally friendly firms. In addition, separation can also occur with only low-value firms adopting the blockchain. Non-environmentally friendly firms prefer the blockchain if they have sufficient incentives to evade traditional institutions (sufficiently high γ) and adoption offers cost savings ($C << 0$). Environmentally friendly firms would remain outside, incur the relative cost disadvantage, and receive a high level of assurance by traditional institutions. In both types of equilibria, there is a degree of substitutability between the strength of traditional institutions and the relative adoption costs—the weaker (stronger) the traditional institutions, the lower is the relative cost (relative benefit) cutoff for separation to be sustainable.

The lined areas depict partially separating equilibria. For positive adoption costs ($C > 0$), all but the low-value, good-fit firms are willing to contribute data to the blockchain for sufficiently weak traditional institutions. In this case, the blockchain's abilities to generate information becomes comparably strong and non-environmentally

[29] We first exploit the implied ordering of incentives to join the blockchain to restrict the set of equilibrium candidates, see Appendix C.5.1. We then characterize the parameter ranges supporting a given equilibrium candidate separately for the case where the blockchain is more expensive than traditional institutions ($C \geq 0$, Appendix C.5.2) and where it is cheaper ($C < 0$, Appendix C.5.3). Appendix C.5.4 characterizes the mixed-strategy equilibria.

friendly firms with easy to analyze carbon emissions data would likely be identified by the blockchain. They therefore prefer to at least avoid the adoption costs in equilibrium. For negative adoption costs ($C < 0$), it is the high-value, bad-fit firms that have no incentive to join the others in using the blockchain-based disclosure application. These environmentally friendly firms are willing to forego the relative cost savings from adopting the blockchain if the traditional institutions can provide a sufficiently strong service. In contrast, the high-value, good-fit firms—environmentally friendly firms with analyzable carbon emissions data—still adopt because the blockchain is again comparably strong in equilibrium. The combination of higher within-blockchain expected payoffs and cost savings is sufficient to induce adoption. The partially separating equilibria share that the blockchain's distributed ledger capabilities generate comparably informative signals about adopting firms.

A key insight from the generalized setting is the existence of a novel equilibrium in which both high-value and low-value firms are present inside and outside the blockchain. Specifically, there are parameter constellations for which only high-value, good-fit firms and low-value, bad-fit firms adopt in equilibrium. This *mixed-adoption equilibrium* stands out because both information provision channels do not function to their full potential. The presence of both value-types inside and outside the blockchain implies that firms' adoption decisions are not an efficient means of separation. Moreover, the reach, and thus the blockchain's abilities to identify firms, is only intermediate. Although it outperforms traditional institutions for firms with a good fit, it underperforms for firms with an inherently bad fit. As illustrated by the dark-gray area in Figure 4.6, the equilibrium may materialize both when the blockchain is cheaper and when it is costlier than traditional institutions. We next investigate this potentially undesirable situation in more detail.

4.4.3 An undesirable situation?

We begin by explicitly deriving the necessary and sufficient condition for the existence of the mixed-adoption equilibrium. Specifically, we establish a condition on the relationship between the proportion of firm-types in the economy and the strength of traditional institutions γ such that the equilibrium exists for a non-empty range of relative costs C.

Note that for the strategy profile $\{1,0,1,0\}$ to constitute an equilibrium, all firms must weakly prefer their respective adoption choice, i.e.,

$$\Delta_{hg} \geq C \wedge \Delta_{hb} \leq C \wedge \Delta_{lb} \geq C \wedge \Delta_{lg} \leq C. \tag{4.17}$$

Given Lemma 4.1, we know $\Delta_{hg} \geq \Delta_{hb}$ and $\Delta_{lg} \leq \Delta_{lb}$ so that C satisfying (4.17) exist if and only if

$$\min\{\Delta_{hg}, \Delta_{lb}\} \geq \max\{\Delta_{hb}, \Delta_{lg}\} \iff \rho = \sigma_{hg} + \sigma_{lb} \geq \gamma \geq \beta(\sigma_{hg} + \sigma_{lb}) = \rho\beta, \tag{4.18}$$

where we have used the implied reach of the blockchain in the conjectured equilibrium, $\rho = \sigma_{hg} + \sigma_{lb}$.

The explicit bounds on the relative cost C can be obtained using the implied pooling prices:

$$p^O = \frac{\sigma_{hb}}{\sigma_{hb} + \sigma_{lg}} \text{ and } p^I = \frac{(1 - \sigma_{hg} - \sigma_{lb})\sigma_{hg}}{(\sigma_{hg} + \sigma_{lb})(1 - \sigma_{hg} - \beta\sigma_{lb})}. \tag{4.19}$$

This also allows us to derive conditions for the equilibrium being supported when the blockchain is cheaper and costlier than traditional institutions, respectively.

Proposition 4.2 *There exist* $\underset{\sim}{C}_b(\gamma), \tilde{C}_b(\gamma)$ *such that* $\{1,0,1,0\}$ *can be supported in equilibrium for* $C \in \left[\underset{\sim}{C}_b(\gamma), \tilde{C}_b(\gamma)\right]$ *if and only if* $\beta(\sigma_{hg}+\sigma_{lb}) \leq \gamma \leq \sigma_{hg}+\sigma_{lb}$. *Moreover,*

(i) $\exists\gamma \in [0,1] : \tilde{C}_b(\gamma) > 0 \iff \frac{\sigma_{hb}\sigma_{lb}}{\sigma_{hg}\sigma_{lg}} < 1.$

(ii) $\exists\gamma \in [0,1] : \underset{\sim}{C}_b(\gamma) < 0 \iff \frac{\sigma_{lb}\sigma_{hb}}{\sigma_{hg}\sigma_{lg}} > \frac{(1-(\sigma_{hg}+\sigma_{lb}))^2}{(1-\beta(\sigma_{hg}+\sigma_{lb}))^2}$

Proof. Proof of Proposition 4.2. Given (4.18), we can simply define $\underset{\sim}{C}_b \equiv \max\{\Delta_{hb}, \Delta_{lg}\}$ and $\tilde{C}_b \equiv \min\{\Delta_{hg}, \Delta_{lb}\}$ so that the proposition follows. The derivations of the conditions in (i) and (ii) is contained in the general characterization of all equilibria in Appendix C.5, see (C.21) and (C.38). □

Proposition 4.2 offers several insights. First, the heterogeneity in firms' fit is an essential factor inducing the equilibrium. More heterogeneous firms (low β) increase the parameter space supporting the mixed-adoption equilibrium. In addition, a higher proportion of good-fit firms in the economy increases (decreases) the likelihood that the equilibrium materializes for positive (negative) relative adoption cost. It is therefore not sufficient to subsidize an economy-wide blockchain adoption to rule out potentially inefficient information generation.

Second, in the equilibrium, the blockchain has to provide a more informative signal than traditional institutions for good-fit firms such that hg-type firms adopt and lg-type firms remain outside. The opposite needs to hold for bad-fit firms. As such, the blockchain's equilibrium reach has to be intermediate. Similarly, traditional institutions have to be of intermediate strength too. Whenever they are sufficiently strong—where hg-type firms would prefer to rely on traditional institutions—or sufficiently weak—where even hb-type firms would prefer to adopt—the scope for the mixed-adoption equilibrium is limited.

Third, blockchain technology induces a coordination game with potentially adverse consequences. Given the equilibrium reach $\rho = \sigma_{hg}+\sigma_{lb}$, traditional institutions provide more information for bad-fit firms whereas the blockchain performs better for good-fit firms. To maximize information generation about each firm—taking the reach of the blockchain as given—it should be good-fit firms who rely on the blockchain and bad-fit firms who rely on traditional institutions. However, in the equilibrium, low-value firms pick the option that minimizes their likelihood of being detected.[30]

In summary, there are two types of inefficiencies: the blockchain's reach is only intermediate, and, conditional on the reach, coordination problems result in low-value firms' adoption decisions to be inefficient from an information perspective.

Average mispricing in the economy

To assess the overall information provision, we next compare the average mispricing in the equilibrium with a scenario in which blockchain technology does not exist.[31] In our model, mispricing occurs whenever firms' values are not revealed by the blockchain or traditional institutions—they are then priced at the respective pooling prices.

Without blockchain, all firms have to rely on traditional institutions. With probability γ, they are priced correctly, and with probability $(1-\gamma)$ they are mispriced by the absolute difference between their true value and the pooling price $p = \sigma_{hg} + \sigma_{hb}$ of non-identified firms. The average mispricing without blockchain technology, denoted AMP_{noBC}, is therefore given by:

$$\begin{aligned} AMP_{noBC} &= (1-\gamma)\cdot\Big[(\sigma_{hg}+\sigma_{hb})\cdot(1-p) + (1-\sigma_{hg}-\sigma_{hb})\cdot(p-0)\Big] \\ &= 2(1-\gamma)(\sigma_{hg}+\sigma_{hb})(1-\sigma_{hg}-\sigma_{hb}). \end{aligned} \tag{4.20}$$

Notably, AMP_{noBC} only depends on the strength of the traditional institutions γ and the proportion of high-value firms $\sigma_{hg}+\sigma_{hb}$ because the firm-specific fit does not affect information provision by traditional institutions. Mispricing is decreasing when tradi-

[30]Note that this is distinct from the general incentive to avoid detection for low-value firms. In other equilibria, some low-value firms choose the more informative disclosure channel in equilibrium because they are compensated with a high pooling price following an uninformative message.

[31]A complete welfare analysis would require a micro-foundation for investors' behavior to properly determine the cost of mispricing. As any such specification would be inherently arbitrary, we focus on mispricing itself.

tional institutions become stronger as firms are more likely to be priced correctly, and increasing in value heterogeneity.[32]

The average mispricing in the mixed-adoption equilibrium strategy profile, $AMP_{\{1,0,1,0\}}$, obtains from summing over the type-specific probabilities that the firms' values are not correctly revealed times the difference between firms' true values and the respective pooling price inside or outside:

$$\begin{aligned} AMP_{\{1,0,1,0\}} &= \sigma_{hg} \cdot (1-\rho) \cdot (1-p^I) + \sigma_{lb} \cdot (1-\rho\beta) \cdot (p^I - 0) \\ &+ \sigma_{hb} \cdot (1-\gamma) \cdot (1-p^O) + \sigma_{lg} \cdot (1-\gamma) \cdot (p^O - 0). \end{aligned} \quad (4.21)$$

Substituting p^I and p^O from (4.19) and simplifying yields:

$$AMP_{\{1,0,1,0\}} = 2\left[\frac{(1-\gamma)\sigma_{hb}\sigma_{lg}}{\sigma_{hb}+\sigma_{lg}} + \frac{\sigma_{hg}\sigma_{lb} \cdot (1-\sigma_{hg}-\sigma_{lb})(1-\beta(\sigma_{hg}+\sigma_{lb}))}{(\sigma_{hg}+\sigma_{lb})(1-\sigma_{hg}-\beta\sigma_{lb})}\right]. \quad (4.22)$$

Comparing (4.20) and (4.22) shows that the mixed-adoption equilibrium may indeed lead to lower information provision. Specifically, we can rewrite $AMP_{\{1,0,1,0\}} > AMP_{noBC}$ as a condition on the strength of the traditional institutions γ:

$$\gamma > 1 - \frac{\sigma_{hg}\sigma_{lb}(1-\sigma_{hg}-\sigma_{lb})^2(1-\beta(\sigma_{hg}+\sigma_{lb}))}{(\sigma_{hg}+\sigma_{lb})(1-\sigma_{hg}-\beta\sigma_{lb})\left(\sigma_{hg}(1-\sigma_{hb}-\sigma_{hg})^2 - \sigma_{hg}\sigma_{lb} + (\sigma_{hb}+\sigma_{hg})^2\sigma_{lb}\right)} \equiv \hat{\gamma}. \quad (4.23)$$

The condition $\gamma > \hat{\gamma}$ indicates that for average mispricing to be higher with blockchain technology, traditional institutions must be sufficiently strong. As such, economies with strong existing institutions are not immune to the undesirable situation. However, (4.23) only considers the difference in average mispricing *conditional* on the mixed-adoption equilibrium. We therefore also need to account for the implied bounds on the traditional institutions' strength for the equilibrium to materialize (see Proposi-

[32] The distribution of firm values in the economy is fully described by the share of high-value firms. (4.20) is thus maximized for $\sigma_{hg} + \sigma_{hb} = \frac{1}{2}$, i.e., when the value heterogeneity is at its maximum, and equal to zero for $\sigma_{hg} + \sigma_{hb} = 0$ or $\sigma_{hg} + \sigma_{hb} = 1$ when the pooling price is correct because all firms share the same value and valuation.

tion 4.2), i.e., assess where $\hat{\gamma}$ lies relative to the lower bound, $\beta(\sigma_{hg} + \sigma_{lb})$, and the upper bound, $(\sigma_{hg} + \sigma_{lb})$. For $\hat{\gamma} < \beta(\sigma_{hg}, \sigma_{lb})$, all mixed-adoption equilibria would increase average mispricing, while no mixed-adoption equilibria would have this effect for $\hat{\gamma} > (\sigma_{hg} + \sigma_{lb})$.

Proposition 4.3 summarizes the compatibility of $\gamma > \hat{\gamma}$ with both the lower bound and upper bound for the mixed-adoption equilibrium from Proposition 4.2 to be sustainable. For ease of exposition, we consider the case of firms' fit and values being independent, with λ denoting the probability of a firm's value being high and ω denoting the probability of a firm's fit being good.[33]

Proposition 4.3 *The availability of blockchain may harm the information environment by leading to an adverse mixed-adoption equilibrium with increased mispricing. This materializes for a non-empty set of (γ, C)-combinations provided that the heterogeneity in fit is sufficiently large, i.e., provided that β does not exceed an upper bound $\tilde{\beta}(\lambda, \omega)$. For $\beta > \tilde{\beta}(\lambda, \omega)$, no adverse mixed-adoption equilibrium exists. Formally, (i) $\hat{\gamma} > \beta(\sigma_{hg} + \sigma_{lb})$ and (ii) $\beta \leq \tilde{\beta}(\lambda, \omega) \implies \hat{\gamma} < \sigma_{hg} + \sigma_{lb}$.*

Proof. Proof of Proposition 4.3. See Appendix C.6, which also analytically characterizes $\tilde{\beta}(\lambda, \omega)$. □

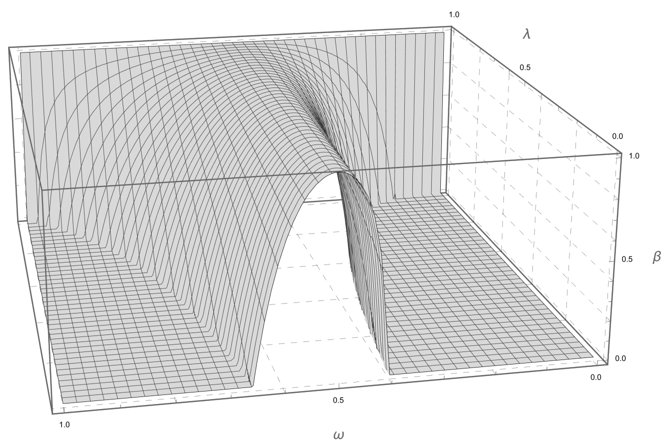
There are two main takeaways from Proposition 4.3. First, as $\hat{\gamma} > \beta(\sigma_{hg} + \sigma_{lb})$, information provision does not always deteriorate in the mixed-adoption equilibrium. Specifically, when γ is close to the lower bound $\beta(\sigma_{hg} + \sigma_{lb})$ such that the equilibrium can be supported, both information provision channels remain impeded but average mispricing still decreases compared to a situation without blockchain. Essentially, traditional institutions are sufficiently weak so that the blockchain can more easily outperform them. Second, average mispricing may nonetheless increase depending on the relationship between the fit β and the distribution of firm types.

[33]The distribution of firm types becomes: $\sigma_{hg} = \lambda\omega\,, \sigma_{hb} = \lambda(1-\omega)\,, \sigma_{lg} = (1-\lambda)\omega\,, \sigma_{lb} = (1-\lambda)(1-\omega)$.

Figure 4.7 illustrates the threshold level of the fit parameter β for which the *adverse mixed-adoption equilibrium with increased average mispricing* materializes. Information provision only deteriorates if firms' fit heterogeneity is sufficiently high (ω closer to 0.5 and β small), i.e., their data profiles are sufficiently different. As such, if all firms' environmental friendliness is driven by carbon emissions alone, the blockchain's emergence is less likely to adversely affect the overall informativeness of environmental disclosures. However, if some firms' environmental friendliness is driven by easy to analyze carbon emissions but others' to a sufficient degree by biodiversity, the heterogeneity in firms' fit both increases the scope for the mixed-adoption equilibrium and weakens the overall efficacy of the blockchain. Intuitively, the difficult to analyze biodiversity data contributed by bad-fit firms are more likely to lead to mispricing. For the same reason, the bound on the fit parameter β and the likelihood that the adverse equilibrium materializes are both higher whenever the probability of a firm having a good fit ω is intermediate—which implies a comparable fraction of good-fit and bad-fit firms, and thus, already a large heterogeneity in firm-specific fit.

Figure 4.7: Parameter constellations for equilibria with increased average mispricing

This figure illustrates the threshold level of the fit parameter β as a function of the likelihood of a firm being of high value, λ, and the likelihood of a firm being of good fit, ω. Equilibria in which average mispricing increases exist for a positive mass of (γ, C)-combinations whenever β falls below this threshold.



Moreover, information provision is more likely to decrease under blockchain technology when the share of high-value firms λ is higher. As such, an economy with more environmentally friendly firms should be more likely to suffer from less informative environmental disclosures when blockchain technology becomes available, even if they are relatively homogeneous with either carbon emissions or biodiversity determining their environmental friendliness. This is due to the coordination game induced by the emergence of the technology, where even intermediate heterogeneity in fit can result in an overall adverse effect on information provision.[34]

Coordination issue or inherently bad technology?

Proposition 4.3 highlights that information provision only decreases when the strength of traditional institutions is intermediate. Economies with sufficiently strong traditional institutions are more likely to suffer from a loss in average informativeness, unless they are so strong to preclude the mixed-adoption equilibrium. In principle, increased mispricing in the mixed-adoption equilibrium can result from the blockchain-induced coordination game, or blockchain being an inherently bad technology to analyze some firms' data so that information provision is on average worse even under (mandated) full adoption.

When we explicitly consider the mispricing induced under full adoption, the pooling price following an uninformative message is $p^I = \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}$, which implies the following average mispricing:

$$AMP_{\text{full}} = (1-\beta)\sigma_{hb}(1-p^I) + (1-\beta)\sigma_{lb}p^I = 2(1-\beta)\frac{\sigma_{hb}\sigma_{lb}}{\sigma_{hb}+\sigma_{lb}}. \tag{4.24}$$

Thus, blockchain increases mispricing even under full adoption if and only if:

$$AMP_{\text{full}} > AMP_{\text{noBC}} \iff \beta < \gamma + (1-\gamma)\left[2\sigma_{hg} + \sigma_{hb} - \frac{\sigma_{hg}-\sigma_{hg}^2}{\sigma_{hb}} - \frac{(1-\sigma_{hg}-\sigma_{hb})(\sigma_{hg}+\sigma_{hb})}{\sigma_{lb}}\right]. \tag{4.25}$$

In the independent fit and value parameterization, (4.25) further reduces to $\beta < \frac{\gamma-\omega}{1-\omega}$, highlighting that blockchain is more likely to be an inherently bad technology if

[34] While the overall impact of blockchain technology is more likely to be negative, the absolute amount of mispricing is lower when firms are more homogeneous in the value dimension.

traditional institutions are sufficiently strong (high γ), there is a sufficient fraction of bad-fit firms (low ω), or the technology is sufficiently bad in analyzing bad-fit firms (low β).

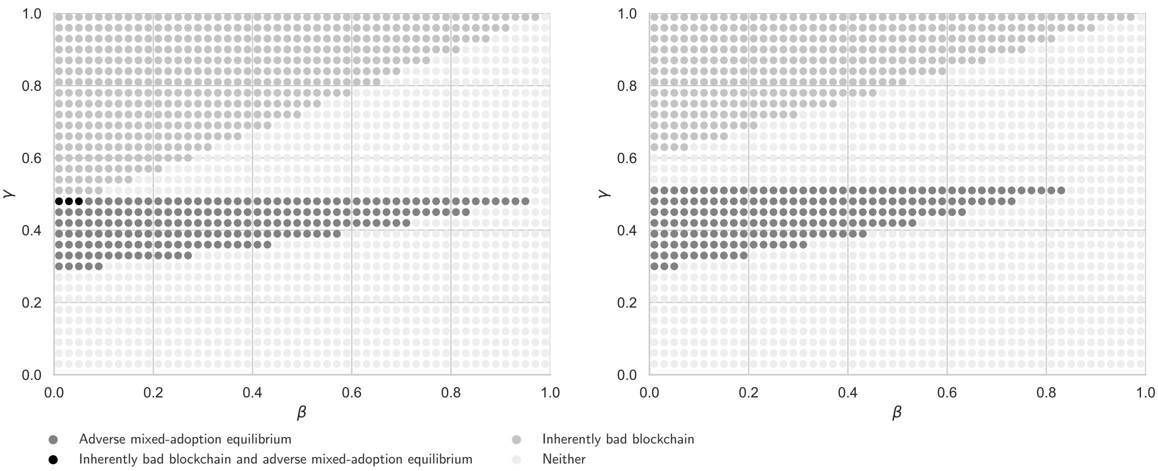
The above conditions resemble situations in which large variation between firms renders the adoption of uniform reporting standards undesirable (see, e.g., Ray, 2018). As such, mandating the adoption of blockchain-based services is not necessarily desirable from a policy perspective. While a mandate provides the benefit of avoiding the coordination problem, it carries the risk of harming the information environment in case the blockchain is an inherently bad technology. Furthermore, the direct adoption costs would need to be carried by all firms, including smaller ones, which may render mandatory adoption welfare-reducing, despite a positive impact on information provision. When there is a low proportion of bad-fit firms, the adoption costs determine whether mandatory adoption is beneficial, whereas a high proportion of bad-fit firms can render mandatory adoption welfare-reducing even absent high adoption costs. In the context of environmental disclosure, such a high proportion of bad-fit firms would be more likely in economies closer to achieving carbon neutrality because environmental performance will depend more on other aspects, such as a firm's impact on biodiversity, that are inherently challenging for the blockchain to analyze.

Moreover, the blockchain can adversely affect the information environment even when it is not inherently bad. The blockchain-induced coordination game can render the in principle viable technology—in the sense that (4.25) is violated—unfit for information provision by limiting its reach and lowering the signaling value of firms' adoption decisions.

Figure 4.8 illustrates combinations of the fit parameter β and the strength of traditional institutions γ for which the blockchain is an inherently bad technology and for which the mixed-adoption equilibrium results in increased average mispricing. The adverse mixed-adoption equilibrium generally materializes whenever the blockchain is *not* an inherently bad technology. The blockchain can both be inherently bad and

Figure 4.8: Adverse mixed-adoption equilibrium or inherently bad technology

This figure illustrates combinations of the fit parameter β and strength of traditional institutions γ for which the blockchain is an inherently bad technology and the mixed-adoption equilibrium features increased average mispricing (black area), the mixed-adoption equilibrium features increased average mispricing (dark gray area), the blockchain is an inherently bad technology (gray area), or neither materializes (light gray area). Both panels are based on the firms' fit and value being independent; the left panel considers $\lambda = 0.65$ and $\omega = 0.45$, and the right panel $\lambda = 0.65$ and $\omega = 0.6$.



result in the mixed-adoption equilibrium, as illustrated in the left panel. However, the two areas are typically disjoint, as in the right panel. Intuitively, for the blockchain to be an inherently bad technology, traditional institutions need to be sufficiently strong. Strong traditional institutions in turn create incentives for high-value firms to remain outside the blockchain, making the mixed-adoption equilibrium less likely.

The fact that the adverse mixed-adoption equilibrium occurs when the blockchain is in principle a viable technology offers scope for policy interventions. While an ex-ante mandate to adopt the technology may adversely affect information provision, encouraging further dissemination of the technology after its emergence can in fact be beneficial. An increase in the blockchain's reach can improve information provision if regulators can properly identify the mixed-adoption equilibrium and detect the initial negative impact on the information environment.

4.5 Additional considerations

In this section, we discuss variations of our model and implications, focusing primarily on the mixed-adoption equilibrium and its impact on information provision.

4.5.1 Scalability of blockchain capabilities

In the model, the blockchain's reach affects firm-specific information provision linearly. However, the blockchain's capabilities to analyze a given set of data may scale differently. Let the firm-specific information provision be $Pr\{m^i = v^i | D^i = 1\} = \tilde{\eta}^i = \rho^s \cdot f^i$, with s parametrizing the technology's scalability. As $\rho \in [0, 1]$, a small (large) parameter s implies that even a small (even a large) mass of firms allows the blockchain to perform well (to only exhibit a limited performance).[35]

Firms' incentives to join the blockchain for a given mass of adopting firms may increase (for high-value firms and $s < 1$, or for low-value firms and $s > 1$) or decrease (for high-value firms and $s > 1$, or for low-value firms and $s < 1$) relative to the main model. However, the ordering of firms' adoption incentives remains, with conditions reflecting the change in the blockchain's reach. Interestingly, a more efficient blockchain (s being small) increases the range of traditional institutions γ for which the mixed-adoption equilibrium is sustainable. While this effect needs to be traded off against the more informative signal generated by the blockchain for a given mass of adopters, it nonetheless implies that efficiency gains can have adverse consequences.

4.5.2 Continuous type spaces

We characterize firms using discrete types along the dimensions of firm value and fit with blockchain technology. To analyze the robustness of our results, we next consider

[35] For a detailed analysis, see Appendix C.8.

firms' fit to be continuously distributed while retaining the binary value-types.[36] Because firms' equilibrium behavior derives from a system of equations involving higher-order polynomials, we implement a numerical solution.

Figure 4.9: Illustration of equilibria with continuous fit-type space

This figure illustrates the combinations of the relative adoption cost C and strength of traditional institutions γ for which the mixed-adoption equilibrium features increased average mispricing (black area), the mixed-adoption equilibrium features decreased average mispricing (dark gray area), or a corner solution arises in equilibrium (light gray area). Both panels are based on the continuous-fit variant of the model; the left panel considers $\lambda = 0.65$, and the right panel $\lambda = 0.85$.

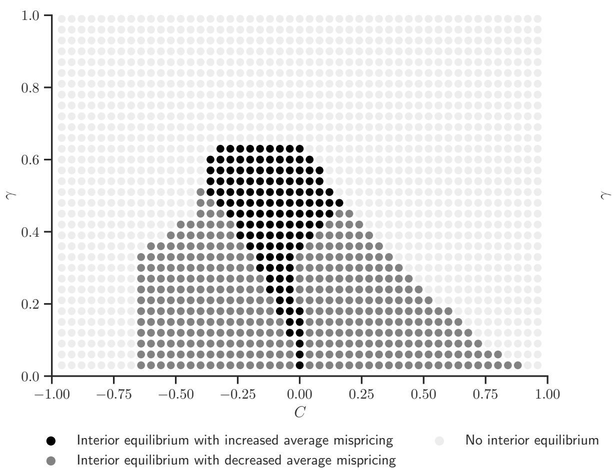


Figure 4.9 depicts combinations of the relative adoption cost C and the strength of traditional institutions γ for different proportions of high-value firms λ and a given fit distribution. In the light-gray area, no interior equilibrium exists, i.e., all equilibria feature at least one value-type adopting or not adopting the blockchain irrespective of the fit. In the dark-gray area, the mixed-adoption equilibrium exists and the information environment improves. Lastly, in the black area, the mixed-adoption equilibrium exists and the information environment deteriorates relative to the scenario without blockchain. As such, the potential adverse impact of the blockchain is robust to departing from the discrete type space. The adverse equilibrium can again materialize both when the blockchain is potentially cheaper *or* costlier than traditional institutions, and

[36]For a detailed analysis, see Appendix C.9. The case where the fit is binary and value-type continuous follows an analogous setup and yields similar results.

is again more likely for intermediate traditional institutions or a larger proportion of high-value firms.

4.5.3 Firms' contribution to the blockchain

In the model, all firms contribute equally to the blockchain. Although a firm's fit matters for the firm-specific component of information provision η_i, only the total mass of adopting firms, and not their types, is relevant for the reach component. We next consider two variants in which firms' contributions to the blockchain's reach vary with their characteristics, in particular their fit.[37]

First, suppose firms' fit is associated with their reporting quality, meaning that bad-fit firms are—independent of their value—characterized by unintentionally providing false data for a random fraction of $(1 - \beta)$ of their transactions. Because false entries inhibit the analysis of correct data entries, bad-fit firms contribute less to the reach of the blockchain than good-fit firms. Although the reach in any equilibrium, given by $\rho' = q_{hg}\sigma_{hg} + \beta q_{hb}\sigma_{hb} + q_{lg}\sigma_{lg} + \beta q_{lb}\sigma_{lb}$, reflects the lower contribution of bad-fit firms compared to the main model, the analysis remains unchanged. The range of outside verification γ supporting the mixed-adoption equilibrium shifts downwards and shrinks, reflecting the overall lower efficacy of the blockchain relative to the traditional institutions. However, the blockchain's lower efficacy also increases the likelihood that information provision decreases if the mixed-adoption equilibrium materializes.

Second, suppose firms have an inherently different fit—as in the main model—but can strategically submit false data entries. In such a setting, low-value firms in the blockchain naturally have incentives to limit its efficacy to reduce the likelihood of being identified. However, allowing for strategic misreporting has a similar impact as unintentional false entries. Low-value firms' misreporting reduces the blockchain's efficacy, affecting its reach in any equilibrium. The range of outside verification γ for which the mixed-adoption equilibrium is supported again shrinks and shifts downwards, but

[37] For a detailed analysis, see Appendix C.10.

the likelihood that information provision decreases in the mixed-adoption equilibrium increases. Notably, strategic misreporting results in an additional tension for low-value firms. While misreporting is desirable conditional on entering the blockchain, low-value firms generally benefit more from sustaining the adverse equilibrium in which overall information provision is lower. As such, it is not clear a priori whether firms would use their ability to falsify data because misreporting decreases the likelihood that the mixed-adoption equilibrium materializes.

4.5.4 The blockchain alongside traditional institutions

In the main model, we treat blockchain technology and traditional institutions as rivals and firms that adopt the blockchain forgo the services of the traditional institutions. While this scenario seems appropriate for new disclosure settings, such as ESG reporting, blockchain is less likely to act as a pure rival when traditional institutions are well establish or even entrenched by regulations, as in mandatory financial reporting or auditing.

In such scenarios, blockchain is more likely to be adopted alongside traditional institutions, which would most likely strategically respond to the technology. While a full characterization of the institutions' objectives—including, e.g., competition, litigation risk, or compensation—is outside the scope of this paper, we consider a setup in which traditional institutions aim to balance the expected probability of an informative message inside and outside the blockchain.[38] This resembles a setting in which traditional institutions are homogeneous and commit to a certain level of overall in-

[38]The case where the blockchain is purely on top of traditional institutions leads to the same implications as the baseline setting with muted outside verification. Denoting Δ'_θ the incentives to adopt the blockchain for a firm of type θ, we obtain

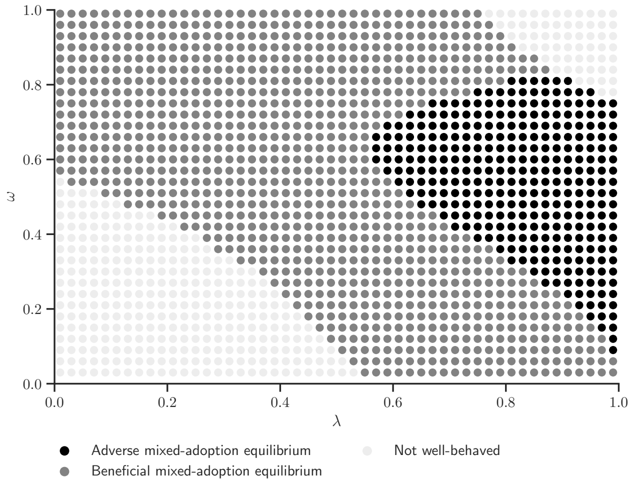
$$\begin{aligned}
\Delta'_{hg} - \Delta'_{hb} &= \rho(1-\beta)(1-\gamma)(1-p^I) \geq 0 \\
\Delta'_{hb} - \Delta'_{lb} &= \rho\beta(1-\gamma) \geq 0 \\
\Delta'_{lb} - \Delta'_{lg} &= \rho(1-\beta)(1-\gamma)p^I \geq 0.
\end{aligned}$$

for the relative adoption incentives, so that the ordering from the baseline carries over. Since information provision under blockchain technology is strictly better compared to without the technology, each firm's adoption decision again becomes a costly signal and the information environment improves.

formation provision, corresponding to γ in our model. For example, courts regularly resort to established auditing standards as benchmarks for auditors' due care, and auditors have to commit to an audit quality based on these benchmarks (e.g. Schwartz, 1998; Simunic et al., 2017).

Figure 4.10: Illustration of equilibria considering strategic response

This figure illustrates combinations of the proportion of high-value firms λ and good-fit firms ω for which the mixed-adoption equilibrium features increased average mispricing (black area), the mixed-adoption equilibrium features decreased average mispricing (dark gray area), or the mixed-adoption equilibrium is not well-behaved (light gray area). The figure is based on the model setup where the blockchain exists alongside traditional institutions; the panel considers $\beta = 0.45$ and $\gamma = 0.75$.



Because blockchain is essentially a substitute for information generation by traditional institutions, the latter respond by lowering their efforts for adopting firms.[39] The new effort level, denoted γ^{BC}, is set such that traditional institutions provide the committed level of information provision γ in expectation. However, because traditional institutions cannot condition on firms' unobservable fit and value types, they set a uniform informativeness for all firms in the blockchain. This implies that the mixed-adoption equilibrium generically exists because information provision is still higher for good-fit firms inside the blockchain, but lower for bad-fit firms.

Figure 4.10 illustrates the main takeaways from the setting using fixed values of the traditional institutions' strength and the fit of bad-fit firms. In the light-gray area, the conjectured mixed-adoption equilibrium is not well-behaved, with the blockchain's

[39]For a detailed analysis, see Appendix C.11.

detection probabilities exceeding 1 for good-fit firms. In the dark-gray area, relative adoption cost supporting the mixed-adoption equilibrium exist, and information provision improves as a result of the blockchain's emergence. However, in the black area, the adverse mixed-adoption equilibrium exists, resulting in a deterioration of the information environment. Although traditional institutions ensure a constant *expected* probability of type revelation, the asymmetric impact on good-fit and bad-fit firms in the blockchain, coupled with the asymmetric impact on the pooling prices, harms capital market participants' ability to extract information. The main forces determining whether the blockchain adversely affect the information environment again carry over from the main model. The information environment is more likely to deteriorate because of blockchain when firms' fit heterogeneity is large, i.e., the proportion of good-fit and bad-fit firms is more comparable, and there are more high-value firms. Overall, treating blockchain as a substitute in the strategic response of traditional institutions does not resolve the potential undesirable impact of the technology on the information environment.

4.6 Interim conclusion

Most blockchain applications started as digitization projects, but quickly evolved into larger ecosystems. Consortia, such as Hyperledger and the Ethereum Alliance, or tech companies, such as SAP or Oracle, are promoting private blockchain platforms that leverage the distributed ledger technology to generate information while addressing firms' privacy needs.[40] While financial reporting-related applications are mostly confined to assurance services, other applications are increasingly engaging in disclosure tasks, such as the publication of sustainability metrics, credit scores, or food safety information. We provide a model that directly speaks to the emergence of blockchain in

[40] For example, SAP recently secured a US patent for a side-chain to verify data from two or more independent blockchains (SAP, 2020). The side-chain hosts an engine that verifies data stored on firms' accounting systems and creates a verification token. In the application, firms' accounting systems are considered private blockchains for compatibility reasons, but the data could also be stored on existing server-based networks.

such contexts, and our results have implications for regulators and investors monitoring the technology.

In the model, heterogeneous firms of privately known types simultaneously decide whether to rely on an exogenous disclosure regime—the traditional institutions—or adopt a disclosure regime with endogenous and firm-specific strength—the blockchain application. The blockchain leverages its distributed ledger architecture and makes use of all participating firms' data while ensuring the privacy of individual data entries. The application's ability to generate information about a firm's type depends on (i) its *fit* for analyzing a given firm's data and (ii) its *reach* into the economy. The setting gives rise to two potential information provision channels. First, firms' adoption decisions may serve as a credible signal about firms' types. Second, the blockchain may outperform traditional institutions in generating information based on participating firms' data. However, we show that the blockchain's potential to enhance information provision may not materialize, and that the information environment can even deteriorate due to its emergence. Specifically, we provide sharp conditions for an equilibrium in which both low-value and high-value firms are inside and outside the blockchain—harming the efficacy of the two information provision channels—and for information provision to decline not only for individual firms, but also in aggregate.

Our model demonstrates that firms' fit heterogeneity not only impedes the blockchain's capabilities to analyze data, but also by weakens the signaling value of firms' endogenous adoption decisions. The emergence of blockchain technology results in a complex coordination game in which firm heterogeneity makes a lack of coordination more likely. As such, policymakers and investors should pay close attention to the composition of adopting firms and settings implying such heterogeneity, e.g., large blockchain ecosystems are more likely to host a variety of differing firms. Policymakers may try to identify potential adopters and provide incentives to keep heterogeneity low by offering monetary incentives or regulatory relief. Theoretically, policymakers could also contemplate to address the heterogeneity in data profiles directly by adapting reporting requirements. For example, the SEC could ask firms to only report metrics based on easy to analyze environmental data in its proposed ESG reporting mandate. However, while this may alleviate the blockchain's shortcomings, the underlying data may no longer provide an accurate picture of firms' sustainability. Tailoring reporting requirements to the blockchain may break the link between the underlying economic value and its accounting representation.

We further highlight that blockchain's success in the corporate context heavily depends on existing traditional institutions. Economies with intermediate traditional institutions are more likely to suffer from a decrease in information provision, unless the institutions are strong enough to rule out the mixed-adoption equilibrium. The blockchain could in principle just be an inherently bad technology that is easily outperformed by sufficiently strong traditional institutions. However, we show that the deterioration of the information environment mainly results from the adverse outcome of a blockchain-induced coordination game. Setting the stage for blockchain by strengthening traditional institutions can prevent the adverse outcome because fit heterogeneity only becomes critical if traditional institutions cannot support full separation via firms' adoption decisions.

Our findings also have broader implications for policymakers and investors because there is no simple immediate regulatory solution. For example, mandating the adoption of a federated blockchain for all firms is not unambiguously optimal concerning overall welfare. Again, this does not require blockchain to be an inherently bad technology for information provision. Although network effects are strongest when all users coordinate on a given platform, such as a federated blockchain, some firms may simply be unable to bear the adoption cost. Thus, even if information provision improves, it may come at the expense of some firms being driven out of business.

Our study is naturally subject to limitations. Our analysis suggests that blockchain technology may lead to a deterioration of the information environment even when traditional institutions respond to the emergence of the blockchain as a substitute. However, these strategic responses and the blockchain's endogenous strength offer a wide range of interesting considerations, especially concerning potential structural changes in different markets and the need for regulatory interventions. Governments are trying to attract the blockchain industry by offering favorable regulatory conditions, which may not only lead to regulatory arbitrage, but affect the competitive landscape. Future work may focus on traditional institutions' response while accounting for the impact of third-party actions, e.g., consortia offering blockchain-based applications and the effect on the market structure when third parties compete for clients via their pricing. In a similar vein, even if the main drivers of our model remain in play because the composition of all adopting firms at a given moment impact the pooling prices, analyzing the fully dynamic interplay between current blockchain adoption and firms' incentives to adopt in the future may yield additional insights. Lastly, we take the blockchain's mechanism design as a given, with firms choosing between two disclosure regimes to inform the capital market. The optimal mechanism design choices that reflect the fundamental premises of the blockchain's reach and firm-specific fit, and potential ecosystem-level challenges, seem to offer interesting research opportunities.

5 Conclusion

This dissertation examines the impact of changes in firms' disclosure environment on their disclosure decisions. Over the last decades, firms have been experiencing revolutionary changes in their operating environment. First, they are no longer evaluated by financial performance alone. Consequently, a growing demand for firms' non-financial information has arisen. Second, recent technological development has changed how information is collected and processed. Such societal and technological transformations affect how firms operate and, naturally, also penetrate their disclosure decision-making process.

The growing environmental crisis has made emission reduction a crucial task for society. However, many firms still avoid unveiling their GHG emission information despite existing disclosure regulations.[1] Less clear is whether and how firms are involved in fighting against climate change. The first model in the thesis investigates firms' disclosure behavior concerning their GHG emissions. This information, on the one hand, measures firms' environmental performance and consequently influences product demand. On the other hand, it reveals firms' proprietary information about their production and operation process. Firms thus need to trade off the conflicting reactions from customers and competitors to make their disclosure decisions.

For high-emission firms, disclosing their private information may lead to demand reduction, but at the same time may generate competitive advantage by intimidating

[1] Examples of such regulations include the US Environmental Protection Agency's Greenhouse Gas Reporting Program (2010), the UK Companies Act 2006 (Strategic Report and Directors' Report) Regulations 2013, and the Directive (EU) 2014/95, etc.

their competitors. Precisely the opposite works for low-emission type. The model identifies conditions under which different firm types find it optimal to disclose their emission intensity levels. The results potentially reconcile different empirical observations concerning the relationship between firms' environmental performance and their disclosure behavior. I further show how firms decide on their emission reductions and how the reductions influence disclosure decisions. Intuitively, firms are only willing to make an effort to reduce emissions when the potential benefits outweigh the costs. Forcing firms that would otherwise keep silent about their emission intensity level may negatively influence their emission reduction incentives.

The second model in the thesis examines how imperfect certification impacts firms' disclosure behavior. Firms tend to lie if the disclosed information cannot be easily verified by information receivers, especially when the gain is large enough. Products' sustainable characteristics fall into the category. To alleviate the concerns of cheap talk, firms may engage a third-party certifier to increase information credibility. However, only part of the consumers - the socially conscious consumers care about these hidden attributes and are willing to pay a higher price for them. The certification decision is thus not to reduce information asymmetry in general but to target these consumers. The model therefore combines a signaling game with a matching problem. Whereas the main result that certification cost determines the firms' signaling decisions echoes the results from most signaling games, the model assesses the impact of different shares of socially conscious consumers and different firm sizes on the equilibrium conditions. Interestingly, increasing the share of conscious consumers does not monotonically increase all firms' incentives to seek certification. Moreover, although asymmetric firm size negatively influences the occurrence of all pure strategy equilibria, product allocation schemes play an important role in the magnitude of such negative effects.

The third model presented in Chapter 4 investigates the potential and limits of privacy-preserving blockchain technology to rival information provision by third-party intermediaries. Technology innovations such as blockchains provide an opportunity to satisfy the increasing demand for more timely and credible disclosures. However, the blockchain's ability to generate information about a firm depends on the firm-specific data profile and endogenous adoption decisions across all firms. The model shows that blockchains can improve the information environment because firms' adoption decisions may serve as a credible signal of firms' values, and information provision by the blockchain itself may outperform traditional institutions. More importantly, the model also identifies an equilibrium in which neither of the two channels realizes its potential. In this equilibrium, information provision may even decline in aggregate.

To summarize, the results of the models presented in this thesis illustrate how changes in the disclosure environment may alter firms' disclosure strategies. Responding to the increasing demand for GHG emission information, firms do not unravel but carefully evaluate the disclosure costs and benefits. The same is true when firms face changes in the proportion of information receivers that care about relevant information. Furthermore, because of firms' strategic disclosure behavior, technological development does not necessarily improve information provision unambiguously. Thereby, the models provide insights into the evolving disclosure dynamics and enhance our understanding of the potential economic consequences of disclosure regulations.

Notably, there is still a need for more research in this area to answer important questions. For instance, how do different disclosure regulations indirectly influence firms' environmental investments? Or, how will the information provision vary if new technologies such as blockchains are in the hands of several strategic players? These questions are essential to allow disclosure not only to depict but also to enhance our economic underlying.

Appendices

A Appendix Chapter 2

A.1 Variable definitions

I summarize the notations throughout the analysis in Table A.1.

Table A.1: Notations in the setup

Var.	Definition	Notes
i, j	Two firms competing in the game	$i, j \in \{1, 2\}$, $i \neq j$
a_i	Firm i's initial emission intensity level	$a_i \in A = [1, \bar{a}]$, with p.d.f. $f(.)$, c.d.f. $F(.)$
$\bar{a}$	Upper bound of initial emission intensity level	$\bar{a} > 1$
μ	Ex-ante expectation of initial emission intensity level	$\mu = \mathrm{E}[a_i] \in (1, \bar{a})$
q_i	Firm i's output quantity	$q_i = a_i \cdot x_i$
x_i	Firm i's input quantity	$x_i \geq 0$
c_i	Firm i's input cost	$c_i \in [\underline{c}, \bar{c}]$
s_i	Firm i's abatement decision	$s_i \in \{0, s\}$
s	Abatement level	$s \in (0, 1)$
$C_i(s_i)$	Firm i's abatement cost	$C_i(s_i) \in \{0, k\}$
k	Abatement cost to reduce intensity level by s	$k > 0$
d_i	Firm i's disclosure decision	$d_i \in \{(a_i, s_i), a_i, s_i, \emptyset\}$
b	The size of the market	
γ	Product substitution degree	$\gamma \in [0, 1]$
β	Customers' dislike level over emissions	$\beta \geq 0$
p_i	Product price determined by linear demand function	
π_i	Firm i's period end profit	
π_i^P	Firm i's product market profit	
H	Ex-ante coveriance between a_i and x_i	$H = \mathrm{E}[\mathrm{Cov}[a_i, x_i]]$
N	Nondisclosure set	$N \subseteq A$
$\widehat{\ }$	Posterior belief following a given disclosure strategy	
$.^b$	Superscription for baseline model (i.e., without abatement)	
$.^s$	Superscription for case with positive abatement	

A.2 No information asymmetry

Criteria imposed on the parameters

To ensure a meaningful discussion, I impose criteria on the parameters so that even the "least favorable combination" of cost and technology input-output ratio can result in positive production quantities for both firms. Later analysis can show that the firm' input quantity increases with firm's emission abatement level. To consider the least favorable condition, I set the abatement level to 0 in this part.

Under the condition where no information asymmetry exists, all parties know perfectly the firms' productivity level a_i. Without abatement activities, firm i's profit is thus:[1]

$$\pi_i^{sym} = (b - \beta a_i - a_i x_i - \gamma a_j x_j) a_i x_i - c_i x_i \tag{A.1}$$

Both firms set up the production quantities to maximize the (expected) profit. By setting the first-order derivative to zero

$$\frac{\partial \pi_i^{sym}}{\partial x_i^{sym}} = (b - \beta a_i - \gamma a_j x_j) a_i - 2a_i^2 x_i - c_i \stackrel{!}{=} 0,$$

we reach the mutual best response function as follows:[2]

$$x_i = \frac{(b - \beta a_i) a_i - c_i}{2a_i^2} - \frac{\gamma a_j}{2a_i} x_j^{Conj} \tag{A.2}$$

The equilibrium quantity under the information-symmetric case is then:

$$x_i^{sym*} = \frac{a_i a_j [2(b - \beta a_i) - \gamma(b - \beta a_j)] + \gamma a_i c_j - 2a_j c_i}{(4 - \gamma^2) a_i^2 a_j} \tag{A.3}$$

We need to ensure $x_i^{sym*} \geq 0$ even under the least favorable condition. We have $\frac{\partial x_i^{sym*}}{\partial c_i} = -\frac{2}{(4-\gamma^2)a_i^2} < 0$, $\frac{\partial x_i^{sym*}}{\partial c_j} = \frac{\gamma}{(4-\gamma^2)a_i a_j} > 0$. The lowest quantity is thus material-

[1]Superscription sym indicates the case with no information asymmetry.

[2]It is easy to see that $\partial^2 \pi_i^{sym} / \partial x_i^{sym2} = -2a_i^2 < 0$.

ized when $c_j = \underline{c}$ and $c_i = \bar{c}$. In addition, ex ante, we have $E[a_i] = E[a_j] = \mu$. Inserting them into (A.3) leads to:

$$\frac{\mu^2[2(b-\beta\mu) - \gamma(b-\beta\mu)] + \gamma\mu\underline{c} - 2\mu\bar{c}}{(4-\gamma^2)\mu^2\mu} \geq 0 \tag{A.4}$$

To ensure a non-negative input quantity, we need the numerator to be non-negative. Consequently, we reach:

$$b > \beta\mu + \frac{2\bar{c} - \gamma\underline{c}}{\mu(2-\gamma)}. \tag{A.5}$$

Comparative statics

Without information asymmetry, we can derive

$$\begin{aligned}
&\mathrm{E}[(\pi_i^P)^{sym*}] \\
=&\Big(b - \beta a_i - a_i x_i^{sym*} - \gamma a_j \cdot x_j^{sym*}\Big) \cdot a_i x_i^{sym*} - c_i x_i^{sym*} \\
=&\bigg(\Big(b - \beta a_i - a_i \cdot \frac{a_i a_j[2(b-\beta a_i) - \gamma(b-\beta a_j)] + \gamma a_i c_j - 2a_j c_i}{(4-\gamma^2)a_i^2 a_j} \\
&- \gamma a_j \cdot \frac{a_i a_j[2(b-\beta a_j) - \gamma(b-\beta a_i)] + \gamma a_j c_i - 2a_i c_j}{(4-\gamma^2)a_j^2 a_i}\Big) \cdot a_i - c_i\bigg) \\
&\cdot \frac{a_i a_j[2(b-\beta a_i) - \gamma(b-\beta a_j)] + \gamma a_i c_j - 2a_j c_i}{(4-\gamma^2)a_i^2 a_j} \\
=&a_i^2 \cdot (x_i^{sym*})^2
\end{aligned} \tag{A.6}$$

That is to say, without abatement activities, $\pi_i^{sym*} = \pi_i^{P \cdot sym*} = (x_i^{sym*})^2 \cdot a_i^2$.

We further have

$$\begin{aligned}
\mathrm{Cov}[a_i, x_i^{sym*}] &= \mathrm{Cov}[a_i, \frac{a_i a_j[2(b-\beta a_i) - \gamma(b-\beta a_j)] + \gamma a_i c_j - 2a_j c_i}{(4-\gamma^2)a_i^2 a_j}] \\
&= \mathrm{Cov}[a_i, -\frac{2\beta a_j}{(4-\gamma^2)a_j} + \frac{a_j[2b - \gamma(b-\beta a_j)] + \gamma c_j}{(4-\gamma^2)a_j} \cdot \frac{1}{a_i} - \frac{2a_j c_i}{(4-\gamma^2)a_j} \cdot \frac{1}{a_i^2}] \\
&= 0 + \frac{a_j[2b - \gamma(b-\beta a_j)] + \gamma c_j}{(4-\gamma^2)a_j} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}] - \frac{2c_i}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i^2}]
\end{aligned} \tag{A.7}$$

I conduct some comparative statics analyses for the case where all parties perfectly know everything.

$$\frac{\partial \pi_i^{sym*}}{\partial c_i} = 2a_i^2 x_i \frac{\partial x_i^{sym*}}{\partial c_i} = -2a_i^2 x_i \frac{2}{(4-\gamma^2)a_i^2} < 0 \tag{A.8}$$

$$\frac{\partial \pi_i^{sym*}}{\partial c_j} = 2a_i^2 x_i \frac{\partial x_i^{sym*}}{\partial c_j} = 2a_i^2 x_i \frac{\gamma}{(4-\gamma^2)a_i a_j} > 0 \tag{A.9}$$

$$\frac{\partial \pi_i^{sym*}}{\partial a_i} = 4x_i \cdot \frac{\gamma(-\beta a_i^2 + c_i)}{(4-\gamma^2)a_i} \quad \Leftrightarrow \quad sgn(\frac{\partial \pi_i^{sym*}}{\partial a_i}) = sgn(-\beta a_i^2 + c_i) \tag{A.10}$$

$$\frac{\partial \pi_i^{sym*}}{\partial a_j} = 2a_i x_i \cdot \frac{\gamma(\beta a_j^2 - c_j)}{(4-\gamma^2)a_j^2} \quad \Leftrightarrow \quad sgn(\frac{\partial \pi_i^{sym*}}{\partial a_j}) = sgn(\beta a_j^2 - c_j) \tag{A.11}$$

The impact of both the firm's initial emission level (a_i) and the competitor's (a_j) on the firm's profit is not monotone.

$$\frac{\partial \pi_i^{sym*}}{\partial a_i} > 0 \quad \text{when} \quad \beta < \frac{c_i}{a_i^2} \tag{A.12}$$

$$\frac{\partial \pi_i^{sym*}}{\partial a_i} < 0 \quad \text{when} \quad \beta > \frac{c_i}{a_i^2}, \tag{A.13}$$

and,

$$\frac{\partial \pi_i^{sym*}}{\partial a_j} > 0 \quad \text{when} \quad \beta > \frac{c_j}{a_j^2} \tag{A.14}$$

$$\frac{\partial \pi_i^{sym*}}{\partial a_j} < 0 \quad \text{when} \quad \beta < \frac{c_j}{a_j^2}, \tag{A.15}$$

A.3 Baseline model

This section shows the derivation of the Nash equilibrium input quantity and the disclosure strategies in the baseline model. Here, no abatement activities are considered.

A.3.1 Equilibrium input quantity in the baseline model

Following the given disclosure strategy $d_i(d_j)$, both the competitor and customers form the posterior belief $E[a_i|d_i]$ ($E[a_j|d_j]$). Both firms then determine their input quantity holding such beliefs. I use $x_{i/j}^{Conj}$ to indicate the conjectured input quantity.

Since abatement activities are ignored in the baseline model, both firms determine the input quantities by maximizing the expected product market profit:

$$\begin{aligned}
&\max_{x_i^b} \mathrm{E}[\pi_i^P|d_i, d_j] \\
=&\max_{x_i^b}(b - \beta\mathrm{E}[a_i|d_i] - a_i x_i^b - \gamma\mathrm{E}[q_j|d_j]^{b\cdot Conj}) \cdot a_i x_i^b - c_i x_i^b \\
=&\max_{x_i^b}(b - \beta\mathrm{E}[a_i|d_i] - a_i x_i^b - \gamma\mathrm{E}[a_j \cdot x_j|d_j]^{b\cdot Conj}) \cdot a_i x_i^b - c_i x_i^b.
\end{aligned} \tag{A.16}$$

Take the first-order derivative of the product market profit with respect to input quantity. We show the best response function as follows:

$$x_i^b = \frac{(b - \beta\mathrm{E}[a_i|d_i])a_i - c_i}{2a_i^2} - \frac{\gamma\mathrm{E}[a_j \cdot x_j|d_j]^{b\cdot Conj}}{2a_i}. \tag{A.17}$$

Similarly, we have

$$x_j^b = \frac{(b - \beta\mathrm{E}[a_j|d_j])a_j - c_j}{2a_j^2} - \frac{\gamma\mathrm{E}[a_i \cdot x_i|d_i]^{b\cdot Conj}}{2a_j}. \tag{A.18}$$

We know that $E[a_i \cdot x_i|d_i]^{b\cdot Conj} = \mathrm{E}[a_i|d_i] \cdot x_i^{b\cdot Conj} + \mathrm{Cov}[a_i, x_i^{b\cdot Conj}|d_i]$. Substituting (A.18) into (A.17) by using posteriors, we have:

$$\begin{aligned}
x_i^b =& \frac{(b - \beta\mathrm{E}[a_i|d_i])a_i - c_i}{2a_i^2} - \frac{\gamma \cdot \mathrm{Cov}[a_i, x_j^{b\cdot Conj}|d_j]}{2a_i} \\
&- \frac{\gamma\mathrm{E}[a_j|d_j]}{2a_i} \cdot \Big[\frac{(b - \beta\mathrm{E}[a_j|d_j])\mathrm{E}[a_j|d_j] - c_j}{2\mathrm{E}[a_j|d_j]^2} - \frac{\gamma\mathrm{E}[a_i|d_i] \cdot x_i^{b\cdot Conj}}{2\mathrm{E}[a_j|d_j]} - \frac{\gamma \cdot \mathrm{Cov}[a_i, x_i^{b\cdot Conj}|d_i]}{2\mathrm{E}[a_j|d_j]}\Big]
\end{aligned} \tag{A.19}$$

In equilibrium, $x_i^b = x_i^{b \cdot Conj}$. We thus can derive the equilibrium quantity as follows:

$$x_i^{b*} = \frac{a_i \mathrm{E}[a_j|d_j]\Big[2(b-\beta\mathrm{E}[a_i|d_i]) - \gamma(b-\beta\mathrm{E}[a_j|d_j])\Big] - 2\mathrm{E}[a_j|d_j]c_i + \gamma a_i c_j}{(4a_i - \gamma^2\mathrm{E}[a_i|d_i])a_i\mathrm{E}[a_j|d_j]} - \frac{a_i\mathrm{E}[a_j|d_j]\Big[2\gamma\mathrm{Cov}[a_j,x_j|d_j] - \gamma^2\mathrm{Cov}[a_i,x_i|d_i]\Big]}{(4a_i-\gamma^2\mathrm{E}[a_i|d_i])a_i\mathrm{E}[a_j|d_j]} \tag{A.20}$$

Note that when firm i discloses its emission intensity level, i.e., $d_i = a_i$, we have $\mathrm{Cov}[a_i, x_i|d_i = a_i] = 0$.

The expected product market profit then follows

$$\begin{aligned}
&\mathrm{E}[\pi_i^{P*}|d_i,d_j] \\
=&\Big(b-\beta\mathrm{E}[a_i|d_i] - a_i x_i^{b*} - \gamma(\mathrm{E}[a_j|d_j]\cdot\mathrm{E}[x_j^b|d_j] + \mathrm{Cov}[a_j,x_j|d_j])\Big)\cdot a_i x_i^{b*} - c_i x_i^{b*} \\
=&\Big(b-\beta\mathrm{E}[a_i|d_i] - a_i x_i^{b*} - \gamma\mathrm{E}[a_j|d_j]\cdot(\frac{(b-\beta\mathrm{E}[a_j|d_j])\mathrm{E}[a_j|d_j]-c_j}{2\mathrm{E}[a_j|d_j]^2} - \frac{\gamma[\mathrm{E}[a_i|d_i]x^{b*} + \mathrm{Cov}[a_i,x_i|d_i]]}{2\mathrm{E}[a_j|d_j]}) \\
&-\gamma\mathrm{Cov}[a_j,x_j|d_j]\Big)\cdot a_i x_i^{b*} - c_i x_i^{b*} \\
=&\frac{x_i^{b*}}{2\mathrm{E}[a_j|d_j]^2}\Big\{2a_i\mathrm{E}[a_j|d_j]^2(b-\beta\mathrm{E}[a_i|d_i]) - \gamma a_i\mathrm{E}[a_j|d_j]^2(b-\beta\mathrm{E}[a_j|d_j]) + \gamma a_i\mathrm{E}[a_j|d_j]c_j \\
&+\gamma^2 a_i\mathrm{E}[a_j|d_j]^2\mathrm{Cov}[a_i,x_i|d_i]] - 2\gamma a_i\mathrm{E}[a_j|d_j]^2\mathrm{Cov}[a_j,x_j|d_j] + 2\mathrm{E}[a_j|d_j]^2c_j \\
&-2a_i^2\mathrm{E}[a_j|d_j]^2x_i^{b*} + \gamma^2 a_i\mathrm{E}[a_j|d_j]^2\mathrm{E}[a_i|d_i]x^{b*}\Big\} \\
=&\frac{x_i^{b*}}{2\mathrm{E}[a_j|d_j]^2}\Big\{\mathrm{E}[a_j|d_j]x_i^{b*}(4a_i-\gamma^2\mathrm{E}[a_i|d_i])a_i\mathrm{E}[a_j|d_j] - 2a_i^2\mathrm{E}[a_j|d_j]^2x_i^{b*} + \gamma^2a_i\mathrm{E}[a_j|d_j]^2\mathrm{E}[a_i|d_i]x^{b*}\Big\} \\
=&\frac{(x_i^{b*})^2\cdot a_i}{2}\Big\{4a_i - \gamma^2\mathrm{E}[a_i|d_i] - 2a_i + \gamma^2\mathrm{E}[a_i|d_i]\Big\} \\
=&a_i^2\cdot(x_i^{b*})^2
\end{aligned} \tag{A.21}$$

We again have $\pi_i^{P*} = a_i^2 \cdot (x_i^b)^2$.

A.3.2 Disclosure strategies in baseline model

In the following analysis, I use the notation "$\widehat{\ }$" to indicate the posterior belief following the given disclosure strategy.

Prior the disclosure decision is made, in expectation, $\mathrm{E}[a_j] = \mathrm{E}[\mathrm{E}[a_j|d_j]] = \lambda + (1-\lambda)\bar{a} = \mu$. We further let $H = \mathrm{E}[\mathrm{E}[\mathrm{Cov}[a_j, x_j|d_j]]] = \mathrm{E}[\mathrm{Cov}[a_j, x_j]]$ indicating the ex ante covariance. Following (A.7), we have:

$$\begin{aligned} H &= \frac{\mu[2b-\gamma(b-\beta\mu)]+\gamma c_j}{(4-\gamma^2)\mu}\cdot \text{Cov}[a_i,\frac{1}{a_i}] - \frac{2c_i}{4-\gamma^2}\cdot \text{Cov}[a_i,\frac{1}{a_i^2}] \\ &= \underbrace{\frac{\mu[2-\gamma]b+\gamma c_j}{(4-\gamma^2)\mu}\cdot \text{Cov}[a_i,\frac{1}{a_i}] - \frac{2c_i}{4-\gamma^2}\cdot \text{Cov}[a_i,\frac{1}{a_i^2}]}_{K} + \frac{\gamma\beta\mu}{4-\gamma^2}\cdot \text{Cov}[a_i,\frac{1}{a_i}] \end{aligned} \quad \text{(A.22)}$$

Insert them into (A.20). We get the expected optimal input quantity following disclosure decision d_i as follows:

$$E[x_i^{b*}|d_i] = \frac{2a_i\mu(b-\gamma H-\beta\widehat{a}_i)-\gamma a_i\mu(b-\beta\mu)-2\mu c_i+\gamma a_i c_j + a_i\mu\gamma^2\text{Cov}[a_i,x_i|d_i]}{(4a_i-\gamma^2\widehat{a}_i)a_i\mu}. \quad \text{(A.23)}$$

Disclosure first causes contradictory effects on the firm's input quantity because of different information recipients: competition effect (denominator) vs. the demand effect (numerator). Moreover, it has an information update effect (the covariance factor changes).

We know that $E[\pi_i^{P*}] = a_i^2 * x_i^{*2}$. Consequently, for firm i with the initial emission intensity level a_i, comparing the expected product market profits under two different disclosure strategies is equivalent to comparing the expected input quantities. That is to say, firm i chooses a disclosure strategy d_i over another d_i' if

$$E[x_i^{b*}|d_i] \geq E[x_i^{b*}|d_i']$$

Assume information receivers form a posterior belief upon observing nondisclosure: $a_p^b = E[a_i|d_i^b=\emptyset]$.[3] In the baseline model, firms then compare $E[x_i^{b*}|d_i^b=a_i]$ and $E[x_i^{b*}|d_i^b=\emptyset]$ to make their disclosure decisions. Note that:

$$E[x_i^{b*}|d_i^b=a_i] = \frac{2a_i\mu(b-\gamma H-\beta a_i)-\gamma a_i\mu(b-\beta\mu)-2\mu c_i+\gamma a_i c_j}{(4a_i-\gamma^2 a_i)a_i\mu} \quad \text{(A.24)}$$

[3]The posterior belief follows Bayes' rule whenever is possible. Given full disclosure, I assume the off-path belief to be $a_p^b = E[a_i|d_i^b=\emptyset] = \mu$ and $\text{Cov}[a_i,x_i|d_i^b=\emptyset] = H$.

$$E[x_i^{b*}|d_i^b = \emptyset] = \frac{2a_i\mu(b - \gamma H - \beta a_p^b) - \gamma a_i\mu(b - \beta\mu) - 2\mu c_i + \gamma a_i c_j + a_i\mu\gamma^2\text{Cov}[a_i, x_i|\emptyset]}{(4a_i - \gamma^2 a_p^b)a_i\mu} \tag{A.25}$$

Clearly, firms prefer to disclose their initial emission intensity level if $E[x_i^{b*}|d_i^b = a_i] > E[x_i^{b*}|d_i^b = \emptyset]$, and to nondisclose otherwise.

$$E[x_i^{b*}|d_i^b = a_i] > E[x_i^{b*}|d_i^b = \emptyset]$$

$$\Leftrightarrow$$

$$2a_i\mu[b\gamma^2 - \gamma^3 H - 4\beta a_i](a_i - a_p^b) + (-\gamma a_i\mu(b - \beta\mu) - 2\mu c_i + \gamma a_i c_j)\gamma^2(a_i - a_p^b) > (4 - \gamma^2)\gamma^2 a_i^2\mu\text{Cov}[a_i, x_i|\emptyset]]$$

$$\Leftrightarrow$$

$$(a_i - a_p^b)\Big[-8\beta\mu a_i^2 + \gamma^2\Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j\Big)a_i - 2\gamma^2\mu c_i\Big] > (4 - \gamma^2)\gamma^2 a_i^2\mu\text{Cov}[a_i, x_i|\emptyset]$$

$$\Leftrightarrow$$

$$(a_i - a_p^b)(a_i - a_l^b)(a_i - a_h^b) < -\frac{(4 - \gamma^2)\gamma^2\text{Cov}[a_i, x_i|\emptyset]}{8\beta} \cdot a_i^2, \tag{A.26}$$

where

$$a_l^b = \frac{\gamma^2\Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j\Big) - \sqrt{\gamma^4\Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j\Big)^2 - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}, \tag{A.27}$$

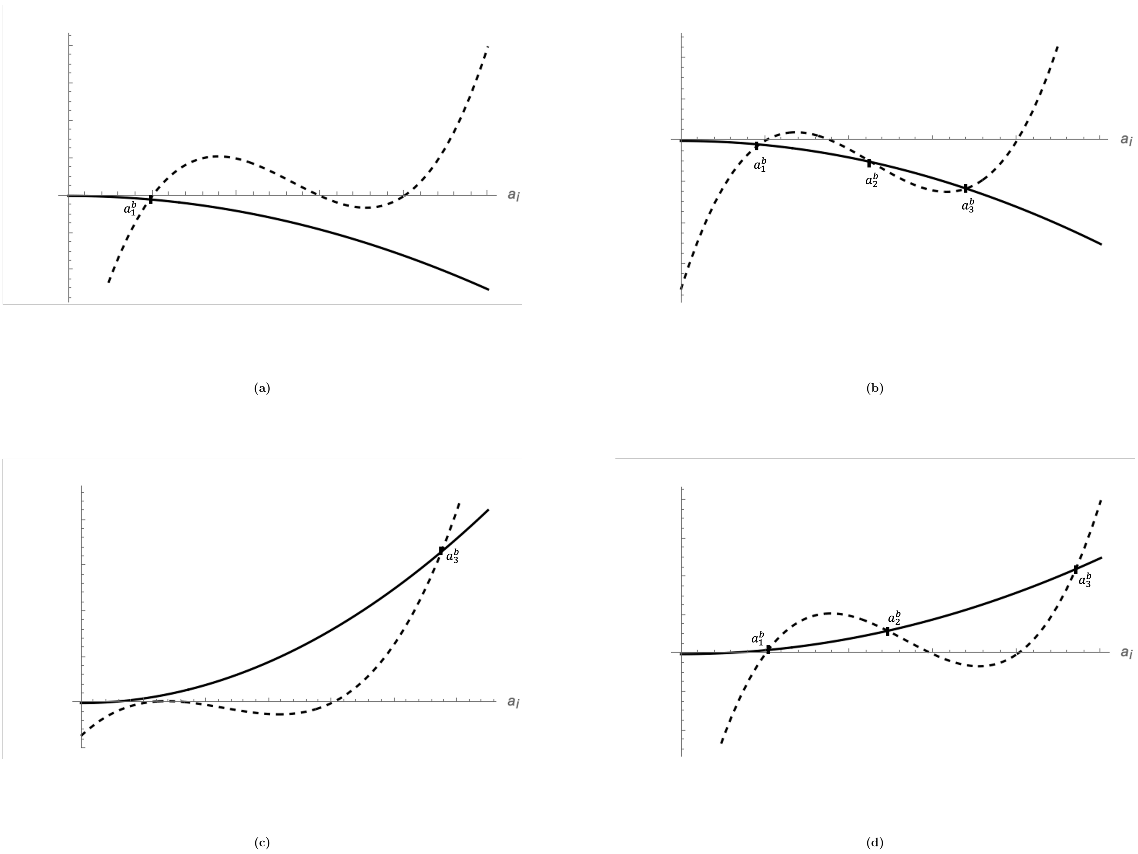
and

$$a_h^b = \frac{\gamma^2\Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j\Big) + \sqrt{\gamma^4\Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j\Big)^2 - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}. \tag{A.28}$$

We can illustrate the inequality problem (A.26) in Figure A.1.

Figure A.1: Illustration of potential solutions

This figure illustrates the potential solutions for (A.26). The dashed line indicates the shape of the right-hand-side (RHS) of the inequation and the solid line shows the potential left-hand-side (LHS). Depending on the sign of ex-ante covariance ($\mathrm{Cov}[a_i, x_i|\emptyset]$), we may face Figure A.1 (a) and Figure A.1 (b) ($\mathrm{Cov}[a_i, x_i|\emptyset] > 0$), or Figure A.1 (c) and Figure A.1 (d) ($\mathrm{Cov}[a_i, x_i|\emptyset] < 0$). Whenever the dashed line lies above the solid line, firm i with a_i prefers not to disclose its initial emission intensity level.



Nondisclosure Equilibrium

If

$$E[x_i^{b*}|d_i^b = a_i] \leq E[x_i^{b*}|d_i^b = \emptyset], \quad \forall a_i \in [1, \bar{a}]$$

nondisclosure equilibrium occurs. Now $a_p^b = \mu$ and $\mathrm{Cov}[a_i, x_i|\emptyset] = H$ (see (A.22)).

The condition supporting nondisclosure equilibrium thus can be written as

$$(a_i - \mu)(a_i - a_l)(a_i - a_h) \geq -\frac{(4-\gamma^2)\gamma^2 H}{8\beta} \cdot a_i^2, \quad \forall a_i \in [1, \bar{a}] \tag{A.29}$$

We can derive that the inequality does not hold whenever $H < 0$. This is because, when $H < 0$, we have potential scenarios demonstrated in Figure A.1 (c) or Figure A.1 (d). To have nondisclosure, we must have $a_1^b < 1 < \bar{a} < a_2^b$ or $a_3^b < 1$, neither of the conditions allow $\mu \in [1, \bar{a}]$.

Moreover

$$(a_i - \mu)(a_i - a_l)(a_i - a_h) \geq -\frac{(4-\gamma^2)\gamma^2 H}{8\beta} \cdot a_i^2, \quad \forall a_i \in [1, \bar{a}]$$

$$\Leftrightarrow$$

$$\begin{cases} \beta \leq \beta_{thres}^b, & \text{for} \quad a_i < \mu \\ \beta \geq \beta_{thres}^b, & \text{For} \quad a_i > \mu, \end{cases} \tag{A.30}$$

where,

$$\beta_{thres}^b = \frac{\gamma^2\Big((b\mu(2-\gamma) - 2\mu\gamma K + \gamma c_j)a_i - 2\mu c_i - \frac{(4-\gamma^2)\mu K a_i^2}{a_i-\mu}\Big)}{\mu a_i\Big(8a_i - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2}\text{Cov}[a_i, \frac{1}{a_i}] + \frac{\gamma^3 a_i \mu}{a_i-\mu}\text{Cov}[a_i, \frac{1}{a_i}]\Big)} \tag{A.31}$$

Full disclosure Equilibrium

C ontrary to the nondisclosure equilibrium, when

$$(a_i - \mu)(a_i - a_l)(a_i - a_h) < -\frac{(4-\gamma^2)\gamma^2 H}{8\beta} \cdot a_i^2, \quad \forall a_i \in [1, \bar{a}] \tag{A.32}$$

full disclosure equilibrium occurs. This follows the off-path belief being $a_p^b = E[a_i|d_i^b = \emptyset] = \mu$ and $\text{Cov}[a_i, x_i|d_i^b = \emptyset] = H$.

The full disclosure equilibrium thus occurs if and only if

$$\begin{cases} \beta > \beta_{thres}^b, & \text{for} \quad a_i < \mu \\ \beta < \beta_{thres}^b, & \text{for} \quad a_i > \mu \end{cases} \tag{A.33}$$

In addition, contrary to the nondisclosure equilibrium, the inequality does not hold whenever $H > 0$. This is because when $H > 0$, we have potential scenarios demonstrated in Figure A.1 (a) or Figure A.1 (b). To have full disclosure, we must require $\bar{a} < a_1^b$ or $a_2^b < 1 < \bar{a} < a_3^b$. Neither of the conditions allows $\mu \in [1, \bar{a}]$.

Partial disclosure equilibrium

Now we turn to potential partial disclosure equilibrium. Let's assume that $a_i = a_1^b$, $a_i = a_2^b$ and $a_i = a_3^b$ solve the following equation with $a_1^b \leq a_2^b \leq a_3^b$ (see Figure A.1):

$$(a_i - a_p^b)(a_i - a_l^b)(a_i - a_h^b) = -\frac{(4-\gamma^2)\gamma^2 \mathrm{Cov}[a_i, x_i|\emptyset]}{8\beta} \cdot a_i^2. \tag{A.34}$$

The potential nondisclosure area is then

$$a_1^b \leq a_i \leq a_2^b \quad \& \quad a_i \geq a_3^b.$$

Note that, by setup $a_i \in A = [1, \bar{a}]$, the nondisclosure area is

$$N^b = [1, \bar{a}] \cup \Big([a_1^b, a_2^b] \cap [a_3^b, \infty)\Big), N^b \subset A. \tag{A.35}$$

Hence

$$a_p^b = \mathrm{E}[a_i|a_i \in N^b], \tag{A.36}$$

$$\begin{aligned}\mathrm{Cov}[a_i, x_i|a_i \in N] = & \tfrac{\mu[2b-\gamma(b-\beta\mu)]+\gamma c_j}{(4-\gamma^2)\mu} \cdot \mathrm{Cov}[a_i, \tfrac{1}{a_i}|a_i \in N^b] \\ & -\tfrac{2c_i}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \tfrac{1}{a_i^2}|a_i \in N^b].\end{aligned} \tag{A.37}$$

The problem of identifying the partial disclosure equilibrium is thus equivalent to solving three equations for three variables.

Necessary conditions for Disclosure equilibria - Proof of Corollary 2.1

Depending on how a_1^b, a_2^b and a_3^b locate relative to a_i's lower bound (1) and upper bound ($\bar{A}$), we may face nondisclosure area with different . Moreover, note that a_p^b is endogenously determined. The compatibility of a_p^b thus imposes restrictions on the existence of the partial disclosure equilibrium. I summarize the potential scenario in Table A.2.[4]

Table A.2: Potential nondisclosure area

$1, \bar{a}$	Interval				Potential
lies in	$[0, a_1^b]$	$[a_1^b, a_2^b]$	$[a_2^b, a_3^b]$	$[a_3^b, \infty]$	Nondisclosure Set
Case 1	$1, \bar{a}$				$\emptyset$
Case 2	1	$\bar{a}$			$[a_1^b, \bar{a}]$
Case 3	1		$\bar{a}$		$[a_1^b, a_2^b]$
Case 4	1			$\bar{a}$	$[a_1^b, a_2^b] \cup [a_3^b, \bar{a}]$
Case 5		$1, \bar{a}$			$[1, \bar{a}]$
Case 6		1	$\bar{a}$		$[1, a_2^b]$
Case 7		1		$\bar{a}$	$[1, a_2^b] \cup [a_3^b, \bar{a}]$
Case 8			$1, \bar{a}$		$\emptyset$
Case 9			1	$\bar{a}$	$[a_3^b, \bar{a}]$
Case 10				$1, \bar{a}$	$[1, \bar{a}]$

We need to examine whether $a_p^b = \mathrm{E}[a_i | a_i \in N]$ and $a_p^b \in [1, \bar{a}]$ can be satisfied at the same time. Before we proceed through these cases one by one, we first derive the following relationships, which facilitate the later analysis:

- $a_l^b < a_h^b$.
- For $\mathrm{Cov}[a_i, x_i | a_i \in N] < 0$, we have $a_2^b < a_h^b < a_3^b$.
- For $\mathrm{Cov}[a_i, x_i | a_i \in N] > 0$, we have $a_1^b < a_l^b < a_2^b$.

[4] In the table, I assume $a_1^b < a_2^b < a_3^b$. When $a_1^b = a_2^b$ and/or $a_2^b = a_3^b$, the only potential partial disclosure equilibrium is a generalized condition for case 2. The discussion will be included in the case 2 analysis.

Next, let's define

$$\beta_1^b = \frac{\gamma^2[(2-\gamma)\mu b - 2\gamma\mu K + \gamma c_j]}{\mu(16\bar{a} - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.38}$$

$$\beta_2^b = \frac{\gamma^2[(2-\gamma)\mu b - 2\gamma\mu K + \gamma c_j]}{\mu(16 - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.39}$$

$$\beta_3^b = \frac{\gamma^2[(2-\gamma)\mu b - 2\gamma\mu K - 2\mu c_i + \gamma c_j]}{\mu(8 - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.40}$$

$$\beta_4^b = \frac{\gamma^2[(2-\gamma)\bar{a}\mu b - 2\gamma\bar{a}\mu K - 2\mu c_i + \gamma\bar{a} c_j]}{\bar{a}\mu(8\bar{a} - \gamma^3\mu + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.41}$$

We can easily see that $\beta_1^b < \beta_2^b$.

Note that cases 1, 5, 8, and 10 are included in the nondisclosure and full disclosure equilibria analysis. We thus focus on the potential partial disclosure equilibrium.

i Only dirty firms talk - case 6

This can occur only if $a_1^b < 1 < a_2^b < \bar{a} < a_3^b$, and $1 < a_p^b < a_2^b$. This is not compatible when $\mathrm{Cov}[a_i, x_i | a_i \in N^b] < 0$.

When $\mathrm{Cov}[a_i, x_i | a_i \in N^b] > 0$, the necessary condition is $a_l^b < \bar{a}$ & $a_h^b > \bar{a}$. This leads to

$$\beta < \beta_4^b \tag{A.42}$$

ii Only clean firms disclose - cases 2 & 9

- Case 2 requires $1 < a_1^b < \bar{a} < a_2^b$. We thus have $a_p^b \in [a_1^b, \bar{a}]$. This is again not compatible when $\mathrm{Cov}[a_i, x_i | a_i \in N^b] < 0$.

  Moreover, when $\mathrm{Cov}[a_i, x_i | a_i \in N^b] > 0$, note that given $a_2^b = a_3^b$ (or $a_1^b = a_2^b = a_3^b$) and $1 < a_1^b < \bar{a}$, we also face the potential nondisclosure area to be $[a_1^b, \bar{a}]$. The necessary condition this equilibrium can reach is $a_l^b > 1$. This leads to

$$\beta_3^b < \beta < \beta_2^b \tag{A.43}$$

– Case 9 instead has $a_2^b < 1 < a_3^b < \bar{a}$. It again can only occur when $\text{Cov}[a_i, x_i | a_i \in N^b] > 0$. Moreover, we need $a_h^b < 1$. We thus have

$$\beta > \max \{\beta_2^b, \beta_3^b\} \tag{A.44}$$

– Condition supporting partial disclosure equilibrium where only clean firms disclose is

$$\beta > \beta_3^b \tag{A.45}$$

iii Mediocre firms do not disclose - case 3

Here we have $1 < a_1^b < a_2^b < \bar{a} < a_3^b$ and ${}_p^b \in [a_1^b, a_2^b]$. This is not compatible when $\text{Cov}[a_i, x_i | a_i \in N^b] < 0$.

When $\text{Cov}[a_i, x_i | a_i \in N^b] > 0$, we have $1 < a_l^b < \bar{a}$ & $a_h^b > \bar{a}$. We then reach

$$\begin{cases} \text{either} & \max\{\beta_1^b, \beta_3^b\} < \beta < \min\{\beta_2^b, \beta_4^b\} \\ \text{or} & \beta_3^b < \beta < \min\{\beta_1^b, \beta_4^b\} \end{cases} \tag{A.46}$$

iv. Partial disclosure equilibrium with two separate nondisclosure intervals - both cleanest and dirtiest firms withhold information - case 4

In case 4, we have

$$1 < a_1^b < a_2^b < a_3^b < \bar{a}$$

When $\text{Cov}[a_i, x_i | a_i \in N^b] < 0$, the necessary condition is then $1 < a_h^b < \bar{a}$. This requires

$$\begin{cases} \text{either} & \max\{\beta_1^b, \beta_4^b\} < \beta < \beta_2^b \\ \text{or} & \max\{\beta_2^b, \beta_4^b\} < \beta < \beta_3^b. \end{cases} \tag{A.47}$$

When $\text{Cov}[a_i, x_i | a_i \in N^b] > 0$, we thus have $1 < a_h^b < \bar{a}$. This requires

$$\begin{cases} \text{either} & \max\{\beta_1^b, \beta_3^b\} < \beta < \beta_2^b \\ \text{or} & \beta_3^b < \beta < \min\{\beta_1^b, \beta_4^b\} \end{cases} \tag{A.48}$$

v. Partial disclosure equilibrium with two separate nondisclosure intervals - dirtiest firms and some mediocre firms withhold their information - case 7

Here we have

$$a_1^b < 1 < a_2^b < a_3^b < \bar{a}.$$

When $\text{Cov}[a_i, x_i | a_i \in N^b] < 0$, we still have $1 < a_h^b < \bar{a}$. This again leads to the same β constraint as in (A.47).

However, when $\text{Cov}[a_i, x_i | a_i \in N^b] > 0$, the necessary condition is only $a_l^b < \bar{a}$ & $a_h^b > 1$. This requires

$$\begin{cases} \text{either} & \beta_1^b < \beta < \beta_3^b \\ \text{or} & \beta < \min\{\beta_1^b, \beta_4^b\}. \end{cases} \tag{A.49}$$

A.4 General model

In the general model, the objective function is now extended to:

$$\begin{aligned} \max_{s_i, d_i, x_i} E[\pi_i] &= \max_{s_i, d_i, x_i} E[\pi_i^P] - C_i(s_i) \\ &= \max_{s_i, d_i, x_i} (b - \beta E[e_i^R | d_i] - a_i x_i - \gamma E[q_j | d_j]^{Conj}) \cdot a_i x_i - c_i x_i - C_i(s_i) \end{aligned} \tag{A.50}$$

Under the given s_i and d_i, we can derive the optimal production decision as follows:

$$x_i^{s*} = \frac{2a_i\widehat{a_j}\Big[b - \beta(\widehat{a_i} - \widehat{s_i})\Big] - \gamma a_i\widehat{a_j}\Big[b - \beta(\widehat{a_j} - \widehat{s_j})\Big] - 2\widehat{a_j}c_i + \gamma a_i c_j}{(4a_i - \gamma^2\widehat{a_i})a_i\widehat{a_j}} - \frac{a_i\widehat{a_j}\Big[2\gamma \text{Cov}[a_j, x_j|d_j] - \gamma^2 \text{Cov}[a_i, x_i|d_i]\Big]}{(4a_i - \gamma^2\widehat{a_i})a_i\widehat{a_j}} \tag{A.51}$$

A.4.1 Disclosure decisions

We differentiate two cases: (1) no emission abatement is executed by firm i at stage 2; (2) firm i has initiated the emission reduction project and reduced the emission intensity level by s.

In case (1), at the disclosure stage, since no abatement activity is conducted, firms again can only decide to disclose the initial emission intensity level or not. The analysis then fully coincides with the baseline model analysis.

In case (2), let us assume firms always disclose the positive abatement level. At the disclosure stage, firms thus choose to fully disclose the emission-related information ($d_i = (a_i, s_i)$) or only disclose their abatement levels ($d_i = s_i$). Moreover, since we consider the abatement activity is an either-or decision, once we have $s_i = s$, if follows $\widehat{s_j} \leq s$. In the following, I use s to replace s_i.

We again denote that the posterior belief upon observing s_i alone is: $a_p^s = \text{E}[a_i|d_i^s = s]$.[5]

Firms thus compare the following input quantities to make their disclosure decisions:

$$E[x_i^{b*}|d_i^s = (a_i, s)] = \frac{2a_i\mu(b - \gamma H - \beta(a_i - s)) - \gamma a_i\mu(b - \beta(\mu - \hat{s_j})) - 2\mu c_i + \gamma a_i c_j}{(4a_i - \gamma^2 a_i)a_i\mu} \tag{A.52}$$

$$E[x_i^{b*}|d_i^s = s] = \frac{2a_i\mu(b - \gamma H - \beta(a_p^b - s)) - \gamma a_i\mu(b - \beta(\mu - \hat{s_j})) - 2\mu c_i + \gamma a_i c_j + a_i\mu\gamma^2 \text{Cov}[a_i, x_i|\emptyset]}{(4a_i - \gamma^2 a_p^b)a_i\mu} \tag{A.53}$$

[5]The off-path belief under full disclosure equilibrium is set to $a_p^s = \mu$ and $\text{Cov}[a_i, x_i|d_i^b = s] = H$.

Non- and full disclosure equilibria

Following the line of argument in the baseline model, nondisclosure (with respect to the emission intensity level) equilibrium, i.e., $d_i = s$, $\forall a_i$, exists if and only if the following condition holds:

$$\max\{\beta^s_{thres}|a_i > \mu\} \leq \beta \leq \min\{\beta^s_{thres}|a_i < \mu\}$$

Full disclosure equilibrium ($d_i = a_i$, $\forall a_i$) exists if and only if the following condition holds:

$$\max\{\beta^s_{thres}|a_i < \mu\} \leq \beta \leq \min\{\beta^s_{thres}|a_i > \mu\}$$

And,

$$\beta^s_{thres} = \frac{\gamma^2\Big((b\mu(2-\gamma) - 2\mu\gamma K + \gamma c_j)a_i - 2\mu c_i - \frac{(4-\gamma^2)\mu K a_i^2}{a_i - \mu}\Big)}{\mu a_i\Big(8a_i - \gamma^3(\mu - \hat{s_j}) - 2\gamma^2 s + \frac{2\gamma^4\mu}{4-\gamma^2}\mathrm{Cov}[a_i, \frac{1}{a_i}] + \frac{\gamma^3 a_i\mu}{a_i-\mu}\mathrm{Cov}[a_i, \frac{1}{a_i}]\Big)}$$

Clearly, $\partial\beta^s_{thres}/\partial s > 0$. Positive abatement level increases high emission firms' (higher than average) incentive to disclose but decreases low emission firms' incentive.

Partial disclosure equilibria

Now consider the partial disclosure equilibrium. We get the same structure of comparison as in the baseline model.

Partial disclosure equilibrium is characterized by the following nondisclosure set

$$N^s = [1, \bar{a}] \cup \Big([a^s_1, a^s_2] \cap [a^s_3, \infty)\Big), N^s \subset A$$

in which $a_i = a^s_1$, $a_i = a^s_2$, $a_i = a^s_3$ solves the following equation with $a^s_1 < a^s_2 < a^s_3$:

$$(a_i - a^s_p)(a_i - a^s_l)(a_i - a^s_h) = -\frac{(4-\gamma^2)\gamma^2\mathrm{Cov}[a_i, x_i|d_s = s]}{8\beta} \cdot a_i^2, \tag{A.54}$$

where,

$$a_p^s = \mathrm{E}[a_i | a_i \in N^s], \tag{A.55}$$

$$\mathrm{Cov}[a_i, x_i | a_i \in N^s] = \frac{\mu[2b - \gamma(b - \beta\mu)] + \gamma c_j}{(4 - \gamma^2)\mu} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i} | a_i \in N^s] - \frac{2c_i}{4 - \gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i^2} | a_i \in N^s]. \tag{A.56}$$

And

$$a_l^s = \frac{\gamma^2 \Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j + 2\mu\beta s - \gamma\mu\beta\widehat{s_j}\Big)}{16\mu\beta} - \frac{\sqrt{\gamma^4 \Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j + 2\mu\beta s - \gamma\mu\beta\widehat{s_j}\Big)^2 - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}, \tag{A.57}$$

and

$$a_h^s = \frac{\gamma^2 \Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j + 2\mu\beta s - \gamma\mu\beta\widehat{s_j}\Big)}{16\mu\beta} + \frac{\sqrt{\gamma^4 \Big(2b\mu - 2\mu\gamma H - \gamma b\mu + \gamma\beta\mu^2 + \gamma c_j + 2\mu\beta s - \gamma\mu\beta\widehat{s_j}\Big)^2 - 64\gamma^2\mu^2\beta c_i}}{16\mu\beta}. \tag{A.58}$$

Let's again define:

$$\beta_1^s = \frac{\gamma^2[(2 - \gamma)\mu b - 2\gamma\mu K + \gamma c_j]}{\mu(16\bar{a} - \gamma^3(\mu - \widehat{s_j}) - 2\gamma^2 s + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.59}$$

$$\beta_2^s = \frac{\gamma^2[(2 - \gamma)\mu b - 2\gamma\mu K + \gamma c_j]}{\mu(16 - \gamma^3(\mu - \widehat{s_j}) - 2\gamma^2 s + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.60}$$

$$\beta_3^s = \frac{\gamma^2[(2 - \gamma)\mu b - 2\gamma\mu K - 2\mu c_i + \gamma c_j]}{\mu(8 - \gamma^3(\mu - \widehat{s_j}) - 2\gamma^2 s + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.61}$$

$$\beta_4^s = \frac{\gamma^2[(2 - \gamma)\bar{a}\mu b - 2\gamma\bar{a}\mu K - 2\mu c_i + \gamma\bar{a} c_j]}{\bar{a}\mu(8\bar{a} - \gamma^3(\mu - \widehat{s_j}) - 2\gamma^2 s + \frac{2\gamma^4\mu}{4-\gamma^2} \cdot \mathrm{Cov}[a_i, \frac{1}{a_i}])} \tag{A.62}$$

Note that $\widehat{s_j} \leq s$, it is clear that $2s - \gamma\widehat{s_j} > 0$. We can compare these boundaries with the ones in the baseline model.

$$\frac{\partial \beta_1^s}{\partial s} > 0 \quad \text{(A.63)} \qquad \beta_1^s > \beta_1^b \quad \text{(A.67)}$$

$$\frac{\partial \beta_2^s}{\partial s} > 0 \quad \text{(A.64)} \qquad \beta_2^s > \beta_2^b \quad \text{(A.68)} \qquad a_l^s < a_l^b \quad \text{(A.71)}$$

$$\frac{\partial \beta_3^s}{\partial s} > 0 \quad \text{(A.65)} \qquad \beta_3^s > \beta_3^b \quad \text{(A.69)} \qquad a_h^s > a_h^b \quad \text{(A.72)}$$

$$\frac{\partial \beta_4^s}{\partial s} > 0 \quad \text{(A.66)} \qquad \beta_4^s > \beta_4^b \quad \text{(A.70)}$$

Furthermore, given the following threshold differences are positive, we have,

$$\beta_2^s - \beta_1^s > \beta_2^b - \beta_1^b \quad \text{(A.73)} \qquad \beta_4^s - \beta_1^s > \beta_4^b - \beta_1^b \quad \text{(A.75)}$$

$$\beta_3^s - \beta_1^s > \beta_3^b - \beta_1^b \quad \text{(A.74)} \qquad \beta_3^s - \beta_2^s > \beta_3^b - \beta_2^b \quad \text{(A.76)}$$

Following Corollary 2.1, we again can summarize the necessary conditions for different partial disclosure equilibria as follows:

i Only dirty firms talk - case 6

This equilibrium again requires $\text{Cov}[a_i, x_i | a_i \in N^s] > 0$, and

$$\beta < \beta_4^s. \quad \text{(A.77)}$$

Since $\beta_4^s > \beta_4^b$, positive abatement activity increases the range of necessary β condition supporting this partial disclosure equilibrium.

ii Only clean firms disclose - case 2 & 9

Condition supporting partial disclosure equilibrium where only clean firms disclose is $\text{Cov}[a_i, x_i | a_i \in N^s] > 0$, and

$$\beta > \beta_3^s \quad \text{(A.78)}$$

Since $\beta_3^s > \beta_3^b$, positive abatement activity decreases the range of necessary β condition supporting this partial disclosure equilibrium.

iii Mediocre firms do not disclose - case 3

The equilibrium does not hold when $\text{Cov}[a_i, x_i | a_i \in N^s] < 0$.

When $\text{Cov}[a_i, x_i | a_i \in N^s] > 0$, the necessary condition is

$$\begin{cases} \text{either} & \max\{\beta_1^s, \beta_3^s\} < \beta < \min\{\beta_2^s, \beta_4^s\} \\ \text{or} & \beta_3^s < \beta < \min\{\beta_1^s, \beta_4^s\} \end{cases} \tag{A.79}$$

iv. Partial disclosure equilibrium with two separate nondisclosure intervals - both cleanest and dirtiest firms withhold information - case 4

When $\text{Cov}[a_i, x_i | a_i \in N^s] < 0$, the necessary condition is then $1 < a_h^s < \bar{a}$. This requires

$$\begin{cases} \text{either} & \max\{\beta_1^s, \beta_4^s\} < \beta < \beta_2^s \\ \text{or} & \max\{\beta_2^s, \beta_4^s\} < \beta < \beta_3^s. \end{cases} \tag{A.80}$$

When $\text{Cov}[a_i, x_i | a_i \in N^s] > 0$, we thus have $1 < a_h^s < \bar{a}$. This requires

$$\begin{cases} \text{either} & \max\{\beta_1^s, \beta_3^s\} < \beta < \beta_2^s \\ \text{or} & \beta_3^s < \beta < \min\{\beta_1^s, \beta_4^s\} \end{cases} \tag{A.81}$$

v. Partial disclosure equilibrium with two separate nondisclosure intervals - dirties firms and some mediocre firms withhold their information - case 7

When $\text{Cov}[a_i, x_i | a_i \in N^s] < 0$, we still have $1 < a_h^s < \bar{a}$. This again leads to the same β constraint as in (A.80).

However, when $\text{Cov}[a_i, x_i | a_i \in N^s] > 0$, the necessary condition is only $a_l^s < \bar{a}$ & $a_h^s > 1$. This requires

$$\begin{cases} \text{either} & \beta_1^s < \beta < \beta_3^s \\ \text{or} & \beta < \min\{\beta_1^s, \beta_4^s\}. \end{cases} \tag{A.82}$$

A.5 Continuous abatement level

Other than considering firms' abatement activities to be project-based (binary decisions), one could also model a continuous abatement level with a convex cost function (see, for example, Wang and Wang, 2015; Anand and Giraud-Carrier, 2020), i.e.,

$$C_i(s_i) = \frac{\rho}{2} s_i^2 \tag{A.83}$$

Importantly, ρ is private information for the firm ex-ante. The marginal abatement cost, such as switching to cleaner technologies, highly depends on technology development and the firm's current process. It is reasonable to assume that outsiders cannot infer it. This assumption ensures that disclosing firms' abatement levels won't reveal their initial emission intensity level.

Instead of deciding on whether or not to conduct the abatement project, the firm now determines the optimal abatement cost to maximize its profit:

$$\begin{aligned} \max_{s_i} E[\pi_i | d_i] &= \max_{s_i} E[\pi_i^P | d_i] - C_i(s_i) \\ &= \max_{s_i} a_i^2 \cdot x_i^2(\widehat{a}_i, s_i, \widehat{s}_j) - \frac{\rho}{2} s_i^2 \end{aligned} \tag{A.84}$$

Taking first-order derivative with respect to s_i gives us:

$$s_i^* = \frac{4\beta a_i\Big[2a_i\mu(b-\gamma H-\beta\widehat{a_i})-\gamma a_i\mu(b-\beta(\mu-\widehat{s_j}))-2\mu c_i+\gamma a_i c_j+a_i\mu\gamma^2\mathrm{Cov}[a_i,x_i|d_i]\Big]}{\mu\Big[\rho(4a_i-\gamma^2\widehat{a_i})^2-8\beta^2a_i^2\Big]} \tag{A.85}$$

To demonstrate the potential adverse effect of the disclosure mandate, I focus on the case that nondisclosure equilibrium occurs under the voluntary disclosure regime. We thus need to compare the abatement level when all firms do not disclose their initial emission intensity level, but only their abatement levels (nd), vs. the case in which firms are forced to disclose all emission-relevant information (md).

In scenario nd, no information is provided regarding firms' initial emission intensity level. Information receivers rely on their prior belief so that $E[a_i|nd] = \mu$. In comparison, under the mandatory disclosure regime, $E[a_i|md] = a_i$. Moreover, $\mathrm{Cov}[a_i, x_i|nd] = H > 0$ when nondisclosure equilibrium occurs (see Proposition 2.1) and $\mathrm{Cov}[a_i, x_i|md] = 0$.

We thus have:

$$s_i^{nd*} = \frac{4\beta a_i\Big[2a_i\mu(b-\gamma H-\beta\mu)-\gamma a_i\mu(b-\beta(\mu-\widehat{s_j}))-2\mu c_i+\gamma a_i c_j+\gamma^2a_i\mu H\Big]}{\mu\Big[\rho(4a_i-\gamma^2\mu)^2-8\beta^2a_i^2\Big]} \tag{A.86}$$

$$s_i^{md*} = \frac{4\beta a_i\Big[2a_i\mu(b-\gamma H-\beta a_i)-\gamma a_i\mu(b-\beta(\mu-\widehat{s_j}))-2\mu c_i+\gamma a_i c_j\Big]}{\mu\Big[\rho(4a_i-\gamma^2a_i)^2-8\beta^2a_i^2\Big]} \tag{A.87}$$

Clearly, $s_i^{nd*}(a_i = \mu) > s_i^{md*}(a_i = \mu)$. Since both functions are continuous, we thus have

$$\exists a_i \in [1, \bar{a}] \quad \text{such that} \quad s_i^{md*} < s_i^{nd*}.$$

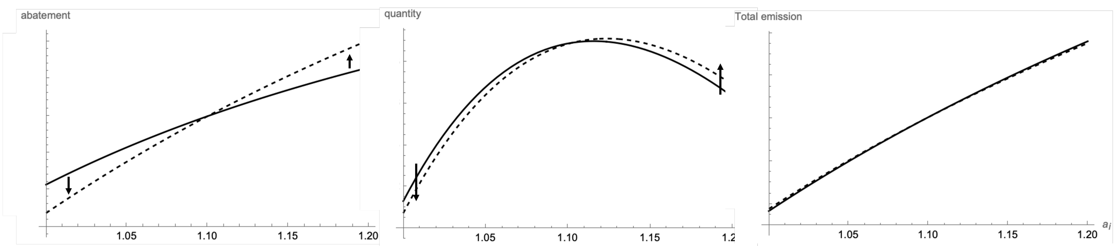
This means that forcing non-disclosing firms to reveal their initial emission intensity level may decrease some firms' abatement levels. We thus again conclude that disclosure mandate may negatively influence some firms' abatement incentives.

Take one step further. Following the numerical example in Figure 2.2, I illustrate the potential effect of disclosure mandates on firms' production quantities and their total emissions in Figure A.2. Note that firms' total emission level can be measured by:

$$E_i = (a_i - s_i) \cdot q_i \tag{A.88}$$

Figure A.2: Nondisclosure vs. mandatory disclosure in a continuous abatement setting

This figure illustrates the comparison of abatement levels (Figure A.2 (a)), production quantities (Figure A.2 (b)), and total emissions (Figure A.2 (c)) under the voluntary disclosure regime (solid lines) and the levels under the mandatory disclosure regime (dashed lines).
The parameter values follow Figure 2.2 except for the abatement level. We have : $b = 30$, $\gamma = 1$, $\mu = 1.1$, $c_i = 10$, $c_j = 4$, $\beta = 2$ and $\rho = 100$.



(a) Abatement level (b) Production quantity (c) Total emissions

Similar to the example in Section 2.4, disclosure mandates decrease the optimal abatement level for firms with lower emission levels and increase the abatement level for higher emission firms. Consequently, firms with lower initial emission intensity levels unambiguously produce less. It is the joint effect of deviating the equilibrium path (nondisclosure) and the decreased abatement level. For firms with higher emission levels, the effect from increased abatement levels is stronger so that these firms can even produce more. As a result, disclosure mandates have little effect on the firms' total emissions.

B Appendix Chapter 3

B.1 Variable definitions

I summarize the notations throughout the analysis in Table B.1.

Table B.1: Notations in the setup

Var.	Definition	Notes
N	Set of consumers populating a credence green market	$N = \{1, \ldots, n\}$
A	A subset of consumers that care about specific product attribute	$A = \{1, \ldots, a\}$, where $a \in \mathbb{Z} : 1 \leq a \leq n$
i	Consumer i	$i \in N$
j	Two firms competing in the market	$j \in F = \{1, 2\}$
m_j	Product quantity provided by firm j	$\sum_j m_j = n$
θ_j	Firm j's product attribute being either green or brown	$\theta_j \in \{g, b\}$
p	Ex ante probability that any product is green	$Pr(\theta_j = g) = p$
e	Additional cost firm bears to produce green product	
$x_{i,j}$	A product allocation scheme	
$v_{i,j}$	The value consumer i grants to product from firm j	$v_{i,j} = v_{i,\theta_j}$
s_j	The revenue firm j gets	
d_j	Firm j's labeling decision	$d_j \in \{0, 1\}$
c	Certification fee	$c > 0$
π_j	Firm j's profit	$\pi_j = S_j - c \cdot d_j$
π_j^d	Firm j's profit when deviate from the equilibrium path	
r_j	The labeling status of the firm j's products, i.e., labeled or unlabeled	$r_j \in \{l, ul\}$
λ	The probability that the brown products get identified and not labeled, given the firm seeks certification	$Pr(r_j = l \mid \theta_j = b, d_j = 1) = 1 - \lambda$

B.2 Focus on symmetric Bayesian Equilibria

Theoretically, we have four firm types' signaling strategies $\{d_1(\theta_1 = g), d_1(\theta_1 = b), d_2(\theta_2 = g), d_2(\theta_2 = b)\}$ under consideration, which leads us to sixteen strategy profiles for further analysis.

However, since green products face a higher probability of being labeled, any strategic profiles in which the firm with brown products seeks certification whereas the one with green products does not cannot be an equilibrium. This eliminates seven profiles. Moreover, if firm j applies separating strategies, namely seeking certification when it has green quality products and not seeking when it has brown quality products, firm $\neg j$ is not willing to play pooling equilibrium. A similar argument applies to profiles in which one firm always seeks certification whereas the other always not. We are thus left with potential equilibrium constitutions in which the same type firms play the same strategy. $\{1, 0, 1, 0\}$, $\{1, 1, 1, 1\}$, $\{0, 0, 0, 0\}$.

B.3 Equilibria analysis with symmetric firms

We start the analysis with considering symmetric firms. The detailed analysis of separating equilibrium is in Section 3.3.2. In this section, I provide a detailed elaboration on partial pooling and pooling equilibria.

Partial pooling equilibrium

We then consider the equilibrium in which both types of firms seek for certification. Note that:

$$Pr(r_j = l|\theta_j = g, d_j = 1) = 1$$

$$Pr(r_j = l|\theta_j = b, d_j = 1) = 1 - \lambda$$

In equilibrium, consumers update their beliefs as follows:

$$Pr(\theta_j = g|r_j = l) = \frac{p}{p + (1-p)(1-\lambda)}, \tag{B.1}$$

and

$$Pr(\theta_j = g|r_j = ul) = 0, \tag{B.2}$$

Consequently, for $i \in A$, we have

$$E[v_{i,j}|r_j = l] = \frac{p\beta + (1-p)(1-\lambda)}{p + (1-p)(1-\lambda)}$$

and

$$E[v_{i,j}|r_j = ul] = 1.$$

Since $E[v_{A,j}|r_j = l] > E[v_{A,j}|r_j = ul]$, conscious consumers again choose to buy labeled products first, if they appear on the market. We now consider the firms' signaling strategies.

For firm j with $\theta_j = g$, it chooses $d_j = 1$ and gets its $n/2$ units of product all labeled.

$$\begin{aligned}
&E[v_{i,j}|d_j = 1] \\
=&E[v_{i,j}|r_j = l] \cdot Pr(r_j = l|\theta_j = g, d_j = 1) + E[v_{i,j}|r_j = ul] \cdot Pr(r_j = ul|\theta_j = g, d_j = 1) \\
=&E[v_{i,j}|r_j = l] \\
=&v_{i,g} \cdot Pr(\theta_j = g|r_j = l) + v_{i,b} \cdot Pr(\theta_j = b|r_j = l) \\
=&v_{i,g} \cdot \frac{p}{p + (1-p)(1-\lambda)} + v_{i,g} \cdot \frac{(1-p)(1-\lambda)}{p + (1-p)(1-\lambda)}
\end{aligned} \tag{B.3}$$

Ex-ante, the firm has the following expectations:

- With probability p, firm j also faces a green quality firm. All n units of the product on the market are labeled. As a result, both firms equally share the socially conscious and non-conscious consumers. Firm j's payoff under such condition is thus:

$$-c + \frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1 \tag{B.4}$$

- With probability $1-p$, firm j faces a brown quality firm also seeking certification. However, only with probability $1 - \lambda$, all n units of the product on the market are labeled. The payoff here is again:

$$-c + \frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1 \tag{B.5}$$

- With probability $(1-p)\lambda$, firm j faces a brown quality firm, but its products are not labeled. In this scenario, conscious consumers first choose to buy firm j's products (labeled). This leads the following payoff:

$$-c + \min\{a, \frac{n}{2}\} \cdot E[v_{A,j}|d_j = 1] + \max\{\frac{n}{2} - a, 0\} \cdot 1 \tag{B.6}$$

The on-path payoffs for green firms is thus:

$$\begin{aligned}\pi_g = -c + p \cdot \Big(\frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1\Big) \\ (1-p)(1-\lambda)\Big(\frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1\Big) \\ + (1-p)\lambda\Big(\min\{a, \frac{n}{2}\} \cdot E[v_{A,j}|d_j = 1] + \max\{\frac{n}{2} - a, 0\} \cdot 1\Big)\end{aligned} \tag{B.7}$$

For firm j with $\theta_j = b$, it also chooses $d_j = 1$. However, only with probability $1 - \lambda$ the firm gets its $n/2$ units of the product all labeled and gets the revenue like the green firm. On the contrary, with probability λ, its products are not labeled. The firm earns $n/2$.

$$\pi_b = (1-\lambda)(\pi_g + c) + \lambda\frac{n}{2} - c \tag{B.8}$$

Now, if both firms types decide to deviate and seek no labeling for their products, they always get $\frac{n}{2}$. Comparing such incentives with the payoffs under the equilibrium path, we can conclude that type b's incentive imposes the equilibrium constraint:

$$\begin{aligned} c \leq & (1-\lambda)\Big[p \cdot \Big(\frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1\Big) \\ & (1-p)(1-\lambda)\Big(\frac{a}{2} \cdot E[v_{A,j}|d_j = 1] + (\frac{n}{2} - \frac{a}{2}) \cdot 1\Big) \\ & + (1-p)\lambda\Big(\min\{a, \frac{n}{2}\} \cdot E[v_{A,j}|d_j = 1] + \max\{\frac{n}{2} - a, 0\} \cdot 1\Big) - \frac{n}{2}\Big] \end{aligned} \tag{B.9}$$

I again summarize the condition in Proposition 3.1.

Pooling Equilibrium

In this equilibrium, no additional information is provided to the consumers.

$$Pr(\theta_j = g|r_j = ul) = p, \tag{B.10}$$

And

$$\begin{aligned} E[v_{i,j}|d_j = 0] &= E[v_{i,j}|r_j = ul] \\ &= v_{i,g} \cdot Pr(\theta_j = g|r_j = ul) + v_{i,b} \cdot Pr(\theta_j = b|r_j = ul) \\ &= v_{i,g} \cdot p + v_{i,g} \cdot (1-p) \end{aligned} \tag{B.11}$$

Further, we need to define off-path beliefs. That is to say, what the conscious consumers believe in case a labeled product appears. Without predefining the absolute probability, we assume

$$Pr(\theta_j = g|r_j = l) = \kappa \tag{B.12}$$

Consequently, for $i \in A$, we have $E[v_{i,j}|r_j = l] = 1 + \kappa \cdot (\beta - 1)$ and $E[v_{i,j}|r_j = ul] = 1 + p(\beta - 1)$. Clearly, if the conscious players assign $\kappa \leq p$, they would prefer unlabeled products to labeled products. Deviating the equilibrium strategy brings no benefit even for the green firms. Under such belief, this pooling equilibrium is always supported.

Only if $\kappa > p$,[1] we need to impose equilibrium conditions further.

Staying with the equilibrium strategy leads to the same payoff for green and brown firms, which is

$$\frac{a}{2} \cdot E[v_{A,j}|d_j = 0] + (\frac{n}{2} - \frac{a}{2}). \tag{B.13}$$

Since the green firms have a higher chance to get labeled, they have a stronger incentive to deviate from pooling than brown firms. Deviating generates the green firm a payoff of

$$-c + \min\{a, \frac{n}{2}\} \cdot E[v_{A,j}|d_j = 1] + \max\{\frac{n}{2} - a, 0\} \cdot 1, \tag{B.14}$$

where

$$E[v_{A,j}|d_j = 1] = E[v_{A,j}|r_j = l],$$

since green firm gets labeled with certainty once it seeks certification.

Comparing these payoffs, we can derive the equilibrium condition. I apply the Intuitive criterion by considering $\kappa = 1$ (reaching highest payoff from deviating) and get the corresponding equilibrium condition as follows:

$$c \geq \min\{a, \frac{n}{2}\} \cdot (1 + \beta - 1) + \max\{\frac{n}{2} - a, 0\} \cdot 1 - \frac{a}{2} \cdot (1 + p(\beta - 1)) + (\frac{n}{2} - \frac{a}{2}). \tag{B.15}$$

The condition is summarized in Proposition 3.1.

B.4 Equilibria analysis with asymmetric firms

With asymmetric firms, the equilibrium analysis needs to consider the disclosure strategies for all four potential firm-types (firm 1 with g, firm 1 with b, firm 2 with g, firm 2 with b). Note that under the equilibrium conditions, conscious consumers still update their beliefs like in the symmetric case.

[1]Examples could be when we assume that labeled products can only be green type ($\kappa = 1$). Or when we assume both types may deviate with the same probability. In this case, $\kappa = \frac{p}{p+(1-p)(1-\lambda)}$.

B.4.1 Random allocation scheme

With random allocation mechanism, the incentives to deviate from equilibrium strategies are proportionate to the size of the firm (the firm's product quantity). The symmetry case discussed in Section 3.3.2 can be seen as a special case here. With asymmetric firms, we now need to consider deviation incentives for more firm-types. Since the equilibrium condition always takes the most stringent requirement, intuitively, we observe less probable occurrence of all three equilibria.

Separating equilibrium

Clearly, the separating equilibrium now entails both $1-g$ and $2-g$ firm-type labeling their products and $1-b$ and $2-b$ not.

For firm j, if its products are with green quality, the equilibrium disclosure strategy is $d_j(\theta_j = g) = 1$, the payoffs following the equilibrium path are:

Table B.2: Separating equilibrium: On-path payoffs for $\theta_j = g$

w. Probability	Encounters	Payoffs
p	$m_{\neg j}$ labelled products	$-c + \frac{a}{n} \cdot m_j \cdot E[v_{A,j} \mid d_j = 1] + (m_j - \frac{a}{n} \cdot m_j) \cdot 1$
$1-p$	$m_{\neg j}$ unlabelled products	$-c + \min\{a, m_j\} \cdot E[v_{A,j} \mid d_j = 1] + \max\{m_j - a, 0\} \cdot 1$

Deviating from the equilibrium strategy will leave the firm with m_j.

Given that firm j is with brown quality, the equilibrium disclosure strategy is $d_j(\theta_j = b) = 0$, which leads to the payoff of m_j. Deviating from the equilibrium will lead to the following:

Table B.3: Separating equilibrium: Deviation payoffs for $\theta_j = b$

w. Probability	Encounters	Payoffs	
		w/p. λ	w/p. $1-\lambda$
p	$m_{\neg j}$ labelled products	$-c + m_j$	$-c + \frac{a}{n} \cdot m_j \cdot E[v_{A,j} \mid d_j = 1] + (m_j - \frac{a}{n} \cdot m_j) \cdot 1$
$1-p$	$m_{\neg j}$ unlabelled products	$-c + m_j$	$-c + \min\{a, m_j\} \cdot E[v_{A,j} \mid d_j = 1] + \max\{m_j - a, 0\} \cdot 1$

Comparing the incentives, we can derive the conditions that sustain equilibrium strategies. Let's define:

$$k_1(m_j) \equiv (\beta - 1)(p \cdot \frac{a}{n} \cdot m_j + (1-p) \cdot a), \tag{B.16}$$

and

$$k_2(m_j) \equiv (\beta - 1)(p \cdot \frac{a}{n} + (1-p))m_j. \tag{B.17}$$

The upper bound of the equilibrium when $a < m_1$ is then $min\{k_1(m_1), k_1(m_2)\} = k_1(m_1)$. We can summarize the equilibrium conditions as follows:

$$\begin{cases} (1-\lambda)k_1(m_2) \leq c \leq k_1(m_1) \quad \text{when} \quad a \leq m_1 \\ (1-\lambda)\max\{k_2(m_1), k_1(m_2)\} \leq c \leq \min\{k_2(m_1), k_1(m_2)\} \quad \text{when} \quad m_1 < a \leq m_2 \\ (1-\lambda)k_2(m_2) \leq c \leq k_2(m_1) \quad \text{when} \quad a > m_2 \end{cases} \tag{B.18}$$

Note that, the upper bound (when $a \leq \frac{n}{2}$) for the separating equilibrium with symmetric firms in Proposition 3.1 is $(\beta - 1)(1 - \frac{p}{2})a = k_1(\frac{n}{2})$. It's easy to see that $k_1(m_1) < k_1(\frac{n}{2})$. A similar comparison can be done for other thresholds. We thus can conclude that the equilibrium condition with asymmetric firms are tighter. Furthermore, the larger the size difference is (smaller m_1 and larger m_2), the less probable that the separating equilibrium occurs.

Partial pooling equilibrium

Following the analysis in the symmetric case, we know that the incentive for firms with brown quality products determines the upper bound of the cost. We again demonstrate the equilibrium payoff of these firms in

Table B.4: Partial pooling: On-path payoffs for $\theta_j = b$

w. Probability	Encounters	Payoffs	
		w/p. λ	w/p. $1-\lambda$
p	$m_{\neg j}$ labelled products	$-c+m_j$	$-c+\frac{a}{n}\cdot m_j\cdot E[v_{A,j}\|d_j=1]+(m_j-\frac{a}{n}\cdot m_j)\cdot 1$
$(1-p)\lambda$	$m_{\neg j}$ unlabelled products	$-c+m_j$	$-c+\min\{a,m_j\}\cdot E[v_{A,j}\|d_j=1]+\max\{m_j-a,0\}\cdot 1$
$(1-p)(1-\lambda)$	$m_{\neg j}$ labelled products	$-c+m_j$	$-c+\frac{a}{n}\cdot m_j\cdot E[v_{A,j}\|d_j=1]+(m_j-\frac{a}{n}\cdot m_j)\cdot 1$

We again define:

$$k_3(m_j) \equiv (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)(p\cdot\frac{a}{n}\cdot m_j+(1-p)(1-\lambda)\cdot\frac{a}{n}\cdot m_j+(1-p)\lambda\cdot a), \tag{B.19}$$

and

$$k_4(m_j) \equiv (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)(p\cdot\frac{a}{n}+(1-p)(1-\lambda)\cdot\frac{a}{n}+(1-p)\lambda)m_j. \tag{B.20}$$

The equilibrium conditions are then:

$$\begin{cases} c \leq k_3(m_1) \quad \text{when} \quad a \leq m_1 \\ c \leq \min\{k_4(m_1), k_3(m_2)\} \quad \text{when} \quad m_1 < a \leq m_2 \\ c \leq k_4(m_1) \quad \text{when} \quad a > m_2 \end{cases} \tag{B.21}$$

Similar to in the separating equilibrium, we can show that the thresholds here are lower than thresholds in the partial pooling equilibrium with symmetric firms.

Pooling Equilibrium

In this equilibrium, the incentive for firms with green quality products determines the lower bound of the labeling cost.

Clearly, staying with the equilibrium allows the green quality firm j to get

$$\frac{a}{n}m_j\cdot(1+p(\beta-1))+m_j-\frac{a}{n}m_j.$$

In addition, only if the off-path belief $Pr(\theta_j = g|r_j = l) = \kappa > p$, firms have incentives to deviate at all. By doing so, firm j gets

$$\min\{m_j, a\} \cdot (1 + \kappa(\beta - 1)) + max\{m_j - a, 0\} - c.$$

We define:

$$k_5(m_j) \equiv (\beta - 1)(\kappa - \frac{m_j}{n} \cdot p) \cdot a, \tag{B.22}$$

and

$$k_6(m_j) \equiv (\beta - 1)(\kappa - \frac{a}{n} \cdot p) \cdot m_j. \tag{B.23}$$

The equilibrium conditions are then:

$$\begin{cases} c \geq \max\{k_5(m_1), k_5(m_2)\} = k_5(m_1) \quad \text{when} \quad a \leq m_1 \\ c \geq \max\{k_6(m_1), k_5(m_2)\} \quad \text{when} \quad m_1 < a \leq m_2 \\ c \geq k_6(m_2) \quad \text{when} \quad a > m_2 \end{cases} \tag{B.24}$$

We can easily see that the thresholds here are higher than the lower bound of the pooling equilibrium with symmetric firms.

B.4.2 Quasi-ranking allocation

Under the quasi-ranking allocation, the incentives to deviate from equilibrium strategies are no longer proportionate to the firm's product quantity. We now get to the equilibria one by one.

Separating equilibrium

We know from the above analysis that the green quality firms determine the upper bound of the equilibrium. We thus start with their payoffs under equilibrium strategy $(d_j(\theta_j = g) = 1)$ (see Table B.5).

Table B.5: Separating equilibrium: On-path payoffs for $\theta_j = g$

<table>
<tr><th rowspan="2">w. Probability</th><th rowspan="2">Encounters</th><th colspan="2">Payoffs</th></tr>
<tr><th>w/p. λ</th><th>w/p. $1-\lambda$</th></tr>
<tr><td>p</td><td>m_2 labelled products</td><td colspan="2">$-c + \min\{m_1, \frac{a}{2}\} \cdot E[v_{A,j}|d_j = 1] + \max\{m_1 - \frac{a}{2}, 0\} \cdot 1$</td></tr>
<tr><td>$1-p$</td><td>m_2 unlabelled products</td><td colspan="2">$-c + \min\{m_1, a\} \cdot E[v_{A,j}|d_j = 1] + \max\{m_1 - a, 0\} \cdot 1$</td></tr>
</table>

Table Table B.5 (a): $\theta_1 = g$

<table>
<tr><th rowspan="2">w. Probability</th><th rowspan="2">Encounters</th><th colspan="2">Payoffs</th></tr>
<tr><th>w/p. λ</th><th>w/p. $1-\lambda$</th></tr>
<tr><td>p</td><td>m_1 labelled products</td><td colspan="2">$-c + \max\{a - m_1, \frac{a}{2}\} \cdot E[v_{A,j}|d_j = 1] + \min\{m_2 - \frac{a}{2}, m_2 - (a - m_1)\} \cdot 1$</td></tr>
<tr><td>$1-p$</td><td>m_1 unlabelled products</td><td colspan="2">$-c + \min\{m_2, a\} \cdot E[v_{A,j}|d_j = 1] + \max\{m_2 - a, 0\} \cdot 1$</td></tr>
</table>

Table Table B.5 (b): $\theta_2 = g$

Deviating from the equilibrium path always gets the green quality firm j payoff of m_j. We can summarize the requirements that keep the green quality firms to stay with the equilibrium strategy in Table B.6

Table B.6: Separating equilibrium: Requirements for $\theta_j = g$

When	Requirement
$1 \leq a < m_1$	$c \leq (\beta - 1)(1 - \frac{p}{2})a$
$m_1 \leq a < 2m_1$	$c \leq (\beta - 1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1)$
$2m_1 \leq a \leq n$	$c \leq (\beta - 1) \cdot m_1$

Table B.6 (a): Condition to stay on-path for $\theta_1 = g$

<table>
<tr><th colspan="2">When</th><th>Requirement</th></tr>
<tr><td rowspan="3">$2m_1 > m_2$</td><td>$1 \leq a < m_2$</td><td>$c \leq (\beta - 1)(1 - \frac{p}{2})a$</td></tr>
<tr><td>$m_2 \leq a < 2m_1$</td><td>$c \leq (\beta - 1)(p \cdot \frac{a}{2} + (1-p) \cdot m_2)$</td></tr>
<tr><td>$2m_1 \leq a \leq n$</td><td>$c \leq (\beta - 1)(p \cdot (a - m_1) + (1-p) \cdot m_2)$</td></tr>
<tr><td rowspan="3">$2m_1 < m_2$</td><td>$1 \leq a < 2m_1$</td><td>$c \leq (\beta - 1)(1 - \frac{p}{2})a$</td></tr>
<tr><td>$2m_1 \leq a < m_2$</td><td>$c \leq (\beta - 1)(p \cdot (a - m_1) + (1-p) \cdot a)$</td></tr>
<tr><td>$m_2 \leq a \leq n$</td><td>$c \leq (\beta - 1)(p \cdot (a - m_1) + (1-p) \cdot m_2)$</td></tr>
</table>

Table B.6 (b): Condition to stay on-path for $\theta_2 = g$

We can illustrate the upper bound of the equilibrium as follows:

- When $2m_1 > m_2 \implies \frac{n}{3} < m_1 < \frac{n}{2}$,

$$c \leq \begin{cases} (\beta-1)(1-\frac{p}{2})a, \quad \text{when} \quad 1 \leq a < m_1 \\ (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_1 \leq a < m_2 \\ (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_2 \leq a < 2m_1 \\ (\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < n \end{cases} \tag{B.25}$$

- When $2m_1 < m_2 \implies m_1 < \frac{n}{3}$,

$$c \leq \begin{cases} (\beta-1)(1-\frac{p}{2})a, \quad \text{when} \quad 1 \leq a < m_1 \\ (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_1 \leq a < 2m_1 \\ (\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < m_2 \\ (\beta-1)m_1, \quad \text{when} \quad m_2 \leq a < n \end{cases} \tag{B.26}$$

A similar analysis can be done for the lower bound. We summarize the equilibrium conditions as follows:

- When $2m_1 > m_2 \implies \frac{n}{3} < m_1 < \frac{n}{2}$,

$$\begin{cases} (1-\lambda)(\beta-1)(1-\frac{p}{2})a \leq c \leq (\beta-1)(1-\frac{p}{2})a, \quad \text{when} \quad 1 \leq a < m_1 \\ (1-\lambda)(\beta-1)(1-\frac{p}{2})a \leq c \leq (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_1 \leq a < m_2 \\ (1-\lambda)(\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_2) \leq c \leq (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_2 \leq a < 2m_1 \\ (1-\lambda)(\beta-1)(p(a-m_1) + (1-p) \cdot m_2) \leq c \leq (\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < n \end{cases} \tag{B.27}$$

- When $2m_1 < m_2 \implies m_1 < \frac{n}{3}$,

$$\begin{cases} (1-\lambda)(\beta-1)(1-\frac{p}{2})a \leq c \leq (\beta-1)(1-\frac{p}{2})a, \quad \text{when} \quad 1 \leq a < m_1 \\ (1-\lambda)(\beta-1)(1-\frac{p}{2})a \leq c \leq (\beta-1)(p \cdot \frac{a}{2} + (1-p) \cdot m_1), \quad \text{when} \quad m_1 \leq a < 2m_1 \\ (1-\lambda)(\beta-1)(p(a-m_1) + (1-p) \cdot a) \leq c \leq (\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < m_2 \\ (1-\lambda)(\beta-1)(p(a-m_1) + (1-p) \cdot m_2) \leq c \leq (\beta-1)m_1, \quad \text{when} \quad m_2 \leq a < n \end{cases} \tag{B.28}$$

Comparing the separating equilibrium condition with symmetric firms in Proposition 3.1, we can see that for a low number of conscious consumers ($a < m_1$), the equilibrium condition remains the same. On the contrary, once the number exceeds the quantity provided by firm 1, the equilibrium condition becomes tighter. Interestingly, the more conscious consumers there are, the larger is this negative impact. The larger the size difference ($m_2 - m_1$) is, the larger is the negative impact on the equilibrium occurrence.

Partial pooling equilibrium

We know that the deviation incentives for the brown quality firms constitute the upper bound of the equilibrium conditions here.

Shifting the possibility of facing either labelled or unlabelled competing products from the separating equilibrium, we can easily derive the results as follows:

- When $2m_1 > m_2 \implies \frac{n}{3} < m_1 < \frac{n}{2}$,

$$c \leq \begin{cases} (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot a), & \text{when} \quad 1 \leq a < m_1 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot m_1), & \text{when} \quad m_1 \leq a < m_2 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot m_1), & \text{when} \quad m_2 \leq a < 2m_1 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < n \end{cases} \tag{B.29}$$

- When $2m_1 < m_2 \implies m_1 < \frac{n}{3}$,

$$c \leq \begin{cases} (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot a), & \text{when} \quad 1 \leq a < m_1 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot m_1), & \text{when} \quad m_1 \leq a < 2m_1 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)m_1, \quad \text{when} \quad 2m_1 \leq a < m_2 \\ (1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)m_1, \quad \text{when} \quad m_2 \leq a < n \end{cases} \tag{B.30}$$

Note that the upper bounds of the partial pooling equilibrium with symmetric firms can be expressed as

$$(1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot a) \quad \text{when} \quad a\leq\frac{n}{2},$$

and

$$(1-\lambda)\frac{p}{p+(1-p)(1-\lambda)}(\beta-1)((p+(1-p)(1-\lambda)\cdot\frac{a}{2}+(1-p)\lambda\cdot\frac{n}{2}) \quad \text{when} \quad a>\frac{n}{2},$$

Comparing these thresholds, we can see that, similar to the case of separating equilibrium, when there are only small number of socially conscious consumers, here, $a \leq m_1$, the equilibrium condition has not changed. However, when more than half of the consumers are conscious consumers, the firms' size asymmetry has a negative impact on the occurrence of the equilibrium. The larger the size difference is (smaller m_1), the less probable the equilibrium occurs.

Pooling Equilibrium

We know that the deviation incentives for the brown quality firms constitute the upper bound of the equilibrium conditions here.

Consider firm 1 with $\theta_1 = g$. The payoff of taking the equilibrium path is

$$\pi_1 = \min\{m_1, \frac{a}{2}\} \cdot E[v_{A,j}|d_j = 0] + \max\{m_1 - \frac{a}{2}, 0\}. \tag{B.31}$$

Deviating from the equilibrium strategy leads to

$$\pi_1^d = \min\{m_1, a\} \cdot E[v_{A,j}|d_j = 0] + \max\{m_1 - a, 0\} - c. \tag{B.32}$$

The firms' size difference lead to a different payoffs for firm 2. We express them as follows:

$$\pi_2 = \max\{a - m_1, \frac{a}{2}\} \cdot E[v_{A,j}|d_j = 0] + \min\{m_2 - \frac{a}{2}, m_2 - (a - m_1)\}, \qquad \text{(B.33)}$$

and

$$\pi_2^d = \min\{m_2, a\} \cdot E[v_{A,j}|d_j = 0] + \max\{m_2 - a, 0\} - c. \qquad \text{(B.34)}$$

We can summarize the requirements that keep the green quality firms to stay with the equilibrium strategy in Table B.7

Table B.7: Pooling equilibrium: Requirements for $\theta_j = g$

When	Requirement
$1 \leq a < m_1$	$c \geq (\beta - 1)(\kappa \cdot a - p \cdot \frac{a}{2})$
$m_1 \leq a < 2m_1$	$c \geq (\beta - 1)(\kappa \cdot m_1 - p \cdot \frac{a}{2})$
$2m_1 \leq a \leq n$	$c \geq (\beta - 1)(\kappa \cdot m_1 - p \cdot m_1)$

Table B.7 (a): $\theta_1 = g$

When		Requirement
$2m_1 > m_2$	$1 \leq a < m_2$	$c \geq (\beta - 1)(\kappa \cdot a - p \cdot \frac{a}{2})$
	$m_2 \leq a < 2m_1$	$c \geq (\beta - 1)(\kappa \cdot m_2 - p \cdot \frac{a}{2})$
	$2m_1 \leq a \leq n$	$c \geq (\beta - 1)(\kappa \cdot m_2 - p \cdot (a - m_1))$
$2m_1 < m_2$	$1 \leq a < 2m_1$	$c \geq (\beta - 1)(\kappa \cdot a - p \cdot \frac{a}{2})$
	$2m_1 \leq a < m_2$	$c \geq (\beta - 1)(\kappa \cdot a - p \cdot (a - m_1))$
	$m_2 \leq a \leq n$	$c \geq (\beta - 1)(\kappa \cdot m_2 - p \cdot (a - m_1))$

Table B.7 (b): $\theta_2 = g$

The equilibrium condition is then:

- When $2m_1 > m_2 \implies \frac{n}{3} < m_1 < \frac{n}{2}$,

$$c \geq \begin{cases} (\beta - 1)(\kappa \cdot a - p \cdot \frac{a}{2}), & \text{when} \quad 1 \leq a < m_1 \\ (\beta - 1)(\kappa \cdot a - p \cdot \frac{a}{2}), & \text{when} \quad m_1 \leq a < m_2 \\ (\beta - 1)(\kappa \cdot m_2 - p \cdot \frac{a}{2}), & \text{when} \quad m_2 \leq a < 2m_1 \\ \max\{(\beta - 1)(\kappa \cdot m_1 - p \cdot m_1), (\beta - 1)(\kappa \cdot m_2 - p \cdot (a - m_1))\}, & \text{when} \quad 2m_1 \leq a < n \end{cases} \qquad \text{(B.35)}$$

- When $2m_1 < m_2 \implies m_1 < \frac{n}{3}$,

$$c \geq \begin{cases} (\beta-1)(\kappa \cdot a - p \cdot \frac{a}{2}), & \text{when} \quad 1 \leq a < m_1 \\ (\beta-1)(\kappa \cdot a - p \cdot \frac{a}{2}), & \text{when} \quad m_1 \leq a < 2m_1 \\ (\beta-1)(\kappa \cdot a - p \cdot (a - m_1)), & \text{when} \quad 2m_1 \leq a < m_2 \\ \max\{(\beta-1)(\kappa \cdot m_1 - p \cdot m_1), (\beta-1)(\kappa \cdot m_2 - p \cdot (a - m_1))\}, & \text{when} \quad m_2 \leq a < n \end{cases} \tag{B.36}$$

Comparing these thresholds with the ones in pooling equilibrium with symmetric firms, we can see that when $a \leq \min\{m_2, 2m_1\}$

C Appendix Chapter 4

C.1 Variable definitions

I summarize the notations throughout the analysis in Table C.1.

Table C.1: Notations in the setup

Variable	Definition	Notes
v^i	Firm i's value being either low or high	$v_i \in \{l, h\}$, with $l = 0$, $h = 1$
f^i	Firm i's fit with the blockchain technology being either bad or good	$f_i \in \{b, g\}$, with $b = \beta \in (0, 1)$, $g = 1$
θ^i	Firm i's type as the combination of value and fit	$\theta^i \in \Theta = \{hg, hb, lb, lg\}$
σ_θ	The proportion of type $\theta \in \Theta$ in the economy	
p^1	The price an investor is willing to pay for a share in firm i	
D^i	The decision of firm i to enter the blockchain ($D^i = 1$) or not ($D^i = 0$)	$D^i \in \{0, 1\}$
C_B	Cost to enter the blockchain	$C_B \in \mathbb{R}_+$
C_T	Cost to have the traditional institution	$C_T \in \mathbb{R}_+$
$C \equiv C_B - C_T$	Cost difference	$C \in \mathbb{R}$
m^i	A message generated by firm i	$m^i \in \{v^i, \emptyset\}$
ρ	The (equilibrium) reach of the blockchain, i.e., the equilibrium mass of firms adoption the blockchain	
η^i	The blockchain reveals a firm's type with a firm-specific probability	$\eta^i = \rho \cdot f^i$
γ	Traditional institutions provide a credible signal about a firm's type with exogenous probability	$\gamma \in [0, 1)$
p^I	The pooling prices inside the blockchain (equal to the posterior beliefs) following an uninformative message	
p^O	The pooling prices outside the blockchain (equal to the posterior beliefs) following an uninformative message	
λ	The probability of a firm's value being high when assume independence between firms' fit and values	
ω	The probability of a firm's fit being good when assume independence between firms' fit and values	

C.2 Proof of Lemma 4.1

Following (4.7), we obtain:

$$\Delta_{hg} - \Delta_{hb} = (1-\beta)\rho(1-p^I) \geq 0 \tag{C.1}$$

$$\Delta_{lg} - \Delta_{lb} = -(1-\beta)\rho p^I \leq 0, \tag{C.2}$$

where $\rho \geq 0$, and $p^I \in [0,1]$ are determined by the other firms' equilibrium decisions.

C.3 Proof of Lemma 4.3

This follows directly from the fact that any mixed-strategy profile, which constitutes an equilibrium for $\gamma = 0$ and $C > 0$ must be contained in the set:

$$\{\{q_{hg}, q_{hb}, 0, 0\}, \{1, 1, q_{lb}, 0\}, \{1, 1, 1, q_{lg}\}\}, \tag{C.3}$$

as all other profiles violate Lemma 4.2. The only exception is $\{1,1,1,1\}$ in which all firms adopt. However, this profile fails because it requires $C = 0$—otherwise, lg-types, which are revealed inside the blockchain with probability 1 and hence obtain an expected payoff of 0, would strictly prefer to not join, irrespective of the perceived quality outside the blockchain.

C.4 Proof of Proposition 4.1

We proceed through the three mixed strategy profiles from Lemma 4.3 and assess under which conditions they constitute equilibria. This also yields the pure strategy equilibria by considering $q_\theta \in \{0,1\}$ as special cases.

Profile $\{q_{hg}, q_{hb}, 0, 0\}$ Consider first the special case $q_{hg} = q_{hb} = 0$, which requires $\Delta_\theta \leq C, \forall\theta$. As $C \geq 0$, and as an equilibrium strategy profile of $\{0,0,0,0\}$ allows to freely specify the off-path belief about the value of unverified firms inside the blockchain, the belief that induces $p^I = 0$ always gives $\Delta_\theta = 0 - p^O < 0 \leq C$. This can therefore always be supported in equilibrium for any $C \geq 0$.

Thus, we can restrict our attention to candidates where $q_{hg} + q_{hb} > 0 \implies \rho > 0$. If this constitutes an equilibrium, $p^I = 1$ and thus, $\Delta_{hg} = \Delta_{hb}$. Any such equilibrium necessarily features $\Delta_{hg} = \Delta_{hb} > \Delta_{lb} \geq \Delta_{lg}$. We need to distinguish two cases: the case where high-value firms *strictly* prefer to join the blockchain, and the case where they are *indifferent*.

If high-value firms strictly prefer to join the blockchain, we have $\Delta_{hg} = \Delta_{hb} > C$ and thus, $q_{hg} = q_{hb} = 1$, $p^I = 1$, $p^O = 0$. This can hence be supported in equilibrium whenever $C \in [\Delta_{lb}, \Delta_{hg})$ where the lower bound on C stems from the lb-type being incentivized not to join the blockchain, and the upper bound from the high value-types being incentivized to join. We can compute these bounds explicitly and have that $\{1, 1, 0, 0\}$ can be supported in equilibrium whenever $C \in [1 - \beta [\sigma_{hg} + \sigma_{hb}], 1)$.

If high-value firms are indifferent, we have $\Delta_{hg} = \Delta_{hb} = C$ and $p^I = 1$. This gives as a necessary condition:

$$C = 1 - p^O = \frac{\sigma_{lb} + \sigma_{lg}}{(1 - q_{hg})\sigma_{hg} + (1 - q_{hb})\sigma_{hb} + \sigma_{lb} + \sigma_{lg}} \equiv \tilde{C}(q_{hg}, q_{hb}). \tag{C.4}$$

$\tilde{C}(q_{hg}, q_{hb})$ is increasing in both q_{hg} and q_{hb}. For each $C \in \left(\tilde{C}(0,0), \tilde{C}(1,1)\right] = (1 - (\sigma_{hb} + \sigma_{hg}), 1]$, there hence exist $q_{hg}, q_{hb} \in [0, 1]$ with $q_{hg} + q_{hb} > 0$ such that $\{q_{hg}, q_{hb}, 0, 0\}$ constitutes an equilibrium. Notably, for $C = \tilde{C}(1,1) = 1$, this is the pure strategy equilibrium $\{1, 1, 0, 0\}$. Moreover, $\tilde{C}(1,0)$ and $\tilde{C}(0,1)$ characterize the unique cost levels such that $\{1, 0, 0, 0\}$ and $\{0, 1, 0, 0\}$ can be supported in equilibrium, respectively.

Profile $\{1, 1, q_{lb}, 0\}$ In equilibrium, this implies $\rho > 0$, $p^O = 0$, and $p^I > 0$. It follows that $\Delta_{hg} \geq \Delta_{hb} > \Delta_{lb} > \Delta_{lg}$. We can explicitly compute p^I and obtain:

$$p^I = \frac{(1 - \rho)\sigma_{hg} + (1 - \rho\beta)\sigma_{hb}}{(1 - \rho)\sigma_{hg} + (1 - \rho\beta)(\sigma_{hb} + q_{lb}\sigma_{lb})}. \tag{C.5}$$

We need to distinguish cases, specifically whether lb-types strictly prefer to join the blockchain ($\Delta_{lb} > C$), are indifferent ($\Delta_{lb} = C$), or prefer not to join ($\Delta_{lb} < C$).

For lb-types to be indifferent, $C = \Delta_{lb}$ is required. Plugging (C.5) into Δ_{lb}, we obtain as a necessary condition:

$$C = (1-\rho\beta)p^I = \frac{\left(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb})\right)\left[(\sigma_{lg}+(1-q_{lb})\sigma_{lb})\sigma_{hg}+(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb}))\sigma_{hb}\right]}{(\sigma_{lg}+(1-q_{lb})\sigma_{lb})\sigma_{hg}+(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb}))(\sigma_{hb}+q_{lb}\sigma_{lb})} \equiv \tilde{C}'(q_{lb}). \tag{C.6}$$

Inspection shows that $\tilde{C}'$ is decreasing in q_{lb}. Thus, for each $C \in \left[\tilde{C}'(1), \tilde{C}'(0)\right]$, there exists a q_{lb} such that $\{1, 1, q_{lb}, 0\}$ can be supported in equilibrium. We can explicitly derive:

$$\begin{aligned} \tilde{C}'(1) &= (1-\beta(1-\sigma_{lg}))\frac{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg}))\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg}))(\sigma_{hb}+\sigma_{lb})} \equiv \bar{C}, \\ \tilde{C}'(0) &= 1-\beta\left(\sigma_{hg}+\sigma_{hb}\right). \end{aligned} \tag{C.7}$$

The case where $\Delta_{lb} < C$ implies $q_{lb} = 0$, and hence, that we consider the profile $\{1, 1, 0, 0\}$, which has been covered previously. Whenever $\Delta_{lb} > C$, we consider the profile $\{1, 1, 1, 0\}$, which, to be supported in equilibrium, requires $C \in \left[\Delta_{lg}, \tilde{C}'(1)\right)$. We can explicitly write Δ_{lg} in this case as:

$$\Delta_{lg} = (1-\rho)p^I = \sigma_{lg}\frac{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg})\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg})(\sigma_{hb}+\sigma_{lb})} \equiv \underline{C}. \tag{C.8}$$

Including the limit case where the lb-type is indifferent, $\{1, 1, 1, 0\}$ can hence be supported in equilibrium whenever $C \in \left[\underline{C}, \bar{C}\right]$.

<u>*Profile* $\{1, 1, 1, q_{lg}\}$</u> $q_{lg} = 1$ is not feasible due to $C > 0$. Moreover, the case $q_{lg} = 0$ was covered in the previous case. We can hence restrict our attention to $q_{lg} \in (0, 1)$, which requires that the lg-type is indifferent. This is both necessary and sufficient as $q_{lg} \in (0, 1)$ in this case implies $\rho > 0$, $p^O = 0$, $0 < p^I < 1$, and hence, $\Delta_{hg} > \Delta_{hb} > \Delta_{lb} > \Delta_{lg}$.

C therefore needs to satisfy:

$$C = \Delta_{lb} = (1-\rho\beta)p^I = \frac{(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb}))[(\sigma_{lg}+(1-q_{lb})\sigma_{lb})\sigma_{hg}+(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb}))\sigma_{hb}]}{(\sigma_{lg}+(1-q_{lb})\sigma_{lb})\sigma_{hg}+(1-\beta(1-\sigma_{lg}-(1-q_{lb})\sigma_{lb}))(\sigma_{hb}+q_{lb}\sigma_{lb})} \equiv \tilde{C''}(q_{lg}). \tag{C.9}$$

$\tilde{C''}$ is decreasing in q_{lg}. For any $C \in \left(\tilde{C''}(1), \tilde{C''}(0)\right)$, there hence exists a $q_{lg} \in (0, 1)$ such that $\{1, 1, 1, q_{lg}\}$ is an equilibrium profile. We can derive:

$$\tilde{C''}(1) = 0, \tag{C.10}$$

$$\tilde{C''}(0) = \sigma_{lg}\frac{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg})\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1-\beta(1-\sigma_{lg})(\sigma_{hb}+\sigma_{lb})} = \underline{C}. \tag{C.11}$$

Summarizing the analysis yields the proposition.

C.5 Analysis of General setting

To characterize all equilibria of the general setting, we first focus on pure-strategy equilibria. Appendix C.5.1 uses the implied orderings of type-specific adoption incentives to restrict the set of strategy profiles that are equilibrium candidates. We then separately characterize the specific conditions so that these candidates are supported as equilibria for the blockchain being costlier and cheaper than traditional institutions in Appendix C.5.2 and Appendix C.5.3. Finally, we characterize the mixed-strategy equilibria in Appendix C.5.4.

C.5.1 Pure-strategy equilibrium candidates

To identify the equilibrium candidates, we first establish several helpful observations.

Lemma C1 *Adoption (Non-Adoption) by all firms can be supported in equilibrium if and only if* $C \leq \min\{0, \beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - \gamma\}$ *(*$C \geq -(1-\gamma)\sigma_h$*).*

Proof. Proof: Consider adoption by all firms, i.e., $\{1, 1, 1, 1\}$. Good fit firms are identified with probability 1 and bad fit firms with probability β. On path, hg-firms receive

$1-C$, whereas lg-firms receive $-C$, hb-firms $\beta+(1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}-C$, and lb-firms $(1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}-C$. If low-value firms do not adopt, they receive $(1-\gamma)\cdot p^O$, with p^O being determined by off-path beliefs. The most pessimistic off-path beliefs yield $p^O=0$ so that for lg-types it needs to hold that $-C\geq 0 \iff C\leq 0$. For high-value firms, the payoff outside is $\gamma+(1-\gamma)\cdot p^O$. By the same logic, we hence require $\beta+(1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}-C\geq\gamma \iff C\leq\beta+(1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}-\gamma$.

Consider next non-adoption by all firms, i.e., {0,0,0,0}. On-path, we obtain a payoff of $\gamma+(1-\gamma)\cdot\sigma_h$ for high-value firms, and $(1-\gamma)\sigma_h$ for low-value firms. Deviating and adopting gives an off-path payoff for all firms of p^I-C, as the reach of the blockchain is 0. This is determined by off-path beliefs. It is hence straightforward that non-adoption by all firms can be supported in equilibrium if and only if $(1-\gamma)\sigma_h\geq -C \iff C\geq -(1-\gamma)\sigma_h$. □

Lemma C2 *Any equilibrium in which only low-value types adopt (do not adopt) the blockchain requires $C\leq 0$ ($C\geq 0$).*

Proof. Proof: When only low-value types adopt the blockchain, they receive a payoff of $-C$. By deviating and not adopting, they receive at least a valuation of 0. Thus, $C\leq 0$ is a necessity. Similarly, they receive 0 when only low-value types do not adopt. Adopting the blockchain would at least yield a payoff of $-C$. This gives $C\geq 0$. □

Lemma C3 *Any equilibrium in which only high-value types adopt the blockchain requires $C>0$. Any equilibrium in which only high-value types do not adopt requires $C<0$.*

Proof. Proof: Consider first a conjectured equilibrium in which only high-value types adopt. Low-value types could obtain $1-C$ by adopting. For $C\leq 0$, this always dominates non-adoption alternative, which yields $(1-\gamma)p^O<1$ as $p^O<1$.

Consider next a conjectured equilibrium in which only high-value types do not adopt. Low-value types could obtain 1 by not adopting the blockchain. Adopting gives them $\underbrace{(1-\eta^i)\cdot p^I}_{<1} - C$, so $C < 0$ is necessary. □

Using these results and Lemma 4.1, we can substantially restrict the set of equilibrium candidates, accounting for whether adopting the blockchain is relatively cheaper or more costly than relying on traditional institutions. This is summarized in Table C.2.

Table C.2: Equilibrium candidates

Equilibrium Candidate	$C < 0$	$C \geq 0$
{1,1,1,1}	for $C \leq \min\{0, \beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - \gamma\}$, see Lemma C 1	potentially if $C = 0$
{1,1,1,0}	not possible, see Lemma C 2	possible
{1,1,0,1}	not possible b/w lb and lg as $\rho > 0$ and $p^I > 0$, see Lemma 4.1	
{1,0,1,1}	possible	not possible, see Lemma C 3
{0,1,1,1}	not possible b/w hg and hb as $\rho > 0$ and $p^I < 1$, see Lemma 4.1	
{1,1,0,0}	not possible, see Lemma C 2	possible
{1,0,1,0}	possible	
{0,1,1,0}	not possible b/w hg and hb as $\rho > 0$ and $p^I < 1$, see Lemma 4.1	
{1,0,0,1}	not possible b/w lb and lg as $\rho > 0$ and $p^I > 0$, see Lemma 4.1	
{0,0,1,1}	possible	not possible, see Lemma C 2
{0,1,0,1}	not possible b/w hg and hb as $\rho > 0$ and $p^I < 1$, see Lemma 4.1	
{1,0,0,0}	not possible, see Lemma C 3	possible
{0,1,0,0}	not possible, see Lemma C 3	possible
{0,0,1,0}	possible	not possible, see Lemma C 2
{0,0,0,1}	possible	not possible, see Lemma C 2
{0,0,0,0}	possible for $C \geq -(1-\gamma)\sigma_h$, see Lemma C 1	possible always, see Lemma C 1

Having characterized the equilibrium candidates, we proceed by separately characterizing the specific parameter constellations supporting respective candidates as equilibria for $C \geq 0$, i.e., the blockchain being more costly than traditional institutions, and for $C < 0$, i.e. the blockchain being cheaper.

C.5.2 Pure-strategy equilibria for $C \geq 0$

For now, we consider $C \geq 0$. Given Table C.2, we restrict our attention to the pure strategy equilibrium candidates {1,1,0,0}, {1,0,1,0} and {1,1,1,0}, as well as the knife-edge candidates {1,0,0,0} and {0,1,0,0}. {0,0,0,0} is always sustainable in equilibrium irrespective of γ and $C \geq 0$, while the condition for {1,1,1,1} follows immediately from Lemma C 1. We proceed by analyzing each candidate individually below. Throughout, we derive constraints on the combination of C and γ given the other fundamentals σ_θ and β such that a given candidate can be supported in equilibrium.

{1,1,0,0} If this constitutes an equilibrium, payoffs are given by $1 - C$ for high-value types, and 0 for low-value types. Both high-value types face the same deviation incentives as the detection probability outside the blockchain is independent of the fit; the payoffs from deviating and not adopting would be γ. We hence require $1 - C \geq \gamma \iff C \leq 1 - \gamma$.

Between the low-value types, the lb-type faces a lower detection (and hence higher pooling) probability than the lg-type upon joining the blockchain. To deter adoption by this type, we require $0 \geq (1 - \beta\sigma_h) \cdot 1 - C \iff C \geq 1 - \beta\sigma_h$. This is independent of γ.

The region where {1,1,0,0} can be supported in equilibrium is hence given by a triangle in the γ-C-space. The upper left end of the triangle is at $\gamma = 0$, $C = 1$.

{1,1,1,0} Consider first the on-path payoffs. The lg-type receives 0 as he is identified by the adoption decision. Within the blockchain, we have $\rho = 1 - \sigma_{lg}$ and

$$p^I = \frac{(1-\rho)\sigma_{hg} + (1-\rho\beta)\sigma_{hb}}{(1-\rho)\sigma_{hg} + (1-\rho\beta)(\sigma_{hb} + \sigma_{lb})} = \frac{\sigma_{lg}\sigma_{hg} + (1-\beta+\beta\sigma_{lg})\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1-\beta+\beta\sigma_{lg})(\sigma_{hb}+\sigma_{lb})} \qquad \text{(C.12)}$$

and

$$\begin{aligned} \pi_{hg} &= (1-\sigma_{lg}) + \sigma_{lg}p^I - C \\ \pi_{hb} &= (1-\sigma_{lg})\beta + (1-\beta+\beta\sigma_{lg})p^I - C \\ \pi_{lb} &= (1-\beta+\beta\sigma_{lg})p^I - C. \end{aligned} \qquad \text{(C.13)}$$

We know that $\Delta_{hg} \geq \Delta_{hb}$ so that we need to consider three possible deviations.

(a) hb-types not adopting the blockchain. This requires $\pi_{hb} \geq \gamma$. Clearly, as $\pi_{hb} \leq 1 - C$ (due to $p^I < 1$), this constraint gives a tighter upper bound on C than the bound for the {1,1,0,0} equilibrium. We obtain

$$(1-\sigma_{lg})\beta + (1-\beta+\beta\sigma_{lg})p^I - C \geq \gamma$$

$$\iff C \leq (1-\sigma_{lg})\beta + (1-\beta+\beta\sigma_{lg})p^I - \gamma \equiv \tilde{C}_{hb}(\gamma). \tag{C.14}$$

(b) lb-types not adopting the blockchain. If they don't adopt, they receive 0. Deterring this requires $(1-\beta+\beta\sigma_{lg})p^I - C \geq 0 \iff C \leq (1-\beta+\beta\sigma_{lg})p^I \equiv \tilde{C}_{lb}$. Note that this upper bound lies strictly below the lower bound on C in the {1,1,0,0} equilibrium. This is because that lower bound is given by

$$\begin{aligned} 1-\beta\sigma_h &= 1-\beta(1-\sigma_l) \\ &= 1-\beta+\beta\sigma_{lg}+\beta\sigma_{lb} \\ &> 1-\beta+\beta\sigma_{lg} \\ &> (1-\beta+\beta\sigma_{lg})\cdot p^I. \end{aligned} \tag{C.15}$$

(c) lg-types adopting the blockchain. If they adopt, they receive $\sigma_{lg}p^I - C$, so that we require $C \geq \sigma_{lg}p^I \equiv \tilde{C}_{lg}$ to deter this. Note that $\tilde{C}_{lg} < \tilde{C}_{lb}$ due to $\sigma_{lg} < 1$. Plugging in for p^I, we get

$$\tilde{C}_{lg} = \sigma_{lg}\frac{\sigma_{lg}\sigma_{hg} + (1-\beta+\beta\sigma_{lg})\sigma_{hb}}{\sigma_{lg}\sigma_{hg} + (1-\beta+\beta\sigma_{lg})(\sigma_{hb}+\sigma_{lb})}.$$

We have hence characterized the region such that {1,1,1,0} can be sustained. This represents a trapezoid in the γ-C-space which lies strictly below the triangle characterizing the {1,1,0,0} equilibrium region.

{1,0,1,0} First, note that in this candidate equilibrium, $\hat{\rho} = \sigma_{hg} + \sigma_{lb}$, $\hat{p}^O = \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}}$ and $\hat{p}^I = \frac{(1-\sigma_{hg}-\sigma_{lb})\sigma_{hg}}{(1-\sigma_{hg}-\sigma_{lb})\sigma_{hg}+(1-\beta(\sigma_{hg}+\sigma_{lb}))\sigma_{lb}} = \frac{(1-\sigma_{hg}-\sigma_{lb})\sigma_{hg}}{(\sigma_{hg}+\sigma_{lb})(1-\sigma_{hg}-\beta\sigma_{lb})}$.

The on-path payoffs are given by:

$$\begin{aligned}\pi_{hg} &= (\sigma_{hg} + \sigma_{lb}) + (1 - \sigma_{hg} - \sigma_{lb})p^I - C,\\ \pi_{hb} &= \gamma + (1-\gamma)p^O,\\ \pi_{lb} &= (1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I - C,\\ \pi_{lg} &= (1-\gamma)p^O.\end{aligned}$$

We need to consider deviations by all four types.

(a) hg-types not adopting. They would receive a payoff of $\gamma + (1-\gamma)p^O$. So we require that:

$$\begin{aligned}&(\sigma_{hg} + \sigma_{lb}) + (1 - \sigma_{hg} - \sigma_{lb})p^I - C \geq \gamma + (1-\gamma)p^O\\ \iff &C \leq \left[(\sigma_{hg} + \sigma_{lb}) + (1 - \sigma_{hg} - \sigma_{lb})p^I\right] - p^O - (1-p^O)\gamma \equiv \hat{C}_{hg}(\gamma) \quad \text{(C.16)}\end{aligned}$$

This gives an upper bound on C and is a linear constraint decreasing in γ.

(b) hb-types adopting. They would receive $\beta(\sigma_{hg} + \sigma_{lb}) + (1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I - C$, so we require:

$$\begin{aligned}&\gamma + (1-\gamma)p^O \geq \beta(\sigma_{hg} + \sigma_{lb}) + (1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I - C\\ \iff &C \geq \left[\beta(\sigma_{hg} + \sigma_{lb}) + (1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I\right] - p^O - (1-p^O)\gamma \equiv \hat{C}_{hb}(\gamma). \quad \text{(C.17)}\end{aligned}$$

This gives a lower bound on C and is a linear constraint decreasing in γ. Note that this constraint has the same slope and lies strictly below $\hat{C}_{hg}(\gamma)$.

(c) lb-types not adopting. They would receive a payoff of $(1-\gamma)p^O$, so we require that:

$$\begin{aligned}&(1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I - C \geq (1-\gamma)p^O\\ \iff &C \leq (1 - \beta(\sigma_{hg} + \sigma_{lb}))p^I - (1-\gamma)p^O \equiv \hat{C}_{lb}(\gamma). \quad \text{(C.18)}\end{aligned}$$

This gives an upper bound on C and is a linear constraint increasing in γ.

(d) lg-types adopting. They would receive a payoff of $(1-(\sigma_{hg}+\sigma_{lb}))p^I - C$, so we require that:

$$
\begin{aligned}
& (1-\gamma)p^O \geq (1-(\sigma_{hg}+\sigma_{lb}))p^I - C \\
\iff \ & C \geq (1-(\sigma_{hg}+\sigma_{lb}))p^I - (1-\gamma)p^O \equiv \hat{C}_{lg}(\gamma). \qquad \text{(C.19)}
\end{aligned}
$$

Overall, this characterizes the region such that {1,0,1,0} can be sustained in equilibrium. So far, we have not imposed $C \geq 0$; it is always non-empty when allowing for both $C \geq 0$ and $C \leq 0$. To check whether this is an equilibrium for $C \geq 0$, note that the highest C at which this can be supported obtains for γ such that $\hat{C}_{lb}$ and $\hat{C}_{hg}$ intersect. This is given by $\gamma = \hat{\rho} - \hat{\rho}(1-\beta)p^I$. Plugging in, we obtain:

$$
\gamma = \frac{(1-\sigma_{hg})\beta\sigma_{hg} + (1-2\beta\sigma_{hg})\sigma_{lb} - \beta\sigma_{lb}^2}{1-\sigma_{hg}-\beta\sigma_{lb}} \qquad \text{(C.20)}
$$

and thus as highest feasible C:

$$
\hat{C}^{max} = \frac{(1-\beta(\sigma_{hg}+\sigma_{lb}))(\sigma_{hg}\sigma_{lg} - \sigma_{hb}\sigma_{lb})}{(\sigma_{hg}+\sigma_{lb})(1-\sigma_{hg}-\beta\sigma_{lb})}. \qquad \text{(C.21)}
$$

Observe that $\hat{C}^{max} > 0 \iff \sigma_{hg}\sigma_{lg} > \sigma_{hb}\sigma_{lb}$. If this is violated, {1,0,1,0} cannot be sustained for positive C, irrespective of γ.

Finally, it can be established that the region supporting this equilibrium is disjoint from the one supporting {1,1,0,0}, but may overlap with {1,1,1,0} and even extend beyond it, i.e. be sustainable for γ-C-combinations which lie above the constraint given by $\tilde{C}_{hb}$.[1]

[1] We establish this by showing that the upper bound on the {1,0,1,0}-region lies below the upper bound of the {1,1,1,0}-region as given by $\tilde{C}_{lb}$. This holds as (i) the lowest point of the region supporting {1,0,1,0} lies below the lower bound on {1,1,1,0}, and (ii) the difference between the lowest C and highest C in the {1,0,1,0}-region is lower than the difference between the lower and upper bound of the {1,1,1,0}-region. The detailed derivations are cumbersome and not very instructive. We thus omit them for brevity. They are available upon request, as is a Mathematica file verifying them.

<u>*{1,0,0,0}*</u> Note that only hg-types join which implies $p^I = 1$. Hence, $\Delta_{hg} = \Delta_{hb}$ (see the proof of Lemma 4.1). Both high-value firms hence need to be indifferent between adopting and not adopting the blockchain, which implies that:

$$\Delta_{hg} = \Delta_{hb} = 0 \iff 1 - C = \gamma + (1-\gamma)p^O \iff C = \left(1 - \frac{\sigma_{hb}}{1-\sigma_{hg}}\right) \cdot (1-\gamma), \quad \text{(C.22)}$$

where we used $p^O = \frac{\sigma_{hb}}{1-\sigma_{hg}}$. Amongst low-value types, lb-types have a stronger incentive to deviate and adopt the blockchain due to the lower detection probability. Given $\rho = \sigma_{hg}$, we hence require:

$$(1-\gamma)\frac{\sigma_{hb}}{1-\sigma_{hg}} \geq (1 - \beta\sigma_{hg}) - C \iff C \geq 1 - \beta\sigma_{hg} - (1-\gamma)\frac{\sigma_{hb}}{1-\sigma_{hg}}. \quad \text{(C.23)}$$

The two conditions are compatible if and only if $\gamma \leq \beta\sigma_{hg}$.

<u>*{0,1,0,0}*</u> As only hb-types join, we have $p^I = 1$ and thus $\Delta_{hg} = \Delta_{hb}$. This implies:

$$\Delta_{hg} = \Delta_{hb} = 0 \iff 1 - C = \gamma + (1-\gamma)p^O \iff C = \left(1 - \frac{\sigma_{hg}}{1-\sigma_{hb}}\right) \cdot (1-\gamma), \quad \text{(C.24)}$$

where we used $p^O = \frac{\sigma_{hg}}{1-\sigma_{hb}}$. To deter low-value types (specifically lb-types) from deviating, we require:

$$(1-\gamma)\frac{\sigma_{hg}}{1-\sigma_{hb}} \geq (1 - \beta\sigma_{hb}) - C \iff C \geq 1 - \beta\sigma_{hb} - (1-\gamma)\frac{\sigma_{hg}}{1-\sigma_{hb}}. \quad \text{(C.25)}$$

The two conditions are compatible if and only if $\gamma \leq \beta\sigma_{hb}$. The following Proposition summarizes the analysis.

Proposition C1 (Pure Strategy Equilibria for $C \geq 0$) *The following pure strategy profiles can be supported in equilibrium depending on the adoption cost $C \geq 0$ and the degree of outside information generation γ.*

(i) There exist disjoint regions in the γ-C-space such that {1,1,0,0} and {1,1,1,0} can be supported in equilibrium. For γ for which both equilibria exist for differential C, {1,1,0,0} requires a higher cost range than {1,1,1,0}.

(ii) If $\frac{\sigma_{hb}\sigma_{lb}}{\sigma_{hg}\sigma_{lg}} < 1$, there exists a region in the γ-C-space such that {1,0,1,0} can be supported in equilibrium. This region is disjoint from the {1,1,0,0}-region, but may overlap with the {1,1,1,0}-region.

(iii) There exist (γ,C)-combinations such that {1,0,0,0} and {0,1,0,0} can be supported in equilibrium. In the γ-C-space, these combinations represent lines which are either identical ($\sigma_{hg} = \sigma_{hb}$) or do not cross.

(iv) Irrespective of γ, {0,0,0,0} is sustainable in equilibrium for all $C \geq 0$.

(v) For $C = 0$ and $\gamma < \beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}$, {1,1,1,1} can be supported in equilibrium.

C.5.3 Pure-strategy equilibria for $C \leq 0$

Consider now $C < 0$ and denote $B \equiv -C$ to ease the exposition. The conditions for {0,0,0,0} and {1,1,1,1} follow immediately from Lemma C 1. In addition to these full (non-)adoption equilibria, we only need to consider the following pure strategy profiles:

$$\{1,0,1,1\}\,,\ \{1,0,1,0\}\,,\ \{0,0,1,1\}\,,\ \{0,0,1,0\}\,,\ \{0,0,0,1\}$$

We proceed through these equilibrium candidates one by one.

{0,0,1,1} Payoffs in this case are given by B for low-value types, and 1 for high-value types. Both low-value types face the same deviation incentives as the detection probability outside the blockchain is independent of the fit. The payoff from deviating and not adopting would be $(1-\gamma)\cdot 1$. Hence, the condition from the low-value types determining the existence of this equilibrium is $B \geq (1-\gamma)$.

Due to $\Delta_{hg} \geq \Delta_{hb}$, we only need to consider possible deviations by hg-types. They would get $\rho + B$ upon adopting, where $\rho = \sigma_l$. So we also require $\sigma_l + B \leq 1 \iff B \leq 1 - \sigma_l$. Note that this is independent of γ.

In the γ-B-space, the region supporting {0,0,1,1} as an equilibrium is thus given by a triangle, with the lower right end of the triangle at $\gamma = 1, B = 0$.

{1,0,1,1} First, consider the on-path payoffs. hb-types receive 1. Inside the blockchain, the reach is given by $\tilde{\rho} = (1 - \sigma_{hb})$. Hence,

$$\tilde{p}^I = \frac{\sigma_{hb}\sigma_{hg}}{\sigma_{hb}(\sigma_{hg} + \sigma_{lg}) + (1 - \beta + \beta\sigma_{hb})\sigma_{lb}}. \tag{C.26}$$

Payoffs on the equilibrium path are therefore given by:

$$\begin{aligned} \pi_{hg} &= (1 - \sigma_{hb}) + \sigma_{hb}\tilde{p}^I + B, \\ \pi_{lg} &= \sigma_{hb}\tilde{p}^I + B, \\ \pi_{lb} &= (\beta\sigma_{hb} + (1 - \beta))\tilde{p}^I + B. \end{aligned} \tag{C.27}$$

As $\Delta_{lb} \geq \Delta_{lg}$, there are three deviations we need to consider.

(a) hb-types adopting the blockchain. The hb-type would obtain $\tilde{\rho}\beta + (1 - \tilde{\rho}\beta)\tilde{p}^I + B = (1 - \sigma_{hb})\beta + (\beta\sigma_{hb} + (1 - \beta))\tilde{p}^I + B$. To deter this deviation, we hence require:

$$B \leq 1 - (1 - \sigma_{hb})\beta + (\beta\sigma_{hb} + (1 - \beta))\tilde{p}^I \equiv \tilde{B}_{hb}. \tag{C.28}$$

We can plug in for $\tilde{p}^I$ and simplify. This gives:

$$\tilde{B}_{hb} = (1 - (1 - \sigma_{hb})\beta)\frac{\sigma_{hb}\sigma_{lg} + (1 - (1 - \sigma_{hb})\beta)\sigma_{lb}}{\sigma_{hb}(\sigma_{hg} + \sigma_{lg}) + (1 - (1 - \sigma_{hb})\beta)\sigma_{lb}}. \tag{C.29}$$

Notably, $\tilde{B}_{hb}$ can lie both above or below the upper bound for the {0,0,1,1} equilibrium region given by $1 - \sigma_l$. To see this, consider the parametrization given by $\sigma_{hg} = \sigma_{lg} = 0.2$, $\sigma_{hb} = \sigma_{lb} = 0.3$ and contrast $\beta = \frac{5}{6}$ and $\beta = \frac{2}{6}$.

(b) hg-types not adopting the blockchain. This would give a payoff of 1, so that we require:

$$B \geq 1 - \left[(1-\sigma_{hb}) + \sigma_{hb}\tilde{p}^I\right] \equiv \tilde{B}_{hg} > 0. \tag{C.30}$$

Clearly, $\tilde{B}_{hg} < \tilde{B}_{hb}$ due to $\Delta_{hg} > \Delta_{hb}$ from Lemma 4.1.

(c) lg-types not adopting the blockchain. This would yield $(1-\gamma)\tilde{p}^O$. To deter this deviation, we hence require:

$$B \geq 1 - \gamma - \sigma_{hb}\tilde{p}^I \equiv \tilde{B}_{lg}(\gamma). \tag{C.31}$$

It immediately follows that $\tilde{B}_{lg}(\gamma) < 1-\gamma$, i.e. that this constraint is more permissible regarding B than the constraint required to sustain the $\{0,0,1,1\}$-equilibrium. Thus, this equilibrium is sustainable for some γ-B-combinations where the other one is not, even if $\tilde{B}_{hb}$ lies below the constraint for the {0,0,1,1} equilibrium.

{1,0,1,0} This analysis mirrors the one for $C \geq 0$ for this equilibrium candidate, see Appendix C.5.2. The constraints are identical to the ones obtained there, with $B = -C$. To summarize, we require:

$$\begin{aligned}
B &\geq \gamma + (1-\gamma)\hat{p}^O - \left[(\sigma_{hg}+\sigma_{lb}) + (1-\sigma_{hg}-\sigma_{lb})\hat{p}^I\right] \equiv \hat{B}_{hg}(\gamma) && \text{(C.32)}\\
B &\leq \gamma + (1-\gamma)\hat{p}^O - \left[\beta(\sigma_{hg}+\sigma_{lb}) + (1-\beta(\sigma_{hg}+\sigma_{lb}))\hat{p}^I\right] \equiv \hat{B}_{hb}(\gamma) && \text{(C.33)}\\
B &\geq (1-\gamma)\hat{p}^O - (1-\beta(\sigma_{hg}+\sigma_{lb}))\hat{p}^I \equiv \hat{B}_{lb}(\gamma) && \text{(C.34)}\\
B &\leq (1-\gamma)\hat{p}^O - (1-(\sigma_{hg}+\sigma_{lb}))\hat{p}^I \equiv \hat{B}_{lg}. && \text{(C.35)}
\end{aligned}$$

This does not yet impose $B \geq 0$. To address this, note that the maximal B, denoted $\hat{B}^{max}$, such that this is sustainable materializes at the intersection of $\hat{B}_{lg}$ and $\hat{B}_{hb}$. This obtains at $\hat{\gamma} = \rho\beta + \rho\hat{p}^I(1-\beta)$. Plugging in, we obtain:

$$\hat{\gamma} = \frac{\sigma_{hg}\left(1-\sigma_{lb}\left(1+\beta^2\right)\right) + (1-\beta\sigma_{lb})\beta\sigma_{lb} - \sigma_{hg}^2}{1-\sigma_{hg}-\beta\sigma_{lb}}, \tag{C.36}$$

which in turn implies:

$$\hat{B}^{max} = \frac{\sigma_{lb}\sigma_{hb}(1-\beta(\sigma_{hg}+\sigma_{lb}))^2 - \sigma_{hg}\sigma_{lg}(1-(\sigma_{hg}+\sigma_{lb}))^2}{(1-\sigma_{hg}-\beta\sigma_{lb})(\sigma_{hb}+\sigma_{lg})(\sigma_{hg}+\sigma_{lb})} \tag{C.37}$$

Hence, we have that:

$$\hat{B}^{max} > 0 \iff \frac{\sigma_{lb}\sigma_{hb}}{\sigma_{hg}\sigma_{lg}} > \frac{(1-(\sigma_{hg}+\sigma_{lb}))^2}{(1-\beta(\sigma_{hg}+\sigma_{lb}))^2}. \tag{C.38}$$

Finally, we establish that the {1,0,1,0} equilibrium region is disjoint from the other two pure strategy equilibria characterized above. For this, it is sufficient to show that:

$$\gamma = \sigma_{hg} + \sigma_{lb} \implies \hat{B}_{lg}(\gamma) < \tilde{B}_{lg}(\gamma). \tag{C.39}$$

This is because $\tilde{B}_{lg}$ characterizes the most permissive constraint of {0,0,1,1} and {1,0,1,1}, while $\tilde{B}'_{lg}(\gamma) = -1 < -\hat{p}^O = \hat{B}'_{lg}(\gamma)$. As $\gamma = \sigma_{hg} + \sigma_{lb}$ characterizes the highest γ such that {1,0,1,0} can be supported, this is sufficient for disjointness.

We hence need to compare:

$$\tilde{B}_{lg}(\sigma_{hg}+\sigma_{lb}) = 1 - \sigma_{hg} - \sigma_{lb} - \sigma_{hb}\tilde{p}^I, \tag{C.40}$$

with:

$$\hat{B}_{lg}(\sigma_{hg}+\sigma_{lb}) = (1-\sigma_{hg}-\sigma_{lb})\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}} - (1-(\sigma_{hg}+\sigma_{lb}))\hat{p}^I. \tag{C.41}$$

To do this, observe the following:

(i) $1-\sigma_{hg}-\sigma_{lb} > (1-\sigma_{hg}-\sigma_{lb})\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}}$ as $\hat{p}^O = \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}} < 1$

(ii) $\sigma_{hb} < 1-(\sigma_{hg}+\sigma_{lb}) = \sigma_{hb}+\sigma_{lg}$

(iii) $\tilde{p}^I < \hat{p}^I$. Given $\hat{\rho} < \tilde{\rho}$, it follows that:

$$\hat{p}^I = \frac{(1-\hat{\rho})\sigma_{hg}}{(1-\hat{\rho})\sigma_{hg} + (1-\beta\hat{\rho})\sigma_{lb}} > \frac{(1-\tilde{\rho})\sigma_{hg}}{(1-\tilde{\rho})\sigma_{hg} + (1-\beta\tilde{\rho})\sigma_{lb}}, \tag{C.42}$$

and thus:

$$\hat{p}^I > \frac{(1-\tilde{\rho})\sigma_{hg}}{(1-\tilde{\rho})\sigma_{hg} + (1-\beta\tilde{\rho})\sigma_{lb}} > \frac{(1-\tilde{\rho})\sigma_{hg}}{(1-\tilde{\rho})\sigma_{hg} + (1-\beta\tilde{\rho})\sigma_{lb} + (1-\tilde{\rho})\sigma_{lg}} = \tilde{p}^I. \tag{C.43}$$

Combining (i), (ii), and (iii) yields $\hat{B}_{lg}(\sigma_{hg} + \sigma_{lb}) < \tilde{B}_{lg}(\sigma_{hg} + \sigma_{lb})$.

{0,0,0,1} In this case, only lg-types join the blockchain and obtain a payoff of 0. This payoff would also be achieved by lb-types joining, and therefore we require $\Delta_{lg} = \Delta_{lb} = 0$. With $p^O = \frac{\sigma_{hg}+\sigma_{hb}}{1-\sigma_{lg}}$, this gives:

$$\Delta_{lg} = \Delta_{lb} = 0 \iff B = (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lg}}. \tag{C.44}$$

In addition, hg-types must prefer to not adopt (hb-types then are also deterred).

$$\sigma_{lg} + B \leq \gamma + (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lg}} \iff B \leq \gamma + (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lg}} - \sigma_{lg}. \tag{C.45}$$

The two conditions are compatible iff $\gamma \geq \sigma_{lg}$.

{0,0,1,0} As before, we have $\Delta_{lg} = \Delta_{lb} = 0$. With $p^O = \frac{\sigma_{hg}+\sigma_{hb}}{1-\sigma_{lb}}$, this gives:

$$\Delta_{lg} = \Delta_{lb} = 0 \iff B = (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lb}}. \tag{C.46}$$

To deter hg-types, it also needs to hold that:

$$\sigma_{lb} + B \leq \gamma + (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lb}} \iff B \leq \gamma + (1-\gamma)\frac{\sigma_{hg} + \sigma_{hb}}{1-\sigma_{lb}} - \sigma_{lb}. \tag{C.47}$$

The two conditions are compatible iff $\gamma \geq \sigma_{lb}$. The following proposition summarizes the analysis.

Proposition C2 *The following pure strategy profiles can be supported in equilibrium depending on the adoption benefits $B \geq 0$ and the degree of outside information generation γ.*

(i) There exist regions in the γ-B-space such that {1,0,1,1} and {0,0,1,1} can be supported in equilibrium. These regions always overlap. When both equilibria coexist, {1,0,1,1} pareto-dominates from a firm's perspective. There always exist (γ, B)-combinations such that {0,0,1,1} ({1,0,1,1}) can be supported in equilibrium while {1,0,1,1} ({0,0,1,1}) cannot.

(ii) If $\frac{\sigma_{lb}\sigma_{hb}}{\sigma_{hg}\sigma_{lg}} > \frac{(1-(\sigma_{hg}+\sigma_{lb}))^2}{(1-\beta(\sigma_{hg}+\sigma_{lb}))^2}$, there exists a region in the γ-B-space such that {1,0,1,0} can be supported in equilibrium. This region is disjoint from the {0,0,1,1} and {1,0,1,1} regions.

(iii) There exist (γ,B)-combinations such that {0,0,1,0} and {0,0,0,1} can be supported in equilibrium. In the γ-B-space, these combinations represent lines which are either identical ($\sigma_{lg} = \sigma_{lb}$) or do not cross.

(iv) {1,1,1,1} is sustainable in equilibrium for $B \geq \max\left\{0, \gamma - \left(\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}\right)\right\}$.

(v) For (γ, B) such that $B \leq (1-\gamma)\sigma_h$, {0,0,0,0} is sustainable in equilibrium.

C.5.4 Mixed strategy equilibria

To characterize the mixed-strategy equilibria, we proceed as in the characterization of pure strategy equilibria. We first reduce the set of equilibrium candidates by exploiting the ordering of the incentives to join the blockchain across the different fit-value-types. We then characterize the specific conditions under which the remaining equilibrium types are sustainable (in the sense of the parameter constellations supporting the respective equilibrium). In general, note that the mixed-strategy equilibria "fill in the gaps" between pure-strategy equilibria in the sense that borders of the regions under which a given mixed-strategy equilibrium candidate can be supported for varying values of the mixing probability coincide with the borders of the respective limiting pure-strategy equilibrium.

Equilibrium candidates To characterize the possible equilibrium candidates, we proceed as follows. We start by setting a particular type $\theta \in \{hg, hb, lb, lg\}$ to be indifferent. We then exploit this indifference ($\Delta_\theta = 0$) together with the ordering given by Lemma 4.1 and the comparisons of joining incentives in (4.9), (4.10), (4.11) and (4.12) to assess which combinations of pure- and mixed-strategies of the remaining types we need to consider.

hg-type mixes

Suppose that the hg-type mixes, that is, joins the blockchain with probability $q_{hg} \in (0,1)$. This requires $\Delta_{hg} = 0$. Given Lemma 4.1, there are hence two cases. If $p^I = 1$, $\Delta_{hg} = \Delta_{hb}$ and the hb-type is also indifferent, where $p^I = 1$ requires that $q_{lb} = q_{lg} = 0$. In contrast, if $p^I < 1$, we know that $\Delta_{hg} > \Delta_{hb}$ and hence that $q_{hb} = 0$ is required. At the same time, $q_{hg} > 0$ implies $p^I > 0$ and hence that $\Delta_{lb} > \Delta_{lg}$. It follows that at most one of the low-value types can mix. Overall, the following equilibrium candidates need to be considered. Note that in lising the candidates, we explicitly differentiate between "strict" mixed strategies, $q_\theta \in (0,1)$, and pure strategies.

$$\{q_{hg}, 1, 0, 0\}, \{q_{hg}, 0, 0, 0\}, \{q_{hg}, q_{hb}, 0, 0\}, \{q_{hg}, 0, q_{lb}, 0\}, \{q_{hg}, 0, 1, 0\}, \{q_{hg}, 0, 1, 1\}, \{q_{hg}, 0, 1, q_{lg}\} \tag{C.48}$$

hb-type mixes

Suppose next that the hb-type mixes, that is, joins the blockchain with probability $q_{hb} \in (0,1)$. The case where both hg-types and hb-types are indifferent was already covered. It requires that no low-value types adopt the blockchain and admits additional candidates $\{1, q_{hb}, 0, 0\}$ and $\{0, q_{hb}, 0, 0\}$. Otherwise, the presence of low-value types in the blockchain implies $0 < p^I < 1$, and there is a strict ordering of joining incentives for low-value firms due to $\Delta_{lb} > \Delta_{lg}$. Thus, at most one low-value type can mix. The additional equilibrium candidates we need to consider are hence as follows:

$$\{0, q_{hb}, 0, 0\}, \{1, q_{hb}, 0, 0\}, \{1, q_{hb}, 1, 0\}, \{1, q_{hb}, 1, 1\}, \{1, q_{hb}, q_{lb}, 0\}, \{1, q_{hb}, 1, q_{lg}\}. \tag{C.49}$$

lb-type mixes

Suppose next that the lb-type mixes, that is, joins the blockchain with probability $q_{lb} \in (0, 1)$. If $p^I = 0$, we have $\Delta_{lb} = \Delta_{lg}$. In contrast, if $p^I > 0$, then $\Delta_{lb} > \Delta_{lg}$ which implies that the lg-type does not join the blockchain. As there are some low-value types in the blockchain, we have $p^I < 1$ and thus $\Delta_{hg} > \Delta_{lb}$ so that at most one of the high-value types can mix. We therefore obtain the following additional equilibrium candidates:

$$\{0, 0, q_{lb}, 1\}, \{0, 0, q_{lb}, 0\}, \{0, 0, q_{lb}, q_{lg}\}, \{1, 1, q_{lb}, 0\}, \{1, 0, q_{lb}, 0\}. \tag{C.50}$$

lg-type mixes

The case where $p^I = 0$ and hence $\Delta_{lg} = \Delta_{lb}$ has been covered already and admits $\{0, 0, 0, q_{lg}\}$ and $\{0, 0, 1, q_{lg}\}$ as candidates. Otherwise, we have $p^I > 0$ where $p^I < 1$ immediately follows as some low-value firms adopt the blockchain. This implies that $\Delta_{lb} > \Delta_{lg}$ and $\Delta_{hg} > \Delta_{hb}$. Note that the case where either hg-types or hb-types mix are already covered by the previous cases. As such, the only added equilibrium candidates are as follows:

$$\{0, 0, 0, q_{lg}\}, \{0, 0, 1, q_{lg}\}, \{1, 1, 1, q_{lg}\}, \{1, 0, 1, q_{lg}\}. \tag{C.51}$$

Equilibrium characterizations Throughout, we characterize the region in the γ-C-space which supports a given equilibrium candidate as an equilibrium. We start by considering the equilibrium candidates, which feature strict mixing by two types.

<u>*Candidate* $\{q_{hg}, q_{hb}, 0, 0\}$</u> In this equilibrium candidate, we have $p^I = 1$ and $\Delta_{hg} = \Delta_{hb}$. As both high-value types need to be indifferent, $\Delta_{hg} = \Delta_{hb} = C$ pins down the relationship between C and γ required to sustain this equilibrium. Specifically, we require that (γ, C) satisfies:

$$C = \frac{(1-\gamma)(\sigma_{lb} + \sigma_{lg})}{\sigma_{lb} + \sigma_{lg} + (1-q_{hg})\sigma_{hg} + (1-q_{hb})\sigma_{lb}} \leq 1. \tag{C.52}$$

This is a line in the γ-C-space. Note that we in addition require that lb-types do not have an incentive to join the blockchain, as this also ensures that lg-types do not wish to join due to $p^I > 0$ and hence $\Delta_{lb} > \Delta_{lg}$. For this, we in turn need $\Delta_{lb} \leq C = \Delta_{hb}$. From (4.10) we know that this is satisfied for $\gamma \leq \rho\beta$, i.e. $\gamma \leq \beta(q_{hg}\sigma_{hg} + q_{hb}\sigma_{hb})$. As such, for any given (q_{hg}, q_{hb}), any $\gamma \in [0, \beta(q_{hg}\sigma_{hg} + q_{hb}\sigma_{hb})]$ admits a unique C such that $\{q_{hg}, q_{hb}, 0, 0\}$ is an equilibrium for this γ and C. Note that the same characterization obtains for $\{1, q_{hb}, 0, 0\}$, $\{0, q_{hb}, 0, 0\}$, $\{q_{hg}, 1, 0, 0\}$ and $\{q_{hg}, 0, 0, 0\}$ as special cases, as all these equilibrium candidates feature $p^I = 1$ and hence $\Delta_{hg} = \Delta_{hb}$.

Note that in the limit for $q_{hg} = q_{hb} = 1$, the cost condition (C.52) simplifies to $C = 1 - \gamma$, which is exactly the condition that high-value types do not prefer to rely traditional institutions in the pure-strategy equilibrium $\{1, 1, 0, 0\}$. Similarly, we can plug in $C = 1 - \gamma$ into $\gamma \leq \beta(q_{hg}\sigma_{hg} + q_{hb}\sigma_{hb})$ to obtain the second limiting constraint $C \geq 1 - \beta(\sigma_{hg} + \sigma_{hb})$ as in the characterization of $\{1, 1, 0, 0\}$. Similarly, we get for $q_{hg} = 1, q_{hb} = 0$ that (C.52) simplifies to $C = (1-\gamma)\frac{\sigma_{lb}+\sigma_{lg}}{1-\sigma_{hg}} = (1-\gamma)\left(1 - \frac{\sigma_{hb}}{1-\sigma_{hg}}\right)$ and $\gamma \leq \beta\rho$ to $\gamma \leq \beta\sigma_{hg}$, as in the characterization of $\{1, 0, 0, 0\}$, and for for $q_{hg} = 0, q_{hb} = 1$ that (C.52) simplifies to $C = (1-\gamma)\frac{\sigma_{lb}+\sigma_{lg}}{1-\sigma_{hb}} = (1-\gamma)\left(1 - \frac{\sigma_{hg}}{1-\sigma_{hb}}\right)$ and $\gamma \leq \beta\rho$ to $\gamma \leq \beta\sigma_{hb}$, as in the characterization of $\{0, 1, 0, 0\}$. We do not obtain such a limiting result for $q_{hg} = q_{hb} = 0$ as in this case the associated pooling price within the blockchain would discontinously change as the characterization of $\{0, 0, 0, 0\}$ assumes the most pessimistic beliefs, i.e. $p^I = 0$.

<u>*Candidate* $\{0, 0, q_{lb}, q_{lg}\}$</u> In this equilibrium candidate, we have $p^I = 0$ and $\Delta_{lb} = \Delta_{lg}$. As both low-value types need to be indifferent, $\Delta_{lb} = \Delta_{lg} = C$ pins down the

relationship between C and γ required to sustain this equilibrium. Specifically, we require that (γ, C) satisfies:

$$C = -\frac{(1-\gamma)(\sigma_{hg}+\sigma_{hb})}{\sigma_{hg}+\sigma_{hb}+(1-q_{lb})\sigma_{lb}+(1-q_{lg})\sigma_{lg}}. \tag{C.53}$$

This is a line in the γ-C-space. Note that due to $p^I < 1$, we have $\Delta_{hg} > \Delta_{hb}$. As such, to support this equilibrium, it needs to be the case that $\Delta_{hg} \leq C = \Delta_{lg}$. From (4.9), we know that this requires $\gamma \geq \rho = q_{lb}\sigma_{lb} + q_{lg}\sigma_{lg}$. As such, for any given (q_{lg}, q_{lb}), any $\gamma \in [q_{lg}\sigma_{lg} + q_{lb}\sigma_{lb}, 1]$ admits a unique C such that $\{0, 0, q_{lb}, q_{lg}\}$ is an equilibrium for this γ and C. Note that the same characterization obtains for $\{0, 0, 1, q_{lg}\}, \{0, 0, 0, q_{lg}\}, \{0, 0, q_{lb}, 1\}$ and $\{0, 0, q_{lb}, 0\}$ as special cases, as all these equilibrium candidates feature $p^I = 0$ and hence $\Delta_{lb} = \Delta_{lg}$.

Note that in the limit for $q_{lg} = q_{lb} = 1$, the cost condition (C.53) simplifies to $C = -(1-\gamma)$, which is exactly the condition that low-value types do not prefer to adopt the blockchain in the pure-strategy equilibrium $\{0, 0, 1, 1\}$. Similarly, we can plug in $C = -(1-\gamma) \iff \gamma = 1 + C$ into $\gamma \geq q_{lg}\sigma_{lg} + q_{lb}\sigma_{lb}$ to obtain the second limiting constraint $C \geq -(1 - \sigma_{lg} - \sigma_{lb})$ as in the characterization of $\{0, 0, 1, 1\}$. Similarly, we get for $q_{lb} = 1, q_{lg} = 0$ that (C.53) simplifies to $C = -(1-\gamma)\frac{\sigma_{hg}+\sigma_{hb}}{1-\sigma_{lb}}$ and $\gamma \geq \rho$ to $\gamma \geq \sigma_{lb}$, as in the characterization of $\{0, 0, 1, 0\}$, and for $q_{lb} = 0, q_{lg} = 1$ that (C.53) simplifies to $C = -(1-\gamma)\frac{\sigma_{hg}+\sigma_{hb}}{1-\sigma_{lg}}$ and $\gamma \geq \rho$ to $\gamma \geq \sigma_{lg}$, as in the characterization of $\{0, 0, 0, 1\}$. Finally, for $q_{lb} = q_{lg} = 0$, (C.53) reduces to $C = -(1-\gamma)(\sigma_{hg} + \sigma_{hb})$, which is exactly the necessary and sufficient condition for $\{0, 0, 0, 0\}$ to be supportable as equilibrium ($\gamma \geq 0 = \rho$ is trivially satisfied).

<u>*Candidates* $\{q_{hg}, 0, q_{lb}, 0\}$*,* $\{q_{hg}, 0, 1, q_{lg}\}$*,* $\{1, q_{hb}, q_{lb}, 0\}$ *&* $\{1, q_{hb}, 1, q_{lg}\}$</u> All of these candidates are supported only for a single combination of γ and C. This is because the two indifference restrictions pin down a unique γ for which the respective equilibrium candidate is sustainable, which in turn leads to a unique C. The exact characterizations are straightforwardly obtained from determining ρ, p^I and p^O for the given equilibrium

candidate, and by then equating the relative joining incentives for the indifferent types. For brevity, we omit the detailed derivations.

Having characterized all mixed-strategy equilibria where more than one type is indifferent, we next consider the remaining mixed-strategy equilibrium candidates with a single indifferent type. For all of these equilibrium ranges, it is straightforward to verify that the respective conditions pinning down the parameter relations—in terms of (C, γ)—supporting a given candidate as equilibrium coincide with the borders of the respective limiting pure-strategy equilibrium range. To streamline the exposition, we omit the detailed derivations which verify this for each equilibrium candidate.

Candidate $\{q_{hg}, 0, 1, 0\}$ In this case, we obtain that (γ, C) need to satisfy $\Delta_{hg} = C$, i.e.,

$$C = \frac{(1-\gamma)\sigma_{lg}}{1 - q_{hg}\sigma_{hg} - \sigma_{lb}} - \frac{\sigma_{lb}(1 - q_{hg}\sigma_{hg} - \sigma_{lb})(1 - q_{hg}\beta\sigma_{hg} - \beta\sigma_{lb})}{(q_{hg}\sigma_{hg} + \sigma_{lb})(1 - q_{hg}\sigma_{hg} - \beta\sigma_{lb})}. \tag{C.54}$$

As $0 < p^I < 1$, Lemma 4.1 implies $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$. To support this equilibrium, we hence additionally require that $\Delta_{hg} \geq \Delta_{lg}$ so that lg-types are unwilling to adopt the blockchain, as well as $\Delta_{lb} \geq \Delta_{hg}$ so that lb-types indeed join. The former requirement imposes $\gamma \leq \rho = q_{hg}\sigma_{hg} + \sigma_{lb} \equiv \bar{\gamma}$, see (4.9). From the latter, we can plug into (4.11) to obtain:

$$\gamma \geq \frac{(1 - q_{hg}\sigma_{hg})q_{hg}\beta\sigma_{hg} + (1 - 2q_{hg}\beta\sigma_{hg})\sigma_{lb} - \beta\sigma_{lb}^2}{1 - q_{hg}\sigma_{hg} - \beta\sigma_{lb}} \equiv \underline{\gamma}. \tag{C.55}$$

Note that $\bar{\gamma} \geq \underline{\gamma}$ so that for every q_{hg} and $\gamma \in [\underline{\gamma}, \bar{\gamma}]$ there exists a unique C given by (C.54) so that $\{q_{hg}, 0, 1, 0\}$ is an equilibrium for this (γ, C).

Candidate $\{q_{hg}, 0, 1, 1\}$ In this case, we obtain that $p^O = 0$. As such, we get from $\Delta_{hg} = C$ that C needs to satisfy:

$$C = -(1 - q_{hg}\sigma_{hg} - \sigma_{lb} - \sigma_{lg}) + \frac{q_{hg}\sigma_{hg}(1 - q_{hg}\sigma_{hg} - \sigma_{lb} - \sigma_{lg})^2}{(q_{hg}\sigma_{hg} + \sigma_{lb} + \sigma_{lg})(1 - q_{hg}\sigma_{hg} - \beta\sigma_{lb} - \sigma_{lg})}. \tag{C.56}$$

This is independent of γ as Δ_{hg} does not feature γ for $p^O = 0$. In this equilibrium candidate, we have $0 < p^I < 1$ which ensures $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. Therefore, we only require $\Delta_{lg} \geq \Delta_{hg}$ in addition to (C.56), which requires $\gamma \geq \rho = q_{hg}\sigma_{hg} + \sigma_{lb} + \sigma_{lg}$, see (4.9). For any q_{hg} and such γ, there hence is a unique C characterized by (C.56) so that $\{q_{hg}, 0, 1, 1\}$ is an equilibrium.

Candidate $\{1, q_{hb}, 1, 0\}$ In this case, indifference by hb-types requires $\Delta_{hb} = C$ and hence:

$$\begin{aligned} C &= -\gamma + \beta(q_{hb}\sigma_{hb} + \sigma_{hg} + \sigma_{lb}) - (1-\gamma)\frac{(1-q_{hb})\sigma_{hb}}{1 - q_{hb}\sigma_{hb} - \sigma_{hg} - \sigma_{lb}} \\ &\quad + \frac{(1-\beta(q_{hb}\sigma_{hb} + \sigma_{hg} + \sigma_{lb}))((q_{hb}\sigma_{hb} + \sigma_{hg})(1 - \beta q_{hb}\sigma_{hb} - \sigma_{hg}) - \sigma_{lb}(\sigma_{hg} + \beta q_{hb}\sigma_{hb}))}{(q_{hb}\sigma_{hb} + \sigma_{hg} + \sigma_{lb})(1 - \beta q_{hb}\sigma_{hb} - \sigma_{hg} - \beta\sigma_{lb})} \end{aligned} \tag{C.57}$$

In this equilibrium candidate, we have $0 < p^I < 1$ and hence $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. As such, we require $\Delta_{lb} \geq \Delta_{hb}$ and $\Delta_{lg} \leq \Delta_{hb}$ in addition to (C.57) to support the equilibrium candidate. These conditions in turn translate into $\gamma \geq \rho\beta = \beta(q_{hb}\sigma_{hb} + \sigma_{hg} + \sigma_{lb}) \equiv \underline{\gamma}$, see (4.10), and $\gamma \leq \rho\beta + (1-\beta)\rho p^I$. Plugging in, we obtain:

$$\gamma \leq \beta(q_{hb}\sigma_{hb} + \sigma_{hg} + \sigma_{lb}) + (1-\beta)\frac{(1 - \beta q_{hb}\sigma_{hb} - \sigma_{hg})(q_{hb}\sigma_{hb} + \sigma_{hg}) - \sigma_{lb}(\beta q_{hb}\sigma_{hb} + \sigma_{hg})}{1 - \beta q_{hb}\sigma_{hb} - \beta\sigma_{lb} - \sigma_{hg}} \equiv \bar{\gamma}. \tag{C.58}$$

Note that $\bar{\gamma} \geq \underline{\gamma}$ so that for every q_{hb} and $\gamma \in [\underline{\gamma}, \bar{\gamma}]$ there exists a unique C given by (C.57) so that $\{1, q_{hb}, 1, 0\}$ is an equilibrium for this (γ, C).

Candidate $\{1, q_{hb}, 1, 1\}$ In this case, note that $p^O = 1$. As such, we obtain from $\Delta_{hb} = C$ that C needs to satisfy:

$$\begin{aligned} C &= -\frac{(1 - \beta + (1-q_{hb})\beta\sigma_{hb})\,\sigma_{lb}(1 - q_{hb}\beta - (1-q_{hb})\beta(\sigma_{hg} + \sigma_{lb}))}{(1 - (1-q_{hb})\sigma_{hb})\,((1-\beta q_{hb})\sigma_{hb} + (1-\beta)\sigma_{lb})} \\ &\quad - \frac{(1 - \beta + (1-q_{hb})\beta\sigma_{hb})\left((1-q_{hb})(1 - \sigma_{hg} - (1+\beta)\sigma_{lb})\sigma_{lg} - (1-q_{hb})\sigma_{lg}^2\right)}{(1 - (1-q_{hb})\sigma_{hb})\,((1-\beta q_{hb})\sigma_{hb} + (1-\beta)\sigma_{lb})}. \end{aligned} \tag{C.59}$$

This is independent of γ as Δ_{hb} does not feature γ for $p^O = 1$. In this equilibrium candidate, we have $0 < p^I < 1$ which ensures $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. Therefore, we require in addition to (C.59) that $\Delta_{lg} \geq \Delta_{hb}$ which requires

$\gamma \geq \rho\beta + (1-\beta)\rho p^I$, see (4.12). Plugging in and simplifying yields:

$$\gamma \geq \beta(1-(1-q_{hb})\sigma_{hb})+(1-\beta)\frac{\sigma_{hb}(q_{hb}(1-\beta+(1-q_{hb})\beta q_{hb})+(1-q_{hb})\sigma_{hg})}{1-(\sigma_{hg}+\sigma_{lg})-\beta(q_{hb}\sigma_{hb}+\sigma_{lb})}. \quad \text{(C.60)}$$

For any q_{hb} and such γ, there hence is a unique C characterized by (C.59) so that $\{1, q_{hb}, 1, 1\}$ is an equilibrium.

Candidate $\{1, 1, q_{lb}, 0\}$ Note that in this case we have $p^O = 0$. As such, we get from $C = \Delta_{lb}$ that C needs to satisfy:

$$C = \frac{((\sigma_{hg}+\sigma_{hb})(1-\beta\sigma_{hb}-\sigma_{hg})-q_{lb}\sigma_{lb}(\beta\sigma_{hb}+\sigma_{hg}))\,(1-\beta(\sigma_{hb}+\sigma_{hg}+q_{lb}\sigma_{lb}))}{(\sigma_{hg}+\sigma_{hb}+q_{lb}\sigma_{lb})(1-\beta(\sigma_{hb}+q_{lb}\sigma_{lb})-\sigma_{hg})}. \quad \text{(C.61)}$$

This is independent of γ as Δ_{lb} does not feature γ given $p^O = 0$. In this equilibrium candidate, we have $0 < p^I < 1$ which ensures $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. Therefore, we require in addition to (C.61) that $\Delta_{hb} \geq \Delta_{lb}$ which requires $\gamma \leq \rho\beta = \beta(\sigma_{hg} + \sigma_{hb} + q_{lb}\sigma_{lb})$, see (4.10). For any q_{lb} and such γ, there hence is a unique C characterized by (C.61) so that $\{1, 1, q_{lb}, 0\}$ is an equilibrium.

Candidate $\{1, 0, q_{lb}, 0\}$ In this case, indifference by lb-types requires $\Delta_{lb} = C$ and hence:

$$C = \frac{\sigma_{hg}(1-\sigma_{hg}-q_{lb}\sigma_{lb})(1-\beta(\sigma_{hg}+q_{lb}\sigma_{lb}))}{(\sigma_{hg}+q_{lb}\sigma_{lb})(1-\sigma_{hg}-\beta q_{lb}\sigma_{lb})} - \frac{(1-\gamma)\sigma_{hb}}{1-\sigma_{hg}-q_{lb}\sigma_{lb}}. \quad \text{(C.62)}$$

In this equilibrium candidate, we have $0 < p^I < 1$ and hence $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. As such, we require $\Delta_{lb} \geq \Delta_{hb}$ and $\Delta_{hg} \geq \Delta_{lb}$ in addition to (C.62) to support the equilibrium candidate. These conditions in turn translate into $\gamma \geq \beta\rho = \beta(\sigma_{hg} + \sigma_{hb} + q_{lb}\sigma_{lb}) \equiv \underline{\gamma}$, see (4.10), and $\gamma \leq \rho - (1-\beta)\rho p^I$, see (4.11). Plugging in, we obtain:

$$\gamma \leq \sigma_{hg} + q_{lb}\sigma_{lb} - (1-\beta)\frac{\sigma_{hg}(1-\sigma_{hg}-q_{lb}\sigma_{lb})}{1-\sigma_{hg}-\beta q_{lb}\sigma_{lb}} \equiv \bar{\gamma}. \quad \text{(C.63)}$$

Note that $\bar{\gamma} \geq \underline{\gamma}$ so that for every q_{lb} and $\gamma \in [\underline{\gamma}, \bar{\gamma}]$ there exists a unique C given by (C.62) so that $\{1, 0, q_{lb}, 0\}$ is an equilibrium for this (γ, C).

Candidate $\{1, 1, 1, q_{lg}\}$ Note that in this case we have $p^O = 0$. As such, we get from $\Delta_{lg} = C$ that C needs to satisfy:

$$C = -\frac{(1-q_{lg})\sigma_{lg}\left((1-\beta)\sigma_{hg}(1-(1-q_{lg})\sigma_{lg}) - (1-\sigma_{lb}-\sigma_{lg})(1-\beta-(1-q_{lg})\beta q_{lg})\right)}{(1-(1-q_{lg})\sigma_{lg})((1-\beta)(1-\sigma_{hg}-\sigma_{lg}) + (1-q_{lg})\sigma_{lg})}, \tag{C.64}$$

which is independent of γ as Δ_{lg} does not feature γ for $p^O = 0$. In this equilibrium candidate, we have $0 < p^I < 1$ and hence $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. To support this candidate as an equilibrium, we therefore require $\Delta_{hb} \geq \Delta_{lg}$ in addition to (C.64). From (4.12), this requires $\gamma \leq \beta\rho + (1-\beta)\rho p^I$. Plugging in and simplifying gives:

$$\begin{aligned}\gamma \leq\ & \frac{1-\beta-\sigma_{lg}-(1-\beta)\sigma_{hg}(1-(1-q_{lg})\sigma_{lg})}{(1-\beta)(1-\sigma_{hg}-\sigma_{lg})+(1-q_{lg})\sigma_{lg}} \\ & + \frac{\beta\sigma_{lg}(2-q_{lg}-(1-q_{lg})^2\sigma_{lg}) - (1-\beta)\sigma_{lb}(1-\beta+(1-q_{lg})\beta\sigma_{lg})}{(1-\beta)(1-\sigma_{hg}-\sigma_{lg})+(1-q_{lg})\sigma_{lg}}.\end{aligned} \tag{C.65}$$

For any q_{lg} and such γ, this is hence an equilibrium provided C is such that (C.64) is satisfied.

Candidate $\{1, 0, 1, q_{lg}\}$ In this case, we require lg-types to be indifferent and hence that $\Delta_{lg} = C$. This gives:

$$C = -\frac{(1-\gamma)\sigma_{hb}}{\sigma_{hb}+(1-q_{lg})\sigma_{lg}} + \frac{\sigma_{hg}(\sigma_{hb}+(1-q_{lg})\sigma_{lg})^2}{(\sigma_{hg}+\sigma_{lb}+q_{lg}\sigma_{lg})(1-\sigma_{hg}-\beta\sigma_{lb}-q_{lg}\sigma_{lg})}. \tag{C.66}$$

In this equilibrium candidate, we have $0 < p^I < 1$ and hence $\Delta_{hg} > \Delta_{hb}$ and $\Delta_{lb} > \Delta_{lg}$ from Lemma 4.1. As such, we require $\Delta_{hb} \leq \Delta_{lg}$ and $\Delta_{hg} \geq \Delta_{lg}$ in addition to (C.66) to support the equilibrium candidate. These conditions in turn translate into $\gamma \leq \rho = \sigma_{hg} + \sigma_{lb} + q_{lg}\sigma_{lg} \equiv \bar{\gamma}$, see (4.9), and $\gamma \geq \rho\beta + (1-\beta)\rho p^I$, see (4.12). Plugging in, we obtain:

$$\gamma \geq \beta(\sigma_{hg} + \sigma_{lb} + q_{lg}\sigma_{lg}) + (1-\beta)\frac{\sigma_{hg}(\sigma_{hb} + (1-q_{lg})\sigma_{lg})}{1 - \sigma_{hg} - \beta\sigma_{lb} - q_{lg}\sigma_{lg}} \equiv \underline{\gamma}. \tag{C.67}$$

Note that $\bar{\gamma} \geq \underline{\gamma}$ so that for every q_{lg} and $\gamma \in [\underline{\gamma}, \bar{\gamma}]$ there exists a unique C given by (C.66) so that $\{1, 0, 1, q_{lg}\}$ is an equilibrium for this (γ, C).

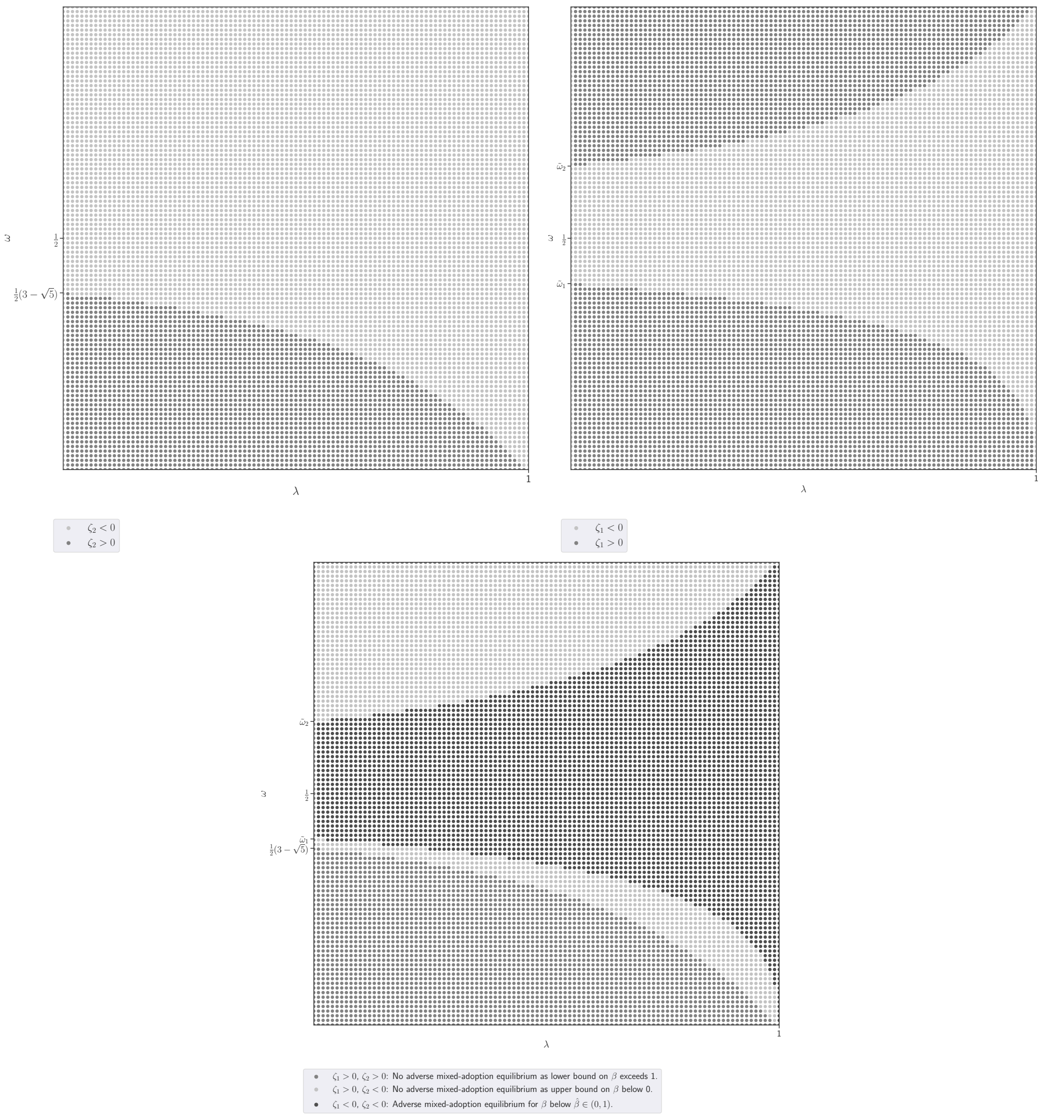
C.6 Proof of Proposition 4.3

To establish Proposition 4.3, we proceed in multiple steps. Recall that the existence of adverse mixed-adoption equilibria for some γ-C-combinations depends on the compatibility of the condition that *mispricing increases in the mixed-adoption equilibrium*, $\gamma > \hat{\gamma}$ (see (4.23)), with the conditions that the *mixed-adoption strategies constitute an equilibrium*, $\beta(\sigma_{hg}+\sigma_{lb}) \leq \gamma$ and $\gamma \leq \sigma_{hg}+\sigma_{lb}$ (see Proposition 4.2). We first establish that the lower bound on γ from the existence condition is always satisfied when the average mispricing increases in the mixed-adoption equilibrium due to $\hat{\gamma} > \beta(\sigma_{hg}+\sigma_{lb})$, see Lemma C 4.

The remainder—and bulk—of the proof therefore assesses the compatibility of $\gamma > \hat{\gamma}$ and $\gamma \leq \sigma_{hg}+\sigma_{lb}$. Unfortunately, the compatibility condition that we establish depends on the proportions of the different firms in non-trivial ways. We therefore consider the restricted parameter space in which the fit and value of a firm are independent and show that the compatibility depends on the sign of $\beta\zeta_2(\lambda,\omega) - \zeta_1(\lambda,\omega)$, see Lemma C 5. The fact that this expression is linear in β greatly facilitates the analysis, which nonetheless retains the issue that ζ_2 and ζ_1 are non-trivial functions of the probability that a firm is of high value, λ, and the probability that it exhibits a good fit, ω. In particular, depending on the sign of ζ_2, the threshold $\hat{\beta} = \frac{\zeta_1}{\zeta_2}$ may either be an upper or lower bound for the β that render the overall expression positive and, thus, imply the existence of adverse mixed-adoption equilibria (see Lemma C 6).

Figure C.1: Illustration of approach to prove Proposition 4.3

This figure illustrates the approach behind assessing whether $\beta\zeta_2(\lambda,\omega) - \zeta_1(\lambda,\omega)$ is positive, implying the existence of adverse mixed-adoption equilibria. The top left panel depicts the λ-ω-combinations for which ζ_2 is positive (grey region) and negative (light grey region), respectively. The top right panel repeats this exercise for ζ_1. The bottom panel combines these assessments to conclude that adverse mixed-adoption equilibria may exist only when both ζ_1 and ζ_2 are negative, in which case $\hat{\beta} = \frac{\zeta_1}{\zeta_2}$ provides a well-behaved upper bound on β such that adverse mixed-adoption equilibria exist if and only if $\beta < \hat{\beta}$.



Our approach, which we illustrate in Figure C.1, is as follows. We first characterize the conditions on λ and ω under which ζ_2 (see Lemma C 7) and ζ_1 (see Lemma C 8) are positive and negative, respectively. This is illustrated in the top two panels of Figure C.1. While ζ_2 is positive only if ω is sufficiently small and λ does not exceed an upper bound (left panel), this holds for ζ_1 also when ω is sufficiently large and λ does not exceed an upper bound (right panel). We then combine these assessments in Lemma C 9, illustrated in the bottom panel of Figure C.1. For sufficiently low ω and γ (grey region), both ζ_1 and ζ_2 are positive so that $\hat{\beta}$ constitutes a lower bound on β such that adverse mixed-adoption equilibria exist. However, this lower bound exceeds 1. A similar contradiction obtains in the light grey region for which ζ_1 is positive but ζ_2 negative—$\hat{\beta}$ in this case is an upper bound on β for the existence of adverse mixed-adoption equilibria, but this bound lies below 0. This leaves the dark grey region in which both ζ_1 and ζ_2 are negative, and where $\hat{\beta}$ is a well-behaved upper bound on β ensuring the existence of adverse mixed-adoption equilibria.

We proceed by formally stating and proving the individual Lemmas.

Lemma C4 *It holds that $\hat{\gamma} > \beta(\sigma_{hg} + \sigma_{lb})$.*

Proof. Proof: It is convenient to not always plug in but use $\rho = \sigma_{hg}+\sigma_{lb}$, $\sigma_h = \sigma_{hg}+\sigma_{hb}$ and $\sigma_l = \sigma_{lg} + \sigma_{lb}$ as it simplifies expressions. Doing so allows us to write:

$$\hat{\gamma} = 1 - \frac{\frac{\sigma_{hg}(1-\rho)\sigma_{lb}(1-\rho\beta)}{(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}}}{\kappa}, \tag{C.68}$$

where

$$\begin{aligned}
\kappa &= \sigma_h\sigma_l - \frac{\sigma_{hb}\sigma_{lg}}{1-\rho} \\
&= \frac{\sigma_h\sigma_{lg}\sigma_{hb} + \sigma_h\sigma_{lb}\sigma_{hb} + \sigma_l\sigma_{hg}\sigma_{lg} + \sigma_l\sigma_{hb}\sigma_{lg} - \sigma_{hb}\sigma_{lg}}{\sigma_{hb} + \sigma_{lg}} \\
&= \frac{\sigma_h\sigma_{lb}\sigma_{hb} + \sigma_l\sigma_{hg}\sigma_{lg}}{\sigma_{hb} + \sigma_{lg}} > 0.
\end{aligned} \tag{C.69}$$

Thus, we have that $\hat{\gamma} > \rho\beta$ if and only if:

$$\begin{aligned} 1-\rho\beta &> \frac{\frac{\sigma_{hg}(1-\rho)\sigma_{lb}(1-\rho\beta)}{(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}}}{\kappa} \\ \iff \quad 1 &> \frac{\frac{\sigma_{hg}(1-\rho)\sigma_{lb}}{(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}}}{\kappa} \\ \iff \quad \kappa &> \frac{\sigma_{hg}(1-\rho)\sigma_{lb}}{(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}}. \end{aligned} \tag{C.70}$$

Plugging in for κ, this is equivalent to:

$$\frac{\sigma_h\sigma_{lb}\sigma_{hb}+\sigma_l\sigma_{hg}\sigma_{lg}}{\sigma_{hb}+\sigma_{lg}} > \frac{\sigma_{hg}(1-\rho)\sigma_{lb}}{(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}} \tag{C.71}$$

$$\begin{aligned} \iff \quad [(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb}]\,[\sigma_h\sigma_{lb}\sigma_{hb}+\sigma_l\sigma_{hg}\sigma_{lg}] &> [\sigma_{hb}+\sigma_{lg}]\,[\sigma_{hg}(1-\rho)\sigma_{lb}] \\ &= (1-\rho)^2\sigma_{hg}\sigma_{lb}. \end{aligned} \tag{C.72}$$

To establish (C.72) in turn, note that $\beta \leq 1$ ensures:

$$(1-\rho)\sigma_{hg}+(1-\rho\beta)\sigma_{lb} \geq (1-\rho)(\sigma_{hg}+\sigma_{lb}), \tag{C.73}$$

which implies:

$$\begin{aligned} [\sigma_h\sigma_{lb}\sigma_{hb}+\sigma_l\sigma_{hg}\sigma_{lg}](1-\rho)(\sigma_{hg}+\sigma_{lb}) &\geq \sigma_{hg}\sigma_{lb}(1-\rho)^2 \\ \iff [\sigma_h\sigma_{lb}\sigma_{hb}+\sigma_l\sigma_{hg}\sigma_{lg}](\sigma_{hg}+\sigma_{lb}) &\geq \sigma_{hg}\sigma_{lb}(1-\rho) \qquad \text{(C.74)} \\ \iff [\sigma_h\sigma_{lb}\sigma_{hb}+\sigma_l\sigma_{hg}\sigma_{lg}](\sigma_{hg}+\sigma_{lb}) &\geq \sigma_{hg}\sigma_{lb}(\sigma_{hb}+\sigma_{lg}). \qquad \text{(C.75)} \end{aligned}$$

is sufficient for (C.72) and thus $\hat{\gamma} > \beta(\sigma_{hg}+\sigma_{lb})$. This is straightforward to establish, because it is equivalent to:

$$\begin{aligned} 0 &\leq [\sigma_{hg}\sigma_{lb}\sigma_{hb}+\sigma_{hb}\sigma_{lb}\sigma_{hb}+\sigma_{lg}\sigma_{hg}\sigma_{lg}+\sigma_{lb}\sigma_{hg}\sigma_{lg}]\,[\sigma_{hg}+\sigma_{lb}]-\sigma_{hg}\sigma_{lb}\sigma_{hb}-\sigma_{hg}\sigma_{lb}\sigma_{lg} \qquad \text{(C.76)} \\ &= \sigma_{hg}\sigma_{lb}\sigma_{hb}\left[\underbrace{\sigma_{hg}+\sigma_{lb}+\sigma_{hb}-1}_{-\sigma_{lg}}\right]+\sigma_{hg}\sigma_{lb}\sigma_{lg}\left[\underbrace{\sigma_{lg}+\sigma_{hg}+\sigma_{lb}-1}_{-\sigma_{hb}}\right]+\sigma_{hb}^2\sigma_{lb}^2+\sigma_{lg}^2\sigma_{hg}^2 \qquad \text{(C.77)} \\ &= (\sigma_{hb}\sigma_{lb}-\sigma_{lg}\sigma_{hg})^2, \qquad \text{(C.78)} \end{aligned}$$

which is generically true. □

<u>*Condition such that $\hat{\gamma} < \sigma_{hg} + \sigma_{lb}$.*</u> We thus need to assess whether the condition for increased mispricing is compatible with the upper bound on the existence of the mixed-adoption equilibrium, i.e., whether $\hat{\gamma} < \sigma_{hg} + \sigma_{lb}$. We can write the difference as $\sigma_{hg} + \sigma_{lb} - \hat{\gamma} = \frac{\iota_n}{\iota_d}$, with:

$$\begin{aligned}
\iota_n &= (1-\sigma_{hg}-\sigma_{lb}) \\
&\times \; \left[\sigma_{hg}^5 - \sigma_{hb}^2\sigma_{lb}^2(1-\beta\sigma_{lb}) + \sigma_{hg}^4(2\sigma_{hb} + (2+\beta)\sigma_{lb} - 3)\right. \\
&\quad +\sigma_{hg}\sigma_{hb}\sigma_{lb}\left(2(1-\sigma_{lb})(1-\beta\sigma_{lb}) - (2-\sigma_{lb}-2\beta\sigma_{lb})\sigma_{hb}\right) \\
&\quad +\sigma_{hg}^3\left(3+\sigma_{hb}^2 - (5+\beta)\sigma_{lb} + (1+2\beta)\sigma_{lb}^2 - 2\sigma_{hb}(2-(2+\beta)\sigma_{lb})\right) \\
&\quad +\sigma_{hg}^2\left(\sigma_{hb}^2((2+\beta)\sigma_{lb}-1\right) + 2\sigma_{hb}(1-(3+\beta)\sigma_{lb} + (1+2\beta)\sigma_{lb}^2) \\
&\quad \left. -(1-\sigma_{lb})(1-(2-\beta\sigma_{lb})\sigma_{lb})\right], \qquad \text{(C.79)} \\
\iota_d &= \underbrace{(\sigma_{hg}+\sigma_{lb})}_{>0}\underbrace{(1-\sigma_{hg}-\beta\sigma_{lb})}_{>0}\underbrace{\left(\sigma_{hg}\left[1-\sigma_{hb}-\sigma_{hg}\right]^2 + \sigma_{lb}\left[\sigma_{hb}+\sigma_{hg}\right]^2 - \sigma_{lb}\sigma_{hg}\right)}_{>0}. \qquad \text{(C.80)}
\end{aligned}$$

As $\iota_d > 0$ is unambiguous, the sign of the difference is determined by the sign of ι_n, which in turn is linear in β. Unfortunately, the sign of both the constant and the coefficient on β depend on the relative proportions of the different firms in nontrivial ways. We therefore restrict attention to the reduced parameter space with independent fit and value dimensions, i.e., where $\sigma_{hg} = \lambda\omega$, $\sigma_{hb} = \lambda(1-\omega)$, $\sigma_{lg} = (1-\lambda)\omega$, $\sigma_{lb} = (1-\lambda)(1-\omega)$. We first use this to derive a simplified condition.

Lemma C5 *Let* $\sigma_{hg} = \lambda\omega$, $\sigma_{hb} = \lambda(1-\omega)$, $\sigma_{lg} = (1-\lambda)\omega$, $\sigma_{lb} = (1-\lambda)(1-\omega)$. *Then*

$$\sigma_{hg} + \sigma_{lb} - \hat{\gamma} > 0 \iff \phi_n = \beta\zeta_2 - \zeta_1 > 0 \qquad \text{(C.81)}$$

with

$$\begin{aligned}
\zeta_1 &= \lambda(\omega+(1-2\omega)\lambda)\left(\lambda^2\omega(1-2\omega)^2 - \lambda(1-2\omega)\left(1-\omega-\omega^2-\omega^3\right) - (1-\omega)\omega\left(4+\omega^2\right)+1\right) \\
\zeta_2 &= \lambda(1-\omega)(\omega+(1-2\omega)\lambda)(1-\omega-(1-2\omega)\lambda)(1-(1-2\omega)\lambda-(3-\omega)\omega). \qquad \text{(C.82)}
\end{aligned}$$

Proof. Proof: Plugging $\sigma_{hg} = \lambda\omega$, $\sigma_{hb} = \lambda(1-\omega)$, $\sigma_{lg} = (1-\lambda)\omega$, $\sigma_{lb} = (1-\lambda)(1-\omega)$ in, we obtain:

$$\begin{aligned} \hat{\gamma} &= \frac{(1-\omega)^2(1-(1-\omega)\beta)\omega^2 + \lambda^3(1-2\omega)^2(\beta(1-\omega)^2(1+2\omega)-\omega)}{(\omega^2+(1-2\omega)\lambda)\left((1-\omega-(1-2\omega)\lambda)(1-(1-\lambda)(1-\omega)\beta-\lambda\omega)\right)} \\ &- \frac{\lambda^2(1-2\omega)(1-4\omega^2+\omega^3-2\beta(1-\omega)^2(1-3\omega^2))}{(\omega^2+(1-2\omega)\lambda)\left((1-\omega-(1-2\omega)\lambda)(1-(1-\lambda)(1-\omega)\beta-\lambda\omega)\right)} \\ &+ \frac{\lambda\left(1-3\omega-\omega^2+7\omega^3-3\omega^4-\beta(1-\omega)^2(1-2\omega-4\omega^2+6\omega^3)\right)}{(\omega^2+(1-2\omega)\lambda)\left((1-\omega-(1-2\omega)\lambda)(1-(1-\lambda)(1-\omega)\beta-\lambda\omega)\right)} \qquad \text{(C.83)} \\ \implies \sigma_{hg}+\sigma_{lb}-\hat{\gamma} &= 1-\omega-(1-2\omega)\lambda-\hat{\gamma} = \frac{\phi_n}{\phi_d}, \qquad \text{(C.84)} \end{aligned}$$

where

$$\begin{aligned} \phi_n &= -\overbrace{\lambda(\omega+(1-2\omega)\lambda)\left(\lambda^2\omega(1-2\omega)^2-\lambda(1-2\omega)\left(1-\omega-\omega^2-\omega^3\right)-(1-\omega)\omega\left(4+\omega^2\right)+1\right)}^{\zeta_1} \\ &+ \beta\underbrace{\left[\lambda(1-\omega)(\omega+(1-2\omega)\lambda)(1-\omega-(1-2\omega)\lambda)(1-(1-2\omega)\lambda-(3-\omega)\omega)\right]}_{\zeta_2} \qquad \text{(C.85)} \\ \phi_d &= \underbrace{(1-\omega-(1-2\omega)\lambda)}_{>0}\underbrace{\left((1-2\omega)\lambda+\omega^2\right)}_{>0}\underbrace{(1-\lambda\omega-\beta(1-\lambda)(1-\omega))}_{>0} > 0. \qquad \text{(C.86)} \end{aligned}$$

The individual inequalities and thus $\phi_d > 0$ in (C.86) follow from $\lambda \in (0,1)$ and $\omega \in (0,1)$. We can conclude that:

$$\operatorname{sgn}(\sigma_{hg}+\sigma_{lb}-\hat{\gamma}) = \operatorname{sgn}(\phi_n), \qquad \text{(C.87)}$$

i.e., that whether $\sigma_{hg}+\sigma_{lb}$ exceeds $\hat{\gamma}$ depends only on the sign of $\phi_n = \beta\zeta_2 - \zeta_1$. □

We can now use Lemma C 5 by analyzing the behavior of ζ_1 and ζ_2 as functions of λ and ω—because they define ϕ_n as a linear function of β, this determines a cutoff $\hat{\beta}$ such that $\phi_n > 0$ if β exceeds $\hat{\beta}$ (for $\zeta_2 > 0$) or lies below $\hat{\beta}$ (for $\zeta_2 < 0$), respectively. Towards this, define:

$$\hat{\beta} \equiv \frac{\zeta_1}{\zeta_2} = \frac{\lambda^2\omega(1-2\omega)^2-\lambda(1-2\omega)\left(1-\omega^3-\omega^2-\omega\right)-(1-\omega)\omega\left(\omega^2+4\right)+1}{(1-\omega)((1-\omega)-(1-2\omega)\lambda)(1-(3-\omega)\omega-(1-2\omega)\lambda)} \qquad \text{(C.88)}$$

and observe that:

$$\hat{\beta} > 1 \iff \lambda(1-2\omega) < 1-3\omega+\omega^2. \qquad \text{(C.89)}$$

We summarize in Lemma C 6.

Lemma C6 *Consider $\hat{\beta}$ as defined in* (C.88). *Then*

(i) $\hat{\beta} > 0 \iff \zeta_1 \cdot \zeta_2 > 0.$

(ii) $\hat{\beta} > 1 \iff \lambda(1-2\omega) < 1 - 3\omega + \omega^2 \iff \omega < \frac{1}{2}(\sqrt{5}-3) < \frac{1}{2}.$

Moreover, we have $\phi_n > 0 \iff \beta > \hat{\beta}$ *for* $\zeta_2 > 0$ *and* $\phi_n > 0 \iff \beta < \hat{\beta}$ *for* $\zeta_2 < 0$.

Proof. Proof: (i) follows immediately from the definition of $\hat{\beta}$. For (ii), note that $1-3\omega+\omega^2 > 0 \iff \omega < \frac{1}{2}(\sqrt{5}-3)$ given $\omega \in (0,1)$. Moreover, we have for $\omega \in (0,1)$ that $1-3\omega+\omega^2 = 1-2\omega-\omega(1-\omega) < 1-2\omega$. For $\omega < \frac{1}{2}$, the necessary and sufficient condition hence follows, while for $\omega > \frac{1}{2}$, we would require $\lambda > \frac{1-3\omega+\omega^2}{1-2\omega} > 1$, which is not possible. □

We next separately assess the behavior of ζ_2 and ζ_1, which we summarize in Lemma C 7 and Lemma C 8, respectively.

Lemma C7 *Define* $\lambda_3 = \frac{1-3\omega+\omega^2}{1-2\omega}$. *Then*

(i) For $\omega > \frac{1}{2}$, *we have* $\zeta_2 < 0$ *for all* $\lambda \in (0,1)$.

(ii) For $\omega \in \left(\frac{1}{2}(3-\sqrt{5}, \frac{1}{2}\right]$, *we have* $\zeta_2 < 0$ *for any* $\lambda \in (0,1)$.

(iii) For $\omega < \frac{1}{2}(3-\sqrt{5})$, *we have* $\zeta_2 < 0$ *for* $\lambda > \lambda_3$ *and* $\zeta_2 > 0$ *for* $\lambda < \lambda_3$.

Proof. Proof: Recall:

$$\zeta_2 = \lambda(1-\omega)(\omega+(1-2\omega)\lambda)(1-\omega-(1-2\omega)\lambda)(1-(1-2\omega)\lambda-(3-\omega)\omega) \quad \text{(C.90)}$$

Because $\lambda > 0$, $1-\omega > 0$, we have $\text{sgn}(\zeta_1) = \text{sgn}(\xi)$, where:

$$\xi = (1-\omega-(1-2\omega)\lambda)(1-(1-2\omega)\lambda-(3-\omega)\omega). \quad \text{(C.91)}$$

Note that ξ is cubic in λ with a coefficient on λ^3 of $(1-2\omega)^3$ and roots $\lambda_1 = \frac{1-\omega}{1-2\omega}$, $\lambda_2 = \frac{-\omega}{1-2\omega}$ and $\lambda_3 = \frac{1-3\omega+\omega^2}{1-2\omega}$. We thus need to distinguish three cases:

(i) $\omega = \frac{1}{2}$. Then $\zeta_2 < 0$ immediately follows from plugging in.

(ii) $\omega < \frac{1}{2}$. Then $\lambda_1 > 1 > \lambda_3 > \lambda_2$ and $\lambda_2 < 0$ immediately follow, while $\lambda_3 > 0 \iff \omega < \frac{1}{2}(3-\sqrt{5}) \approx 0.382$. Because the coefficient on λ^3 in ξ is positive for $\omega < \frac{1}{2}$, we can conclude that for $\omega < \frac{1}{2}$ it holds that $\zeta_2 > 0$ iff $\lambda \in (0, \lambda_3)$ which is nonempty only for $\omega < \frac{1}{2}(3-\sqrt{5})$.

(iii) $\omega > \frac{1}{2}$. Then $\lambda_2 > \lambda_3 > 1 > 0 > \lambda_1$ immediately follows. Because the coefficient on λ^3 in ξ is negative for $\omega > \frac{1}{2}$, this implies that $\zeta_2 < 0$ for all $\lambda \in (0, 1)$.

Collecting these observations pins down the sign of ζ_2 as a function of λ and ω and yields the Lemma. □

Lemma C8 *Define*

$$\lambda_2' = \frac{1-3\omega+\omega^2+\omega^3+2\omega^4-(1-3\omega+2\omega^2)\sqrt{1-4\omega+6\omega^2+\omega^4}}{2\omega(1-4\omega+4\omega^2)} \tag{C.92}$$

$$\lambda_3' = \frac{1-3\omega+\omega^2+\omega^3+2\omega^4+(1-3\omega+2\omega^2)\sqrt{1-4\omega+6\omega^2+\omega^4}}{2\omega(1-4\omega+4\omega^2)}. \tag{C.93}$$

and denote by $\tilde{\omega}_1 \approx 0.402$ *and* $\tilde{\omega}_2 \approx 0.656$ *the first and second real root of* $1-4\omega+4\omega^2-\omega^3+\omega^4$*, respectively. Then*

(i) For $\omega > \tilde{\omega}_2$*, we have* $\zeta_1 > 0$ *for* $\lambda \in (0, \lambda_3')$ *and* $\zeta_1 < 0$ *for* $\lambda \in (\lambda_3', 1)$.

(ii) For $\omega \in [\tilde{\omega}_1, \tilde{\omega}_2]$*, we have* $\zeta_1 < 0$ *for any* $\lambda \in (0, 1)$.

(iii) For $\omega < \tilde{\omega}_1$*, we have* $\zeta_1 > 0$ *for* $\lambda \in (0, \lambda_2')$ *and* $\zeta_1 < 0$ *for* $\lambda \in (\lambda_2', 1)$.

Proof. Proof: Recall:

$$\zeta_1 = \lambda(\omega+(1-2\omega)\lambda)\left(\lambda^2\omega(1-2\omega)^2 - \lambda(1-2\omega)\left(1-\omega-\omega^2-\omega^3\right) - (1-\omega)\omega\left(4+\omega^2\right)+1\right), \tag{C.94}$$

and observe that, due to $\lambda > 0$, we know $\text{sgn}(\zeta_1) = \text{sgn}(\xi')$ with:

$$\xi' = (\omega + (1-2\omega)\lambda)(\lambda^2\omega(1-2\omega)^2 - \lambda(1-2\lambda)(1-\omega-\omega^2-\omega^3) - (1-\omega)\omega(4+\omega^2) + 1). \tag{C.95}$$

ξ' is cubic in λ with roots $\lambda_1' = \frac{-\omega}{1-2\omega}$ and

$$\lambda_2' = \frac{1 - 3\omega + \omega^2 + \omega^3 + 2\omega^4 - (1 - 3\omega + 2\omega^2)\sqrt{1 - 4\omega + 6\omega^2 + \omega^4}}{2\omega(1 - 4\omega + 4\omega^2)} \tag{C.96}$$

$$\lambda_3' = \frac{1 - 3\omega + \omega^2 + \omega^3 + 2\omega^4 + (1 - 3\omega + 2\omega^2)\sqrt{1 - 4\omega + 6\omega^2 + \omega^4}}{2\omega(1 - 4\omega + 4\omega^2)}. \tag{C.97}$$

We distinguish three cases:

(i') $\omega = \frac{1}{2}$. Then $\zeta_1 < 0$ immediately follows by plugging in.

(ii') $\omega < \frac{1}{2}$. Then $\lambda_1' < 0$ and $\lambda_3' > 1 > \lambda_2'$ immediately follow, while $\lambda_2' > 0$ if and only if ω does not exceed the first real root of $1 - 4\omega + 4\omega^2 - \omega^3 + \omega^4$, which we denote $\tilde{\omega}_1$ and which is approximately 0.402. Because the coefficient on λ^3 in ξ' is positive for $\omega < \frac{1}{2}$, this implies that $\zeta_1 > 0$ iff $\lambda \in (0, \lambda_2')$ which is nonempty only for $\omega < \tilde{\omega}_1$.

(iii') $\omega > \frac{1}{2}$. Then $\lambda_1' > \lambda_2' > 1 > \lambda_3'$ immediately follow, while $\lambda_3' > 0$ iff ω exceeds the second real root of $1 - 4\omega + 4\omega^2 - \omega^3 + \omega^4$, which we denote $\tilde{\omega}_2$ and which is approximately 0.656. Because the coefficient on λ^3 in ξ' is negative for $\omega > \frac{1}{2}$, this implies that $\zeta_1 > 0$ for all $\lambda \in (0, \lambda_3')$ which is nonempty only for $\omega > \tilde{\omega}_2$.

Collecting these observations pins down the sign of ζ_1 as a function of λ and ω and yields the Lemma. □

Having fully characterized the behavior of ζ_1 and ζ_2 as functions of λ and ω in Lemma C 7 and Lemma C 8, we can combine these ingredients to fully determine under which parameter values in the (λ, ω, β)-space $\hat{\gamma}$ lies below $\sigma_{hg} + \sigma_{lb}$, which implies the existence of (γ, C)-combinations such that the mixed-adoption strategies constitute an equilibrium that leads to increased average mispricing.

Lemma C9 *Let* $\sigma_{hg} = \lambda\omega$, $\sigma_{hb} = \lambda(1-\omega)$, $\sigma_{lg} = (1-\lambda)\omega$, $\sigma_{lb} = (1-\lambda)(1-\omega)$. *Then* $\sigma_{hg} + \sigma_{lb} - \hat{\gamma} > 0 \iff \beta < \tilde{\beta}(\lambda,\omega)$ *where*

$$\tilde{\beta}(\lambda,\omega) = \begin{cases} \hat{\beta} = \frac{\lambda^2\omega(1-2\omega)^2 - \lambda(1-2\omega)\left(1-\omega^3-\omega^2-\omega\right) - (1-\omega)\omega\left(\omega^2+4\right)+1}{(1-\omega)((1-\omega)-(1-2\omega)\lambda)(1-(3-\omega)\omega-(1-2\omega)\lambda)} & \text{if} \quad \begin{array}{c} 0<\omega<\tilde{\omega}_1 \textit{ and } \lambda > \lambda_2' \\ \textit{or} \\ \omega \in [\tilde{\omega}_1, \tilde{\omega}_2] \\ \textit{or} \\ \tilde{\omega}_2 < \omega < 1 \textit{ and } \lambda > \lambda_3' \end{array} \\ 0 & \textit{otherwise} , \end{cases} \tag{C.98}$$

where

$$\lambda_2' = \frac{1-3\omega+\omega^2+\omega^3+2\omega^4-(1-3\omega+2\omega^2)\sqrt{1-4\omega+6\omega^2+\omega^4}}{2\omega(1-4\omega+4\omega^2)} \tag{C.99}$$

$$\lambda_3' = \frac{1-3\omega+\omega^2+\omega^3+2\omega^4+(1-3\omega+2\omega^2)\sqrt{1-4\omega+6\omega^2+\omega^4}}{2\omega(1-4\omega+4\omega^2)}. \tag{C.100}$$

and $\tilde{\omega}_1 \approx 0.402$ *and* $\tilde{\omega}_2 \approx 0.656$ *are the real roots of* $1-4\omega+4\omega^2-\omega^3+\omega^4$.

Proof. Proof: Recall that we want to derive conditions under which $\phi_n = \beta\zeta_2 - \zeta_1$ is positive. Making use of the previous Lemmas yields the following:

- If $\zeta_2 > 0$, then $\phi_n > 0 \iff \beta > \hat{\beta}$.

  (a) If $\zeta_1 < 0$, this would hence be generically satisfied as then $\hat{\beta} < 0$. But this is in fact not possible. $\zeta_2 > 0$ requires $\omega < \frac{1}{2}(3-\sqrt{5})$ and $\lambda < \lambda_3$ by Lemma C 7. For $\zeta_1 < 0$ we would require $\lambda > \lambda_2'$ by Lemma C 8. But for $\omega < \frac{1}{2}$ we have $\lambda_2' > \lambda_3$, so that this is impossible.

  (b) If $\zeta_1 > 0$, we also get a contradiction. This is because $\lambda < \lambda_3$ and $\omega < \frac{1}{2}$ imply that $\hat{\beta} > 1$ (see Lemma C 6.(ii)), so that $\beta > \hat{\beta}$ cannot be satisfied.

- If $\zeta_2 < 0$, then $\phi_n > 0 \iff \beta < \hat{\beta}$.

(a) For $\omega > \frac{1}{2}$, we know that $\zeta_2 < 0$ generically holds by Lemma C 7. For $\zeta_1 > 0$, $\hat{\beta} < 0$ would thus follow and that we obtain a contradiction. We can thus focus on the cases where $\zeta_1 < 0$. This is always the case if $\omega < \tilde{\omega}_2$ by Lemma C 8. If instead $\omega > \tilde{\omega}_2$, we know that $\zeta_1 < 0$ is only possible if $\lambda > \lambda'_3$. Overall, we can thus conclude that $\hat{\beta}$ is an upper bound on β such that $\phi_n > 0$ for $\omega > \frac{1}{2}$, but that this upper bound is negative (and thus leads to a contradiction) unless $\omega < \tilde{\omega}_2$ or $\lambda > \lambda'_3$. If it is positive, it is well-behaved in the sense that $\hat{\beta} \leq 1$ due to $\omega > \frac{1}{2} > \frac{1}{2}(3 - \sqrt{5})$ by Lemma C 6.(ii).

(b) For $\omega < \frac{1}{2}$, we know from Lemma C 7 that $\zeta_2 < 0$ requires $\omega > \frac{1}{2}(3 - \sqrt{5})$ or $\omega \leq \frac{1}{2}(3 - \sqrt{5})$ and $\lambda > \lambda_3$. If $\zeta_1 > 0$, then we would have $\hat{\beta} < 0$ and thus a contradiction. We therefore require $\zeta_1 < 0$, which for $\omega < \frac{1}{2}$ obtains if $\omega > \tilde{\omega}_1$ or $\omega < \tilde{\omega}_1$ and $\lambda > \lambda'_2$, see Lemma C 8. Note that for $\omega \in (0, \frac{1}{2})$, we always have $\lambda'_2 > \lambda_3$, so that $\zeta_1 < 0$ is sufficient for $\zeta_2 < 0$ whenever $\omega < \frac{1}{2}$, allowing us to focus on these conditions. Overall, this implies that $\hat{\beta}$ provides an upper bound on β such that $\phi_n > 0$ for $\frac{1}{2} > \omega > \tilde{\omega}_1$, while for $\tilde{\omega}_1 \geq \omega > 0$ this obtains only if $\lambda > \lambda'_2$. In both cases, the upper bound is well behaved in the sense that $\hat{\beta} \leq 1$: for $\omega > \frac{1}{2}(3-\sqrt{5})$ this directly follows from Lemma C 6.(ii), while for $\omega \leq \frac{1}{2}(3 - \sqrt{5}) < \tilde{\omega}_1$ the requirement that $\lambda > \lambda'_2 > \lambda_3$ violates (C.89).

Summarizing yields the Lemma. □

C.7 Mixed-adoption equilibrium vs. inherently bad blockchain

To obtain the graphical illustration in Figure 4.8, we proceed as follows. We fix the values for the (independent) probabilities for a given firm to be of high value, λ, and to have a good fit vis-a-vis the blockchain, ω. For each combination of the fit parameter $\beta \in \{0.01, 0.03, 0.05, \ldots, 0.99\}$ and strength of traditional institutions $\gamma \in \{0.03, 0.06, 0.09, \ldots, 0.99\}$, we then

(i) Check whether the blockchain is inherently a bad technology, i.e., whether $\beta < \frac{\gamma-\omega}{1-\omega}$.

(ii) Check whether the mixed-adoption equilibrium $\{1, 0, 1, 0\}$ can be supported for some relative cost C, i.e., whether $\beta\rho \leq \gamma \leq \rho$ for $\rho = \lambda\omega + (1-\lambda)(1-\omega)$.

(iii) If the mixed-adoption equilibrium can be supported, we check whether $AMP_{noBC} < AMP_{\{1,0,1,0\}}$ by plugging $\sigma_{hg} = \lambda\omega, \sigma_{hb} = \lambda(1-\omega), \sigma_{lb} = (1-\lambda)(1-\omega), \sigma_{lg} = (1-\lambda)\omega$ in (4.20) and (4.22).

We then plot each combination in black if all of (i), (ii) and (iii) are satisfied; in dark-gray if (ii) and (iii) are satisfied but (i) is not; in light-gray if (i) is satisfied but (ii) or (iii) is not; and in very light gray if (i) is not satisfied and so is at least one of (ii) and (iii).

The code to run the above for arbitrary parameters is available from the authors upon request. The left panel in Figure 4.8 is obtained by setting $\lambda = 0.4$ and $\omega = 0.45$; the right panel obtains with $\lambda = 0.4$ and $\omega = 0.65$.

Additional considerations

C.8 Scalability

Consider the model setup as outlined in Section 4.5.1, i.e., where the firm-specific information provision is given by $Pr\{m^i = v^i | D^i = 1\} = \tilde{\eta}^i = \rho^s \cdot f^i$. The analogue to the necessary and sufficient condition on γ for the emergence of the undesirable equilibrium, i.e., (4.18), still reflects that high-value bad-fit firms need to have lower incentives to adopt the blockchain than low-value bad-fit firms, whereas high-value good-fit firms need to adopt and low-value good-fit firms need to rely on traditional institutions.

Specifically, we require:

$$\beta(\sigma_{hg} + \sigma_{lb})^s \leq \gamma \leq (\sigma_{hg} + \sigma_{lb})^s. \tag{C.101}$$

Assessing the likelihood of the undesirable equilibrium by the size of the interval $l(s) = (1 - \beta)(\sigma_{hg} + \sigma_{lb})^s$, we get:

$$\frac{\partial l(s)}{\partial s} = \underbrace{(1-\beta)}_{>0} \cdot \underbrace{(\sigma_{hg} + \sigma_{lb})^s}_{>0} \cdot \underbrace{\log \overbrace{(\sigma_{hg} + \sigma_{lb})}^{<1}}_{<0} < 0. \tag{C.102}$$

This implies that a limited scalability (a larger s) decreases the range of γ for which the undesirable equilibrium is sustainable. Hence, it is important to consider the specific form in which the blockchain provides information when assessing the potential dangers of an underprovision of information. Perhaps surprisingly, the more efficient the blockchain technology is in analyzing firms' data, the more likely it is that the undesirable equilibrium occurs. At the same time, this effect needs to be traded off with the improved information provision within the blockchain for a given reach—as s decreases, the efficiency of data analysis improves and so does the information provision by the blockchain. Overall, this highlights that it is not per se necessary that an increased efficiency of the blockchain improves the overall outcome in terms of the information provision in the economy.

C.9 Continuous types

To assess the robustness of our discrete main model, we consider the following setup which dispenses with the discreteness assumption in the fit dimension. There is a continuum of firms of mass 1. Each atomistic firm is of high value with probability λ, while its fit is drawn from the symmetric beta distribution with parameter $b \in (0, 1]$

so that the CDF $G(f)$ is given by $G(f) = I_f(b,b)$.[2] This parametrization allows us to vary the heterogeneity in fit via the parameter b: for $b \to 0$, the distribution becomes bi-modal and approaches the main model with independent fit and value dimensions and $\omega = \frac{1}{2}$, while $b = 1$ implies that the fit is uniformly distributed.

The remainder of the setup is unchanged. Firms simultaneously decide whether to adopt the blockchain. The informativeness of the blockchain's message depends on the mass of adopting firms ρ and the firm-specific fit f^i. Pooling prices are obtained by Bayes' rule.

It is clear that for high-value firms (low-value firms) the incentives to adopt (not adopt) are strictly increasing (decreasing) in the fit whenever a positive mass of firms adopts in equilibrium. We focus on a conjectured interior equilibrium characterized by cutoff fit levels f_h and f_l such that all high-value firms with $f^i \geq f_h$ adopt the blockchain, while all low-value firms with $f^i < f_l$ rely on traditional institutions of strength γ.

In this conjectured equilibrium, we obtain for the reach ρ:

$$\rho(f_h, f_l) = \lambda(1 - G(f_h)) + (1 - \lambda)G(f_l), \tag{C.103}$$

which in turn gives pooling prices:

$$p^I(f_h, f_l) = \frac{\lambda \int_{f_h}^{1} (1 - \rho(f_h, f_l)f)g(f)df}{\lambda \int_{f_h}^{1} (1 - \rho(f_h, f_l)f)g(f)df + (1 - \lambda) \int_{0}^{f_l} (1 - \rho(f_h, f_l)f)g(f)df} \tag{C.104}$$

$$p^O(f_h, f_l) = \frac{\lambda G(f_h)}{\lambda G(f_h) + (1 - \lambda)(1 - G(f_l))}. \tag{C.105}$$

[2]The corresponding PDF is $g(x) = \frac{x^{b-1}(1-x)^{b-1}}{B(b,b)}$, where $B(b,b) = \frac{\Gamma(b)^2}{\Gamma(2b)}$.

For the conjectured interior equilibrium, the cutoff types f_h and f_l need to be indifferent, which implies that they must solve:

$$\gamma + (1-\gamma)p^O(f_h, f_l) = \rho(f_h, f_l)f_h + (1-\rho(f_h, f_l)f_h)p^I - C \quad \text{(C.106)}$$

$$(1-\gamma)p^O(f_h, f_l) = \rho(f_h, f_l)f_l + (1-\rho(f_h, f_l)f_l)p^I - C. \quad \text{(C.107)}$$

For any given γ, C, and distribution parameters λ, b this can be implemented numerically. To illustrate the necessity of a numerical implementation, consider the case where $b = 1$ which implies that the fit is uniformly distributed so that $g(f) = 1$ and $G(f) = f$. In this case, we obtain:

$$\rho(f_h, f_l) = \lambda(1-f_h) + (1-\lambda)f_l \quad \text{(C.108)}$$

$$p^I(f_h, f_l) = \frac{\lambda(1-f_h)(2-\rho(1+f_h))}{\lambda(1-f_h)(2-\rho(1+f_h)) + (1-\lambda)f_l(2-\rho f_l)} \quad \text{(C.109)}$$

$$p^O(f_h, f_l) = \frac{\lambda f_h}{\lambda f_h + (1-\lambda)(1-f_l)}. \quad \text{(C.110)}$$

The equilibrium is therefore characterized by the solution to the system of equations:

$$f_l \frac{\lambda(1-f_h)(2-\lambda+\lambda f_h^2 - (1-\lambda)(1+f_h)f_l)}{2-\lambda+\lambda f_h^2-(1-\lambda)f_l^2}$$

$$= \frac{\lambda(1-f_h)(2-\lambda+\lambda f_h^2) - (1-\lambda)\lambda(1-f_h^2)f_l}{(\lambda(1-f_h)+(1-\lambda)f_l)(2-\lambda+\lambda f_h^2-(1-\lambda)f_l^2)} - \frac{(1-\gamma)\lambda f_h}{\lambda f_h + (1-\lambda)(1-f_l)} - C \quad \text{(C.111)}$$

$$f_h \frac{(1-\lambda)f_l(2-\lambda(1-f_h)f_l-(1-\lambda)f_l^2)}{2-\lambda+\lambda f_h^2-(1-\lambda)f_l^2}$$

$$= C + \gamma + \frac{(1-\gamma)\lambda f_h}{\lambda f_h + (1-\lambda)(1-f_l)} - \frac{\lambda(1-f_h)(2-\lambda+\lambda f_h^2) - (1-\lambda)\lambda(1-f_h^2)f_l}{(\lambda(1-f_h)+(1-\lambda)f_l)(2-\lambda+\lambda f_h^2-(1-\lambda)f_l^2)}, \quad \text{(C.112)}$$

which cannot be solved analytically.

For the numerical implementation which yields Figure 4.9 we proceed as follows. First, we fix the proportion of high-value firms λ and the fit-parameter b (for Figure 4.9, we set $b = 0.6$). Subsequently, we consider all combinations of $C \in \{-0.96, -0.92, \ldots, 0.92, 0.96\}$ and $\gamma \in \{0.03, 0.06, 0.09, \ldots, 0.99\}$ and:

(i) Numerically solve the system of equations given by (C.106) and (C.107) for the cutoff fits f_h and f_l.

(ii) If an interior solution $f_h \in (0,1), f_l(0,1)$ exists, we can compute the average mispricing in the interior equilibrium. Specifically, it stems from non-identified firms and is given by

$$\begin{aligned} AMP_{\text{intEQ}} &= (1-p^I(f_h,f_l)) \cdot \int_{f_h}^{1} (1-\rho(f_h,f_l)fg(f)df + p^I(f_h,f_l) \cdot \int_{0}^{f_l} (1-\rho(f_h,f_l)fg(f)df \\ &\quad +(1-\gamma)G(f_h)(1-p^O(f_h,f_l)) + (1-\gamma)(1-G(f_l))p^O(f_h,f_l). \end{aligned} \tag{C.113}$$

We can then compare whether it exceeds or does not exceed the average mispricing if blockchain were not available:

$$AMP_{\text{noBC}} = 2(1-\gamma)\lambda(1-\lambda). \tag{C.114}$$

We then plot each combination in black if an interior equilibrium exists and $AMP_{\text{intEQ}} > AMP_{\text{noBC}}$, in dark gray if an interior equilibrium exists and $AMP_{\text{intEQ}} < AMP_{\text{noBC}}$, and in very light gray if no interior equilibrium exists which implies existence of a corner equilibrium. The code to run the above for arbitrary parameters is available from the authors upon request.

C.10 Heterogeneous contribution to the blockchain

This appendix considers two extensions in which the type-specific probability of being identified, η_j, is modified relative to the main model. Specifically, we analyze a variant in which a bad fit does not result from an exogenous difference in transaction profiles but from differences in reporting qualities. We also analyze a variant in which low-value firms *strategically* falsify data entries.

For both model variants, we show that the undesirable $\{1,0,1,0\}$-equilibrium, which is the focus of our analysis, persists under conditions qualitatively similar to the main model. The main difference is that the reduced efficacy of the blockchain shrinks and shifts the range of outside verification levels γ that supports the undesirable equilibrium for a non-empty relative cost range of adopting the blockchain downwards due to the lowered marginal contribution of bad-fit (non-strategic misreporting) and low-value (strategic misreporting) types, respectively.

C.10.1 Non-strategic misreporting

Suppose a firm's fit relates to its reporting quality, with good-fit firms recording all of their transactions correctly and bad-fit firms recording their transactions correctly with probability β_b. False entries are non-strategic, i.e., the errors are unintentional. Consequently, a part of the bad-fit firms' transactions become unverifiable even if all counterparties in the transactions adopt the blockchain. As such, we incorporate the fact that false entries also exert a negative externality on the remaining firms in the blockchain, e.g., even if a counterparty in the transaction correctly records a given transaction, it would not be verified by the system because of the false entry.

Formally, we obtain the following. Denoting by q_j the probability that a $j \in \{hg, hb, lb, lg\}$-type firm adopts the blockchain, the firm-specific probabilities η_j of revealing the type within the blockchain become:

$$\begin{aligned} \eta_{Hg} &= \eta_{Lg} &&= \sigma_{hg}q_{hg} + \sigma_{lg}q_{lg} + \beta_b\left(\sigma_{hb}q_{hb} + \sigma_{lb}q_{lb}\right) \\ \eta_{Hb} &= \eta_{Lb} &&= \beta_b(\sigma_{hg}q_{hg} + \sigma_{lg}q_{lg}) + \beta_b^2\left(\sigma_{hb}q_{hb} + \sigma_{lb}q_{lb}\right). \end{aligned} \tag{C.115}$$

These probabilities arise from the fact that a good-fit firm contributes marginally more to the efficacy of the blockchain in terms of providing information about the other firms than any bad-fit firm. As in the main model, a good-fit firm continues to benefit more from the presence of another firm in the blockchain than a bad-fit firm.

From (C.115), it follows that the incentives to join the blockchain remain ordered for firms of the same value, i.e., $\Delta_{hg} \geq \Delta_{hb}$ and $\Delta_{lb} \geq \Delta_{lg}$, irrespective of the composition of firms within the blockchain, because the likelihood of being identified inside the blockchain remains higher for firms with a better fit. In general, it is straightforward that the qualitative results from the main model analysis directly carry over to this setting, with the only change being that the reach of the blockchain in a given equilibrium is instead given by $\rho = q_{hg}\sigma_{hg} + \beta q_{hb}\sigma_{hb} + q_{lg}\sigma_{lg} + \beta q_{lb}\sigma_{lb}$.

In particular, the undesirable $\{1,0,1,0\}$-equilibrium can be supported for some relative adoption costs C provided that:

$$\Delta_{hg} \geq \Delta_{lg} \wedge \Delta_{hb} \leq \Delta_{lb}. \tag{C.116}$$

In the conjectured $\{1,0,1,0\}$-equilibrium, we obtain $p_I = \frac{\sigma_{hg}\left(1-\sigma_{hg}-\beta_b\sigma_{lb}\right)}{\sigma_{hg}+\sigma_{lb}-\left(\sigma_{hg}+\beta_b\sigma_{lb}\right)^2}$ and $p_O = \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}}$. Together with (C.115), we can derive the Δ_j for each type $j \in \{hg, hb, lb, lg\}$. This gives:

$$\text{(C.116)} \iff \beta_b\left(\sigma_{hg} + \beta_b\sigma_{lb}\right) \leq \gamma \leq \sigma_{hg} + \beta\sigma_{lb}. \tag{C.117}$$

The finding is intuitive. Non-strategic misreporting transforms the reach of the blockchain in the equilibrium from $\sigma_{hg} + \sigma_{lb}$ (main model setting) to $\sigma_{hg} + \beta\sigma_{lb}$ as lb-firms contribute less to its efficacy. It follows that the overall range of outside verification levels γ supporting the undesirable equilibrium behaves qualitatively as the range in the main model but is adjusted downwards and shrinks, reflecting the overall lower efficacy of the blockchain relative to the traditional institutions.

C.10.2 Strategic misreporting

We next consider strategic misreporting. In our setting, low-value firms in the blockchain naturally have incentives to limit its efficacy to reduce the likelihood of being identified. However, they also face incentives to report correctly from considerations that are outside the model (e.g., enforcement, private litigation, etc.). Denote by β_s the minimum level of transactions that a low-value firm is willing to record correctly. To simplify expressions, we further assume that the transactions that are strategically misreported are random. As a result, low-value firms in the blockchain record exactly β_s of their transactions correctly to reduce information provision. The remaining assumption from the main model concerning the firms' fit still apply. Bad-fit firms have only a fraction β of in principle verifiable transactions, while all firms contribute equally to the blockchain's efficacy unless entries are strategically misreported.

Denoting by q_j the probability that a $j \in \{hg, hb, lb, lg\}$-type firm adopts the blockchain, the firm-specific probabilities η_j of revealing the type within the blockchain become:

$$\begin{aligned}
\eta_{Hg} &= \sigma_{hg}q_{hg} + \sigma_{hb}q_{hb} + \beta_s[\sigma_{lg}q_{lg} + \sigma_{lb}q_{lb}] \\
\eta_{Hb} &= \beta\left(\sigma_{hg}q_{hg} + \sigma_{hb}q_{hb} + \beta_s[\sigma_{lg}q_{lg} + \sigma_{lb}q_{lb}]\right) \\
\eta_{Lg} &= \beta_s\left(\sigma_{hg}q_{hg} + \sigma_{hb}q_{hb} + \beta_s[\sigma_{lg}q_{lg} + \sigma_{lb}q_{lb}]\right) \\
\eta_{Lb} &= \beta\beta_s\left(\sigma_{hg}q_{hg} + \sigma_{hb}q_{hb} + \beta_s[\sigma_{lg}q_{lg} + \sigma_{lb}q_{lb}]\right).
\end{aligned} \tag{C.118}$$

High-value firms record all in principle verifiable transactions correctly, while low-value firms only record β_s of them correctly. Hence, within the blockchain, counterparties have $\sigma_{hg}q_{hg} + \sigma_{hb}q_{hb} + \beta_s[\sigma_{lg}q_{lg} + \sigma_{lb}q_{lb}]$ of correctly recorded transactions, which need to be weighed by β if the firm itself is a bad-fit firm, and by β_s if it is a strategically misreporting low-value firm.

(C.118) implies that $\Delta_{hg} \geq \Delta_{hb}$ and $\Delta_{lb} \geq \Delta_{lg}$, irrespective of the composition of firms in the blockchain, because the detection probability is higher for good-fit firms of the same value. Focussing again on the conjectured $\{1, 0, 1, 0\}$-equilibrium, we obtain:

$$\begin{aligned}
p_I &= \frac{\sigma_{hg}(1-\sigma_{hg}-\beta_s\sigma_{lb})}{\sigma_{hg}(1-\sigma_{hg}-\beta_s\sigma_{lb}) + \sigma_{lb}\left(1-\beta\beta_s\left[\sigma_{hg}+\beta_s\sigma_{lb}\right]\right)} \\
p_O &= \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}}
\end{aligned} \tag{C.119}$$

and the condition for the existence of cost ranges supporting the equilibrium is given by:

$$
\begin{aligned}
& \Delta_{hg} \geq \Delta_{lg} \wedge \Delta_{hb} \leq \Delta_{lb} \\
\iff \quad & \gamma \leq \frac{(\sigma_{hg} + \beta_s \sigma_{lb})\left(\beta_s \sigma_{hg}(1 - \sigma_{hg} - \beta \sigma_{lb}) + \sigma_{lb}(1 - \beta_s^2(\sigma_{hg} + \beta \sigma_{lb}))\right)}{\sigma_{hg}(1 - \sigma_{hg} - \beta_s \sigma_{lb}) + \sigma_{lb}(1 - \beta \beta_s(\sigma_{hg} + \beta_s \sigma_{lb}))} \\
\wedge \quad & \gamma \geq \beta \frac{(\sigma_{hg} + \beta_s \sigma_{lb})\left(\beta_s \sigma_{hg}(1 - \sigma_{hg} - \beta \sigma_{lb}) + \sigma_{lb}(1 - \beta_s^2(\sigma_{hg} + \beta \sigma_{lb}))\right)}{\sigma_{hg}(1 - \sigma_{hg} - \beta_s \sigma_{lb}) + \sigma_{lb}(1 - \beta \beta_s(\sigma_{hg} + \beta_s \sigma_{lb}))}
\end{aligned}
\tag{C.120}
$$

Let

$$
\hat{\gamma} \equiv \frac{(\sigma_{hg} + \beta_s \sigma_{lb})\left(\beta_s \sigma_{hg}(1 - \sigma_{hg} - \beta \sigma_{lb}) + \sigma_{lb}(1 - \beta_s^2(\sigma_{hg} + \beta \sigma_{lb}))\right)}{\sigma_{hg}(1 - \sigma_{hg} - \beta_s \sigma_{lb}) + \sigma_{lb}(1 - \beta \beta_s(\sigma_{hg} + \beta_s \sigma_{lb}))}, \tag{C.121}
$$

we can rewrite (C.120) as $\beta\hat{\gamma} \leq \gamma \leq \hat{\gamma}$.

The relation of $\hat{\gamma}$ and $\sigma_{hg}+\sigma_{lb}$ determines how low-value firms' strategic misreporting affects the sustainability of the equilibrium. As expected, $\hat{\gamma} < \sigma_{hg} + \sigma_{lb}$ holds, i.e., the reduced efficacy of the blockchain due to strategic misreporting shifts the range of outside verification levels γ supporting the undesirable equilibrium downwards.

Lemma C10 *It holds that $\hat{\gamma} \leq \sigma_{hg} + \sigma_{lb}$.*

Proof. Proof: Note that $\hat{\gamma}$ is implicitly defined via $\Delta_{hg} = \Delta_{lg}$, where

$$
\Delta_{hg} = \eta_{Hg} + (1 - \eta_{Hg})p^I - \left[\gamma + (1 - \gamma)p^O\right] \text{ and } \Delta_{lg} = (1 - \eta_{Lg})p^I - (1 - \gamma)p^O. \tag{C.122}
$$

We get

$$
\begin{aligned}
\Delta_{hg} = \eta_{Hg} - (\eta_{Hg} - \eta_{Lg})p^I = \eta_{Hg} - (\eta_{Hg} - \beta_s \eta_{Hg})p^I &= \eta_{Hg}\left[1 - (1 - \beta_s)p^I\right] && \text{(C.123)} \\
&< \eta_{Hg} = \sigma_{hg} + \beta_s \sigma_{lb} && \text{(C.124)} \\
&< \sigma_{hg} + \sigma_{lb}, && \text{(C.125)}
\end{aligned}
$$

where (C.124) uses $q_{Hg} = q_{Lb} = 1, q_{hb} = q_{lg} = 0$ in the $\{1, 0, 1, 0\}$-equilibrium based on which these incentives are evaluated. □

It follows that the range of γ supporting the undesirable equilibrium—allowing for strategic misreporting gives a range of $[\beta\hat{\gamma}, \hat{\gamma}]$—also shrinks compared to the main model as:

$$(1-\beta)\hat{\gamma} \overset{LemmaC\ 10}{<} (1-\beta)(\sigma_{hg} + \sigma_{lb}). \tag{C.126}$$

C.11 Hybrid model

We consider the following setup. Let traditional institutions be as in the main model setup with their strength denoted by γ. The key difference is that traditional institutions also play a role for firms who adopt the blockchain. Specifically, for a firm adopting the blockchain, the probability of an informative message is given by $\rho \cdot f^i + \gamma^B$, where γ^B is the strength of traditional institutions for firms within the blockchain. We impose a one-to-one substitution whereby γ^B is set such that the expected probability of information revelation remains constant. We focus on the mixed-adoption equilibrium $\{1, 0, 1, 0\}$ where high-value good-fit and low-value bad-fit firms join the blockchain. In this equilibrium, we have $\rho = \sigma_{hg} + \sigma_{lb}$ and γ^B therefore solves:

$$\frac{\sigma_{hg}(\sigma_{hg} + \sigma_{lb} + \gamma^B) + \sigma_{lb}\left(\beta(\sigma_{hg} + \sigma_{lb}) + \gamma^B\right)}{\sigma_{hg} + \sigma_{lb}} = \gamma \iff \gamma^B = \gamma - \sigma_{hg} - \beta\sigma_{lb}. \tag{C.127}$$

Naturally, this imposes constraints to ensure $\gamma^B \geq 0$ and $\sigma_{hg} + \sigma_{lb} + \gamma^B = \gamma + (1 - \beta)\sigma_{lb} < 1$, i.e., to ensure that traditional institutions do not "destroy" information for firms inside the blockchain, while the detection probability for high-value good-fit types inside does not exceed one. As long as these are satisfied, the mixed-adoption equilibrium can always be supported for some level of relative adoption costs C. This is because the analogue to the condition in Proposition 4.2 is given by:

$$\rho + \gamma^B \geq \gamma \geq \rho\beta + \gamma^B, \tag{C.128}$$

which is generically satisfied as plugging in and simplifying yields:

$$\sigma_{hg}+\sigma_{lb}+\gamma-\sigma_{hg}-\beta\sigma_{lb} = \gamma+(1-\beta)\sigma_{lb} \geq \gamma \geq \gamma-(1-\beta)\sigma_{hg} = (\sigma_{hg}+\sigma_{lb})\beta+\gamma-\sigma_{hg}-\beta\sigma_{lb} \tag{C.129}$$

We can therefore obtain the pooling price inside the blockchain:

$$p^I = \frac{\sigma_{hg}(1-\gamma-(1-\beta)\sigma_{lb})}{(1-\gamma)(\sigma_{hg}+\sigma_{lb})}, \tag{C.130}$$

while the pooling price outside is as in the main model $p^O = \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lg}}$. If follows that the average mispricing in the economy in the mixed-adoption equilibrium is given by:

$$\begin{aligned} AMP_{ma} =& \sigma_{hg}(1-\sigma_{hg}-\sigma_{lb}-\psi)(1-p^I)+\sigma_{lb}(1-\beta(\sigma_{hg}+\sigma_{lb})-\psi)p^I \\ &+\sigma_{hb}(1-\gamma)(1-p^O)+\sigma_{lg}(1-\gamma)p^O \qquad \text{(C.131)} \\ =& 2\frac{\sigma_{hg}\sigma_{lb}\sigma_{lg}\left(1-\gamma+(1-\beta)\sigma_{hg}\right)\left(1-\gamma-(1-\beta)\sigma_{lb}\right)}{(1-\gamma)(\sigma_{hg}+\sigma_{lb})(\sigma_{hb}+\sigma_{lg})} \\ &+2\frac{\sigma_{hb}\left(\sigma_{hg}\sigma_{lb}(1-\gamma+(1-\beta)\sigma_{hg})(1-\gamma-(1-\beta)\sigma_{lb})+(1-\gamma)^2\sigma_{lg}(\sigma_{hg}+\sigma_{lb})\right)}{(1-\gamma)(\sigma_{hg}+\sigma_{lb})(\sigma_{hb}+\sigma_{lg})}. \end{aligned} \tag{C.132}$$

By comparing (C.132) with the average mispricing when the blockchain is not available, see (4.20), we can determine whether the negative impact of the blockchain's availability prevails when traditional institutions strategically respond. A full analytical treatment of this issue is beyond the scope of this paper, but we can obtain a straightforward numerical implementation which verifies that this is the case.

Specifically, we proceed as follows. We again restrict attention to the firm's value and fit being independent, with the probability of the firm being of high value given by λ and that of having a good fit vis-a-vis the blockchain given by ω. We then fix the fit parameter β and the strength of traditional institutions γ. Subsequently, we consider all combinations of $\lambda \in \{0.01, 0.03, 0.05, \ldots, 0.99\}$ and $\omega \in \{0.03, 0.06, 0.09, \ldots, 0.99\}$ and:

(i) Check whether the conjectured mixed-adoption equilibrium is well-behaved, i.e., satisfies:

$$0 \leq \gamma^B = \gamma - \overbrace{\lambda\omega}^{\sigma_{hg}} - \beta\overbrace{(1-\lambda)(1-\omega)}^{\sigma_{lb}} \text{ and } \gamma + (1-\beta)\overbrace{(1-\lambda)(1-\omega)}^{\sigma_{lb}} < 1.$$

(ii) If it is well-behaved, we check whether $AMP_{noBC} < AMP_{ma}$ by plugging $\sigma_{hg} = \lambda\omega, \sigma_{hb} = \lambda(1-\omega), \sigma_{lb} = (1-\lambda)(1-\omega), \sigma_{lg} = (1-\lambda)\omega$ in (4.20) and (C.132).

We then plot each combination in black if (i) is satisfied and $AMP_{noBC} < AMP_{ma}$, in gray if (i) is satisfied and $AMP_{noBC} > AMP_{ma}$, and in very light gray if (i) is not satisfied.

The code to run the above for arbitrary parameters is available from the authors upon request. Figure 4.10 obtains for $\beta = 0.45$ and $\gamma = 0.75$.

C.12 Refinements – Intuitive Criterion

This section analyzes whether applying the Intuitive Criterion helps to further restrict the regions under which the full adoption ({1,1,1,1}) and non-adoption ({0,0,0,0}) equilibria are sustainable, respectively. The intuitive criterion eliminates equilibria if there are types who benefit from a deviation that yields them a payoff above their equilibrium payoff as long as other players do not assign a positive probability to the deviation having been made by types for whom this action is equilibrium dominated.

Non-Adoption Equilibrium

We start by considering {0,0,0,0}. We have established that this can be supported in equilibrium if and only if $C \geq -(1-\gamma)\sigma_h$, see Lemma C 1. Denote by μ the belief held by the market about the value of non-identified adopting firm. μ is not determined on the equilibrium path, but naturally constrained to be $\mu \in [0,1]$. Off the equilibrium path, all firms earn $\mu - C$ upon deviating as the blockchain's reach is equal to zero – this is maximized for $\mu = 1$. On the equilibrium path, high value firms earn $\gamma + (1-\gamma)\sigma_h$, while low value firms earn $(1-\gamma)\sigma_h$. It follows immediately that adoption is equilibrium dominated for low value firms if and only if $(1-\gamma)\sigma_h > 1 - C \iff C > 1-(1-\gamma)\sigma_h$. For sufficiently high costs, it would hence be clear that an adopting firm can not be of low value – the intuitive criterion would eliminate this equilibrium provided that high value firms prefer to deviate, i.e. provided that $1 - C > \gamma + (1-\gamma)\sigma_h \iff C < 1-\gamma-(1-\gamma)\sigma_h$. Clearly, this cannot hold simultaneously with the previous restriction. As such, the intuitive criterion does not reduce the region for which {0,0,0,0} is supported.

Note that this is intuitive – to eliminate the equilibrium, adoption would need to be associated with high value firms *and* low value firms need to still prefer to not adopt. But because high value firms earn a higher payoff on-path while off-path payoffs are identical (and driven solely by off-path beliefs), they then also prefer not to adopt.

Full Adoption Equilibrium

We next consider {1,1,1,1}. This can be supported in equilibrium if and only if:

$$C \leq \min\{0, \beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - \gamma\}. \tag{C.133}$$

On-path payoffs are given by $1-C$ for hg-firms, $\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - C$ for hb-types, $(1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - C$ for lb-types, and $-C$ for lg-types. Off-path, low value firms would earn $(1-\gamma)\mu$, while high value firms would earn $\gamma + (1-\gamma)\mu$, respectively, where μ parametrizes the off-path belief that a non-identified non-adopting firm is of high value. Note that non-adoption is equilibrium dominated for lg-types whenever $(1-\gamma) < -C \iff C < -(1-\gamma)$, equilibrium dominated for lb-types whenever:

$$(1-\gamma) < (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - C \iff C < -(1-\gamma) + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}, \tag{C.134}$$

and never equilibrium dominated for high value firms.

Consider hence first the case where $C < -(1-\gamma)$. If the market observes non-adoption, they would know that it could not have been by a low-value firm. An hg-firm would also not choose to not adopt as it earns $1 - C > 1 \geq \gamma + (1-\gamma)\mu$ on path. Thus, the Intuitive Criterion would eliminate this equilibrium only if we have for hb-firms that:

$$\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} - C < 1 \iff C > -\left[1 - \left(\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}\right)\right]. \quad \text{(C.135)}$$

The question is therefore whether the two inequalities can hold simultaneously. For this, we require that:

$$\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} < \gamma \iff \frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}} < \frac{\gamma-\beta}{1-\beta}. \quad \text{(C.136)}$$

If this condition holds, the Intuitive Criterion eliminates the {1,1,1,1}-equilibrium for intermediate benefits of adoption, $C \in \left(-\left[1 - \left(\beta + (1-\beta)\frac{\sigma_{hb}}{\sigma_{hb}+\sigma_{lb}}\right)\right], -(1-\gamma)\right)$.

When $C \geq -(1-\gamma)$, non-adoption is not equilibrium dominated for lb-type firms. Hence, the intuitive criterion cannot eliminate this equilibrium in this case as the off-path belief $\mu = 0$ remains viable.

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Curriculum Vitae

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