IT Service Disruptions and Provider Choice

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Digital supply chains are increasingly interconnected and vulnerable to disruption, causing service interruptions impacting many firms and their customers. Combating threats to the digital supply chain is the top challenge for leaders in most supply chain industries, demonstrated by the tacit approval of nation-states for cyber-attacks on corporate supply chains to disrupt downstream firms.

Disruptions to digital supply chains are not new. In April 2019, hundreds of flights in the United States were delayed when a critical service provider, AeroData, had a computer systems failure. AeroData delivers flight planning services to many airlines, including Southwest, United, American, and Delta. All flight operations for AeroData's more than 100 clients simultaneously ceased, and thousands of customers were stranded at airports across the country. In an increasingly connected business environment, competitors may be simultaneously disrupted due to a common service provider, impacting all affected firms' demand.

The synchronization of disruptions for firms that use a common service provider has implications for service provider choice and investment. We use a two-stage game to model how a firm's customer demand is impacted by disruptions at a service provider, and how this subsequently affects the firms' choices in managing service provider risk. Considering downstream demand effects from upstream service disruptions, the contribution of this article is the examination of how risk synchronization impacts provider choice decisions and profits. In addition, we illustrate how these choices impact upstream industry concentration.

CCS Concepts: • **Applied computing** → **Supply chain management**; *Economics*; • **Security and privacy** → **Economics of security and privacy;**

Additional Key Words and Phrases: Digital supply chain strategy, service provider choice, service disruption, risk synchronization

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1 Introduction

Service supply chains are vulnerable to digital disruption. Russia has purportedly endorsed cyber-attacks on corporate supply chains in an attempt to disrupt downstream firms [52, 67]. According to Gartner [3], the security of internet-connected facilities and assets is the top challenge for leaders in supply chain industries, generating increased interest in research on supply chain risk and resilience [65]. Regardless of the cause of digital disruption, suppliers seldom serve a single firm, and effects of disruptions fan out to affect many downstream firms and their customers. For example, in April 2019, hundreds of flights in the United States were delayed when a critical service provider, AeroData, had a computer systems failure [18]. AeroData delivers flight planning services to many airlines, including Southwest, United, American, and Delta. All flight operations for AeroData's more than 100 clients simultaneously ceased. This illustrates how, in an increasingly connected business environment, client firms (who may even be competitors) are simultaneously impacted by disruptions in the digital supply chain. Contrast this with a similar disruption with weight calculation impacting only Alaska Airlines and Horizon (wholly owned by Alaska) customers [62].

Firms across a variety of markets often use common service providers, especially in the **information technology (IT)**-enabled digital supply chain context, where service providers offer data management and IT-enabled functionality that would be too expensive for firms to produce in-house [47]. Disruptions at these upstream service providers can negatively impact their downstream client firms' demand [8, 14, 34]. Disruptions can occur for both small and large providers but are more visible when they happen at large-scale providers. For example, disruptions at Amazon Web Services have caused major outages in Netflix, Airbnb, Dropbox, Instagram, and many other firms over the past decade, and have disrupted these firms' demand [37]. Moreover, IT has penetrated utility networks resulting in complex IT-driven systems such as the smart grid, where the security and reliability are critical and disruptions catastrophic [43]. These disruptions are not limited to service interruptions but also security breaches of the firms' information assets. We refer to security and reliability risks to downstream firms due to incidents, breaches, and attacks at the upstream service provider collectively as *disruptions.*

Other than the direct impact on affected client firms, when a disruption occurs, it may indirectly impact a non-disrupted firm through spillovers. The spillover depends on the structure of competition between competing firms and the customer attribution of responsibility to the firms. In case of customers attributing responsibility for the disruption to a specific firm, customers may switch to an unaffected firm. In this case, there is a positive spillover of end-customer demand from one downstream firm to another due to the disruption. In other cases, disruptions may be attributed to an intrinsic characteristic of the industry, and customers may abandon the industry or product/service altogether, at least temporarily, in the event of a disruption. In other words, there is a negative spillover from disruptions. This appears to be especially true in emerging technology markets, where customers tend to lose trust in case of a service disruption. For example, it is believed that users lost trust in smart speakers after it was revealed that user conversations were being leaked [25, 64]. In another example, an exploited vulnerability within the smart contracts platform of a prominent blockchain software (Ethereum) caused a customer backlash for many platforms using smart contracts, including in contexts of buyer-supplier relationships and the sharing economy [40, 59]. Such spillovers are also of interest to risk assessment and aggregation in the context of cyber-security risk, where catastrophic disruptions can have industry-wide implications for multi-party losses or cascading service disruptions [57, 58].

If firms use a common service provider, there is an increased probability of simultaneous disruptions in multiple downstream firms' operations originating from disruptions at the upstream provider. For example, a breach at Experian affected 15 million T-Mobile customers [49]; breached automatic update servers of the Korean software company ESTsoft spread malware to its customers resulting in a data breach affecting 35 million South Koreans [35]; a vulnerability in Adobe Acrobat Reader impacted all users of the software [13]; and an Epsilon breach exposed customer names and e-mail addresses for a wide range of clients including Chase and Best Buy [12]. Although firms cannot eliminate the probability of a disruption at their service providers, they can desynchronize the impact of provider disruptions on their demands by choosing different providers from their competitors. Moreover, firms not only pay to use services from providers such as AeroData but also must invest in interoperability to connect their systems and those of the service provider, where interoperability is with respect to functionality, reliability, and security. Interoperability is particularly important for technology-enabled supply chains that need to integrate their business processes and information systems [60]. For AeroData, this includes data on flight loading and plane capacity to calculate flight planning. In many cases, especially for small upstream service providers in niche markets, this investment indirectly benefits the provider's operations and service. Through transfer of knowledge and adoption of best practices, firms' investments help providers improve the service for all clients. In other cases, the investment in provider quality may be more explicit through contracting mechanisms such as price rebates and warranties [32, 63].

We focus on disruptions in digital supply chains, although physical supply chains are also subject to digital disruption. Physical supply chains involve the movement and management of physical goods from suppliers to end consumers, and require robust logistics and transportation networks and storage facilities to move goods. Scalability is complex and requires resources and time. In contrast, digital supply chains manage digital products and services, such as software, digital media, and online services, and focus on the efficient movement of data and information rather than physical goods. Instant delivery is possible, and no physical storage (or warehousing) is needed. Scalability is typically more easily achievable in digital supply chains and can be dynamic in nature. Digital supply chains require robust cyber-security measures to protect against data breaches and intellectual property theft. Combining the near-instant lead times with security concerns, disruptions in digital supply chains can traverse the entire chain nearly instantaneously, offering little (or no) ability for downstream partners to intervene or make alternate arrangements. Both types of supply chains are critical in their respective domains and can also overlap, such as when a company deals in both physical products and digital services.

One author's extensive prior discussions with a major auto manufacturer in Shanghai from 2011 to 2013 provided initial inspiration for this project. These discussions focused on investment options to induce their parts suppliers to join their ERP platform. The decision to share a supplier in this setting could mean splitting the cost of moving the supplier onto ERP, or it could mean that your competitor free-rides off of your investment. Disruptions in the ERP context came from disruptions in the supply chain and customization of the ERP software. An understudied aspect related to the supply chain selection problems of the Shanghai auto manufacturer is the selection of IT suppliers based on the synchronization of disruption risks due to common service providers.

To understand what issues organizations (firms) face with respect to the synchronization of disruption risks in the IT context, we engaged in informal discussions with executives and managers from a variety of industries and holding different positions within their firms. We spoke with a founder of a software firm, operations managers, security managers, and customer support managers. Our discussions included professionals at start-up companies as well as well-established firms. Some are providers of cloud-based services themselves, whereas others are solely consumers of such services. From these conversations, we heard that knowing a competitor might share an IT supplier is a consideration, given first that potential providers meet functionality requirements. Some executives remarked how there is only one provider that can fully meet their functionality requirements, so even though it might be nice to de-couple disruptions from their competitors, it may not always be feasible. Another executive mentioned they made strategic choices about using providers that had their 'aspirational' competitors as customers. In other words, they looked at which providers the "next size up" competitors in their industry use, choosing the same vendors as them to build a path for growth. Thus, there is a very clear awareness of who the significant competitors are and which upstream providers each competitor is using, and the cost of downtime by upstream providers is clearly understood. The preceding examples indicate that the problem examined in this article is relevant to practitioners.

We investigate a firm's choice of whether to synchronize upstream provider disruptions with other firms by using a common service provider or to de-synchronize provider disruptions by using different providers, in the presence of firms' downstream demand reactions to disruptions. Upstream disruptions at a particular service provider that propagates to a downstream firm causes a direct negative effect on the demands of firms using that provider, an effect we call *demand loss*. In addition, a disruption realized at one firm may positively or negatively impact the demands of other firms (that may be disrupted or not), an indirect effect we call *spillover*. The spillover from a disruption can either be positive or negative, depending on what the customers attribute a disruption to, as explained earlier.

We find that if service providers are similarly effective in addressing disruptions, then a firm's choice to synchronize disruptions through the use of a common provider is optimal only where there is a relatively large positive spillover from disruptions between the firms, as is often the case in industries with well-established demand. Firms choose different providers if either (a) spillover is negative, (b) there is no spillover, or (c) they have a limited positive spillover. The choice of different providers is especially desirable where the spillover is negative, such as in emerging technology industries where customer demand is less established. If one of the upstream providers (either common or different) is more effective in addressing disruptions, then, as expected, firms' preference for that provider increases. Specifically, only where the common provider offers higher effectiveness than the different providers would firms with negative spillover choose a common provider. We also find that if the disruptions to different service providers are correlated, such as where providers use similar technologies or standards, then the common provider is preferred. However, if one firm's demand is more sensitive to disruptions, then that firm's preference for the common provider diminishes due to free-riding from the less sensitive firm.

Our work provides implications for service providers and their client firms. We show that the synchronization or de-synchronization of disruptions through use of a common provider or different providers, respectively, is an underappreciated factor that should be considered when choosing providers. Contrary to the literature on service provider choice, which predicts an indifference between common and different providers, we show that even if providers offer the same effectiveness in their service, firms may choose either a common provider or different providers given the risk of demand reactions to disruptions. In choosing providers, firms should consider not only the basic characteristics of providers such as price, effectiveness, and compatibility but also the potential for demand spillovers from disruptions with their competitors. Additionally, our work proposes an alternative mechanism by which the downstream demand spillover from disruptions impacts upstream industry's concentration and competition. As described previously, a large positive disruption spillover at firms encourages use of a common provider and therefore increases the upstream industry concentration. This sheds light on a demand mechanism by which upstream providers can become more prominent and concentrated in industries with positive spillover from disruptions. In contrast, the same mechanism encourages more providers and less concentration in industries with negative spillover from disruptions.

2 Literature Review

Service providers, such as AeroData, Amazon Web Services, Experian, and ESTsoft, are important supply chain partners across many industries. The importance of supply chains is such that the survival of firms in the modern business environment is ascribed more to the competition among supply chains rather than competition among firms [27].

Supply chain disruptions are generally more severe than disruptions occurring at firms, and supply chain design is a key factor in moderating the severity of a supplier-induced disruption [24]. The supply chain literature has addressed several important issues related to such partnerships. For example, risk pooling has been suggested as a beneficial tool for inventory management under demand uncertainty, whereas risk diversification is preferred when the threat of supply chain disruption is high [48] or when disruptions are rare but cause catastrophic damage [33].

In supply chains for physical products, lead times play a large role in mitigating disruption risks and inform decisions to cluster suppliers near the firm or develop a geographically dispersed set of suppliers [39]. When faced with an unreliable shared supplier, studies have examined when to dual-source with a separate supplier [19, 68] or invest directly in the shared supplier to improve its reliability despite possible spillover benefits to their competitor [70]. We consider supply chain strategies in the context of digital supply chains with non-significant lead times.

More recently, disruptions in digital supply chains have raised concern. Most of the research in this area focuses on building robust infrastructures which facilitate multiple users in both single- and multi-tenant cloud-hosting service environments [9, 26]. The rise of multi-tenancy in provision of digital services, especially cloud services, has also given rise to elevated concerns about security and homogeneity of disruptions [50]. The correlation of disruptions in cyber-security is particularly of interest to cyber-insurance [56].

Service provider networks with multiple client firms have emerged in some markets where generic products or services allow providers to transfer knowledge and expertise to downstream firms, attracting additional firms that operate in the same market [66]. Although customers may benefit from such capacity and expertise pooling, there remains a risk where intellectual property may leak between client firms [66] or tainted ingredients and components make their way into products or services of all or many client firms [23]. In an interdependent risk setting with one retailer and multiple suppliers, security decisions made independently lead to under-investment by all participants due to free-riding while joint decision making improves security outcomes [46]. We do not consider sharing or pooling of resources or information; rather, we study the effects of the synchronization or de-synchronization of disruptions stemming from the choice of service provider.

Demand reaction in response to security or service failures has been used to study firm security investments, outsourcing choices, and innovation [17, 44, 72]. Unlike Kolfal et al. [44], who use a continuous time Markov chain model to analyze the impact of downstream demand reaction to disruptions on firms' security investment, we consider the comparison between common provider or different providers, where firms optimize profits by adjusting their investments. We analyze the optimal choice under different demand loss and spillover scenarios and consider similar interactions between the firms in case of disruptions which result in demand interactions.

How supply chain partners handle disruptions makes a significant difference in outcomes, turning a negative event into an opportunity such as improved customer satisfaction through appropriate communication and recovery actions taken by the supplier [20] or opportunistic innovation if the digital supply chain has sufficient capacity [41]. The impact of disruptions on the choice of cloud-based shared service providers has received less attention.

Provider disruptions in supply chains have been studied in relation to provider competition, diversification, and wholesale prices [6], the supply chain structure and resulting firm profits [11], and for their impact on sourcing and overlap decisions in multi-tier provider networks [2]. Provider diversification as a hedge against provider disruptions is well studied under different settings [6, 21].

In a similar vein, the effectiveness of business continuity programs in limiting damage from supply chain disruptions has been empirically validated by Azadegan et al. [5]. The works mentioned thus far, however, do not study the implications of using common or different providers for the firms. We address the strategic choice of whether to use a common or different service provider from that of competitor firms in presence of downstream demand reactions to disruptions at the supplier level.

Research in the supply chain literature has studied supplier concentration by focusing primarily on the buyer-supplier dynamics. Meena and Sarmah [51] determine both the optimal number of suppliers and order allocation with an MINLP formulation, given there is risk of supply chain disruptions and demand is stochastic. Mis-coordination among downstream firms (buyers) can lead to upstream (supplier) concentration; if buyers are weakly competitive, then equilibrium results in no new supplier entry and higher prices; with moderate competition, there is still no new entry but the prices are not as high; and finally, with strong competition, new entry occurs and prices are lower [28]. Additionally, cooperative investment by downstream firms or even rival firms may be used to improve the product created by an upstream supplier, leading to lower costs for the buyers, although it does not necessarily lead to upstream concentration [30]. These works examine the wholesale buyer-supplier dynamics without including the end-consumer demand impacts on the supply chain.

A related research stream is information sharing in the supply chain, where the focus is on information sharing between partners to improve supply chain efficiency (e.g., 15, 38, 42, 55, 22). For example, in the case of a **Managed Security Service Provider (MSSP)**, providers learn from servicing one firm and this learning naturally accrues to other client firms [16]. Benefits have been found for sharing information regarding IT security across a market, as this learning enables better investment decisions [29, 36], although it may also reduce the competitive advantage for any one firm. Even though we consider interoperability investments that can help providers improve their service, our analysis differs in that we consider firms' risks from using a common service provider to that of competitors and the impact of risk synchronization on provider choice.

Much of the work on choosing a cloud-based service provider focuses on defining and enforcing service level agreements, contract negotiation, and monitoring. Given the complexity of requirements in choosing a cloud service provider, multi-criteria decision analysis has become a popular approach [53, 69]. Research relevant to our study centers around versioning and vertical differentiation. Vendors provide different versions of software with different prices if version-specific security externalities are present [4], and capacity constraints affect firms' decisions on pricing and service level offerings [73]. Vertical differentiation has also been shown to have an impact on the quality of product offerings [10]. Wu et al. [71] study the investments of both MSSPs and clients when clients outsource security to an MSSP, and propose different types of contracts to address moral hazard issues. In our article, we consider such potential investments by clients to ensure interoperability with the provider's systems. This may be accomplished through mechanisms identified in the literature on contracting, where providers are encouraged to invest a portion of firm spending in improving quality or capacity [7, 32, 45, 63]. Along with investment, contracts may also use incentives and inspection as levers to align quality goals of supplier and buyer [45].

Outsourcing decisions in the development or support of software are often important aspects to study. For example, Zimmermann et al. [74] analyze make-or-buy decisions in the context of web services where there is an option to sell the product of internal development. Treating the synchronization or desynchronization of disruptions as exogenous, Cezar et al. [17] study how upstream *provider* characteristics (quality and interdependency) impact the decision to in-source or outsource IT security services. We extend this avenue of work by studying the impact of downstream firms' demand loss and spillover from provider disruptions on provider choice. We provide insights that both complement and contrast with the findings of Cezar et al. [17], demonstrating that even when upstream service providers are similarly robust to disruptions, the choice of common or different providers depends on the degree and the direction (sign) of spillover from disruptions among competitors.

To summarize, reliable supply chains are critical in modern enterprises. Studies of physical supply chains provide only partial guidance for digital supply chains; there remains much we do not understand. This work is a step toward better understanding the complex system of markets, firms, and digital service providers in the digital supply chain, where lead times are not significant. By studying the demand effects of the synchronization or de-synchronization of disruptions stemming from the choice of service provider, we can better understand where market forces may lead to increased digital service provider concentration or diversification. While we consider interoperability investments that can help providers improve their service, our analysis differs from existing literature in that we consider firms' risks from using a common service provider to that of competitors and the impact of risk synchronization on provider choice.

With Table 1, we summarize the general literature and situate our work in the larger body of work in supply chain disruptions. While we have identified many dimensions of risk impacts in the literature, to our knowledge, there are no other studies that examine how downstream demand reactions to disruptions impact a firm's decision to use the same or a different provider than its rival firm. By explicitly modeling the link between end-customer demand and firms' choices, we further contribute to greater understanding of consolidation or diversification of upstream, provider industries.

3 Setup, Notation, and Assumptions

We consider a setting with two symmetric profit-maximizing firms. Each firm $i \in \{1, 2\}$ plans to source the intermediate service or product it needs from a provider. Without loss of generality, we use the terms *service* and *service provider* to refer to both the service and products. Firms can choose between a common provider or different providers, which are similarly effective in addressing disruptions *ex ante*. Firms also decide their investment in provider as well as interoperability to connect their systems with those of their chosen service provider, where interoperability increases functionality, reliability, and security of their provider [60]. The service provider market is competitive and includes suppliers whose investment in interoperability can be influenced by a contract with the firm, which focuses our analysis on small and niche providers. The investment can improve the provider's service indirectly, such as through transfer of knowledge and expertise from firms to the provider [16, 29], or through explicitly defined terms in the contract between firms and provider which allocate a portion of firm spending to be invested in a provider's operations and service. Contract design offers tools for contracting a portion of the firms' spending to

Table 1. Summary of Relevant Literature

Related Literature	SC Context		Risk ID & Impact		Risk Mitigation & Strategic Decisions						
	Physical	Digital	Disruption & Failure	Demand Reaction	Quality	Information Sharing	SLAs, Contracts	Outsource Infrastructure	Outsource Development	Diversify	Consolidate
Jeong et al. [41] Opportunistic innovation in the age of digital services. *JOM*, 2022.		X	X						X	X	
Yeo et al. [72] How customer demand reactions impact technology innovation and security. *ACM TMIS*, 2022.		X	X	X	X						
Goldschmidt et al. [33] Strategic sourcing under severe disruption risk: Learning failures and under-diversification bias. *MSOM*, 2021.	X		X							X	X
Wu et al. [71] Managing information security outsourcing in a dynamic cooperation environment. *JAIS*, 2021.		X					X				
Azadegan et al. [5] Supply chain disruptions and business continuity: An empirical assessment. *Dec. Sci.*, 2020.	X		X								
Cheng et al. [20] When is the supplier's message "loud and clear"? *Dec. Sci.*, 2020.	X		X	X							
Li and Xu [46] Cybersecurity investments in a two-echelon supply chain with third-party risk propagation. *IJPR*, 2020	X		X	X							
Mohamed and Abdelsalam [53] A multicriteria optimization model for cloud service provider selection in multicloud environments. *Software: P&E*, 2020		X									
Tricomi et al. [69] Optimal selection techniques for cloud service providers. *IEEE Access*, 2020.		X			X						
Bimpikis et al. [11] Supply disruptions and optimal network structures. *Mgmt. Sci.*, 2020.	X		X	X							
Chod et al. [21] Supplier diversification under buyer risk. *Mgmt. Sci.*, 2019.	X									X	
Gambardella and von Hippel [30] Open sourcing as a profit-maximizing strategy for downstream firms. *Strat. Sci.*, 2019.	X				X						
Maroc and Zhang [50] Cloud services security evaluation for multi-tenants. *IEEE ICSPCC*, 2019.		X			X						
Lee and Li [45] Supplier quality management: Investment, inspection, and incentives. *POM*, 2018.	X		X		X		X				
Ang et al. [2] Disruption risk and optimal sourcing in multi-tier supply networks. *Mgmt. Sci.*, 2017.	X		X	X							
Cezar et al. [17] Sourcing information security operations: The role of risk interdependency and competitive externality in outsourcing decisions. *POM*, 2017.		X	X	X				X			

(Continued)

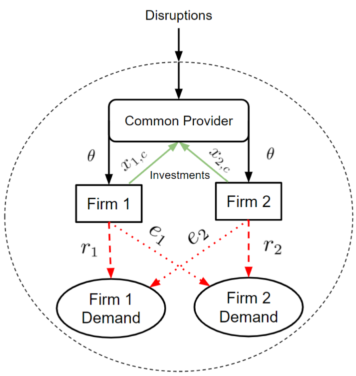
Table 1. Continued

Related Literature	SC Context		Risk ID & Impact		Risk Mitigation & Strategic Decisions						
	Physical	Digital	Disruption & Failure	Demand Reaction	Quality	Information Sharing	SLAs, Contracts	Outsource Infrastructure	Outsource Development	Diversify	Consolidate
Gao et al. [32] Incentives for quality improvement efforts coordination in supply chains with partial cost allocation contract. *IJPR*, 2016.	X						X				
Zimmermann et al. [74] Exposing and selling the use of web services—An option to be considered in make-or-buy decision making. *DSS*, 2016.		X							X		
Habermann et al. [39] Keep your friends close? Supply chain design and disruption risk. *Dec. Sci.*, 2015.	X		X							X	X
August et al. [4] Cloud implications on software network structure and security risks. *ISR*, 2014.		X					X			X	
Chen and Guo [19] Strategic sourcing in the presence of uncertain supply and retail competition. *POM*, 2014.	X		X							X	
Meena and Sarmah [51] Mitigating the risks of supply disruption under stochastic demand. *IJSEM*, 2014.	X		X								
Wang et al. [70] Improving reliability of a shared supplier with competition and spillovers. *EJOR*, 2014.	X						X				
Choi et al. [22] Will a supplier benefit from sharing good information with a retailer? *DSS*, 2013.	X					X					
Kolfal et al. [44] Market impact on IT security spending. *Dec. Sci.*, 2013.	X	X	X	X							
Tang and Kouvelis [68] Supplier diversification strategies in the presence of yield uncertainty and buyer competition. *M&SOM*, 2011.	X									X	
Bezemer and Zaidman [9] Multi-tenant SaaS applications: Maintenance dream or nightmare? *Proc. IWPSE-EVOL*, 2010.		X	X					X			X
Zhang et al. [73] Price competition with service level guarantee in web services. *DSS*, 2009.		X	X				X	X	X		
Bhargava and Choudhary [10] Research Note: When is versioning optimal for information goods? *Mgmt. Sci.*, 2008.		X			X						
Cleeren et al. [23] Weathering product-harm crises. *J. Acad. Mark. Sci.*, 2008.	X		X	X							
Demirkan and Cheng [26] The risk and information sharing of application services supply chain. *EJOR*, 2008.		X	X			X		X			

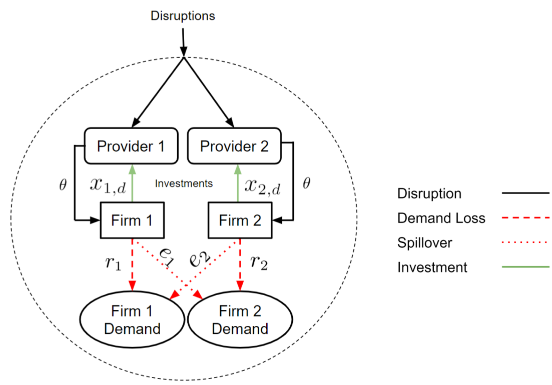
(Continued)

Table 1. Continued

Related Literature	SC Context		Risk ID & Impact		Risk Mitigation & Strategic Decisions						
	Physical	Digital	Disruption & Failure	Demand Reaction	Quality	Information Sharing	SLAs, Contracts	Outsource Infrastructure	Outsource Development	Diversify	Consolidate
Fumagalli and Motta [28] Buyers' miscoordination, entry and downstream competition. *Econ. J.*, 2008.	X										X
Ha and Tong [38] Contracting and information sharing under supply chain competition. *Mgmt. Sci.*, 2008.	X					X	X				
Babich et al. [6] Competition and diversification effects in supply chains with supplier default risk. *MSOM*, 2007.	X		X	X							
Craighead et al. [24] The severity of supply chain disruptions: Design characteristics and mitigation capabilities. *Dec. Sci.*, 2007.	X		X							X	
Ojala and Hallikas [55] Investment decision-making in supplier networks: Management of risk. *IJPE*, 2006.	X						X				
Kelle and Akbulut [42] The role of ERP tools in supply chain information sharing, cooperation, and cost optimization. *IJPE*, 2005.	X					X					
Sturgeon and Lee [66] Industry co-evolution and the rise of a shared supply-base for electronics manufacturing. *N&W Conf.*, 2001.	X									X	X
Cachon and Fisher [15] Supply chain inventory management and the value of shared information. *Mgmt. Sci.*, 2000.	X					X					
Reyniers and Tapiero [63] The delivery and control of quality in supplier-producer contracts. *Mgmt. Sci.*, 1995.	X						X				
Bakos and Brynjolfsson [7] Information technology, incentives, and the optimal number of suppliers. *JMIS*, 1993.		X					X				
Our Contribution		X	X	X				X		X	X



(a) Common Provider



(b) Different Providers

Fig. 1. Interactions among providers, firms, and customers.

be invested to improve the provider's operations and service in a vertical supply chain setting such as ours—for example, through price rebates and after-sales warranties [63], partial cost allocation [32], and other incentives [45].

We take the service provision to be commercially infeasible to be done in-house so that insourcing is not optimal for firms. There is no strategic game between providers in our model. The mechanism for determining to use a common or different provider is as follows. We assume two identical providers $j \in \{1, 2\}$ with equivalent properties in terms of quality. Without loss of generality, Firm 1 chooses its provider first, and Firm 2 follows. Because the two providers are identical, Firm 1 is indifferent in choosing between the two providers. Firm 2's decision, however, determines whether the firms have a *common provider* or *different providers*. If Firm 2 chooses the same provider as Firm 1, then the two firms use that common provider, and otherwise they have different providers. In this article, our focus is on the comparison of the two provider choices in a steady-state (or long-term) equilibrium, where the choices of common or different providers have been established.[1] We discuss the Nash equilibria that result from this setup in Section 4.3. If firms use the common service provider, then both firms may be impacted when a disruption occurs at that provider. In other words, disruptions are synchronized. If firms use different service providers, then a disruption at one provider may only directly impact the firm using that provider. Therefore, when using different service providers, direct firm disruptions are de-synchronized. Figure 1 depicts the two possible provider choice structures. We denote the two possible provider structure choices as $k \in \{c, d\}$, for the common and different provider choices, respectively. Firms then optimize their investment in the provider as well as in interoperability to connect their systems with their chosen service providers, where interoperability refers to functionality, reliability, and security. Investing directly in a provider's reliability has been examined in a physical setting where it is shown to be a rational choice even if there are spillover benefits to the competitor [70]. Our analysis focuses on the comparison of the common and different provider choices. The notation in the figure is explained later in this section. The table of notation is provided in Table 2.

Given firms' service provider choice (common or different), they simultaneously set their investment with their chosen provider. By investing more, firms can acquire more robust service

[1]In most industries, firms' chosen providers are common knowledge, as this can be inferred from the operation and system processes that firms exhibit. Additionally, industry insight publications from consulting firms often expose the supply chain networks and providers themselves advertise their clients to signal prominence. In the long term, firms can use this information to converge to common or different providers as their preferences dictate.

Table 2. Notation

Notation	Definition
$x_{i,k}$	Firm i's investment with its provider per unit of demand under provider structure choice k, $x_{i,k} \in [0, \bar{x}]$
S_k	Set of joint provider states for different ($k = d$) and common ($k = c$) providers
F_k	Set of joint firm states for different ($k = d$) and common ($k = c$) providers
$D_{i,f}$	Firm i's demand when firms are in joint state f
θ	Propagation probability that a disruption at a provider impacts firm(s) using that provider, $\theta \in (0, 1]$
v	Baseline vulnerability or disruption probability, $v \in (0, 1]$
α	Relative effectiveness of different providers to the common provider, $\alpha \in (0, \bar{\alpha}]$
r_i	Firm i's demand loss, $r_i \in [0, 1]$
e_i	Firm i's spillover on firm j, $e_i \in (-1, 1)$
π	Firm's marginal profit before investment, $\pi \geq x_{i,k}$

from the provider, which we translate into a lower probability of disruption at the provider. Moreover, a firm's investment reduces the disruption probability of a provider for all client firms of that provider due to the sharing and transfer of information and technology best practices or through explicitly defined contracts as explained earlier. Disruptions are then realized with their consequent impacts on demand and profit.

We first derive optimal firm investment where firms have chosen the common service provider and where the firms have chosen different providers. Then, we compare the two cases to find the optimal choice of service provision between these two provider structure choices given the equilibrium investments. In our model, providers do not have explicit decisions. Rather, for higher levels of firm investment, a service provider is more robust to disruptions—that is, the provider has a lower disruption probability.

After disruptions are realized, a provider can be in a good state (no disruption in service) or a bad state (disrupted service). We denote these states by G and B, respectively. Denoting the provider states with S_k, the possible provider states where firms choose the common provider are $S_c = \{G, B\}$, and where firms choose different providers are $S_d = \{GG, GB, BG, BB\}$, where, for example, state GB represents the case where Provider 1 (serving Firm 1) is in a good (non-disrupted) state and Provider 2 (serving Firm 2) is in a bad state (disrupted). Next, we provide the details on how the probabilities of these states are determined and our corresponding assumptions.

Each provider faces a baseline vulnerability. Baseline vulnerability reflects the vulnerability of a service provider to disruptions in absence of firm investments and is denoted as $v \in (0, 1]$. The actual vulnerability or disruption probability of a provider depends on its client firms' investments. Each firm chooses a level of investment per unit of demand, which improves the disruption probability of its provider. The effects of these investments are our first assumption.

Assumption 1 (Provider Disruption Probabilities).

(a) The reduction in provider disruption probability is inversely proportional to the investment from all of its client firms, diminishing as investment increases.
(b) The disruptions at providers are independent.

As in the work of Gans [31] and Kolfal et al. [44], we denote firm i's investment per unit of demand under the provider structure choice k by $x_{i,k} \in [0, \bar{x}]$. In settings such as intermediary products and cloud services, the service delivered by the service provider is often contracted per unit of demand or usage. For example, one can consider the different tiers that cloud providers offer and add-on products such as firewalls or verification tools that are contracted based on the number of users. These security tools require physical infrastructure and maintenance, which scale with the usage. Our study does not focus on scenarios in which investments do not depend on the size of the demand, such as R&D investments and development of software. In our model, the investments from firms have a direct impact on providers' disruption probability. In other words, if a firm invests in a provider, that provider can use at least a portion of that investment to improve its operation. This may be through knowledge and expertise transfer commensurate with the amount of investment made [54], or more explicitly through contracts that reserve a portion of the spending to be invested in improving provider's operations and service [7, 32, 45, 63]. Whereas this may not be true in the case of prominent providers, it is indeed the case for smaller providers with few client firms or providers that mainly provide standards and/or frameworks. Our main analysis, therefore, targets such small providers that are impacted by the investment of firms. Our analysis continues to hold qualitatively if only a portion of the investment goes toward improving the provider robustness. In our base model, we consider disruptions at the different providers to be independent. We relax Assumption 1(b) and analyze the impact of correlated arrivals as an extension in Section 6.1.

Even though in our main analysis we focus on the scenario where the two provider choices (common and different) offer the same efficiency, we retain a more general analysis where the providers can have different efficiencies. The difference between providers where firms have chosen the common provider and where firms have chosen different providers is *ex post*—that is, after the firms have chosen their providers. We take $\alpha \in (0, \bar{\alpha}]$ as the relative effectiveness of a provider where the firms have chosen different providers as compared to a provider where both firms have chosen the common provider. Therefore, a provider where the firms have chosen different providers faces an effective investment of $\alpha x_{i,d}$ from firm i.

We use the following functional form for the provider disruption probabilities when firms choose the common service provider, where $P^k_{s \in S_k}$ gives the provider disruption probability in structure $k \in \{c, d\}$ for common and different provider structures, respectively, and S_k gives the provider states for the given provider structure:

$$P^c_G = 1 - \frac{v}{1 + x_{1,c} + x_{2,c}} \qquad \text{and} \qquad P^c_B = \frac{v}{1 + x_{1,c} + x_{2,c}}. \tag{1}$$

We use the following functional form for firms choosing different providers:

$$\begin{aligned} P^d_{GG} &= \left[1 - \frac{v}{1 + \alpha x_{1,d}}\right]\left[1 - \frac{v}{1 + \alpha x_{2,d}}\right], \quad & P^d_{GB} &= \left[1 - \frac{v}{1 + \alpha x_{1,d}}\right]\left[\frac{v}{1 + \alpha x_{2,d}}\right], \\ P^d_{BG} &= \left[\frac{v}{1 + \alpha x_{1,d}}\right]\left[1 - \frac{v}{1 + \alpha x_{2,d}}\right], & P^d_{BB} &= \left[\frac{v}{1 + \alpha x_{1,d}}\right]\left[\frac{v}{1 + \alpha x_{2,d}}\right]. \end{aligned} \tag{2}$$

Our findings are robust to similar reversely proportional functions, including continuous time Markov chains with inversely proportional arrival rates in the work of Kolfal et al. [44]. The parameter α allows us to remove the pooling effect that the common provider enjoys compared to the different providers. By *pooling effect*, we refer to the impact of having access to additional investments, where two firms invest in the common provider, but only one firm in each of the different providers. Where $\alpha = 2$, there is no difference in effectiveness based on whether firms have chosen common or different providers. Where $\alpha > 2$, different providers are more effective than the common provider in reducing disruptions, possibly due to less visibility and/or desirability to attackers. Where $\alpha < 2$, different providers are less effective in reducing disruptions than the common provider, possibly due to the different providers having lower economies of scale in service reliability and security. In Section 6.4, we provide an alternative setup with four firms in two independent industries, which allows us to keep the provider size constant and resolve the disparity in pooling effects between common and different providers. We show that our results are fairly consistent across the two models.

The only difference between firms choosing the common service provider and firms choosing different providers is the structure of the providers, and therefore this setup isolates the effect of disruption synchronization and de-synchronization between the two choices. Similar to the providers, each firm can be in either good (non-disrupted) or bad (disrupted) state, which we denote with the lowercase g and b, respectively. Our next assumption specifies the impact of disruptions at a provider on their client firms.

Assumption 2 (Firm Disruption Probabilities). *A disruption at a service provider carries over to its client firms with a propagation probability of* $\theta \in (0, 1]$.

Using Assumption 2, we can derive the joint firm state probabilities. The set of joint firm states is provided by $F_k = \{gg, gb, bg, bb\}$, where $k \in \{c, d\}$ represents the common provider and different provider structures, respectively, and the probability of being in each of these states is $P^k_{f \in F_k}$.

If firms use the common service provider, we have

$$P^c_{gg} = P^c_G + P^c_B[1-\theta]^2, \qquad P^c_{gb} = P^c_B[1-\theta]\theta,$$
$$P^c_{bg} = P^c_B[1-\theta]\theta, \qquad P^c_{bb} = P^c_B\theta^2. \tag{3}$$

Using (1), the joint firm state probabilities for the firms that use the common service provider can be simplified as

$$P^c_{gg} = 1 - \frac{\theta v[2-\theta]}{1 + x_{1,c} + x_{2,c}}, \quad P^c_{gb} = \frac{\theta v[1-\theta]}{1 + x_{1,c} + x_{2,c}},$$
$$P^c_{bg} = \frac{\theta v[1-\theta]}{1 + x_{1,c} + x_{2,c}}, \quad P^c_{bb} = \frac{\theta^2 v}{1 + x_{1,c} + x_{2,c}}. \tag{4}$$

If firms use different service providers, then we have

$$P^d_{gg} = P^d_{GG} + P^d_{GB}[1-\theta] + P^d_{BG}[1-\theta] + P^d_{BB}[1-\theta]^2, \quad P^d_{bb} = P^d_{BB}\theta^2,$$
$$P^d_{gb} = P^d_{GB}\theta + P^d_{BB}\theta[1-\theta], \qquad P^d_{bg} = P^d_{BG}\theta + P^d_{BB}\theta[1-\theta]. \tag{5}$$

Using (2), the joint firm state probabilities for the firms that use different service providers can be simplified as

$$P^d_{gg} = \frac{[1 + \alpha x_{1,d} - \theta v][1 + \alpha x_{2,d} - \theta v]}{[1 + \alpha x_{1,d}][1 + \alpha x_{2,d}]}, \qquad P^d_{gb} = \frac{[1 + \alpha x_{1,d} - \theta v]\theta v}{[1 + \alpha x_{1,d}][1 + \alpha x_{2,d}]},$$
$$P^d_{bg} = \frac{[1 + \alpha x_{2,d} - \theta v]\theta v}{[1 + \alpha x_{1,d}][1 + \alpha x_{2,d}]}, \qquad P^d_{bb} = \frac{\theta^2 v^2}{[1 + \alpha x_{1,d}][1 + \alpha x_{2,d}]}. \tag{6}$$

Comparing the joint firm state probabilities using common and different service providers, it can be seen that, as expected, the common provider case compared to the different providers case yields a higher probability for firms being in the same state (gg or bb) but lower probability for firms being in different states (gb or bg).

Without loss of generality, we normalize firm demand when there are no disruptions to 1. Firms affected by a disruption at the service provider suffer a proportional *demand loss*. We denote demand loss by $r_i \in [0, 1]$, whereby demand cannot be negative and disruptions at a firm do not increase its demand. In addition to demand loss, a firm's demand either increases (e.g., in some competitive established industries) or diminishes (e.g., in some emerging technology industries) when disruptions impact the other firm. We call this interaction *spillover* between firms due to a disruption, and denote the spillover that firm i imposes on firm j by $e_i \in (-1, 1)$, where e_i is a proportion of firm j's demand. The demand (i.e., customers), firms, and providers for the two provider choices are provided in Figure 1.

The demand for firm i if firms are in joint state $f \in F_k$, denoted by $D_{i,f}$, is derived as

$$\begin{gathered} D_{i,gg} = 1, \qquad D_{i,bb} = 1 - r_i + e_j, \qquad \forall i, j = 1, 2, \text{ and } i \neq j, \\ D_{1,bg} = 1 - r_1, \qquad D_{2,gb} = 1 - r_2, \qquad D_{1,gb} = 1 + e_2, \qquad D_{2,bg} = 1 + e_1, \end{gathered} \tag{7}$$

recalling from earlier that r_i is the demand loss of firm i due to disruptions at firm i, and e_i is the spillover that firm i imposes on firm j, or change in demand of firm j due to disruption at firm i. In the case of positive spillover, firm j gains demand if firm i is disrupted. However, in case of negative spillover, firm j incurs a loss in demand if firm i is disrupted as customers leave the market. There is no spillover if $e_i = 0$. We note that the demand loss and spillover are determined by the conditions of the downstream industry and do not depend on the provider choice. For example, customers may be more sensitive in some industries than others, implying heightened demand loss, and competition between firms may be higher in some industries than others, implying high spillover. Neither of these effects, however, depend on which provider is used by the firms. In other words, customers' knowledge of the provider choice does not impact their reaction to disruptions. We consider an extension where disruption is diminished when both firms are disrupted ($D_{i,bb}$) in Section 6.3.

Firms' marginal profit before investment, π, is known and fixed. Even though we do not consider the impact of pricing in our main model, our analysis captures the competition between firms through their chosen investments. Because we do not consider the pricing of firms, our analysis neatly captures the firms security investment decisions and the implications of risk synchronization. We show in Section 6.5 that our findings are robust if firms also decide on their price instead of taking it as exogenously given. Normalizing firms' costs to zero, a firm's marginal profit (considering investment) under provider structure choice $k \in \{c, d\}$ is taken as $\pi - x_{i,k}$, which we require to be positive as a participation constraint ($\pi - x_{i,k} > 0$). The profit for firm i when firms are in joint state $f \in F_k$ and provider structure choice $k \in \{c, d\}$ (with probability P_f^k) is $D_{i,f}[\pi - x_{i,k}]$. Firms maximize their expected profit, which is derived for firm i under provider choice $k \in \{c, d\}$ as

$$E(\Pi_{i,k}) = \sum_{f \in F_k} P_f^k D_{i,f}[\pi - x_{i,k}] = [P_{gg}^k D_{i,gg} + P_{gb}^k D_{i,gb} + P_{bg}^k D_{i,bg} + P_{bb}^k D_{i,bb}][\pi - x_{i,k}], \tag{8}$$

where P_f^k for $k = c$ and $k = d$ are given in (4) and (6), respectively, and $D_{i,f}$ is given in (7).

Assumption 3 (Technical Assumption).

(a) Spillover is smaller than demand loss in magnitude—that is, $-r_i < e_j < r_i, \ \forall i, j = 1, 2, \ j \neq i$.
(b) We consider $r_i - e_j < 1, \ \forall i, j = 1, 2, \ j \neq i$, *which ensures positive demand.*

We also assume symmetry and drop the subscript i denoting the firm for demand loss and spillover—that is, $r_1 = r_2 = r$ and $e_1 = e_2 = e$. We study asymmetry in demand loss and spillover as an extension in Section 6.2.

4 Analysis

Under each provider structure choice, firms choose investment $x_{i,k}$ to maximize expected profit. Investments improve the robustness of providers to disruptions, and therefore decrease the disruption probability at the provider and, consequently, at its client firm(s).

4.1 Common Provider Case

By substituting the joint firm state probabilities (4) and demand functions (7) into the profit function (8), we obtain the firms' expected profit with the common provider as

$$E(\Pi_{i,c}) = \frac{1 + x_{i,c} + x_{j,c} - \theta v[r-e]}{1 + x_{i,c} + x_{j,c}}[\pi - x_{i,c}], \qquad \forall i,j = 1,2, \quad j \neq i. \tag{9}$$

Maximizing (9) with respect to $x_{i,c}$, the best response investment for each firm from the first-order conditions is given as

$$x^*_{i,c} = \sqrt{\theta v[r-e][\pi + 1 + x_{j,c}]} - [1 + x_{j,c}], \qquad \forall i,j = 1,2, \quad j \neq i. \tag{10}$$

The second derivative of firm i's profit with respect to its investment is $\partial^2 E(\Pi_{i,c})/\partial x^2_{i,c} = -2\theta v[\pi + 1 + x_{j,c}][r-e]/[1 + x_{i,c} + x_{j,c}]^3 < 0$, and therefore the second-order condition is satisfied. Using (10), we take the equilibrium investment for each firm as the positive root of the quadratic function:

$$x^{eq}_{i,c} \equiv x^{eq}_c = \frac{1}{8}[-4 + \theta v[r-e] + \sqrt{\theta v[r-e][8 + 16\pi + \theta v[r-e]]}], \qquad \forall i = 1,2, \tag{11}$$

where the superscript eq denotes equilibrium. This yields the equilibrium (expected) profit of

$$E(\Pi_{i,c})^{eq} \equiv \Pi^{eq}_c = \pi + \frac{1}{8}[4 + 5\theta v[r-e] - 3\sqrt{\theta v[r-e][8 + 16\pi + \theta v[r-e]]}], \qquad \forall i = 1,2. \tag{12}$$

4.2 Different Providers Case

By substituting joint firm state probabilities (6) and demand functions (7) in the profit function (8), we obtain firm i's expected profit with different providers as

$$E(\Pi_{i,d}) = \frac{[1+\alpha x_{i,d}][1+\alpha x_{j,d}] + \theta v[e[1+\alpha x_{i,d}] + r[1+\alpha x_{j,d}]]}{[1+\alpha x_{i,d}][1+\alpha x_{j,d}]}[\pi - x_{i,d}], \quad \forall i,j = 1,2, \text{ and } i \neq j. \tag{13}$$

Maximizing (13) with respect to $x_{i,d}$, we derive the best response investment for each firm from the first-order conditions as

$$x^*_{i,d} = \frac{-\alpha[\theta v e + 1 + \alpha x_{j,d}] + \sqrt{[\theta v e + 1 + \alpha x_{j,d}]\alpha^2 \theta v e[1+\alpha x_{j,d}][1+\alpha\pi]}}{\alpha^2[\theta v e + 1 + \alpha x_{j,d}]}, \quad \forall i,j = 1,2, \text{ and } i \neq j. \tag{14}$$

The second derivative of firm i's profit with respect to its investment is $\partial^2 E(\Pi_{i,d})/\partial x^2_{i,d} = -2\alpha\theta v r[1+\alpha\pi]/[1+\alpha x_{i,d}]^3 < 0$, and therefore the second-order condition is satisfied. Using (14), we derive the equilibrium investment for each firm as the positive root of the quadratic function:

$$x^{eq}_{i,d} \equiv x^{eq}_d = \frac{-2 - \theta v e + \sqrt{\theta v[4r[1+\alpha\pi] + \theta v e^2]}}{2\alpha}, \qquad \forall i = 1,2, \tag{15}$$

which yields the equilibrium profit of

$$E(\Pi_{i,d})^{eq} \equiv \Pi^{eq}_d = \pi + \frac{\theta v[2r^2 - 2re + e^2] + 2r - [2r+e]\sqrt{\theta v[4r[1+\alpha\pi] + \theta v e^2]}}{2\alpha r}, \quad \forall i = 1,2. \tag{16}$$

4.3 Provider Choice Comparison

We compare the choice between common and different providers to identify the optimal choice under different demand loss and spillover conditions. Using the common provider is optimal for firm $i \in \{1,2\}$ if $\Pi^{eq}_c > \Pi^{eq}_d$ and using different providers is optimal otherwise, where Π^{eq}_c and Π^{eq}_d are given in (12) and (16), respectively. The mechanism for how firms may end up in a choice of common or different providers is as explained in model setup. The equilibrium choice can also be

Table 3. Firm Payoffs in the Two-by-Two Game

		Firm 2: Provider 1	Firm 2: Provider 2
Firm 1	Provider 1	(Π_c^{eq}, Π_c^{eq})	(Π_d^{eq}, Π_d^{eq})
	Provider 2	(Π_d^{eq}, Π_d^{eq})	(Π_c^{eq}, Π_c^{eq})

represented in a two-by-two game, where each firm decides between two providers, Provider 1 and Provider 2, as depicted for its normal form in Table 3. In other words, the action set of each firm is given as $a \in \{1, 2\}$. Based on the definition of common and different provider choices, firms choose common providers either if both choose Provider 1 or both choose Provider 2, and they choose different providers otherwise. Without specifying the approach for reaching the equilibrium (e.g., signaling or long-term steady-state analysis), it is straightforward to verify the possible equilibria with symmetric firms as follows. Where $\Pi_c^{eq} > \Pi_d^{eq}$, either of the common provider equilibria outcomes (Provider 1, Provider 1) or (Provider 2, Provider 2) is the equilibrium. This is because the firms do not have an incentive to deviate to other equilibria (different providers equilibria), making these Nash equilibria, noting that these two equilibria yield the same payoff to firms. However, where $\Pi_c^{eq} < \Pi_d^{eq}$, either of the different provider equilibria outcomes (Provider 1, Provider 2) or (Provider 2, Provider 1) are the Nash equilibria, again, because the firms do not have an incentive to deviate to the common provider equilibria.

5 Results

This section first examines how firms' investment decisions change with respect to key parameters, then explains how the firm makes the provider choice. In our main model, we consider the marginal profit before investment (π) to be high enough so that the decision of investment is relevant and firms make positive investments (interior solution) in both common and different providers. Otherwise, firms do not invest at the corner solution, and we analyze this case as an extension in Section 6.6. Proposition 1 provides the properties of the equilibrium firm investment and profit.

Proposition 1 (Firm Investments and Profits).

(a) Equilibrium firm investment under both common and different providers increases with marginal profit before investment, π, demand loss, r, propagation probability, θ, and baseline vulnerability, v, but decreases with spillover, e.

(b) Equilibrium firm investment under the different providers increases with the relative effectiveness of different providers to the common provider, α, where demand loss, r, is relatively low, and decreases with it otherwise.

(c) Equilibrium firm profit increases with marginal profit before investment and spillover, but decreases with demand loss, propagation probability, and baseline vulnerability.

Proof. This is straightforward from the partial derivatives of equilibrium firm investment in (11) and (15), and equilibrium firm profit in (12) and (16), for common and different providers, respectively, with respect to the corresponding parameters. □

From Proposition 1(a), firms invest more if marginal profit before investment is high. Demand loss, spillover, propagation probability, and baseline vulnerability increase the negative impact of

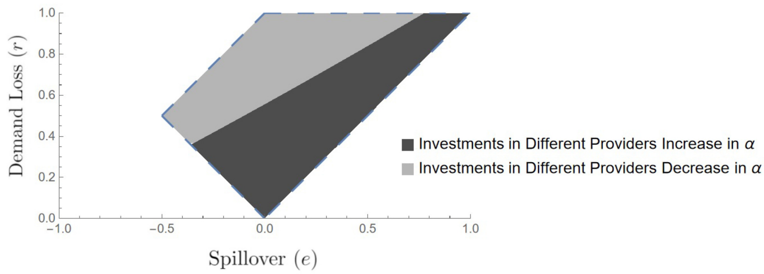


Fig. 2. Impact of relative effectiveness of providers (α) on investment for different providers (x_d^{eq}, $\alpha = 2$).

provider disruptions on firms. Therefore, as these effects increase, firms respond by raising their investment. Considering part (b) of the proposition, as depicted in Figure 2, if demand loss is relatively low (dark gray region in Figure 2), then as the effectiveness of different providers increases, it is profitable for firms to invest more. This is because the effectiveness of investments enables the investments to reduce the disruptions. However, for high demand loss (light gray region in Figure 2), this effect is reversed, where firms reduce their investment as its effectiveness increases. In this region, reduced investment allows the firms to reduce their costs and improve their profit. We note that in this figure, the union of the optimality regions for common and different provider choices outlines the overall feasible region, as characterized by the demand requirements in Assumption 3, and is shown by the dashed boundary lines.

Finally, results from Proposition 1(c) are intuitive. Expected firm profit increases as the marginal profit before investment increases. Demand loss, spillover, propagation probability, and baseline disruption probability contribute to the overall disruption probability at firms, and therefore decrease their expected profit. These results are consistent with findings from similar studies in the literature, including that of Kolfal et al. [44]. We do not directly use these findings, as our focus is on the comparison between common and different providers. That said, these results allow us to better interpret some of our main findings.

Next, we focus on the impact of demand loss and spillover on the optimal service provider choice, as well as how this choice is impacted by the relative effectiveness of service providers. Using the expected equilibrium profit for the two choices in (12) and (16), we examine the optimal service provider choice for different scenarios of relative effectiveness, α. If $\alpha = 2$, then the effectiveness of the different providers is similar to that of the common provider. If $\alpha > 2$ ($\alpha < 2$), then the effectiveness of the different providers is higher (lower) than that of the common provider. We discuss these scenarios next.

5.1 Similar Service Provider Effectiveness ($\alpha = 2$)

In absence of effectiveness difference between the two provider choices (i.e., where $\alpha = 2$), the different providers and the common provider are similarly effective. This scenario can be interpreted as the case where the different service providers are as robust as the common service provider. In this scenario, the only difference between common and different providers is due to the simultaneity of disruptions. For this case, we find that the regions where the common provider is optimal (as determined by comparing firm profits) can be defined solely in terms of demand loss and spillover, as we explain in Proposition 2.

Proposition 2. *In absence of effectiveness differences between the two provider choices (i.e., where $\alpha = 2$), in equilibrium:*

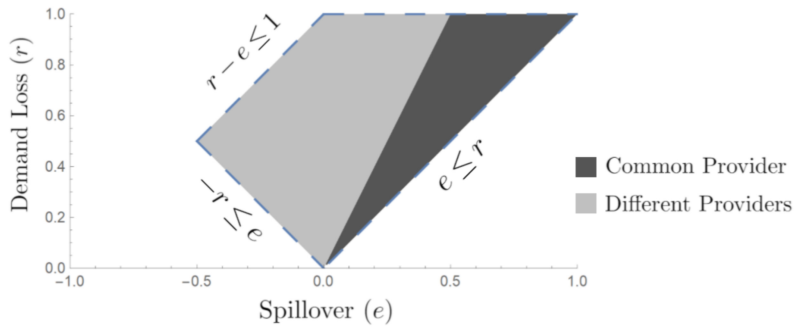


Fig. 3. Optimal service provider regions where $\alpha = 2$.

(a) Firms' investment and demand are higher where they use different provider compared to where they use common providers.
(b) The use of the common provider is optimal if spillover is positive and relatively large ($e > r/2$). Otherwise, the use of different providers is optimal.

Proof.

Part (a): The difference between the investments under common and different provider scenarios when $\alpha = 2$ is given as

$$x_c^{eq} - x_d^{eq} = \frac{\sqrt{\theta v}\left[\sqrt{r-e}\sqrt{\theta v[r-e] + 16\pi + 8} - 2\sqrt{\theta v e^2 + 8\pi + 4}\right] + \theta v[r+e]}{8},$$

which is negative in the feasible region of r and e.

The difference between the total demands under common and different provider scenarios is given as

$$\sum_{f \in F_c} P_f^c D_{i,f} - \sum_{f \in F_d} P_f^d D_{i,f} = \frac{2\sqrt{\theta v}[r-e][-2\sqrt{\theta v e^2 + (8\pi+4)r} + \sqrt{r-e}\sqrt{\theta v[r-e]+16\pi+8} + \sqrt{\theta v}[r+e]]}{[\sqrt{r-e}\sqrt{\theta v[r-e]+16\pi+8} + \sqrt{\theta v}[r-e]][\sqrt{\theta v}e - \sqrt{\theta v e^2 + [8\pi+4]r}]},$$

which is negative in the feasible region of r and e.

Part (b): The difference between the profits under common and different provider scenarios when $\alpha = 2$ is given as

$$\Pi_c^{eq} - \Pi_d^{eq} = -\frac{3r\sqrt{\theta v[r-e][8+16\pi+\theta v[r-e]]} - \theta v[r-2e][r+e]]}{8r} + \frac{[4r-2e]\sqrt{\theta v[[4+8\pi]r + \theta v e^2]]}}{8r},$$

which is positive if $e > r/2$ and is negative if $e < r/2$. □

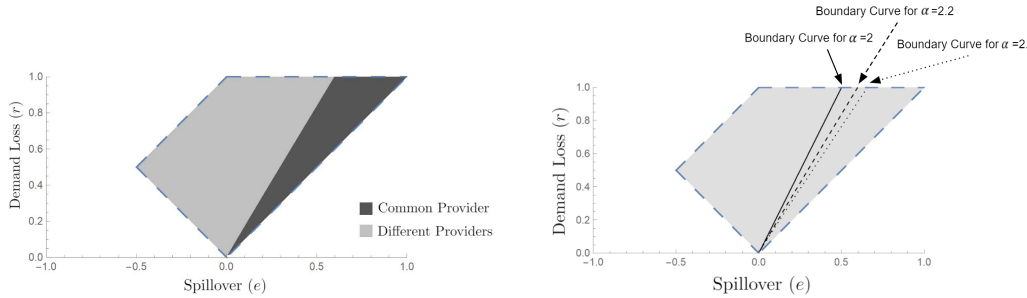
Proposition 2 provides the optimal provider choice with respect to demand loss and spillover, where the common provider and different providers have the same effectiveness ($\alpha = 2$). The denominator of 2 for the limits in this proposition is due to having two firms. A similar behavior is seen for a higher number of firms, although these models are solvable only numerically. The optimal choice regions are illustrated in Figure 3, where a common provider (different providers) is optimal in the dark (light) gray region.

We find that in absence of effectiveness differences between the two provider choices, firms invest more and gain higher demand under different providers compared to common provider. Moreover, when the common provider and different providers are similarly robust, firms use the common provider only if they can gain substantially from disruptions at the other firm. This occurs if firms have positive spillover and customers attribute a disruption to firms and switch, such as in the case of competing firms in established industries. The decision of provider depends on the impact on demand through synchronization (through a common provider) or de-synchronization (through different providers) as well as the investment decisions described in Proposition 1. This implies that if either the positive spillover is limited, there is no spillover, or spillover is negative, then firms use different providers as a competitive advantage, thereby de-synchronizing their risks. However, if spillover is large and positive, then firms benefit from sharing the common provider, which increases the likelihood that disruptions at firms are synchronized.

Because we consider the demand loss and spillover of firms independently of one another, we provide results that extend and contrast the literature on provider choice, specifically [17] that predict indifference between providers with similar quality (similar quality of in-house and outsourcing in their context). The intuition from these results are as follows. If firms have negative spillover, then they do not benefit from synchronization of disruptions through a common provider. Even though de-synchronized disruptions harm both firms with negative spillover if disrupted, use of the common provider is not optimal because of the lack of incentive from either firm to adequately invest. Therefore, firms prefer to de-synchronize disruptions through different providers. If firms have low or moderate positive spillover, then using different providers acts as a competitive advantage in that firms prefer not to be impacted by disruptions at the same time. This is because each firm can capitalize on the other firm being disrupted. However, if spillover is large and positive, then neither firm can bear to suffer de-synchronized disruptions due to using different providers, as this shifts a significant portion of their demand to their competitor. Therefore, in this case, firms prefer to synchronize their disruptions through a common provider. Our results uncover a market mechanism for having a few concentrated providers in industries with positive spillover (i.e., increased upstream concentration), whereas there is a more intense upstream competition (i.e., decreased upstream concentration) in industries with negative spillover. Our analysis provides an alternate explanation for the observation in the work of Fumagalli and Motta [28] where the retailers prefer to use the same provider—downstream firms reduce the risk of having de-synchronized outages when choosing a common provider.

The firms' expected profit is a function of the demand and marginal profit (including investment). As firms invest more, they increase their demand at the cost of marginal profit. These effects are not the same for the two provider choices (common and different). Where spillover is negative, under the common provider, firms invest more and enjoy a higher demand. The effect of higher demand, however, does not outweigh the effect of reduced marginal profit, and therefore the different providers is optimal. However, where spillover is large and positive, firms using the common provider invest less and have lower demand than firms using the different providers, while having a higher marginal profit. In this case, the improved marginal profit outweighs the reduced demand only if spillover is high (i.e., if $e > r/2$). Considering this result for positive spillover, this is due to the double effects of investments: whereas additional investment improves firm demand by reducing disruptions, it comes at a cost. The firms invest more under different providers, and this cost-effectively improves their profit compared to the common provider for moderate levels of positive spillover. However, for higher levels of spillover, the firms under-invest with different providers, and this generates a lower profit compared to the common provider, making the common provider more desirable.

Although we consider demand loss and spillover to be independent of each other, in certain scenarios these may be correlated. For example, in case of competing firms in an established industry such as the airline industry, a disruption at Firm 1 may cause its customers to shift to the competing Firm 2. In this case, the demand gain for Firm 2 may depend on the demand loss that Firm 1 incurs. This relationship can be explained as $e = \beta r$, where $\beta \in [0, 1]$. One can observe that our results continue to qualitatively hold if r and e are correlated, in which case the results can be conditioned on β.



(a) $\alpha = 2.2$ (b) $\alpha = \{2, 2.2, 2.4\}$

Fig. 4. Optimal service provider regions where $\alpha > 2$ ($\pi = 100$, $v = 0.4$, $\theta = 1$).

5.2 Higher Effectiveness at Different Service Providers ($\alpha > 2$)

In this case, the different service providers offer a higher effectiveness in addressing disruptions compared to a common provider. In this case too, firms invest more where they choose different providers as discussed in Proposition 1(b), because the different providers are even more effective compared to the similar service provider effectiveness in the previous section. The common provider could suffer from a lower effectiveness—for example, due to higher visibility or potentially higher rewards to cyber-criminals attacking the common provider in a specific industry. The choice of the common or different providers can again be determined using the expected profits in (12) and (16). Figure 4 illustrates the optimal choice regions in this scenario and shows how these regions change with relative effectiveness (i.e., α).

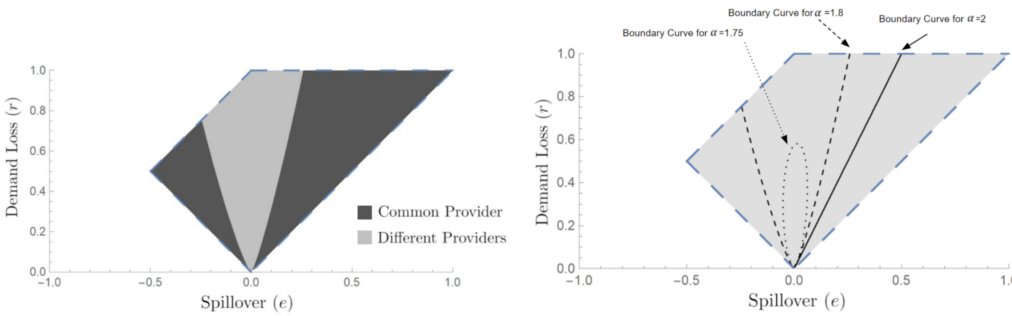
The equilibrium profit for different providers increases as α increases ($\partial E(\Pi_{i,d})^{eq}/\partial\alpha > 0$), but α does not impact the common provider. Therefore, as α increases, the different providers choice becomes more desirable, and this causes the region where different providers are optimal to expand as shown in Figure 4(b). This is intuitive, where the different providers choice becomes more desirable as their effectiveness improves compared to the common provider.

5.3 Lower Effectiveness at Different Service Providers ($\alpha < 2$)

In this case, the relative effectiveness of different providers is lower than that of the common provider. There is some evidence for this scenario, where a common provider yields better efficiencies due to gaining specific knowledge and expertise, economies of scale, or both (61, 9). Again, using profits from (12) and (16), we can determine the optimal provider choice. Figure 5 illustrates optimal provider choice regions with respect to demand loss and spillover.

As the different providers' effectiveness diminishes, firms' investment becomes less effective, resulting in a reduction in investment across all regions of demand loss and spillover. In this case, firms invest less where they choose different providers as discussed in Proposition 1(b), because the different providers are less effective. We find that in this case, the investment by each firm in common provider exceeds that of different providers as provided in Figure 6. In particular, where spillover is relatively low and/or demand loss is relatively low, firms invest more in a common provider compared to different providers. This is because where firms compete for demand (negative spillover), they may end up competing on investments under different providers, whereas common providers can soften this competition on investments.

Comparing the common provider to different providers based on the demand loss and spillover, there are two possible regions for the optimal provider choice. Firms choose different providers if both demand loss and spillover are sufficiently low and choose the common provider if either



(a) $\alpha = 1.8$

(b) $\alpha = \{1.75, 1.8, 2\}$

Fig. 5. Optimal service provider regions where $\alpha < 2$ ($\pi = 100$, $v = 0.4$, $\theta = 1$).

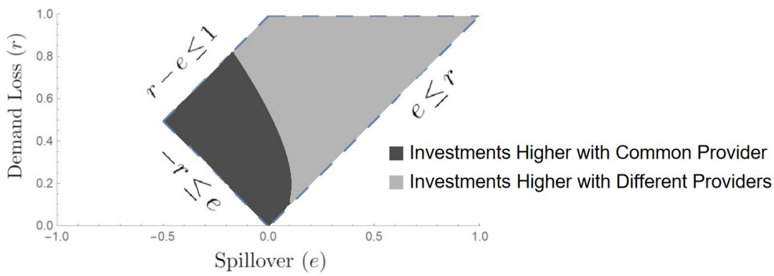


Fig. 6. Comparison of investments in common and different providers ($\alpha = 1.75$).

demand loss is high or spillover is large, whether positive or negative. The interesting region in this scenario as compared to the previous two scenarios is that a common provider is optimal for both positive and negative spillover. In other words, in the scenario where the common provider yields higher effectiveness, firms may use a common service provider even if there is negative spillover from disruptions between firms. The increase in desirability of the common provider for negative spillover region is due to this provider being able to attract higher investments compared to different providers, which allows it to become more resistant to disruptions.

6 Extensions

In this section, we present six extensions to the main model. We first examine how the optimal service provider choice regions change where service provider disruptions are correlated, then examine the impact of asymmetry on our results. Next, we consider an extension to our demand, where the disruptions when both firms are disrupted is less than that when only one firm is disrupted. As an alternative setup to our main model, we present a model with four firms in two independent industries. Then, we introduce endogenous pricing as an extension of our model. Finally, we analyze our model considering corner solutions. We find our results to remain qualitatively robust across all six extensions.

6.1 Correlated Service Provider Disruption Probabilities

In our basic model, we consider disruption at the different service providers to be independent of each other. However, disruptions may be correlated if, for example, they have a shared source or the disruption is coordinated as may be the case for security attacks. To explore this, we introduce a pseudo-correlation parameter, $\gamma \geq 0$, which is an increasing function of the correlation between disruptions at the firm level and represents the likelihood that both firms are in the bad state at the same time (bb). Given that the sole source of disruptions are the providers (not firms directly), we note that defining γ at the level of firms is equivalent to having a similar parameter that defines disruption correlation at the level of providers. Due to the simplicity of the approach with the correlation parameter defined at the level firms, we pursue this approach.

At one extreme, where $\gamma = 0$, this reduces to the basic model without correlated disruptions. The details of how γ impacts correlation of disruptions are as follows. The parameter $\gamma \geq 0$ is added to the model using the following transformations in firm state probabilities:

$$P'_{gg} = P_{gg}, \qquad P'_{gb} = P_{gb} - \gamma, \qquad P'_{bg} = P_{bg} - \gamma, \qquad P'_{bb} = P_{bb} + 2\gamma. \tag{17}$$

For each firm, we define probabilities P_{1g} and P_{2g} for Firm 1 and Firm 2 being in the good states, respectively. Note that $P_{1g} = P_{gg} + P_{gb}$ and $P_{2g} = P_{gg} + P_{bg}$. Considering each firm's state as a random variable following a Bernoulli distribution that is dependent on the other firm's state, we use the Pearson correlation coefficient. The correlation coefficient is defined as $R = [E(XY) - E(X)E(Y)]/[\sigma(X)\sigma(Y)]$, where $E(Z)$ and $\sigma(Z)$ are the expected value and the standard deviation of the random variable Z, respectively, and X and Y are Bernoulli random variables representing the state of the firms as follows:

$$X = \begin{cases} 1 & \text{If Firm 1 is in good state} \\ 0 & \text{If Firm 1 is in bad state} \end{cases},$$

$$Y = \begin{cases} 1 & \text{If Firm 2 is in good state} \\ 0 & \text{If Firm 2 is in bad state} \end{cases}.$$

The correlation coefficient can thus be written as

$$R = \frac{[P_{gg} - P_{1g}P_{2g}]}{[\sqrt{P_{1g}[1 - P_{1g}]}\sqrt{P_{2g}[1 - P_{2g}]}]}.$$

To illustrate the effect of correlation parameter γ, we substitute the transformations in (17) into the preceding correlation coefficient formula:

$$R' = \frac{P'_{gg} - P'_{1g}P'_{2g}}{\sqrt{P'_{1g}[1 - P'_{1g}]}\sqrt{P'_{2g}[1 - P'_{2g}]}} = \frac{P_{gg} - [P_{1g} - \gamma][P_{2g} - \gamma]}{\sqrt{[P_{1g} - \gamma][1 - P_{1g} + \gamma]}\sqrt{[P_{2g} - \gamma][1 - P_{2g} + \gamma]}}. \tag{18}$$

We are interested in cases with positive correlation among the incidents at two firms. To have $0 \geq R \geq 1$, we need to have

$$P_{gb} \geq \gamma, \qquad P_{bg} \geq \gamma, \qquad \gamma \geq P_{1g}, \qquad \gamma \geq P_{2g}. \tag{19}$$

Using (18) and (19), it can be shown that if $P_{1g} > 2/3$ and $P_{2g} > 2/3$, then the correlation coefficient increases with γ. In our setting, the preceding assumptions are fairly realistic in that firms are in the good state most of the time.

We then study the impact of our correlation parameter γ on the optimal regions for common and different provider structures. The analysis remains similar to that of the main model, which we omit for brevity. Figure 7 summarizes the impact of γ on optimal choice regions.

We find that an increase in correlation of disruptions at different service providers favors the common provider. The reason for this is that the probability of synchronized disruptions increases with the correlation of disruptions. Therefore, firms benefit from using the more-robust common

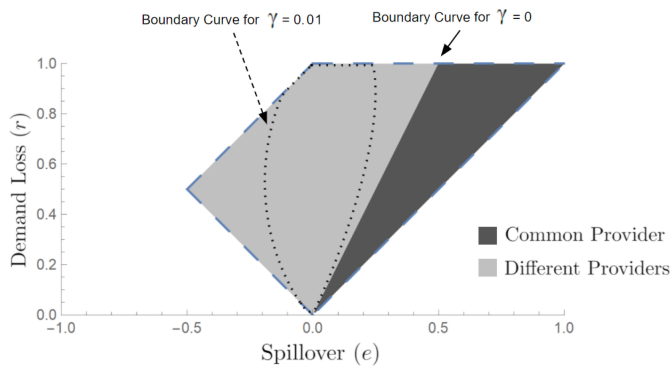


Fig. 7. Impact of disruption correlation on optimal service provider regions ($\pi = 100$, $v = 0.4$, $\theta = 1$, $\alpha = 2$, $\gamma = \{0, 0.01\}$).

service provider. This is intuitive; if the attacks or incidents are correlated, perhaps due to using similar technologies or procedures, then firms can benefit from using a common provider.

6.2 Asymmetry

Asymmetry can be analyzed with respect to either providers or firms. We find the results of asymmetric providers to be straightforward: if the common service provider has an advantage (disadvantage) over different providers in terms of marginal profit before investment in interoperability, or propagation probability, then the common region expands (shrinks). For brevity, we do not present the results here and instead focus on asymmetric firms.

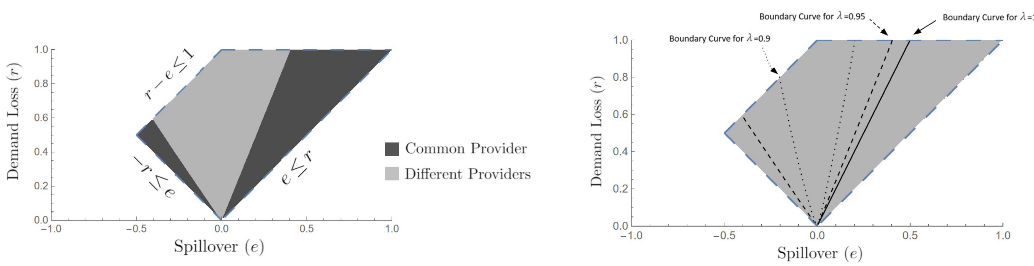
Asymmetric firms may differ in their customer demand reactions (demand loss and spillover), marginal profit before investment in interoperability, and propagation probabilities. We analyze these for a wide range of values in our numerical test suites and report our findings, which are robust among all tested values. We find the effect of asymmetry in all preceding parameters to be similar, and therefore we present results only for one parameter: the demand loss (r).

Without loss of generality, assume Firm 1 to have a a lower demand loss than Firm 2, where $r_2 = r_1 + d$. Parameter d determines the demand loss difference between the two firms. As expected, we find that for either choice of common or different providers, the firm with low demand loss invests less and gains higher profit. We also find that as the difference increases (firms become more asymmetric), the optimal region for the common provider expands for the firm with low demand loss (Firm 1) and shrinks for the firm with high demand loss (Firm 2).

In this setting, the order of decision about provider choice is important. The choice of common or different providers rests on the firm that chooses last. The firm that chooses the provision (i.e., chooses last) defines the boundary between the common provider and different provider choices. If the firm with high demand loss (Firm 2) chooses the provision, then the asymmetry shrinks the region where the common provider is optimal. The reason for this is that the high demand loss firm has an incentive to invest more in interoperability, which allows the less sensitive firms to free-ride. Therefore, the high demand loss firm prefers to use a different provider. However, if the firm with low demand loss (Firm 1) chooses the provision, then the region where the common service provider is optimal expands.

6.3 Diminished Disruption When Both Firms Are Disrupted

In this section, we consider an extension of our model as it relates to the demand. In our main model, we assume that the demand for the state where both firms are disrupted (bb) relies on the



(a) $\lambda = 0.95$ (b) $\lambda = \{1, 0.95, 0.90\}$

Fig. 8. Optimal service provider regions with diminished disruption when both firms are disrupted ($\pi = 100$, $v = 0.4$, $\theta = 1$, $\alpha = 2$).

same demand loss and spillover as when only one firm is disrupted (*gb* or *bg*) per (7). However, it is reasonable to argue that the demand where both firms are disrupted might not be impacted as much, due to customers not having the option to switch to a non-disrupted firm. Therefore, in this section, we consider an adjustment to the demand in the case where both firms are disrupted as

$$D_{i,bb} = 1 - \lambda[r_i - e_j], \qquad \forall i, j = 1, 2, \tag{20}$$

where the parameter $\lambda \in (0, 1)$ represents the degree to which customers' demand effects (demand loss and spillover) are diluted when both firms are in the disrupted state. We note that the analysis and results do not change qualitatively if the parameter λ impacts only either the demand loss (i.e., $D_{i,bb} = 1 - \lambda r_i + e_j$) or spillover (i.e., $D_{i,bb} = 1 - r_i + \lambda e_j$).

We now show that this adjustment in the model does not have a qualitative impact on our results. We follow the analysis similar to that of the main model and derive the equilibrium profit for common provider and different providers cases, the details of which are omitted for brevity. Given that the parameter λ reduces the burden on firms when they are both disrupted, we expect the common provider choice to become more desirable in this setting. This is because the probability of both firms being disrupted is higher under the common provider compared to different providers, therefore having a reduced impact when both firms are disrupted improves the profit under the common provider more than it does under different providers. We find that this change, however, does not qualitatively impact our results. The optimal regions of provider choice for this setting in absence of effectiveness differences between the two provider choices are provided in Figure 8.

6.4 Setup with Four Firms in Two Industries

In this extension, we consider a setting with two markets, each consisting of two profit-maximizing firms. The demands in the two markets are independent of each other, but there are dependencies among the firms in each market. In this section, we keep the provider size constant, which resolves the disparity in pooling effects between common and different providers. This analysis provides a robustness check on our assumption about pooling in our main model, where α moderates the relative effectiveness of the common versus different providers.

We denote the two markets as M and N, and the firms as $i \in \{M_1, M_2, N_1, N_2\}$. We assume two identical providers $j \in \{1, 2\}$ with equivalent properties (e.g., in terms of quality and compatibility) that firms can choose from. We analyze the two possible provider structures: within-market and cross-market. In the within-market structure, firms from the same market share the same provider, whereas in the cross-market structure, firms from the same market use different providers. Accordingly, the within-market structure is comparable to the *common provider* case, and the cross-market provider structure is comparable to the *different providers* case in our main model. We assume that firms coordinate their decisions on provider choice. This decision coordination, rather than a sequential decision process, removes the first-mover advantage (or disadvantage) and focuses only on the impact of risk synchronization on the decision of the firms. The mechanism for determining the provider is similar to that of our main model, and we focus on the comparison of the two provider structures. We examine the focal market M, noting that our analysis applies to both markets. Considering market M, if firms in this industry use different providers, then a disruption at one provider only impacts the firm using that provider. Therefore, firm disruptions are de-synchronized. In the common provider case, however, both firms may be impacted when a disruption occurs at that provider. In other words, disruptions are synchronized.

After disruptions are realized, a provider can be in a good state (no disruption in service) or a bad state (disrupted service). We denote these states by G and B, respectively. The possible provider states are $S_k = \{GG, GB, BG, BB\}$, where, for example, GB represent the case where Provider 1 (serving firms M_1 and M_2 in the common case and firms M_1 and N_1 in the different case) is in a good state and Provider 2 (serving firms N_1 and N_2 in the common case and firms M_2 and N_2 in the different case) is in a bad state, and $k \in \{c, d\}$ denotes common and different providers, respectively. We take the following functional form for the provider disruption probabilities where firms choose a common provider:

$$
\begin{aligned}
P^c_{GG} &= \left[1 - \frac{v}{x_{M_1} + x_{M_2}}\right]\left[1 - \frac{v}{x_{N_1} + x_{N_2}}\right], \qquad & P^c_{GB} &= \left[1 - \frac{v}{x_{M_1} + x_{M_2}}\right]\left[\frac{v}{x_{N_1} + x_{N_2}}\right], \\
P^c_{BG} &= \left[\frac{v}{x_{M_1} + x_{M_2}}\right]\left[1 - \frac{v}{x_{N_1} + x_{N_2}}\right], & P^c_{BB} &= \left[\frac{v}{x_{M_1} + x_{M_2}}\right]\left[\frac{v}{x_{N_1} + x_{N_2}}\right].
\end{aligned} \tag{21}
$$

For the different providers, we use the following functional form:

$$
\begin{aligned}
P^d_{GG} &= \left[1 - \frac{v}{x_{M_1} + x_{N_1}}\right]\left[1 - \frac{v}{x_{M_2} + x_{N_2}}\right], \qquad & P^d_{GB} &= \left[1 - \frac{v}{x_{M_1} + x_{N_1}}\right]\left[\frac{v}{x_{M_2} + x_{N_2}}\right], \\
P^d_{BG} &= \left[\frac{v}{x_{M_1} + x_{N_1}}\right]\left[1 - \frac{v}{x_{M_2} + x_{N_2}}\right], & P^d_{BB} &= \left[\frac{v}{x_{M_1} + x_{N_1}}\right]\left[\frac{v}{x_{M_2} + x_{N_2}}\right].
\end{aligned} \tag{22}
$$

The only difference between the common and different providers are the structure of the providers, and therefore this setup effectively isolates the effect of disruption synchronization and de-synchronization between the two choices.

We can derive the joint firm state probabilities. The set of joint firm states for the focal market M is provided by $F = \{gg, gb, bg, bb\}$, and the probability of being in each of these states is provided as $P_{f \in F}$. For the common provider, we have

$$
\begin{aligned}
P^c_{gg} &= \left[P^c_{GG} + P^c_{GB}\right] + \left[P^c_{BG} + P^c_{BB}\right][1-\theta]^2, \qquad & P^c_{gb} &= \left[P^c_{BG} + P^c_{BB}\right]\theta[1-\theta], \\
P^c_{bg} &= \left[P^c_{BG} + P^c_{BB}\right]\theta[1-\theta], & P^c_{bb} &= \left[P^c_{BG} + P^c_{BB}\right]\theta^2.
\end{aligned} \tag{23}
$$

Using (21), the joint firm state probabilities for the common provider are taken as

$$
P^c_{gg} = 1 - \frac{\theta v[2-\theta]}{x_{M_1} + x_{M_2}}, \quad P^c_{gb} = \frac{\theta v[1-\theta]}{x_{M_1} + x_{M_2}}, \quad P^c_{bg} = \frac{\theta v[1-\theta]}{x_{M_1} + x_{M_2}}, \quad P^c_{bb} = \frac{\theta^2 v}{x_{M_1} + x_{M_2}}. \tag{24}
$$

However, for the different providers, we have

$$
\begin{aligned}
P^d_{gg} &= P^d_{GG} + P^d_{GB}[1-\theta] + P^d_{BG}[1-\theta] + P^d_{BB}[1-\theta]^2, \qquad & P^d_{bb} &= P^d_{BB}\theta^2, \\
P^d_{gb} &= P^d_{GB}\theta + P^d_{BB}\theta[1-\theta], & P^d_{bg} &= P^d_{BG}\theta + P^d_{BB}\theta[1-\theta].
\end{aligned} \tag{25}
$$

Using (22), the joint firm state probabilities for the different providers can be simplified as

$$P^d_{gg} = \frac{[x_{M_1} + x_{N_1} - \theta v][x_{M_2} + x_{N_2} - \theta v]}{[x_{M_1} + x_{N_1}][x_{M_2} + x_{N_2}]}, \qquad P^d_{gb} = \frac{[x_{M_1} + x_{N_1} - \theta v]\theta v}{[x_{M_1} + x_{N_1}][x_{M_2} + x_{N_2}]},$$
$$P^d_{bg} = \frac{\theta v[x_{M_2} + x_{N_2} - \theta v]}{[x_{M_1} + x_{N_1}][x_{M_2} + x_{N_2}]}, \qquad P^d_{bb} = \frac{\theta^2 v^2}{[x_{M_1} + x_{N_1}][x_{M_2} + x_{N_2}]}. \tag{26}$$

The rest of the model and setup, including the demands and profits, are similar to that of the main model in the article. Next, we analyze the results in this model for each of the common and different provider structures, then compare them to find the optimal provider choice.

6.4.1 Common Provider. By substituting the joint firm state probabilities (24) and demand functions (7) into the profit function (8), we obtain the firms' expected profit with a common provider as

$$E(\Pi_{M_i,c}) = \frac{x_{M_i} + x_{M_j} - \theta v[r-e]}{x_{M_i} + x_{M_j}}[\pi - x_{M_i}], \qquad \forall i,j = 1,2, \quad j \neq i. \tag{27}$$

Maximizing (27) with respect to x_{M_i}, the optimal investment for each firm is

$$x^*_{M_i,c} = \sqrt{\theta v[r-e][x_{M_j} + \pi]} - x_{M_j}, \qquad \forall i,j = 1,2, \quad j \neq i. \tag{28}$$

The second derivative is $\partial^2 E(\Pi_{M_i,c})/\partial x^2_{M_i} = -2\theta v[\pi + x_{M_j}][r-e]/[x_{M_i} + x_{M_j}]^3 < 0$, and therefore the second-order condition is satisfied. Using the equations in (28), we take the equilibrium investment for each firm as the positive root of the quadratic function as

$$x^{eq}_{M_i,c} \equiv x^{eq}_c = \frac{1}{8}[\theta v[r-e] + \sqrt{\theta v[r-e][\theta v[r-e] + 16\pi]}] \geq 0, \qquad \forall i = 1,2, \tag{29}$$

which yields the equilibrium expected profit as

$$E(\Pi_{M_i,c})^{eq} \equiv \Pi^{eq}_c = \pi + \frac{1}{8}[5\theta v[r-e] - 3\sqrt{\theta v[r-e][\theta v[r-e] + 16\pi]}], \qquad \forall i = 1,2. \tag{30}$$

6.4.2 Different Providers. By substituting joint firm state probabilities (26) and demand functions (7) in the profit function (8), we obtain firm M_i's expected profit as

$$E(\Pi_{M_i,d}) = [1 - \frac{\theta v[r[x_{M_j} + x_{N_j}] - e[x_{M_i} + x_{N_i}]]}{[x_{M_i} + x_{N_i}][x_{M_j} + x_{N_j}]}][\pi - x_{M_i}], \qquad \forall i,j = 1,2, \text{ and } i \neq j. \tag{31}$$

Maximizing (31) with respect to x_{M_i}, we derive the optimal investment for each firm from the first-order conditions as

$$x^*_{M_i,d} = \frac{\sqrt{[x_{M_j} + x_{N_j}]\theta r v[\pi + x_{N_i}]}}{\sqrt{x_{M_j} + x_{N_j} - \theta e v}} - x_{N_i}, \qquad \forall i,j = 1,2, \text{ and } i \neq j. \tag{32}$$

From Assumption 3(c), we have $x_{M_j} + x_{N_j} - \theta e v \geq 0$, and therefore $x^*_{M_i,d} \in R^+$. The second derivative of firm i's profit with respect to its investment is $\partial^2 E(\Pi_{M_i,d})/\partial x^2_{M_i} = -2\theta r v[\pi + x_{N_i}]/[x_{M_i} + x_{N_i}]^3 < 0$, and therefore the second-order condition is satisfied. Using the equations in (32), we derive the equilibrium investment for each firm as the positive root of the quadratic function as

$$x^{eq}_{M_i,d} \equiv x^{eq}_d = \frac{1}{8}[\theta v[r-2e] + \sqrt{\theta v[16\pi r + \theta v[r-2e]^2]}] \geq 0, \qquad \forall i = 1,2, \tag{33}$$

This yields the equilibrium profit of

$$E(\Pi_{M_i,d})^{eq} \equiv \Pi^{eq}_d = \pi + \tfrac{1}{8r}[\theta v[5r^2 - 8re + 4e^2] - [3r - 2e]\sqrt{\theta v[16\pi r + \theta v[r-2e]^2]}], \qquad \forall i = 1,2. \tag{34}$$

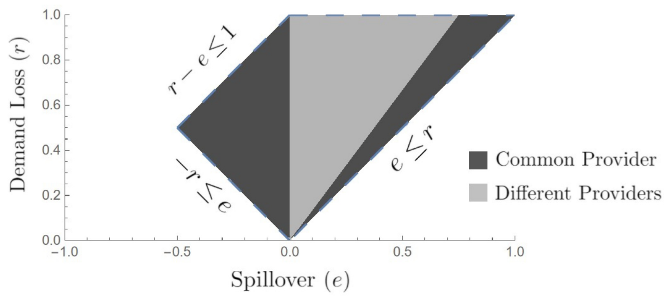


Fig. 9. Equilibrium service provider regions where $\alpha = 1$.

6.4.3 Results. In this case, the region where the common provider is optimal can be defined solely in terms of demand loss and spillover, as explained in Proposition 3.

Proposition 3. *Use of a common provider is optimal if spillover is negative ($e < 0$), or if it is positive and relatively large ($e > 3r/4$). Use of different providers is optimal otherwise.*

Proof. We have the following:

$$\Pi_d^{eq} - \Pi_c^{eq} = \frac{1}{8r}[\theta v e[3r - 4e] + 3r\sqrt{\theta v[r-e][\theta v[r-e] + 16\pi]}] - \frac{1}{8r}[[3r - 2e]\sqrt{\theta v[\theta v[r-2e]^2 + 16r\pi]}], \quad (35)$$

which is negative if $e < 0$ or $e > 3r/4$ and is positive if $0 < e < 3r/4$. □

The optimal decision regions in Proposition 3 are illustrated in Figure 9.

Except for the region of negative spillover, these results are consistent with that of our main model in the article. The firms' expected profit is a function of the demand and marginal profit. As firms invest more in the provider, they increase their demand at the cost of marginal profit. This, however, is not the same for the two provider cases (common and different). Where spillover is negative, in the common case, firms invest more and enjoy a higher demand. The reason for this is that firms compete for investments, which improves the quality of the provider and is beneficial for the firms. The effect of higher demand outweighs the effect of reduced marginal profit, and therefore the common option is optimal in this case.

6.5 Endogenous Prices

In our main model, we consider the marginal profit before investments, π, to be exogenous. This allows our model to neatly capture the effect of firms' competition on quality, where the complicating effects from their pricing decisions are ignored. In this section, we show that our results remain robust where firms decide on both prices and investments. In particular, we consider firms to first decide their investments and then to set prices. We solve this problem using backward induction.

We consider competition on price between firms, reflected in the demand functions. We add the linear price and competition effect to our original demand functions in (7) as

$$D_{i,f} \equiv D_{i,f} - mp_i + np_j, \quad (36)$$

where p_i is firm i's price, m is the price elasticity of demand, and n is the competition effect, with $m > n > 0$. The profit of the firms is updated based on (8) such that we use price instead of marginal profit before investment, and this is given as

$$E(\Pi_{i,k}) = \sum_{f \in F_k} P_f^k D_{i,f}[p_{i,k} - x_{i,k}]. \tag{37}$$

The firm disruption probabilities (P_f^k) remain the same as in our main model. Next, we solve the problems for each of the common and different providers cases.

6.5.1 Common Provider Case. We first solve the pricing problem in the second stage, then solve the investment problem in the first stage. By substituting the joint firm state probabilities (4) and demand functions (36) into the profit function (37), then maximizing with respect to p_i, the equilibrium price for each firm in the common provider case from the first-order conditions is given as

$$p^*_{i,c} = \frac{2x_{i,c}m^2[x_{i,c} + x_{j,c} + 1] + m[x_{j,c}n[x_{i,c} + x_{j,c}] + 2x_{i,c} + x_{j,c}[n+2] - 2\theta V[r-e] + 2] + n[x_{i,c} + x_{j,c} - \theta v[r-e] + 1]}{[x_{i,c} + x_{j,c} + 1][4m^2 - n^2]}, \quad \forall i = 1,2. \tag{38}$$

We confirm that the second-order condition of firm i's profit with respect to its price is satisfied.

Then, in the first stage, firms decide their investment. We substitute the optimal prices from (38) back in the profit function in (37) to find the first stage profit to be maximized. We find the equilibrium investment for each firm using the first-order condition with respect to investment as

$$x^{eq}_{i,c} \equiv x^{eq}_c = \frac{1}{2}\left[\frac{\theta v[1-e][2m+n]}{\sqrt{\theta v[1-e][2m+n][2m^2-n^2]}} - 1\right], \qquad \forall i = 1,2. \tag{39}$$

This yields the equilibrium (expected) profit of

$$E(\Pi_{i,c})^{eq} \equiv \Pi^{eq}_c = \frac{m\left[[6m^2-mn-3n^2]\theta v(r-e) - [m-n+2]\sqrt{\theta v(2m+n)(2m^2-n^2)(r-e)}\right]^2}{4[2m-n]^2[2m+n][2m^2-n^2]\theta v[r-e]}, \qquad \forall i = 1,2. \tag{40}$$

6.5.2 Different Providers Case. Similar to the common provider case, we first solve the pricing problem in the second stage, then solve the investment problem in the first stage. By substituting the joint firm state probabilities (6) and demand functions (36) into the profit function (37), then maximizing with respect to p_i, the equilibrium price for each firm in the different providers case from the first-order conditions is given as

$$p^*_{i,d} = \frac{n + m[2 + 2x_{i,d}m + x_{j,d}n] - \frac{\theta v[2rm - en]}{1 + x_{i,d}} - \frac{\theta v[2em - rn]}{1 + x_{j,d}}}{4m^2 - n^2}, \qquad \forall i = 1,2. \tag{41}$$

We confirm that the second-order condition of firm i's profit with respect to its price is satisfied.

Then, in the first stage, firms decide their investment. We substitute the optimal prices from (41) back in the profit function in (37) to find the first stage profit to be maximized. We find the equilibrium investment for each firm using the first-order condition with respect to investment as

$$x^{eq}_{i,d} \equiv x^{eq}_d = \frac{\sqrt{\theta v \alpha^3[2m^2 - n^2][2mr - ne]} - \alpha[2m^2 - n^2]}{\alpha^2[2m^2 - n^2]}, \qquad \forall i = 1,2. \tag{42}$$

This yields the equilibrium (expected) profit of

$$E(\Pi_{i,d})^{eq} \equiv \Pi^{eq}_d = \frac{m\left[[6m^2-mn-3n^2]\theta v(r-e) - [m-n+2]\sqrt{\theta v(2m+n)(2m^2-n^2)(r-e)}\right]^2}{4[2m-n]^2[2m+n][2m^2-n^2]\theta v[r-e]}, \qquad \forall i = 1,2. \tag{43}$$

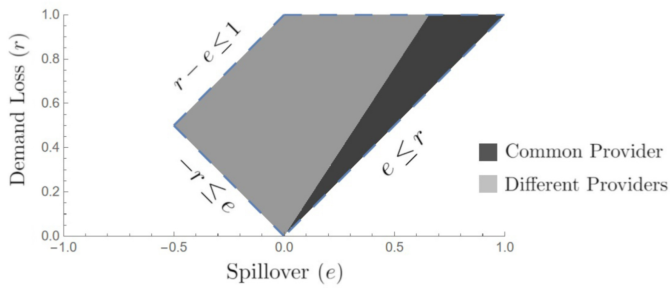


Fig. 10. Optimal service provider regions with endogenous pricing ($v = 0.4, \theta = 1, \alpha = 2, m = 0.05, n = 0.01$).

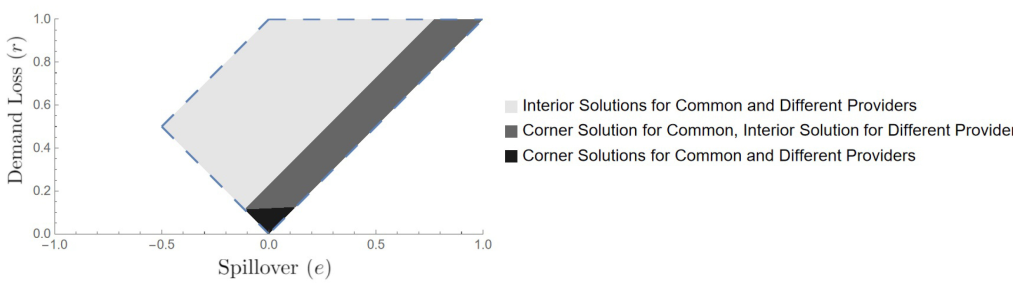


Fig. 11. Interior and corner solution regions ($\pi = 10, v = 0.4, \theta = 1, \alpha = 2$).

6.5.3 Provider Choice Comparison. Similar to our main model, using the equilibrium profit functions from common and different providers in (40) and (43), we can compare the two provider choices. Even though the profits of the firms when choosing common and different providers are derived analytically, due to the complexity of equations, the comparison between them can be done only numerically. This comparison is provided for a representative example in Figure 10.

We confirm that our findings from the model with endogenously chosen prices are consistent with our main model, demonstrating the robustness of our results.

6.6 Considering Corner Solutions

In our main model, we consider the marginal profit before investment to be high enough ($\pi > [1 - \theta v[r-e]]/\theta v[r-e]$) so that the decision of investment is relevant and firms make positive investments in both common and different providers (interior solution). If this assumption is not held, then the firms using a common provider, different providers, or both may not invest (corner solution). We analyze such a scenario in this section.

The requirement for reaching a corner solution in each of the common provider and different providers cases is derived by finding the conditions that make the equilibrium investments negative in these cases in (11) and (15), respectively. Thereby, where $\pi < [1 - \theta v[r-e]]/\theta v[r-e]$, the solution for the common provider case is given by the corner solution of $x_c^{eq} = 0$, and where $\pi < [1 - \theta v r \alpha]/\theta v[r-e]$, the solution for the different providers case is given by the corner solution of $x_d^{eq} = 0$. From the inequalities, it is evident that it is not possible for the different providers case to have a corner solution where the common providers case has an interior solution. Figure 11 depicts the regions for these outcomes for a representative example where corner solutions exist.

Next, we consider the impact of corner solutions on the comparison between common and different providers. For brevity, we focus on the case with $\alpha = 2$. Our next proposition characterizes these findings.

Proposition 4.

(a) If marginal profit before investment is high ($\pi > [1 - \theta v[r - e]]/\theta v[r - e]$), then firms' equilibrium investment in both common and different providers is given as an interior solution, with results provided in Proposition 2.

(b) If marginal profit before investment is moderate ($[1 - \theta v[r - e]]/2\theta vr < \pi < [1 - \theta v[r - e]]/\theta v[r - e]$), then firms' equilibrium investment in a common provider is given as the corner solution with $x_c^{eq} = 0$ and in different providers is given as an interior solution. Compared to the main model, in this region, the common provider case becomes more desirable, as it is less costly to firms.

(c) If marginal profit before investment is low ($\pi < [1 - \theta v[r - e]]/2\theta vr$), then firms' equilibrium investment in both a common provider and different providers is given as the corner solution with $x_c^{eq} = 0$ and $x_d^{eq} = 0$, respectively. Compared to the main model, under these scenario, the choices of common and different providers become equivalent as they yield the same profit to firms.

Proof.

Part (a): This is shown in the proof for Proposition 2, where the investments in both provider choices are given as interior solution.

Part (b): As discussed earlier, where $[1 - \theta v[r - e]]/2\theta vr < \pi < [1 - \theta v[r - e]]/\theta v[r - e]$, the solution in the common provider case is given as a corner solution, whereas the solution under the different providers case is given as the same interior solution in part (a). Thereby, firms do not need to invest in the common provider, even though the different providers are still costly. Therefore, the common provider case becomes more desirable to the firms compared to an interior solution.

Part (c): Where $\pi < [1 - \theta v[r - e]]/2\theta vr$, the investment of firms in both common and separate providers cases is given as the corner solutions $x_c^{eq} = 0$ and $x_d^{eq} = 0$. Substituting these investments of zero in the profit equations for the common and different providers cases in (9) and (13), we get

$$E(\Pi_{i,c})^{eq^{corner}} = E(\Pi_{i,d})^{eq^{corner}} = \pi\left[1 - \theta v[r - e]\right] \quad \forall i = 1, 2.$$

Given that the profits under either common provider or different providers is the same, the firms are indifferent between the two choices and these choices are equivalent.

□

Proposition 4 implies that when profitability in the market is not high enough, firms stop investing in either the common provider choice (part (b)) or both provider choices (part (c)). Where the investment in common provider is given by the corner solution (part (b)), the common provider becomes relatively more desirable to firms, as it minimizes the investments that they have to make. However, where the investment in both provider choices is given by the corner solution (part (c)), the two provider choices become equivalent, because there is no differentiation between them. These findings are shown for a representative example in Figure 12.

Evidently, other than the trivial scenario where both provider choices become equivalent due to a lack of investments (low demand loss and spillover), our findings from the main model remain qualitatively the same when corner solutions are considered.

7 Discussion and Conclusion

Choosing service providers is a complex task, where firms traditionally consider many factors such as quality, features, cost, timeliness, and compatibility. With the increasing digitization of supply

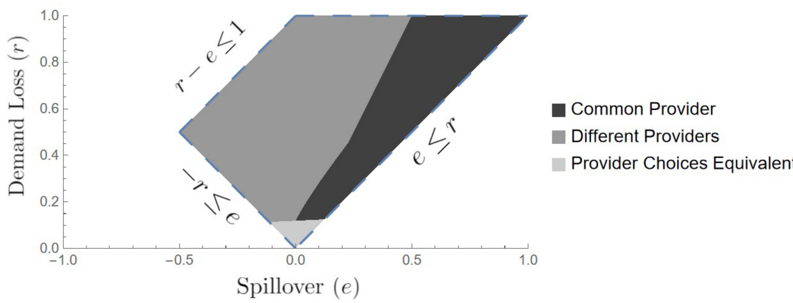


Fig. 12. Optimal service provider regions with corner solutions ($\pi = 10$, $v = 0.4$, $\theta = 1$, $\alpha = 2$).

chains, service providers are a source of potential disruption. Our work provides an alternative explanation on the impact of downstream demand spillover from disruptions on upstream concentration and competition. We uncover a demand mechanism whereby providers may become more prominent and concentrated in industries with positive spillover from disruptions, such as in industries with established demand, which then synchronizes any disruptions and the subsequent effects. However, this mechanism encourages more providers and less concentration in industries with negative spillover from disruptions, such as in emerging technology industries. Our contribution is in considering the diverging disruption risks that come from either sharing or not sharing providers with competitors, and how this results in different supply chain structures (upstream concentration or competition) for different industries according to their demand reactions to disruptions. Our interpretation of ‘upstream concentration’ is stylized where use of a common supplier represents higher upstream concentration and a different supplier represents lower upstream concentration (i.e., higher competition).

In the case where provider capabilities are asymmetric, the argument for sharing the dominant service provider increases. However, where the firms are asymmetric, the optimal region for the common provider expands for the firm with lower demand loss and shrinks for the firm with higher demand loss. The resulting provider choice, then, depends on which firm chooses last—a case of ‘first mover disadvantage.’

7.1 Implications for Practitioners and Policymakers

Our findings impact various stakeholders. We begin by presenting managerial implications and follow with recommendations for policymakers.

7.1.1 Managerial Implications. Decision makers should carefully evaluate the benefits of diversifying their supplier base. Relying on a common supplier—especially one which is shared with competitors—creates synchronized risk where a single disruption, such as a security breach or supply chain failure, affects all downstream firms. By contrast, using different suppliers helps mitigate this risk, reducing the likelihood that all firms will experience the same disruption at the same time. By recognizing the tradeoffs between shared and separate suppliers, decision makers can better design supply chain strategies that balance cost, risk, and resilience, ensuring their firms are better prepared to handle disruptions and maintain competitiveness.

A possible question is whether managers should care about the impact of risk-related market influences resulting from upstream service provider disruptions, such as security breaches, on the choice of service providers. This concern is increasing as digital supply chains grow and security breaches become more devastating. To address this, two factors should be considered. First, security breaches in digital supply chains are a clear and growing danger to downstream firms. Digital supply chains are ubiquitous, and many of the suppliers are small companies without deep pockets for security. The risks that these digital suppliers pose is growing. Second, the impacts of upstream security breaches on downstream demand reactions and the resulting reverberation of upstream provider choice by firms is understudied. Digital technologies, as they are employed by digital supply chains, expose new vulnerabilities resulting from security breaches that were previously difficult to observe or simply did not exist. Fundamental changes to how business is conducted will cause new issues and concerns to emerge, and as such, this phenomenon will be observed more frequently as we continue to build complex, interconnected, and often global digital supply chains.

7.1.2 Suggestions for Policymakers. The strategic decision of whether to share or avoid a supplier used by a competing firm significantly affects how a supplier disruption impacts customer demand across firms. Policymakers can reduce the risk of disruptions by selectively promoting strategic alliances focused on improving supplier resilience, shared risk mitigation measures, and ensuring suppliers are equipped to handle disruptions. However, in some cases, it may be welfare maximizing to encourage the use of separate suppliers. This approach prevents the synchronization of risk, ensuring that disruptions do not ripple through an entire industry when firms share common suppliers. In such instances, regulatory frameworks should encourage diversification by relaxing rules that favor common providers and by incentivizing firms to seek distinct suppliers when it better serves industry stability. Policies that allow for both collaboration and separation—depending on the nature of the risk—can mitigate the impacts of major disruptions like security breaches and privacy violations. Even where firms differ in terms of demand loss or spillover, regulation can encourage either common or different service providers to minimize the negative impacts from disruptions.

In summary, we advocate that both managers and policymakers should include the impact of synchronization and de-synchronization of disruption risk in provider choice decisions. For example, in the airline industry, the AeroData outage suggests that the airlines should be cautioned against using a common provider as the competition between airlines intensifies. Rather, they should focus on using alternative providers which do not provide service to competing airlines. In 2022, the cost of flight disruptions in the United States was estimated to be as much as $34 billion [1], indicating that policymakers may also benefit from encouraging such strategies in industries where system-wide disruptions can have widespread economic ripple effects.

7.2 Contributions to the Literature

The findings in this article extend the literature on provider choice, illustrating that in addition to provider quality, features, cost, timeliness, and compatibility, firms should consider the other client firms of prospective providers. We also show that if firms have a negative spillover, the common provider can be optimal only if it yields better effectiveness than utilizing different providers. Moreover, these findings propose a market mechanism by which downstream demand spillover impacts upstream firm concentration. Through this lens, the downstream demand spillover from disruptions is one of the reasons for observing higher upstream concentration in the case where there is positive spillover from disruptions (as is the case in many well-established industries)—versus lower upstream concentration in the case where there is negative spillover from disruptions (as is often the case in emerging technology industries). We contribute to the literature by considering the synchronization versus de-synchronization of disruptions that come from either sharing or not sharing providers with competitors, and how this results in different supply chain structures for different industries according to their demand reactions to disruptions. This provides a novel view on the problem of choosing problem. This work is a step toward better understanding the complex system of markets, firms, and digital service providers in the digital supply chain.

7.3 Implications for Future Research

A more complex consideration of provider dependencies is expected to be important to future work in this area, as these dependencies affect customer demand reactions. This work considers minimal switching costs for the firms' customers. Introducing high switching costs may have a dampening effect on demand reactions and is an area of needed study. We speculate that switching costs will impact market size, as synchronized risks due to common service providers are expected to be impacted by low versus high barriers to switching. Another path for future research is to consider the firms' pricing strategies that accompany their provider choices, as well as possible investments by providers. Such variables may provide additional nuance to the problem of provider choice.

For policymakers, there is great interest in sustaining and supporting digital supply chains. Understanding how security breaches can impact markets with different demand reactions is a critical component of public policy as well as national security. We have not fully addressed the regulatory and welfare concerns around sharing providers in this study. Future work focusing on these questions is crucial for policymaking.

This work is an early attempt to fully model the impact of common suppliers on customer demand. As firms become more dependent on data services, the issue of common versus different providers is expected to become a more prevalent and increasingly important decision problem in the configuration of digital supply chains.

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