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NETWORK EFFECTS AND DECENTRALIZED GOVERNANCE IN PUBLIC BLOCKCHAIN ECOSYSTEMS

BY

YUKUN YANG

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree

Of

Doctor of Philosophy

In the Robinson College of Business

Of

Georgia State University

GEORGIA STATE UNIVERSITY
ROBINSON COLLEGE OF BUSINESS
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ACCEPTANCE

This dissertation was prepared under the direction of *YUKUN YANG's* Dissertation Committee. It has been approved and accepted by all members of that committee, and it has been accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Business Administration in the J. Mack Robinson College of Business of Georgia State University.

Richard Phillips, Dean

DISSERTATION COMMITTEE

Dr. Likoebe Maruping (Chair)
Dr. Arun Rai
Dr. Ling Xue
Dr. Rajiv Kohli

ABSTRACT

NETWORK EFFECTS AND DECENTRALIZED GOVERNANCE IN PUBLIC BLOCKCHAIN ECOSYSTEMS

BY

YUKUN YANG

July 13th, 2021

Committee Chair: *Dr. Likoebe Maruping*

Major Academic Unit: *Computer Information Systems*

The emergence and increasing adoption of blockchain technologies give rise to a new form of digital platform-enabled ecosystems – decentralized ecosystems. In such ecosystems, multi-side participants collectively enjoy the decision-making rights instead of a central authority orchestrating the overall ecosystem. To understand decentralized ecosystems, this dissertation explores public blockchain ecosystems from two perspectives. First, from the perspective of value co-creation, the first section of this dissertation investigates how interdependent activities enable the functioning of such a non-central authority environment. Second, from the perspective of governance, the second section of this dissertation explores the mechanisms that are enacted to exercise decentralized governance and the impacts of these mechanisms. This dissertation presents a layer-subsystem structure and reveals dynamic and coevolving interactions within and between subsystems across layers. This dissertation also identifies three decision mechanisms and demonstrates the dynamic influences of the mechanisms on other activities at each layer and the interaction between mechanisms across layers.

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CHAPTER 1. INTRODUCTION

BRIEF BACKGROUND AND OVERARCHING OBJECTIVE

Digital platform-enabled ecosystems have drawn much attention in the past decade (Alves et al. 2017; Huber et al. 2017; Schreieck et al. 2016; Wang 2021; Wareham et al. 2014). In these ecosystems, there is usually a central firm (i.e., digital platform owner) that sponsors the core components and interface upon which complementors can develop and offer their complementary products to end-users (Pereira et al. 2019). Decentralized ecosystems supported by blockchain technologies have become popular in recent years. A key feature of such ecosystems is a lack of central authority in control of overall orchestration. Ecosystem participants can take part in decision-making and represent their perspectives (Chen et al. 2021). The primary purpose of these ecosystems is to maximize the overall welfare of all participants rather than the residual profits of the platform owner (Chen et al. 2021).

With the platform owner's intermediation in centralized ecosystems, exchanges between transacting parties become self-reinforcing in the form of network effects—where valuable exchanges attract additional value-creating exchanges among participants involved (Cennamo and Santalo 2013; McIntyre and Srinivasan 2017). Blockchain technologies challenge the existing enforcement mechanisms that platform owners typically leverage to govern the ecosystem (Schmeiss et al. 2019). Existing research has focused on ecosystems with clearly defined and centralized forms of authority. In contrast, there is a lack of understanding about blockchain technology's ability to encourage network effects in environments with decentralized forms of authority (Chen et al. 2021; Wu et al. 2019). The first section of this dissertation aims to understand how network effects generated from value co-creation activities shape a healthy blockchain ecosystem.

In a centralized ecosystem, the platform owner has the overarching power over designing and applying appropriate governance mechanisms and orchestrate the innovation process. Such governance is referred to as centralized governance. Although centralized governance benefits the platform owner in having exclusive governance control and acquiring the most benefits from innovation processes, it may expose the ecosystem to significant risks such as lack of transparency, corruption, regulatory capture, and misuse of power (Atzori 2015; Rietveld et al. 2020). The decentralized governance enabled by blockchain technologies can reduce the concentration of power and achieve automation, transparency, auditability, and cost-effectiveness (Atzori 2015). However, the extant literature on ecosystem governance has tended to place a greater emphasis on centralized forms. Less attention has been paid to decentralized governance regarding what governance mechanisms are enacted and how these mechanisms would affect the activities in the ecosystem. The second section of the dissertation aims to identify specific governance mechanisms in public blockchain ecosystems and explore the impacts of these governance mechanisms.

Based on the overarching objectives, this dissertation is divided into two sections presented in Chapter 2 and Chapter 3. Based on the results of the two sections, I draw a conclusion in Chapter 4. Below I briefly introduce each of the two sections.

SECTION 1

Existing research on platform-enabled ecosystems has placed a great deal of emphasis on platforms with centralized forms of authority while paying less attention to ones with highly decentralized forms. To uncover the functioning of decentralized platform-enabled ecosystems, I introduce layer-subsystem as an important structure of the public blockchain ecosystem. Informed by the theoretical perspective of value co-creation, I theorize how activities within each subsystem react to each other with distinct value co-creation processes and how subsystems interact at the same layer or across different layers. I collect weekly data of a leading public blockchain ecosystem and use a time-series analysis to examine the hypotheses. My findings reveal that network effects in the public blockchain ecosystem are unbalanced (mutual vs. unidirectional) and asymmetric (short-term vs. long-term). I also find that the within-subsystem network effects tend to manifest immediately, while those that are between subsystems or across layers usually take time to manifest.

SECTION 2

Based on the findings from the first section, this section specifically focuses on the decentralized governance perspective. Built on Fama and Jensen's (1983) framework of decision processes in organizations, I conceptualize the decision control mechanism and decision management mechanism and contextualize these governance mechanisms to the layered structure of the public blockchain ecosystem. I examine the dynamic influences of specific governance mechanisms on participants' activities within and across different layers and the interactions between different governance mechanisms. A time-series analysis is conducted using weekly data collected from a leading public blockchain ecosystem. My findings indicate that the decision control mechanism dynamically affects activities at the application layer, and the two decision management mechanisms dynamically affect activities at the architecture layer. The results also show a significant effect of the decision control mechanism on a decision management mechanism across layers.

REFERENCES

Alves, C., de Oliveira, J. A. P., and Jansen, S. 2017. "Software Ecosystems Governance-a Systematic Literature Review and Research Agenda," *ICEIS (3)*, pp. 215-226.

Atzori, M. 2015. "Blockchain Technology and Decentralized Governance: Is the State Still Necessary?." Available at https://ssrn.com/abstract=2709713.

Cennamo, C., and Santalo, J. 2013. "Platform Competition: Strategic Trade-Offs in Platform Markets," *Strategic Management Journal* (34:11), pp. 1331-1350.

Chen, Y., Pereira, I., and Patel, P. C. 2021. "Decentralized Governance of Digital Platforms," *Journal of Management* (47:5), pp. 1305-1337.

Fama, E. F., and Jensen, M. C. 1983. "Separation of Ownership and Control," *The Journal of Law and Economics* (26:2), pp. 301-325.

Huber, T. L., Kude, T., and Dibbern, J. 2017. "Governance Practices in Platform Ecosystems: Navigating Tensions between Cocreated Value and Governance Costs," *Information Systems Research* (28:3), pp. 563-584.

McIntyre, D. P., and Srinivasan, A. 2017. "Networks, Platforms, and Strategy: Emerging Views and Next Steps," *Strategic Management Journal* (38:1), pp. 141-160.

Pereira, J., Tavalaei, M. M., and Ozalp, H. 2019. "Blockchain-Based Platforms: Decentralized Infrastructures and Its Boundary Conditions," *Technological Forecasting and Social Change* (146), pp. 94-102.

Rietveld, J., Ploog, J. N., and Nieborg, D. B. 2020. "Coevolution of Platform Dominance and Governance Strategies: Effects on Complementor Performance Outcomes," *Academy of Management Discoveries* (6:3), pp. 488-513.

Schmeiss, J., Hoelzle, K., and Tech, R. P. 2019. "Designing Governance Mechanisms in Platform Ecosystems: Addressing the Paradox of Openness through Blockchain Technology," *California Management Review* (62:1), pp. 121-143.

Schreieck, M., Wiesche, M., and Krcmar, H. 2016. "Design and Governance of Platform Ecosystems–Key Concepts and Issues for Future Research," in: *European Conference on Information Systems (ECIS)*.

Wang, P. 2021. "Connecting the Parts with the Whole: Toward an Information Ecology Theory of Digital Innovation Ecosystems," *MIS Quarterly* (45:1), pp. 397-422.

Wareham, J., Fox, P. B., and Cano Giner, J. L. 2014. "Technology Ecosystem Governance," *Organization Science* (25:4), pp. 1195-1215.

Wu, K., Peng, B., Xie, H., and Huang, Z. 2019. "An Information Entropy Method to Quantify the Degrees of Decentralization for Blockchain Systems," *IEEE 9th International Conference on Electronics Information and Emergency Communication (ICEIEC)*, pp. 1-6.

CHAPTER 2. NETWORK EFFECTS IN PUBLIC BLOCKCHAIN ECOSYSTEMS: A LAYER-SUBSYSTEM PERSPECTIVE

INTRODUCTION

In a digital platform-enabled ecosystem, the platform functions as an intermediary with policies and mechanisms through which platform owners exert influence over participants on multiple sides of ongoing exchange transactions and coordinate operations in the ecosystem (Parker and Van Alstyne 2005; Song et al. 2018). In this process, the platform owner plays a critical role in encouraging exchanges between transacting parties. In addition to designing and implementing mechanisms and toolkits to support participants (Parker and Van Alstyne 2018), as a trusted third party the platform owner also defines and enforces the rules of exchange (Constantinides et al. 2018; Maruping and Yang 2020). A core value proposition of digital platforms is that, with the platform owner's intermediation, exchanges between transacting parties become self-reinforcing in the form of network effects—where valuable exchanges attract additional value-creating exchanges among participants involved (Cennamo and Santalo 2013; McIntyre and Srinivasan 2017).

Existing research on platform-enabled ecosystems and their enablement of network effects has placed a great deal of emphasis on platforms with clearly defined and centralized forms of authority (Rietveld et al. 2019). The primary purpose of governing a relatively centralized digital platform is for the platform owner to lead stakeholders to create value (Boudreau 2010; Kyprianou 2018; Rietveld et al. 2019). As such, the ability to achieve network effects tends to be tied to actions taken by the platform owner. For example, Song et al. (2018) found that the platform owner's control over app review time and platform update frequency can moderate the dynamic network effects between users and app developers. From a theoretical perspective, we know far less about the mechanism behind the emergence of network effects in digital platforms where authority is more decentralized in nature (Chen et al. 2021). In recent years, the emergence of blockchain technology that supports digital platforms for exchange has raised questions about the ability to encourage network effects in environments with decentralized forms of authority (Wu et al. 2019). On the one hand, blockchain technology provides architecture support for highly decentralized ecosystem governance. On the other hand, it challenges the existing enforcement mechanisms that platform owners typically leverage to govern the ecosystem, as there may be no platform owner in such an ecosystem. As a result, another question it raises is the ecosystem structure that congeals to enable these network effects.

Along a continuum ranging from publicly accessible at one extreme to highly restricted accessibility at the other extreme, blockchain ecosystems can be categorized into three types: public blockchain ecosystems, consortium blockchain ecosystems, and private blockchain ecosystems (Beck et al. 2018; Zheng et al. 2017). The governance of consortium and private blockchain platforms is more centralized as they have an authority that controls the access and consensus process. In contrast, decentralized authority is well-represented in public blockchain platforms (Atzori 2015). As my research interest lies in highly decentralized ecosystems, I specifically focus on public blockchain in this research. This represents a theoretically significant and novel context for theorizing about network effects. If network effects are contingent on the actions of a centralized platform owner, how might they materialize under conditions of decentralized authority? Extant platform literature is limited in providing a compelling explanation with regard to this question.

To establish some conceptual structure for theorizing about decentralized digital platform ecosystems, this research introduces layer-subsystem as an important structure of public blockchain ecosystems. I conceive of this structure of blockchain ecosystems along two key attributes. The first attribute is that they are comprised of a layered architecture. Drawing upon Adomavicius et al. (2008) and Yoo et al.'s (2010) conception of layered architecture, I view public blockchain ecosystems as comprising an assemblage of technology components that collectively enable the platform ecosystem to function. The second attribute is that they are comprised of different subsystems of mutually dependent participants. Through this lens of subsystems, I view the blockchain ecosystem as comprising an assemblage of multiple self-contained communities, each with its own set of participants and incentives that facilitate value-creating exchanges at a given layer of the architecture. This layer-subsystem conceptual lens enables us to illuminate the network effect dynamics in decentralized platform-enabled ecosystems.

I suggest that the layer-subsystem structure surfaces the importance of alignment of participant incentives not only *within* subsystems *at* the same layer but also *between* subsystems *at or across* layers to ensure a robust platform-enabled ecosystem. An absence of such alignment risks a downward spiral of value erosion as the tension between what is desirable within a subsystem versus what is desirable for adjacent subsystems in the broader ecosystem falls out of balance. In light of the layer-subsystem structure, I then theorize the exchange dynamics that facilitate network effects in the public blockchain ecosystem. Drawing on the theoretical lens of value co-creation, I posit that the network effects generated by dynamic interactions between activities in the layer-subsystem structure of a public blockchain ecosystem vary in their nature (direct vs. indirect) and in the duration of their effects (short-term vs. long-term). Specifically, I argue that the network effects within subsystems are direct and can immediately manifest. I also argue that the network effects between subsystems are indirect and can be short-term or long-term within layers but are more likely to be long-term between subsystems across layers. I empirically examine the hypotheses using weekly time-series data collected from Ethereum and its repository on GitHub between January 2016 and October 2019. Using a *vector autoregression with exogenous variable* (VARX) analysis, I examine the dynamics between activities within and between subsystems across different layers.

This research contributes to the platform-enabled ecosystems literature by elucidating previously underexplored ecosystems with a highly decentralized form of governance. With the growing trend of adopting blockchain technologies, it is vital to understand how a platform-enabled ecosystem functions without the intermediation of a central authority. Prior work has primarily emphasized the interactions within a single digital platform as a self-contained community (e.g., Cennamo and Santalo 2013; Song et al. 2018; Tiwana et al. 2010). By developing a subsystem view of a decentralized digital platform-enabled ecosystem, I draw attention to the need for a stronger emphasis on alignment of incentives and rewards within and between subsystems in the ecosystem. My approach also recognizes that the subsystems do not necessarily exist at the same layer of a digital platform. By conceptualizing a layer view, I provide new insight into the different time horizons over which network effects manifest. Specifically, I find that cross-layer network effects are indirect and long term, while within-layer network effects are more short term. Overall, decomposing the ecosystem into layers and subsystems reveals how value co-creation activities interrelate and coevolve in a complex environment. These findings also generate important practical implications as to how the management of public blockchain ecosystems can be improved.

BACKGROUND

Digital Platform-enabled Ecosystems

Drawing from views in biology, the term ecosystem is generally understood as “a set of actors with varying degrees of multilateral, non-generic complementarities that are not fully hierarchically controlled” (Jacobides et al. 2018, p. 2264). Depending on the unit of analysis, empirical studies on ecosystems are grouped into streams—business ecosystems, innovation ecosystems, and platform ecosystems (Jacobides et al. 2018). In a digital platform-enabled ecosystem, the platform serves as the meeting space that enables value-creating interactions between participants by acting as an intermediary that provides mechanisms and toolkits to support participants (Kim 2017; Parker and Van Alstyne 2018) and being a trusted third party to resolve conflicts during the innovation process (Constantinides et al. 2018; Maruping and Yang 2020). Research in this stream has a focus on firm-sponsored platforms, and the relevant activities all take place on a single platform (Adner 2017; Jacobides et al. 2018). In these studies, a platform ecosystem usually consists of a focal firm (i.e., the platform owner or sponsor) and its network of complementors (e.g., app developers, API developers, data aggregators, and third-party service providers) that produce complements to enhance platform value (Adner and Kapoor 2010; Ceccagnoli et al. 2012; McIntyre and Srinivasan 2017). Discussions in this literature revolve around how different parties in the platform ecosystem interact to create value and how the platform acts as an intermediary to facilitate interactions (Grover and Kohli 2012; McIntyre and Srinivasan 2017). For example, Ceccagnoli et al. (2012) find that participation in an ecosystem partnership of a major platform owner can improve the business performance of small independent software vendors (as complementors to the platform ecosystem). Parker et al. (2017) show that platform firms can optimize their intellectual property, thereby creating highly valuable complements for ecosystem users. Rietveld et al. (2019) illustrate that a platform sponsor can manage ecosystem value by selectively promoting individual complements, which nurtures the success of complements and influences end users' perception of the breadth and depth of the ecosystem. These and other studies mainly focus on platform-enabled ecosystems in which platform owners retain authority and are the main arbiters of exchanges between participants. In contrast, much less is known about ecosystems where such authority is distributed to participants rather than being vested in a central authority, limiting the conclusions drawn from extant views (Wang 2021).

Mounting evidence shows decentralized forms of governance as a key feature of thriving blockchain technologies (Wu et al. 2019). Although blockchain technology has started to attract researchers' attention, emerging studies tend to focus on firm-sponsored platforms enabled by blockchain. Consequently, rather than understanding a platform-enabled ecosystem embedded with a highly decentralized mechanism, such approaches reinforce existing orthodoxy surrounding the need for and role of a central authority (Chen et al. 2021; Schmeiss et al. 2019). In the next section, I introduce blockchain technology, public blockchain ecosystems and its decentralized form of organizing.

Public Blockchain Ecosystems

The notion of blockchain was first proposed by Satoshi Nakamoto in 2008 and implemented in Bitcoin, a public transaction ledger of cryptocurrency (Nakamoto 2008). At its core, blockchain technology is a distributed public ledger upon which all transaction information between parties is recorded in a chain of blocks (Yli-Huumo et al. 2016). This chain grows as more blocks of new transactions are appended to it continuously (Zheng et al. 2017). There are four key characteristics of blockchain that pave the foundation for decentralized governance

(Zheng et al. 2017). (1) Non-intermediary: blockchain enables transactions to be validated without the intervention of a central trusted agency (e.g., Federal Reserve Bank); (2) Immutable: once blocks are added to the blockchain, it is nearly impossible for the transactions to be deleted or rolled back; (3) Anonymous: participants do not need to reveal their real identities in order to participate in blockchain activities; and (4) Trackable: all transactions can be easily verified and tracked as each block has a unique hash value that points to the previous block.

There are generally three types of blockchain and they differ with regard to the level of accessibility they offer to general participants (Beck et al. 2018; Zheng et al. 2017). Public blockchain (e.g., Bitcoin and Ethereum) opens all transaction records to the public and allows everyone to participate in the process of block validation. Consortium blockchain (e.g., Hyperledger) allows pre-selected participants to engage in the process of block validation. Private blockchain (e.g., Ripple) allows only participants that are preregistered by a central authority to read blockchain data and submit new transactions. Compared to the governance of public blockchains which is characterized as permissionless and highly decentralized, the governance of consortium blockchains is more centralized as the right to verify transactions is decided by a central authority (Atzori 2015). The governance of private blockchain is even more centralized as a single authority has complete control over the accessibility and verification rights to the blockchain. As already noted, I focus on the public blockchain as it best reflects the core value proposition of blockchain—a distributed public ledger that enables two or more parties to exchange value without having an intermediary in control of the transactions (Angelis and da Silva 2019; Yli-Huumo et al. 2016). Despite variations among blockchain ecosystems, major participants in a blockchain ecosystem include *users* who transact with other users or invoke smart contracts, *contract creators* who deploy smart contracts on the blockchain platform, *miners* who validate the transactions and smart contract deployment, and *protocol developers* who develop and improve the underlying blockchain protocol to support on-platform activities.

In this research, I adopt Adner's (2017) view of ecosystem-as-structure and adapt it to the public blockchain ecosystem. Ecosystem-as-structure emphasizes interactions between participants and views ecosystems as configurations of activity defined by a value proposition. Therefore, in order to understand the functioning of decentralized ecosystems, it is critical to investigate the localized activity configurations and understand how the activities interact to serve the value proposition. The distinct feature that separates the public blockchain ecosystem from other centralized ecosystems is that the value proposition is no longer orchestrated by a focal firm but is implicitly shared by participants in the ecosystem and reflected in alignment of their incentives. Actors in a platform-enabled ecosystem may have different motivations to participate. However, they should have a mutual agreement regarding their roles and the configuration of activities in the overall ecosystem (Adner 2017). When their incentives are aligned, they will collaborate to co-create value to spur the overall ecosystem performance. Otherwise, the overall ecosystem may risk falling apart.

In the theoretical development section, I will first elaborate on network effects as an indicator of incentive alignment and discuss how it manifests from value co-creation. Then, building on the view of ecosystem-as-structure, I will introduce layer-subsystem as the structure to understand the localized activity configuration and their dynamic relationships in a public blockchain ecosystem.

THEORETICAL DEVELOPMENT

Network Effects and Value Co-creation

As a fundamental premise of the interaction network in an ecosystem and an indicator of the alignment of participants' incentives, a *network effect* manifests when participants place a higher value on platforms with a larger number of other participants due to the greater potential value that can be derived from interacting with them (Cennamo and Santalo 2013; McIntyre and Srinivasan 2017). With aligned incentives, a participant may value direct connections with other participants with whom they can interact (direct network effects), or they may anticipate that platforms with more participants will also offer a wider variety of complementary products and services (indirect network effects) (Cennamo and Santalo 2013). The existing literature has demonstrated that the interactions between participants are influenced by network effects and facilitated by platform intermediaries (McIntyre and Srinivasan 2017). In this study, I specifically focus on network effects in terms of the number of activities rather than the number of unique participants for the following two reasons. First, recent literature suggests that network effects are not all about size but are also determined by the nature of network value and the value creation and capture process (Afuah 2013). From this standpoint, value-creating activity is key to understanding network effects. Second, participants in the ecosystem experience network effects through the number of ongoing activities. The blockchain transaction tracking platforms (e.g., Etherscan) usually display the number of activities that are ongoing on the blockchain platform. Participants can perceive the ecosystem's value based on the available information about ongoing activities.

In the ecosystem of a two-sided digital platform, value is created from the dynamic interactions between the two sides of participants. Although value creation is a critical mechanism for participation in platform-enabled ecosystems, there is a lack of reasoning about what value is created and how value is created in such ecosystems. For example, some studies implicitly state that value is created from the products developed by complementors (e.g., Adner and Kapoor 2010; Rietveld et al. 2019). Some argue that value is generated by the platform owner when they implement strategies to spur innovative activities (e.g., Parker et al. 2017). Others posit that value is co-created by the platform owner and complementors (e.g., Parker and Alstyne 2008). An exception is Song et al. (2018), who draw on the value creation perspective by Bowman and Ambrosini (2000), and decompose the value created by app developers and users into use value and exchange value. Users perceive the use value of complements (Lepak et al. 2007). Users use the platform to try complements when the innovative complements that extend the platform's functionality are available on the platform (Adner and Kapoor 2010; Ceccagnoli et al. 2012). Complementors realize the exchange value when users purchase the complements (Lepak et al. 2007; Song et al. 2018). As such, positive network effects are expected in a healthy two-sided platform ecosystem. When the ecosystem is not at its best performance, the platform owner can always exert governance power to orchestrate the interactions. For example, the platform owner can adjust the ecosystem openness to influence the success of complements (Parker et al. 2017).

In a multi-sided platform-enabled ecosystem, there are more than two types of participants, and the dynamics of network effects are more complex than the mere existence of positive network effects on a single digital platform (Afuah 2013; Boudreau and Jeppesen 2015; McIntyre and Srinivasan 2017). For example, some participants may not engage in on-platform activities but still contribute to the functioning of the overall ecosystem. Also, for ecosystems without central orchestration by platform owners, participants need to figure out how to cooperate to create value in a manner that satisfies each party's needs, and the ecosystem functions as a structure that aligns the interdependencies and coordinates the interactions at the levels of both the parts (e.g., participants) and the whole (e.g., ecosystem). In a recent article, Wang (2021) draws on an ecology lens of holon and holarchy and proposes an information ecology theory to direct future studies on investigating the part-whole relations in digital innovation ecosystems. Wang (2021) emphasizes the importance of understanding how the effects of autonomous participants are integrated into a coherent whole and what role do digital technologies play in this integration. To better understand the dynamic interactions in an ecosystem, I decompose the ecosystem into smaller components to understand how each component works and how the components interrelate to each other and contribute to the whole ecosystem.

Layer-Subsystem Structure

A vital feature of the digital platform that makes it distinct from traditional forms of organizations is modularity—an attribute which derives from the modular structure of technology products. Adomavicius et al. (2007) describe modules as subsystems of product components that provide firms more flexibility in product design and manufacturing. Firms have become increasingly dependent on the use of modules to handle increasing complexity of products (Baldwin et al. 2000). Tiwana et al. (2010) apply modularity to a digital platform context. They define a module as an add-on software subsystem that adds functionality to the platform (e.g., Firefox extensions) and modularity as the degree to which changes within a subsystem do not create a ripple effect in the behavior of other parts of the ecosystem. Modules are loosely coupled so that they can independently evolve, unconstrained by having to coordinate or having to know internal details of other modules (Tiwana et al. 2010).

Yoo et al. (2010) combine the modular architecture of a physical product and the layered architecture of digital technology and proposed a layered modular architecture as a hybrid architecture. A layered architecture of digital technology enables separation between device and service and the separation between network and content (Adomavicius et al. 2008), while a modular architecture allows a physical product to be decomposed into loosely coupled components that are interconnected through prespecified interfaces (Baldwin and Clark 2000). The layered modular architecture emphasizes the structure from a technical standpoint and depicts a continuum that enables innovations to spring up independently at any layer through loose couplings across layers (Adomavicius et al. 2008; Yoo et al. 2010).

Although Schilling (2000) points out that increasing modularity is not limited to products but can be applied in many different kinds of systems, previous platform ecosystem studies tend to emphasize modularity from a technology perspective. A related notion to module is subsystem, which has been broadly used in the field of psychology (Briggs and Morgan 2017). Different from the modular view that emphasizes the added functionality in terms of technology, subsystems highlight the interrelationships in terms of self-regulation and value-adding to the broader ecosystem. Entities in each subsystem define their own sets of rules as boundaries. These boundaries not only define the membership of subsystems but also the rules of interaction between those members. The boundaries of subsystems indicate that one subsystem is distinct from the others, while still recognizing the interrelatedness between subsystems (Briggs and Morgan 2017). Such subsystems allow an entity to exist in multiple subsystems simultaneously. In such situations, the entity takes a critical role in connecting two subsystems. In Wang's (2021) notion of ecosystems as holons and holarchies, diverse entities involved in various types of digital innovations may appear as holons at different levels of a "holarchy of digital innovation ecosystems” (Wang 2021, p. 402). Within an ecosystem, a digital innovation can manifest itself at the level of parts where actors innovate interdependently and at the level of the whole where the innovation is co-created as a result. An actor’s engagement with a digital innovation not only helps the actor achieve its own goal, but is also conducive to other actors’ pursuit of their respective goals (Wang 2021). Blockchain technology provides a decentralized way to standardize the terms of interactions among participants, which facilitates the modular structure of the ecosystem (Schmeiss et al. 2019).

Enlightened by the platform literature on layered and modular structures and blockchain technology characteristics, I draw on a value co-creation perspective to conceptually divide blockchain ecosystems into three subsystems that operate at two layers. Based on the functionality that the layer aims to offer to the overall ecosystem, I decompose a blockchain ecosystem into an *application layer* and an *architecture layer*. The *application layer* of a blockchain ecosystem deals with application functionalities that directly serves participants as they engage in exchange of digital assets, implementing smart contracts, and verifying transactions on the blockchain platform. The *architecture layer* of a blockchain ecosystem includes activities that contribute to designing, developing, and implementing the underlying architecture of blockchain technologies, which is at the heart of value creation for participants at the *application layer* (Stabell and Fjeldstad 1998). For participants at the application layer, activities at the architecture layer create use value as the updates applied to the blockchain will be directly used for activities at the application layer. Architecture-layer participants are more likely to perceive the exchange value created from the activities at the application layer, as the use of blockchain technologies will be translated into non-monetary value (e.g., reputation and experience) that encourages activities at the architecture layer. Considering the distinct features that different layers add to the ecosystem, I state that the cross-layer interactions are mainly indirect and delayed, as they usually happen on different interfaces of the ecosystem so that changes may not be perceived by participants across layers immediately. In contrast, interactions at the same layer can be direct or indirect, depending on the value creation and appropriation process.

Although the common purpose of participants at the *application* layer is to use blockchain, their incentives to participate can be different. The incentive structure is essential to understanding participant behavior in a platform-enabled ecosystem as it influences the value generated in the ecosystem from participants' engagement and the formation of subsystem boundaries (Constantinides et al. 2018). In a blockchain ecosystem with aligned incentives, participants tend to choose actions that are consistent with the goal of the incentive structure, thereby bringing greater value to the blockchain ecosystem (Beck et al. 2018). Based on participants' incentives and the value generated from their participation and interaction, I identify two subsystems—the *contract subsystem* and *exchange subsystem*—as existing at the *application layer* and one subsystem—the *protocol subsystem*—as existing at the *architecture layer*. For participants in the exchange subsystem, activities in the contract subsystem offer smart contracts available for use, thus generating use value to meet their needs. For participants in the contract subsystem, activities in the exchange subsystem provide a potential market for them to acquire monetary profits (i.e., exchange value). Table 1 summarizes the key participants and activities in the blockchain subsystems that I have identified.

TABLE 1
Layer-Subsystem Structure and Value Creation

	Participant	Description	Activity	Value to Participant	Co-created Value
Application Layer	**Contract Subsystem**				
	Contract Creators	Participants who create smart contracts and deploy the smart contracts on a blockchain.	Smart Contract Deployment: a transaction that is sent from the contract creator with the purpose of deploying a new contract on the blockchain.	• Pecuniary: profits from use of smart contracts	Available-for-use products based on smart contracts
	Miners	Participants who verify blocks of transactions and contracts and keep complete records of the transaction history.	Mining: a validation process to ensure a block of transactions is valid before adding it to the blockchain.	• Pecuniary: monetary rewards by validating blocks	
	Exchange Subsystem				
	Users	Participants who transfer money (in cryptocurrencies) or invoke smart contracts.	Transaction: a signed data package that stores money or a message sent from one account to another. A transaction can be made from a user to another user, or from a user to a smart contract.	• Pecuniary: profits by investing crypto currencies; value exchange • Non-pecuniary: using smart contracts for non-economic purpose such as personal information storage	Increased exchange value of cryptocurrency
	Miners	Participants who verify blocks of transactions and contracts and keep complete records of the transaction history.	Mining: a validation process to ensure a block of transactions is valid before adding it to the blockchain.	• Pecuniary: monetary rewards by validating blocks	
Architecture Layer	**Protocol Subsystem**				
	Protocol Developers	Participants who create and improve the underlying blockchain protocol.	Protocol Development: code contributions from developers to develop and improve the blockchain protocol.	• Non-pecuniary: blockchain development skills; reputation	Improved blockchain protocol

Activities and Participant Incentives in Layered Subsystems

Subsystem Activities at the Application Layer. *Mining*, *contract deployment*, and *transaction* are three types of activity that can be performed at the *application layer* of the public blockchain ecosystem. Specifically, as the overall purpose of the *contract subsystem* is supporting the implementation of innovative products (i.e., smart contracts), it consists of *contract deployment*—a process to request for smart contracts to be implemented on the blockchain and *mining*—a validation process to ensure a block of transactions and smart contracts are valid before being added to the blockchain. *Exchange subsystem* aims to ensure the proper functioning of daily transactions on the blockchain, which includes *mining* and *transaction*—an exchange process to transfer cryptocurrency or a message from one account to another. It is noteworthy that the relational view allows subsystems to overlap such that actors can participate in multiple subsystems simultaneously (Briggs and Morgan 2017). In the case of blockchain, *mining* exists as a key activity in both the *contract subsystem* and the *exchange subsystem*. Acting as an arbiter, miners verify transactions and smart contracts following the protocol rules defined by the consensus algorithm (Zheng et al. 2017). For example, following the "Proof of Work" consensus algorithm, miners compete to solve a computationally intensive cryptographical puzzle in order to verify a new block (Beck et al. 2018; Cong et al. 2019). The miner who first solves the puzzle can add the block to the blockchain and receive a reward. As such, miners are motivated by the monetary rewards they will receive by successfully mining the block. The higher the reward offered by the transaction sender (or contract creator) and the lower the estimated cost of performing the validation, the more likely that the transaction (or contract deployment) will be verified. In order to verify as many transactions as possible, miners invest heavily in advanced computational power and cooling systems to enhance their mining ability (Zheng et al. 2017).

Contract deployment is the other type of activity in the *contract subsystem*. A smart contract defines the rules and penalties around an agreement and automatically executes and enforces the obligation in the contract without interference from third parties (Beck et al. 2018). For example, a tenant can rent an apartment directly from a landlord through a smart contract with an agreement on rental terms. When the rental ends, the smart contract triggers the payment of the security deposit back to the tenant with an adjustment of charges for damage repair (Karamitsos et al. 2018). Contract creators create a smart contract and request to deploy it on the blockchain. Building on smart contracts, contract creators can further develop decentralized applications (known as DApps). An example is CryptoKitties—a blockchain game which allows players to breed and exchange virtual cats by using a smart contract on the Ethereum blockchain. Contract creators earn a commission from users' usage of smart contracts. The more usage of their contracts, the greater revenue they can generate (Cai et al. 2018).

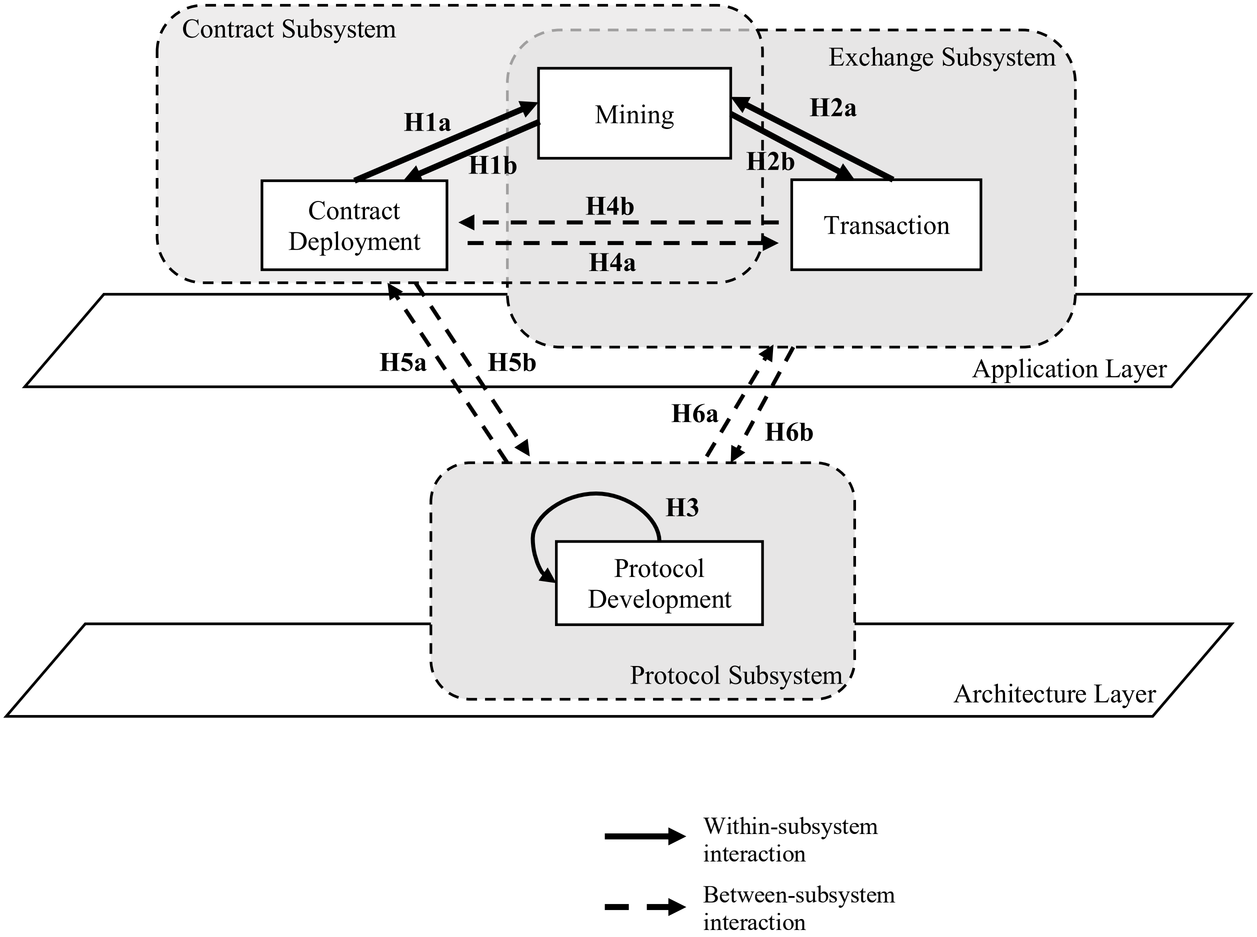
Besides *mining*, the *exchange subsystem* includes *transaction* as a core activity. Transactions initiated by blockchain users serve two general purposes: *user-to-user transactions* for monetary exchange between users and *user-to-contract transactions* for invoking the functions of smart contracts. A transaction is a signed data package that stores cryptocurrency or a message sent from one account to another. A user may send out a transaction with an amount of cryptocurrency to another user for the purpose of exchanging monetary value or investment (Konstantinidis et al. 2018). A user can also send out a transaction with a message or a certain amount of money to a contract account for the purpose of making use of a smart contract (Syed et al. 2019).

Subsystem Activities at the Architecture Layer. The *protocol subsystem* at the *architecture layer* aims to provide technical support for the functioning of the blockchain platform. A blockchain protocol consists of the rules for validating and broadcasting blocks and resolving conflicts (Syed et al. 2019). In an ecosystem without a central authority, the blockchain protocol defines consensus algorithms as a decision-making mechanism to force participants to achieve agreement. Protocol developers engage in *protocol development*, writing software code and testing the underlying protocol to support the appropriate functioning of the blockchain. Protocol development activities usually take place outside the blockchain platform. For instance, Ethereum's protocol is developed on GitHub—a leading open-source software development platform. As resources in the public blockchain ecosystem are public and open, developers voluntarily make code contributions. Protocol developers are motivated to continuously contribute to the improvement of the blockchain protocol when they perceive that doing so can help them enhance their development skills or establish and grow their reputation (von Krogh and von Hippel 2006).

HYPOTHESIS DEVELOPMENT

Viewed through the lens of layer-subsystem structure, I posit that digital platform-enabled ecosystems can be characterized by a complex set of direct and indirect value co-creation relationships between participants within subsystems and between subsystems at different layers of the ecosystem architecture (Stabell and Fjeldstad 1998). Figure 1 conceptually illustrates the research model. In this study, an immediate network effect refers to the case in which the growth of activity on one side of an interaction triggers the growth of activity on the other side in the first week after the change. A long-term network effect refers to cases in which the response in growth of one side of an interaction to the growth of the other side takes a longer time to manifest.

FIGURE 1
Research Model



Cross-side Effects within the Contract Subsystem

In the *contract subsystem*, contract deployment activities and mining activities complement each other to generate value. Contract creators have capabilities to create innovative smart contracts, while miners have resources and facilities to make the smart contracts effective. The direct interaction between miners and contract creators enables them to co-create value by implementing innovative products (e.g., DApps) built on validated smart contracts. A growing number of smart contracts that are pending verification provide increased rewards for miners. Nevertheless, the increased rewards may not always translate into positive network effects. Normally, miners' activities are constrained by their mining ability as the verification process requires an infrastructure that can support massive energy demand and sophisticated computing operations (Zheng et al. 2017). Consequently, miners may have to upgrade their infrastructure to acquire the profits from increased smart contracts. Upgrading such infrastructure usually takes time. For example, miners may need to shut down their system for a while for the upgrade. Therefore, I expect an immediate decrease in mining activities in the subsequent period. In the long term, as the infrastructure upgrade eventually enhances mining ability, miners can conduct more mining activities as a response to the growing contract deployment requests. As such, I expect an increase of *contract deployment* leads to a growth in *mining* in the long term.

Hypothesis 1a. In the contract subsystem, contract deployment exhibits an immediate negative effect and a long-term positive effect on mining.

For contract creators, increased mining activities can boost their confidence that smart contracts will be verified in a timely manner. As contract creators are motivated by revenues from successfully implemented smart contracts, growth in mining activity can attract more contract creators to deploy new smart contracts on the blockchain, resulting in an expedited accumulation of smart contracts that are available for use. I expect positive network effects to manifest both immediately and in the long term after an increase in *mining*. In the short term, because of the direct interaction between miners and contract creators, the enhanced mining capability encourages contract creators to make decisions and roll out smart contracts on the current blockchain platform. In the long term, increased mining activities indicate that the platform is capable of verifying a large number of contract deployment activities, which will attract more smart contract deployment activities. As such, I hypothesize that,

Hypothesis 1b. In the contract subsystem, mining exhibits both immediate and long-term positive effects on contract deployment.

Cross-side Effects within the Exchange Subsystem

Similar to the *contract subsystem*, transactions have to be verified by miners before they become valid on the blockchain (Zheng et al. 2017), and miners in the exchange subsystem gain monetary rewards through verifying transactions successfully. Mining activities and transaction activities complement each other, in that miners and users co-create the exchange value of cryptocurrencies or smart contracts. As in the case of the contract subsystem, constraints to rapidly upgrade mining infrastructure suggest a short-term decrease and a longer-term increase in *mining* in response to an increase in *transaction* volume.

Hypothesis 2a. In the exchange subsystem, transaction exhibits an immediate negative effect and a long-term positive effect on mining.

Users engage in transactions for their need to exchange cryptocurrency, investment, or other non-pecuniary objectives (e.g., voting, information storage). Because such exchanges may happen with high frequency, users prefer for their transactions to be verified as quickly as possible. A large number of mining activities indicates that transactions are more likely to be verified in a timely manner, which motivates more blockchain usage by users. Because the interactions between users and miners are direct, the increase in *transaction* in response to an increase of *mining* will be immediate. In the long term, the growing verification capabilities reflected in a growing number of mining activities sends a positive signal to users, which encourages more transactions. Therefore, I expect a positive long-term network effect from *mining* to *transaction*. In sum, I hypothesize that,

Hypothesis 2b. In the exchange subsystem, mining exhibits both immediate and long-term positive effects on transaction.

Same-side Effects within the Protocol Subsystem

As protocol development activities in a public blockchain ecosystem are voluntary and open to the public, the more protocol development activities taken by previous developers, the more knowledge with greater value is available for the subsequent developers to absorb. As such, developers are more likely to perceive the development community as a more valuable place to participate with the increased available resources they can use and professionals with whom they can work (Cennamo and Santalo 2013). As such, I expect the development activities will increase in the long term. In the short term, an increase of *protocol development* indicates that developers are intensively working on solving issues (e.g., fixing code defects) and improving the functionality of the protocol (e.g., adding new features). It may lead to an immediate decrease of development activities in subsequent periods, as there are fewer tasks for developers to perform. In sum, I hypothesize that,

Hypothesis 3. In the protocol subsystem, protocol development exhibits an immediate negative effect and a long-term positive effect on protocol development.

Cross-subsystem Effects at the Application Layer

As mining activities complement both contract deployment activities and transaction activities, the relationship between the *contract subsystem* and *exchange subsystem* mainly manifests in the indirect network effects between *contract deployment* and *transaction*. Such network effects have been observed in two-sided digital platforms that have been well studied in the platform literature. Specifically, users who make transactions are similar to customers on a digital platform such as Apple’s App Store, and smart contracts are similar to software applications developed by complementors (Cennamo and Santalo 2013). At the *application layer* of a public blockchain ecosystem, users find the ecosystem to be a more valuable place to participate when there are more smart contracts available for use as it offers a greater variety of services (Parker et al. 2016). This value realization process is relatively simple and requires many fewer resource commitments by users. As users do not need an extra value-creation process to capture the use value of smart contracts, their responses do not have to be delayed (Song et al. 2018). Therefore, I expect that an increase in smart contracts that are available for use can attract more transaction activities immediately. In the long term, however, the indirect network effect may be insignificant. The wear-out effect can be used to explain the quick decay in the effectiveness of marketing-related actions over time (Bass et al. 2007) and is reflected in two ways. First, accumulated smart contracts may cause issues with homogeneity. As there is a lack of third-party coordination, the functionality of smart contracts tends to be homogenous over time. Users may lose interest in trying new smart contracts and instead concentrate on the ones that have built a good reputation. Second, the proliferation of new smart contracts may also pose cognitive challenges for users to identify the smart contracts that fit their needs (Grime et al. 2002). In sum, I hypothesize that,

Hypothesis 4a. The contract subsystem exhibits an immediate positive effect on the exchange subsystem but no significant long-term effect.

Contract creators perceive the ecosystem as a more valuable place to participate as a large number of transactions indicates more users who can potentially use their smart contracts (Song et al. 2018). However, this positive indirect network effect may not manifest immediately. One reason is that creating a smart contract and successfully deploying it on the blockchain is a process requiring significant resource commitment (Song et al. 2018). Contract creators need to figure out the users' underlying demand and offer an appropriate reward to miners for faster verification, which makes the response of contract deployment less likely to take effect immediately. Eventually, the positive indirect network effect from *transaction* to *contract deployment* will emerge, but with a time lag. As such, I hypothesize,

Hypothesis 4b. The exchange subsystem exhibits a long-term positive effect on the contract subsystem but no significant immediate effect.

Between-subsystem Effects Across Layers

Protocol developers collaboratively contribute to the blockchain protocol such as fixing bugs and adding new features. At the subsystem level, the *protocol subsystem* serves the *contract subsystem* and *exchange subsystem* in the way that protocol developers improve the blockchain protocol to meet the participants' needs at the application layer. At the participant level, the engagement of contract creators and users is complemented by miners' engagement and influenced by protocol developers' engagement. A smart contract is created based on the rules specified in the blockchain protocol. Developers' active and continuous code contributions on the blockchain protocol can increase the protocol functionality, which meet the increasing need of contract creators (Setia et al. 2012). Miners conduct transaction verification by following the rules defined by the blockchain protocol. Increasing development can create a more stable environment and enhance their experience of using blockchain, resulting in increased mining activity (Song et al. 2018). Active and continuous code contributions on the blockchain protocol indicates that active efforts have been aimed at enhancing the stability of the blockchain system, which boosts users' confidence of getting their transactions verified efficiently. However, the positive effects from the *protocol subsystem* to the *contract subsystem* and *exchange subsystem* are more likely to manifest in the long term rather than immediately. An important reason is that protocol developers usually have their own development pace and schedule to update the changes to the blockchain protocol, while the participants at the *application layer* are more likely to perceive the value of changes only after the release of a new version of the protocol. Therefore, I hypothesize that,

Hypothesis 5a. The protocol subsystem exhibits a long-term positive effect on the contract subsystem but no significant immediate effect.

Hypothesis 6a. The protocol subsystem exhibits a long-term positive effect on the exchange subsystem but no significant immediate effect.

Protocol developers are motivated by non-pecuniary rewards such as improving their protocol development skills and building a good reputation in blockchain communities. On the one hand, a growth of activities in the *contract subsystem* and *exchange subsystem* indicates greater participant interest and thus reveals greater value of the blockchain. Open source developers are usually attracted to projects that garner greater user interest (Stewart et al. 2006). Making important contributions to such a valuable blockchain ecosystem can bring them peer recognition in the area of blockchain development. These can motivate protocol developers to increasingly contribute to the blockchain protocol (Fjeldstad et al. 2012). On the other hand, an increase in the use of blockchain in terms of deploying new contracts, making transactions, and verifying blocks may generate more defect reports and feature requests, which offers more opportunities for protocol developers to apply and hone their development skills, leading to an increase of *protocol development* as well (Parker and Van Alstyne 2005). However, it takes time for protocol developers to identify participant demands, go through these reports and requests, and make decisions on which ones to include in the next release of the blockchain protocol. Further, the development capabilities of protocol developers are usually heterogeneous, which may delay the development process as well. Therefore, it is less likely for the *protocol subsystem* to quickly respond to an increase in the *contract subsystem* or *exchange subsystem*. In sum, I hypothesize.

Hypothesis 5b. The contract subsystem exhibits a long-term positive effect on the protocol subsystem but no significant immediate effect.

Hypothesis 6b. The exchange subsystem exhibits a long-term positive effect on the protocol subsystem but no significant immediate effect.

RESEARCH DESIGN AND METHODOLOGY

Research Context

My empirical setting is Ethereum, one of the largest public blockchain platforms. As of March 2020, Ethereum serves as the platform for over 260,000 smart contracts and almost 92 million users[1]. Ether is the cryptocurrency of Ethereum and is used for exchange between users and as a reward to miners. Contract creators can use smart contracts to release their own digital assets (known as tokens) and DApps. Ethereum adopts the POW consensus algorithm as the core of its protocol. The development activities—including the software coding of the underlying Ethereum protocol—take place on GitHub—one of the primary hosting sites for open-source projects.

The Ethereum blockchain ecosystem is an ideal setting for my research objective for two reasons. (1) The open-source feature makes Ethereum open to the public such that anyone can participate in the transaction, mining, and contract deployment activities on the Ethereum

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[1] https://etherscan.io/tokens, accessed on July 30, 2020.

platform as well as the protocol development activities on GitHub. (2) Ethereum is a public blockchain, which means that all decision-making authority regarding the activities that happen in the Ethereum ecosystem is distributed to participants.

Data and Measurement

I test my hypotheses using data from two sources—BigQuery and GitHub. I wrote queries to collect all details about transactions, mining, and contract deployment activities on Ethereum from an open dataset maintained by Google BigQuery. I also wrote scripts to collect data on code contributions in go-ethereum—the repository for the Ethereum client (an implementation of the Ethereum protocol) on GitHub. The time period for the data collected is from Week 1 in 2016 to Week 43 in 2019 (199 weeks). I used data aggregated at the weekly level because (1) weekly data provides sufficient variation and granularity to reveal ongoing patterns of participant behavior on the blockchain, and (2) a weekly window is sufficient time to observe cross-side exchange activity in a digital platform environment.

I measure *transaction (TXN)* as the total number of user-to-user transactions and user-to-contract transactions that occur in a particular week. To measure *contract deployment (CD)*, I count the accumulated number of smart contracts that have been successfully deployed on the Ethereum blockchain in a particular week. In Ethereum, two different miners may generate the same block simultaneously. In such cases, the block that has fewer follow-up POW consensus from other participants becomes an uncle block. The uncle block miners also receive a smaller amount of reward for their work. In addition, each block has a combination of transactions and contract deployment activities. To reflect the actual number of total mining activities, I measure *mining (MN)* as the total number of mining activities in terms of the transactions and smart contracts that are verified by miners successfully (in real blocks) and unsuccessfully (in uncle blocks) in a particular week.

In GitHub, core developers contribute to the codebase by making commits (i.e., make revisions on the base code directly), while peripheral developers make pull requests with the improved code to be merged into the codebase (Yang and Boodraj 2020). In Ethereum's protocol repository, both types of contributions are voluntary in nature and equally crucial for protocol development. I, therefore, measure *protocol development (PD)* as the total number of commits which includes the contributions by core developers and admitted pull requests from peripheral developers in a particular week.

I also include several control variables. The first one is *ether price* (EP), which reflects the attractiveness of Ethereum and may influence participants' engagement in activities. It is measured using the average price of ether in a particular week. The second control variable is *mining difficulty* (MD), which is measured using the average difficulty to validate a new block on Ethereum in a particular week. Mining difficulty describes the average length of time that it takes for a miner to solve the cryptographic puzzle. High mining difficulty indicates that verifying a block requires greater computing power, which may discourage low-capacity miners from joining the blockchain. The third control variable is *version release* (VR), which is measured by the number of new versions of the blockchain client released in a particular week. Participants may not perceive the changes in protocol unless a new version is released. The fourth control variable is *hard fork* (HF), which represents whether a hard fork is executed in a particular week. A hard fork happens when there are divergent opinions of major changes in the blockchain protocol. I set HF to 0 if there is no hard fork in a given week, and 1 if there is a hard fork. Table 2 shows the definitions and summary statistics of key variables. The average values over the observation period for *contract deployment*, *mining*, *transaction*, and *protocol development* are 5,657,739 (unlogged value), 3,273,408 (unlogged value), 2,916,724 (unlogged value), and 57.769 (unlogged value), respectively.

TABLE 2
Constructs, Measures, and Descriptive Statistics

Variables	Measurement	Mean	S.D.	Min	Max
Transaction (TXN)	Number of user-to-user transactions and user-to-contract transactions in week t (log)	14.27	1.34	11.29	15.93
Contract Deployment (CD)	Accumulated number of smart contracts deployed on Ethereum by week t (log)	14.11	2.33	8.80	16.78
Mining (MINE)	Number of mining activities on Ethereum in week t (log)	14.38	1.34	11.40	16.23
Protocol Development (PD)	Number of code contributions to Ethereum protocol on GitHub in week t (log)	3.77	0.88	0.00	5.62
Ether Price (EP)	Average ether price in week t (log)	4.54	1.62	0.67	7.16
Mining Difficulty (MD)	Average time for mining a new block in week t (log)	6.43	1.84	2.23	8.18
Version Release (VR)	Number of new versions of client are released in week t (log)	0.25	0.37	0.00	1.39
Hard Fork (HF)	Whether a hard fork is conducted in week t	0.03	0.17	0.00	1.00

Notes: N = 199. Variables are logged.

Model Specification and Estimation

As my data is time-series in nature, I employ *vector autoregression with exogenous variable* (VARX) in my model estimation. This method allows us to capture both the short-term and long-term dynamic interdependent relationships of different activities in a blockchain ecosystem (Song et al. 2018). Consistent with prior research, I adopt a standard VARX procedure (e.g., Dekimpe and Hanssens 1999; Song et al. 2018). To address skewness in the distribution, I took the natural log of each of the endogenous variables adjusted by adding 1. I use an augmented Dickey-Fuller test (ADF) to check stationarity. The basic VARX model assumes a stationary time series process (Adomavicius et al. 2012). If the process is not stationary, de-trending of the data can be performed in several ways, among which differencing the data is a commonly used method (Enders 1995; Lütkepohl 2013). With first-difference values, the ADF tests of all endogenous variables reject the null hypothesis of a unit root and suggest stationarity (as shown in Table 3). Therefore, I examine my models using the first-difference values of variables. To determine the appropriate number of lags, I follow the suggestions of the Akaike information criterion (AIC = -5.066) and final prediction error (FPE = 7.5e-0.8) and use the lag of five periods (weeks) as the optimal lag length. I conduct a series of Granger causality tests to explore whether explanatory variables explain the variation of dependent variables (as shown in Table 4). Granger causality is typically tested using Wald tests of the null hypothesis that all coefficients of the corresponding lags are equal to zero (Enders 1995). The results show that there are several significant Granger-causal relationships in the estimated model that reject the null hypothesis[2].

TABLE 3
Unit Root Test Results after First Differences

Variables	**Test Statistic**	***p*-value**
Transaction	-16.909	< 0.001
Contract Deployment	-15.234	< 0.001
Mining	-12.969	< 0.001
Protocol Development	-22.474	< 0.001

TABLE 4
Granger Causality Test (F Statistic)

	Dependent Variables			
	CD	MN	TXN	PD
CD	–	7.533	5.545	14.520**
MN	11.492**	–	62.304***	3.417
TXN	1.059	21.039***	–	4.709
PD	14.004**	9.548*	8.390	23.257*

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

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[2] For equations that have serial correlation or heteroscedasticity issues, the granger test results may not capture the potential causal relationships accurately. In such cases, I refer to IRF graphs as more robust results.

To have an in-depth understanding of how activities dynamically interact, I propose a VARX model to examine each dynamic interaction as proposed in the hypotheses. I include an intercept C, and a deterministic-trend variable T that captures the impact of the omitted, gradually changing trend of the dependent variables. In the VARX model, t is the index of the week, J is the maximum number of lags, and ε is a vector of white-noise disturbances with a normal distribution of $\mathrm{N}(0, \Sigma)$. I also test the existence of serial correlation (Breusch-Godfrey Test) and heteroskedasticity (Breusch-Pagan Test) and use Newey-West HAC Covariance Matrix Estimation to address such issues (Newey and West 1987) (as shown in Table 5).

TABLE 5
Tests for Serial Correlation and Heteroskedasticity

Dependent Variable	Breusch-Godfrey Test	Breusch-Pagan Test
Transaction	6.932 (0.226)	0.460 (0.498)
Contract Deployment	4.814 (0.439)	477.850 (0.000)
Mining	11.663 (0.040)	1.090 (0.297)
Protocol Development	15.739 (0.008)	0.99 (0.320)

Notes: The results show χ^2values with p-values in parentheses.

The VARX specification given in Model (1) is used to capture dynamic interactions in the public blockchain ecosystem. For the within-subsystem relationships, as an example, the direct network effects within the *contract subsystem* are reflected in how *mining* (MN_t) changes over time following a change in *contract deployment* (CD_t), and how *contract deployment* (CD_t) changes over time following a change in *mining* (MN_t). Regarding between-subsystem relationships, for example, the indirect network effects between the *contract subsystem* and *exchange subsystem* are reflected in the change in contract deployment (CD_t) following (and leading to) a change in transaction (TXN_t).

$$\begin{bmatrix} MN_t \\ CD_t \\ TXN_t \\ PD_t \end{bmatrix} = \begin{bmatrix} C_{MN} \\ C_{CD} \\ C_{TXN} \\ C_{PD} \end{bmatrix} + \begin{bmatrix} \delta_{MN} \\ \delta_{CD} \\ \delta_{TXN} \\ \delta_{PD} \end{bmatrix} \times T + \sum_{j=1}^{J} \begin{bmatrix} \varphi_{11}^{j} & \varphi_{12}^{j} & \varphi_{13}^{j} & \varphi_{14}^{j} \\ \varphi_{21}^{j} & \varphi_{22}^{j} & \varphi_{23}^{j} & \varphi_{24}^{j} \\ \varphi_{31}^{j} & \varphi_{32}^{j} & \varphi_{33}^{j} & \varphi_{34}^{j} \\ \varphi_{41}^{j} & \varphi_{42}^{j} & \varphi_{43}^{j} & \varphi_{44}^{j} \end{bmatrix} \times \begin{bmatrix} MN_{t-j} \\ CD_{t-j} \\ TXN_{t-j} \\ PD_{t-j} \end{bmatrix} +$$

$$\sum_{j=1}^{J} \begin{bmatrix} \tau_{11}^{j} & \tau_{12}^{j} & \tau_{13}^{j} & \tau_{14}^{j} \\ \tau_{21}^{j} & \tau_{22}^{j} & \tau_{23}^{j} & \tau_{24}^{j} \\ \tau_{31}^{j} & \tau_{32}^{j} & \tau_{33}^{j} & \tau_{34}^{j} \\ \tau_{41}^{j} & \tau_{42}^{j} & \tau_{43}^{j} & \tau_{44}^{j} \end{bmatrix} \times \begin{bmatrix} EP_{t-j} \\ MD_{t-j} \\ VR_{t-j} \\ HF_{t-j} \end{bmatrix} + \begin{bmatrix} \varepsilon_{MN} \\ \varepsilon_{CD} \\ \varepsilon_{TXN} \\ \varepsilon_{PD} \end{bmatrix} \tag{1}$$

The VARX analysis is supplemented with analyses of impulse response functions (IRFs), allowing us to simulate the over-time impact of a change (or shock) to one variable (over its baseline) on the dynamics of the full multi-equation system (Enders 1995). The VARX estimated coefficients are not usually directly interpretable due to general multicollinearity issues associated with including lagged terms (Sims 1980), so VARX analysis does not typically discuss magnitudes of coefficients and focuses instead on Granger causality test and IRFs (Stock and Watson 2001). Therefore, I report the IRFs results in Figure 2 and use them as the basis for interpreting the results of the model estimation.

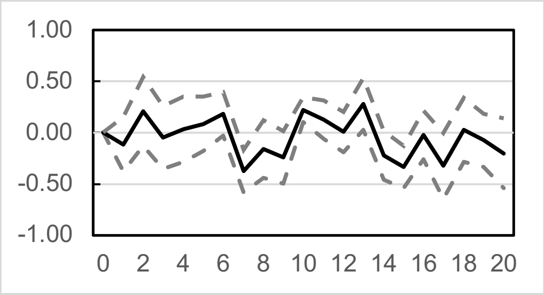
RESULTS

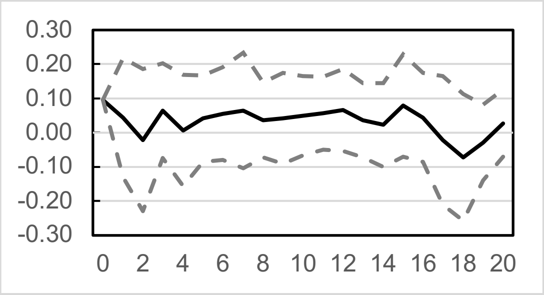
Main Results

My goal in this research was to identify the network effects emerging from activities within each subsystem and the network effects between subsystems. If network effects are indeed present, I expect that the endogenous variables will have dynamic interrelated relationships. Table 4 reports the general estimation results (the estimated model coefficients can be found in Appendix A). Figure 2 illustrates the impulse response functions. Results of the main analysis are summarized in Table 6.

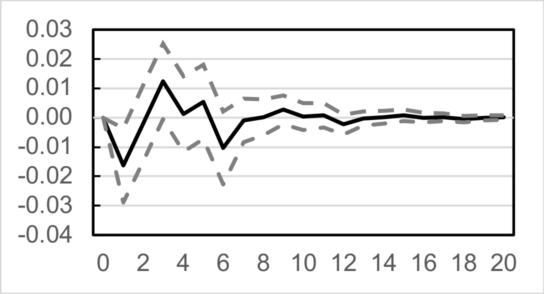
FIGURE 2
Main Results—Impulse Response Functions

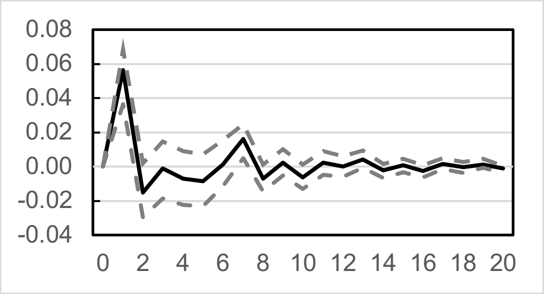
Network Effects in Contract Subsystem


Contract Deployment → Mining (H1a)


Mining → Contract Deployment (H1b)

Network Effects in Exchange Subsystem


Transaction → Mining (H2a)


Mining → Transaction (H2b)

Network Effects in Protocol Subsystem

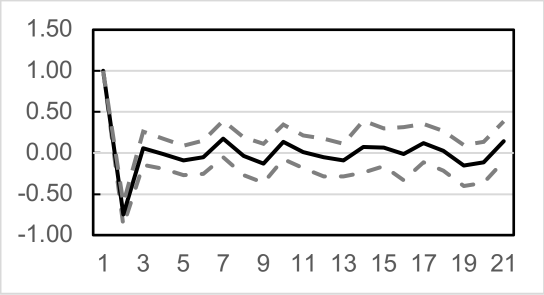
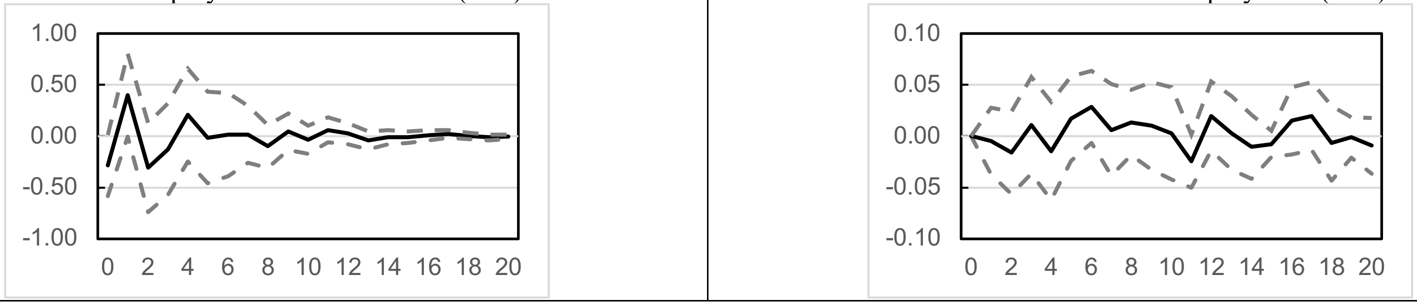

Protocol Development → Protocol Development (H3)

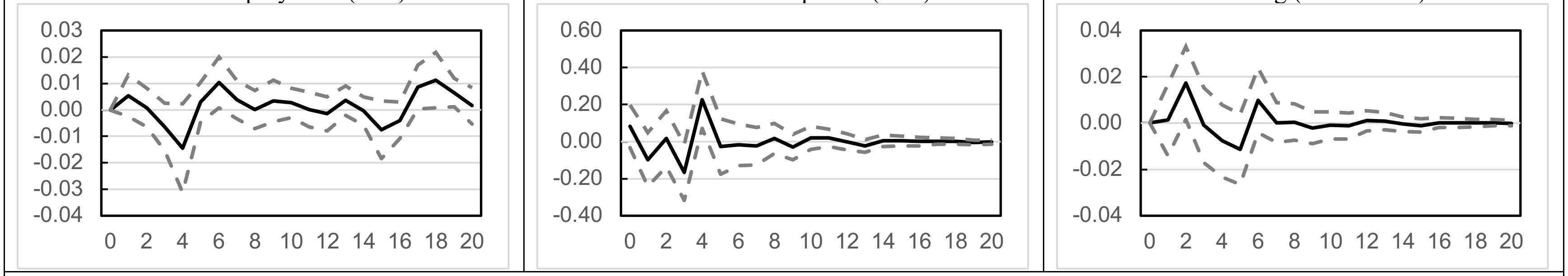
FIGURE 2 (Continued)
Main Results—Impulse Response Functions

Network Effects between Exchange Subsystem and Contract Subsystem


Contract Deployment → Transaction (H4a)

Transaction → Contract Deployment (H4b)

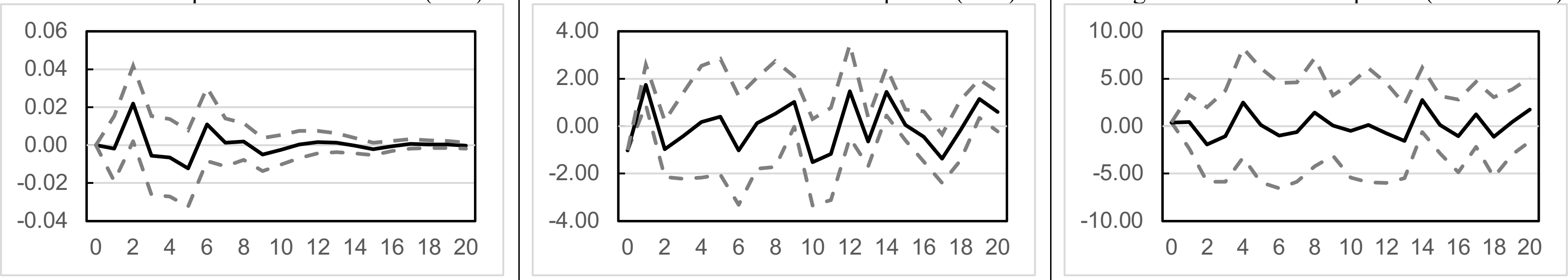
Network Effects between Contract Subsystem and Protocol Subsystem


Protocol Development → Contract Deployment (H5a)

Contract Deployment → Protocol Development (H5b)

Protocol Development → Mining (H5a & H6a)

Network Effects between Exchange Subsystem and Protocol Subsystem


Protocol Development → Transaction (H6a)

Transaction → Protocol Development (H6b)

Mining → Protocol Development (H5b & H6b)

TABLE 6
Results Summary of Main Analysis and Robustness Checks

Hypothesis	**Main Analysis**	**Robustness Check (New Contracts as CD)**	**Robustness Check (Code Commits as PD)**
Within-Subsystem Effects			
H1a. In the contract subsystem, contract deployment exhibits an immediate negative effect and a long-term positive effect on mining.	Not support. The effects of contract deployment on mining are dynamic and long term.	Not support. There is no significant effect of contract deployment on mining.	Not support. The effects of contract deployment on mining are long term and negative.
H1b. In the contract subsystem, mining exhibits both immediate and long-term positive effects on contract deployment.	Not support. There is no significant effect of mining on contract deployment.	Not support. There is no significant effect of mining on contract deployment.	Not support. There is no significant effect of mining on contract deployment.
H2a. In the exchange subsystem, transaction exhibits an immediate negative effect and a long-term positive effect on mining.	Partially support. Transaction has an immediate negative effect on mining. However, it does not have a long-term effect on mining.	Partially support. Transaction has both immediate and long-term negative effects on mining.	Partially support. Transaction has a long-term negative effect on mining. However, there is no immediate effect.
H2b. In the exchange subsystem, mining exhibits both immediate and long-term positive effects on transaction.	Support.	Support.	Support.
H3. In the protocol subsystem, protocol development exhibits an immediate negative effect and a long-term positive effect on protocol development.	Partially support. The immediate effect is negative. However, there is no significant long-term effect.	Partially support. The immediate effect is negative. However, there is no significant long-term effect.	Partially support. Both immediate and long-term effects are negative.
Between-Subsystem Effect at the Application Layer			
H4a. The contract subsystem exhibits an immediate positive effect on the exchange subsystem but no significant long-term effect.	Not support. There is no significant effect of contract deployment on transaction.	Support.	Not support. There is no significant effect of contract deployment on transaction.

H4b. The exchange subsystem exhibits a long-term positive effect on the contract subsystem but no significant immediate effect.	Not support. There is no significant effect of transaction on contract deployment.	Partially support. The long-term effects are dynamic.	Not support. There is no significant effect of contract deployment on transaction.
Between-Subsystem Effects Across Layers			
H5a. The protocol subsystem exhibits a long-term positive effect on the contract subsystem but no significant immediate effect.	Support.	Support.	Partially support. Protocol development has a long-term positive effect on contract deployment. However, it has no significant effect on mining.
H5b. The contract subsystem exhibits a long-term positive effect on the protocol subsystem but no significant immediate effect.	Partially support. Contract deployment has a long-term positive effect on protocol development. However, no significant effect is found from mining to protocol development.	Partially support. The long-term effect of contract deployment on protocol development is dynamic. No significant effect is found from mining to protocol development.	Partially support. Contract deployment has a long-term positive effect on protocol development. However, no significant effect is found from mining to protocol development.
H6a. The protocol subsystem exhibits a long-term positive effect on the exchange subsystem but no significant immediate effect.	Support.	Support.	Not support. There is no significant effect of protocol development on transaction or mining.
H6b. The exchange subsystem exhibits a long-term positive effect on the protocol subsystem but no significant immediate effect.	Not support. Transaction shows immediate and long-term positive effects on protocol development. However, no significant effect is found from mining to protocol development.	Not support. Transaction shows immediate and long-term positive effects on protocol development. However, no significant effect is found from mining to protocol development.	Not support. There is no significant effect between transaction (or mining) and protocol development.

Within-subsystem effects. Regarding the dynamic direct network effects between *mining* and *contract deployment* within the *contract subsystem*. The IRF graphs in Figure 2 indicate that *contract deployment* has long-term negative effects on *mining* (in week 7 and 15), and the effect of *mining* on *contract deployment* is non-significant after addressing the issues of serial correlation and heteroskedasticity. Hypotheses 1a and 1b are not supported. The dynamic direct network effects between *mining* and *transaction* within the exchange subsystem are shown in Table 4 and supplemented by IRF graphs in Figure 2. The Granger causality test results indicate a significant causal relationship between *mining* and *transaction*. The results of the IRF analysis corroborate the results of the Granger causality test. Specifically, the IRF results show that *transaction* has an immediate and significant negative network effect on *mining* but no significant long-term effect. It means that more *transaction* leads to an immediate decrease in *mining* in the subsequent period. However, there is no significant long-term effect. This provides partial support for Hypothesis 2a. I also find positive network effects of *mining* on *transaction* in weeks 1 and 7, meaning that an increase in *mining* in the current period promotes *transaction* immediately (after 1 week following the growth shock to *mining*) and in the long term (after 7 weeks following the growth shock to *mining*), supporting Hypothesis 2b. In terms of the dynamic direct interactions within the *protocol subsystem*, the results in Table 4 and Figure 2 show a significant immediate and negative effect. It indicates that an increase in *protocol development* in the current period decreases *protocol development* in the next period. No long-term effect is found. As such, Hypothesis 3 is partially supported.

Between-subsystem effects. After correcting for serial correlation and heteroskedasticity, I do not find significant relationships between the *contract subsystem* and the *exchange subsystem*. Therefore, Hypothesis 4a and 4b are not supported. Regarding the dynamic relationships between the *contract subsystem* and the *protocol subsystem*, the IRF results in Figure 2 indicate that *protocol development* has significant network effects on *contract deployment* and *mining*. Specifically, *protocol development* shows significant positive network effects on *contract deployment* in the long term (at week 6, 17, 18, and 19). The results also show that *protocol development* has a positive network effect on *mining* at week 2, meaning that a growth of *protocol development* leads to an increase of *mining* after two weeks. In sum, the results provide support for my expectations as stated in Hypothesis 5a. I found that an increase in *contract deployment* triggers a significant decrease of *protocol development* at week 3, while leading to a significant increase of *protocol development* at week 4. However, there is no evidence of significant network effect of *mining* on *protocol development*. This partially supports my Hypothesis 5b. The dynamic interrelationships between the *exchange subsystem* and *protocol subsystem* are shown in Figure 2. The results show that *protocol development* has a positive network effect on *transaction* after two weeks of the growth shock to *protocol development*. I also find a significant positive effect of *protocol development* on *mining* after two weeks. Therefore, Hypothesis 6a is supported. As I find significant and positive network effects from *transaction* to *protocol development* both immediately and in the long term, but no significant effect of *mining* on *protocol development*. Therefore, Hypothesis 6b is not supported.

Robustness Checks

I conduct two additional analyses to verify the robustness of my results. The results of robustness checks are summarized in Table 6. First, I use the number of new smart contracts that are successfully deployed on Ethereum in each week as an alternative measure to characterize *contract deployment*. The reasons for using the incremental increase of smart contracts are twofold: (1) it is possible that a new smart contract attracts a large amount of use at the early stage after its deployment but quickly becomes less attractive. If so, I may not see significant network effects from *contract deployment* to *transaction*. (2) Although an increase in transactions does not lead to a growth in the total number of contracts at the application layer, it may attract new smart contracts instead. The test results and IRF graphs are shown in Appendix B. The results are mostly consistent with the main analysis results. However, I find that contract deployment has an immediate positive effect on *transaction* (in week 1), which supports my Hypothesis 4a. In return, *transaction* exhibits long-term dynamic effects on *contract deployment* (in weeks 10 and 17), which partially supports Hypothesis 4b. These results provide additional insights for understanding the relationship between *contract subsystem* and *exchange subsystem*: newly deployed smart contracts rather than the total available smart contracts are the ones that drive transactions on the blockchain platform.

Second, I use an alternative measure to characterize *protocol development*. I collect the number of code changes in each development commit and aggregate it to the week level. The number of code changes reflects the difficulty of the code commit that a developer makes to the blockchain protocol. It is possible that increased mining activities trigger greater efforts in revising the blockchain protocol but show no significant effects on the number of commits. The test results and IRF graphs are shown in Appendix C. After re-estimating the VARX model, the results remain qualitatively consistent. One exception is that I do not find significant effects from protocol development on *mining* or *transaction*. This indicates that the workload of protocol developers is not the main reason for the growth of transactions or mining activities. This also implies that users and miners may not be aware of or do not care much about how much the protocol has been changed compared to whether developers do their job.

DISCUSSION

In this study, I sought to advance understanding of dynamic network effects in a highly decentralized platform-enabled ecosystem. The public blockchain ecosystem is representative of highly decentralized ecosystems. I identified key participants in a public blockchain ecosystem and the layers and subsystems of which it is composed. Applying the theoretical lens of value co-creation, I hypothesized the mutual functioning of the underlying subsystems across layers. The main results from my longitudinal empirical study revealed several findings at the level of subsystems and their constituent activities.

Overall, the results showed unbalanced and asymmetric network effects in the public blockchain ecosystem. I made three observations. (1) Interactions between activities within or cross subsystems are not always mutual. For example, the network effects between mining and transaction are positive and mutual, while the network effects between mining and protocol development are unidirectional (only *protocol development* → *mining* is significant). (2) The network effects are asymmetric. According to the IRF results in Figure 2, some network effects are short lived (e.g., *transaction* → *mining*), while some exhibit long-term effects (e.g., *protocol development* → *contract deployment*). (3) Network effects can be negative. While the two-sided network effects on digital platforms are mostly found to be positive, I find that network effects in a blockchain ecosystem can be negative. For example, *transaction* has an immediate negative network effect on *mining*.

Another set of findings is subsystem specific. For the *contract subsystem*, I find that accumulated smart contracts closely interact with *protocol development*, while only the incremental smart contracts drive and are influenced by *transaction*. Such findings are reasonable as protocol developers need to maintain the protocol to meet the needs of all smart contracts, including the newly deployed and the ones that have been implemented for a long time. As contract creators implement smart contracts on the blockchain, they are more sensitive to the changes in the blockchain protocol. Users, however, are more likely attracted by smart contracts that are recently implemented. I also find that the shared resource and knowledge within the *protocol subsystem* are not adequate to motivate protocol developers to continuously develop the blockchain protocol (as shown in the immediate negative network effect). The long-term positive network effect from *contract subsystem* and *exchange subsystem* to *protocol subsystem* indicates that the blockchain usage in terms of smart contracts and transactions are the major motivations that drive protocol development. In addition, I find that network effects within a subsystem can show up immediately, while the network effects between subsystems across layers usually take time to manifest. Evidence includes the immediate network effects within the *exchange subsystem* and *protocol subsystem* and the long-term network effects between *contract subsystem* and *protocol subsystem*.

At the activity level, the findings provide unique insight into the dynamic interactions among activities within and between subsystems across layers. First, the results indicate that *protocol development* plays the most critical role in the overall blockchain ecosystem. Specifically, *protocol development* has positive cross-layer network effects on *mining* and *contract deployment*. Second, although smart contract is a salient feature that Ethereum include on its blockchain and the means by which it differentiates itself from Bitcoin, a large number of available smart contracts do not demonstrate a meaningful influence on growing the usage of the Ethereum blockchain (as shown in non-significant network effects between *contract subsystem* and *exchange subsystem* when using accumulated smart contracts as the measurement for *contract deployment*). Instead, users show more interest in newly implemented smart contracts.

The results indicate that many smart contracts may become idle quickly after their debut, which may generate a considerable waste of resources devoted to maintaining an extensive network.

Theoretical Implications

This research has several theoretical implications. First, this research contributes to literature on platform-enabled ecosystems with a specific focus on decentralized ecosystems which are underexplored by prior literature (Chen et al. 2021). I identify the distinctiveness of decentralized ecosystems and stress the importance of understanding how network effects are generated in such ecosystems. A paradox for digital innovation ecosystems is: “the more effectively digital technologies enable the division of labor, the more actors join the ecosystem with their skills and creativity, yet the more difficult it is for the actors to integrate their efforts, and the more likely the ecosystem fails” (Wang 2021, p. 398). Such paradox becomes more salient in a highly decentralized ecosystem like a public blockchain ecosystem. As there is no central authority to orchestrate activities in the ecosystem, the interaction among participants and the network effects generated can be more dynamic. Autonomous participants need to collectively figure out how to create value in a manner that satisfies each party’s needs while adding value to the overall ecosystem as well. From a value co-creation perspective, I explore what specific value is created (or co-created) and how they underlie these dynamic network effects.

Network effects in decentralized ecosystems are more complex and dynamic compared to network effects in centralized ecosystems. As there is no central authority that has ultimate control of the overall ecosystem, participants’ shared governance power makes network effects in decentralized ecosystems more dynamic. Evidence can be seen from the negative-positive-negative network effects from one side to the other. The reason could be that the decentralized governance is more sensitive to the participation of other parties. People who share governance power may observe and learn from other parties and use it as guidance for their subsequent decision-making. In this study, in order to better understand the dynamics of interactions among multi-side participants, I introduce the layer-subsystem structure, which leads to my second theorical contribution.

Second, my study augments understanding of complex platform-enabled ecosystems by decomposing it into layers with different functionalities and self-contained but interrelated subsystems. This research is the first to conceptually and empirically decompose a platform-enabled ecosystem into component parts following recent conceptual work by Wang (2021). Wang (2021) points out that extant ecosystem studies examined the parts while overlooking the ecosystem as a whole. Such a focus on parts missed value that is created between subsystems. Additionally, there is a lack of direct examination of the integration of efforts in ecosystems in prior literature (Wang 2021). I introduce layer-subsystem as a structure to theorize the dynamics of how such ecosystems function. Although some digital platform literature discussed a layered structure or modular structure of a digital platform (e.g., Tiwana et al. 2010), such research focuses primarily on the technological functions of the platform rather than on the interactions among participants. My layer-subsystem structure suggests that a participant may exist in more than one subsystem, which is critical for understanding the nature of participant interactions. This layer-subsystem structure also provides insight into how value co-creation activities generate network effects. In general, network effects tend to be more direct within subsystem and more indirect between subsystems within a layer or across layers.

Third, the insights from my study also contribute to the blockchain literature by developing a theoretical understanding of blockchain from a managerial perspective. Past studies on blockchain concentrate on understanding blockchain from a technical standpoint (Beck et al. 2018). My study focuses on understanding how value is exchanged and whether incentives are aligned and complement interactions among different participants in a layer-subsystem structure. Such a managerial perspective provides guidance for blockchain ecosystem design and governance. For one, the governance of blockchain ecosystems can be understood from the layer-subsystem perspective: there can be a specific type of participant in charge of orchestrating other activities at each layer. The governance practice conducted by participants at different layers may also interact to promote a healthy development of the ecosystem.

Practical Implications

My study also has notable practical contributions. First, my results show that current incentive mechanisms may not be effective to ensure a healthy functioning Ethereum ecosystem. Specifically, I find that *mining* does not increase in response to growing *transaction* and *contract deployment*. A plausible reason may relate to the mechanism of mining difficulty adjustment. As the rules for validating and broadcasting blocks and resolving conflicts are defined in the blockchain protocol (Syed et al. 2019), I suggest protocol developers improve the incentive mechanism to make sure that mining activity increases in line with the increasing demand from users and contract creators so that they benefit from the blockchain technology-in-use.

Second, an incentive mechanism in the *protocol subsystem* is needed to encourage a diversity of developers to engage in protocol development activities. The negative network effects within the *protocol subsystem* indicate that shared resources and knowledge are not adequate to motivate protocol developers to continuously develop the blockchain protocol. Most development activities for a public blockchain ecosystem happen in an open-source development community where developers' commitments are usually described as voluntary (Andersen and

Bogusz 2017). How to integrate developers' efforts to continuously develop and improve the blockchain protocol is a critical question to solve, especially for public blockchain ecosystems that do not have a sponsoring firm behind the protocol development community.

Third, I suggest that both protocol developers and contract creators discover and broaden the application scenarios of smart contracts. The results show that increasing the number of available smart contracts does not lead to a growth in transactions. One reason could be the application potential of smart contracts has not been fully realized given the nascent development and application of blockchain technology in business and society. A direction for the development of public blockchain ecosystems is to explore the application areas of smart contracts to emphasize the important role of contract creators.

Limitation and Future Research

This study has some limitations and creates opportunities for future research. First, this study focuses on the public blockchain in a specific empirical setting. My decision to focus on a public blockchain ecosystem was informed by my theoretical interest in platform-enabled ecosystems without a central authority. Future studies may consider generalizing or expanding insights by examining other types of blockchain ecosystems, such as private blockchain ecosystems and consortium blockchain ecosystems. Second, future studies can examine the impact of different blockchain protocol designs on mining activities in order to develop a better sense of an appropriate incentive mechanism for miners. Current incentives may be too cost-prohibitive to motivate miners to engage. They face dual costs of needing to invest in robust computational infrastructure as well as paying for the energy consumption required by the POW consensus algorithm. There is currently some emerging discussion around proof of stake as a more energy conservation-friendly approach that may be less onerous on miners.

CONCLUSION

My study surfaces the unbalanced and asymmetric features of network effects in the public blockchain ecosystem. My findings reveal mutual effects across sides within the *exchange subsystem* and an immediately negative effect within the *protocol subsystem*. In addition, I find that the *contract subsystem* and *protocol subsystem* are closely interdependent with each other. Overall, my study reveals the dynamic and coevolving interactions within and between subsystems across layers, which helps us understand the functioning of the overall public blockchain ecosystem.

REFERENCES

Adner, R. 2017. "Ecosystem as Structure: An Actionable Construct for Strategy," *Journal of Management* (43:1), pp. 39-58.

Adner, R., and Kapoor, R. 2010. "Value Creation in Innovation Ecosystems: How the Structure of Technological Interdependence Affects Firm Performance in New Technology Generations," *Strategic Management Journal* (31:3), pp. 306-333.

Adomavicius, G., Bockstedt, J., and Gupta, A. 2012. "Modeling Supply-Side Dynamics of It Components, Products, and Infrastructure: An Empirical Analysis Using Vector Autoregression," *Information Systems Research* (23:2), pp. 397-417.

Adomavicius, G., Bockstedt, J. C., Gupta, A., and Kauffman, R. J. 2007. "Technology Roles and Paths of Influence in an Ecosystem Model of Technology Evolution," *Information Technology and Management* (8:2), pp. 185-202.

Adomavicius, G., Bockstedt, J. C., Gupta, A., and Kauffman, R. J. 2008. "Making Sense of Technology Trends in the Information Technology Landscape: A Design Science Approach," *MIS Quarterly* (32:4), pp. 779-809.

Afuah, A. 2013. "Are Network Effects Really All About Size? The Role of Structure and Conduct," *Strategic Management Journal* (34:3), pp. 257-273.

Andersen, J. V., and Bogusz, C. I. 2017. "Patterns of Self-Organising in the Bitcoin Online Community: Code Forking as Organising in Digital Infrastructure," *ICIS 2017 Proceedings*.

Angelis, J., and da Silva, E. R. 2019. "Blockchain Adoption: A Value Driver Perspective," *Business Horizons* (62:3), pp. 307-314.

Atzori, M. 2015. "Blockchain Technology and Decentralized Governance: Is the State Still Necessary?." Available at https://ssrn.com/abstract=2709713.

Baldwin, C. Y., and Clark, K. B. 2000. *Design Rules: The Power of Modularity*. MIT Press: Cambridge, MA.

Baldwin, C. Y., Clark, K. B., and Clark, K. B. 2000. *Design Rules: The Power of Modularity*. MIT press.

Bass, F. M., Bruce, N., Majumdar, S., and Murthi, B. 2007. "Wearout Effects of Different Advertising Themes: A Dynamic Bayesian Model of the Advertising-Sales Relationship," *Marketing Science* (26:2), pp. 179-195.

Beck, R., Müller-Bloch, C., and King, J. L. 2018. "Governance in the Blockchain Economy: A Framework and Research Agenda," *Journal of the Association for Information Systems* (19:10), pp. 1020-1034.

Boudreau, K. 2010. "Open Platform Strategies and Innovation: Granting Access Vs. Devolving Control," *Management Science* (56:10), pp. 1849-1872.

Boudreau, K. J., and Jeppesen, L. B. 2015. "Unpaid Crowd Complementors: The Platform Network Effect Mirage," *Strategic Management Journal* (36:12), pp. 1761-1777.

Bowman, C., and Ambrosini, V. 2000. "Value Creation Versus Value Capture: Towards a Coherent Definition of Value in Strategy," *British Journal of Management* (11:1), pp. 1-15.

Briggs, J. G., and Morgan, D. M. 2017. "Subsystem in Family Systems Theory," in *Encyclopedia of Couple and Family Theorapy*. Springer International Publishing.

Cai, W., Wang, Z., Ernst, J. B., Hong, Z., Feng, C., and Leung, V. C. 2018. "Decentralized Applications: The Blockchain-Empowered Software System," *IEEE Access* (6), pp. 53019-53033.

Ceccagnoli, M., Forman, C., Huang, P., and Wu, D. 2012. "Cocreation of Value in a Platform Ecosystem! The Case of Enterprise Software," *MIS Quarterly* (36:1), pp. 263-290.

Cennamo, C., and Santalo, J. 2013. "Platform Competition: Strategic Trade-Offs in Platform Markets," *Strategic Management Journal* (34:11), pp. 1331-1350.

Chen, Y., Pereira, I., and Patel, P. C. 2021. "Decentralized Governance of Digital Platforms," *Journal of Management* (47:5), pp. 1305-1337.

Cong, L. W., He, Z., and Li, J. 2019. "Decentralized Mining in Centralized Pools," *The Review of Financial Studies* (34:3), pp. 1191-1235.

Constantinides, P., Henfridsson, O., and Parker, G. G. 2018. "Introduction—Platforms and Infrastructures in the Digital Age," *Information Systems Research* (29:2), pp. 381-400.

Dekimpe, M. G., and Hanssens, D. M. 1999. "Sustained Spending and Persistent Response: A New Look at Long-Term Marketing Profitability," *Journal of Marketing Research* (36:4), pp. 397-412.

Enders, W. 1995. *Applied Econometric Time Series*. Wiley, New York.

Fjeldstad, Ø. D., Snow, C. C., Miles, R. E., and Lettl, C. 2012. "The Architecture of Collaboration," *Strategic Management Journal* (33:6), pp. 734-750.

Grime, I., Diamantopoulos, A., and Smith, G. 2002. "Consumer Evaluations of Extensions and Their Effects on the Core Brand," *European Journal of Marketing* (36:11), pp. 1415-1438.

Grover, V., and Kohli, R. 2012. "Cocreating It Value: New Capabilities and Metrics for Multifirm Environments," *MIS Quarterly* (36:1), pp. 225-232.

Jacobides, M. G., Cennamo, C., and Gawer, A. 2018. "Towards a Theory of Ecosystems," *Strategic Management Journal* (39:8), pp. 2255-2276.

Karamitsos, I., Papadaki, M., and Al Barghuthi, N. B. 2018. "Design of the Blockchain Smart Contract: A Use Case for Real Estate," *Journal of Information Security* (9:3), pp. 177-190.

Kim, D. 2017. "Value-Creation Dynamics in Platform Ecosystem: A Firm Theory Lens," *Proceedings of the 50th Hawaii International Conference on System Sciences*.

Konstantinidis, I., Siaminos, G., Timplalexis, C., Zervas, P., Peristeras, V., and Decker, S. 2018. "Blockchain for Business Applications: A Systematic Literature Review," *International Conference on Business Information Systems*, pp. 384-399.

Kyprianou, C. 2018. "Creating Value from the Outside in or the inside Out: How Nascent Intermediaries Build Peer-to-Peer Marketplaces," *Academy of Management Discoveries* (4:3), pp. 336-370.

Lepak, D. P., Smith, K. G., and Taylor, M. S. 2007. "Value Creation and Value Capture: A Multilevel Perspective," *Academy of Management Review* (32:1), pp. 180-194.

Lütkepohl, H. 2013. *Introduction to Multiple Time Series Analysis*. Springer Science & Business Media.

Maruping, L., and Yang, Y. 2020. "Governance in Digital Open Innovation Platforms," in *Oxford Research Encyclopedia of Business and Management*.

McIntyre, D. P., and Srinivasan, A. 2017. "Networks, Platforms, and Strategy: Emerging Views and Next Steps," *Strategic Management Journal* (38:1), pp. 141-160.

Nakamoto, S. 2008. "Bitcoin: A Peer-to-Peer Electronic Cash System." Retrieved 10/26/2020, from https://bitcoin.org/bitcoin.pdf

Newey, W. K., and West, K. D. 1987. "A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelationconsistent Covariance Matrix," *Econometrica* (55), pp. 703-708.

Parker, G., and Alstyne, M. V. 2008. "Managing Platform Ecosystems," *ICIS 2008 Proceedings*, p. 53.

Parker, G., and Van Alstyne, M. 2018. "Innovation, Openness, and Platform Control," *Management Science* (64:7), pp. 3015-3032.

Parker, G., Van Alstyne, M. W., and Jiang, X. 2017. "Platform Ecosystems: How Developers Invert the Firm," *MIS Quarterly* (41:1), pp. 255-266.

Parker, G. G., and Van Alstyne, M. W. 2005. "Two-Sided Network Effects: A Theory of Information Product Design," *Management Science* (51:10), pp. 1494-1504.

Parker, G. G., Van Alstyne, M. W., and Choudary, S. P. 2016. *Platform Revolution: How Networked Markets Are Transforming the Economy–and How to Make Them Work for You*. New York: W.W. Norton Publishing.

Rietveld, J., Schilling, M. A., and Bellavitis, C. 2019. "Platform Strategy: Managing Ecosystem Value through Selective Promotion of Complements," *Organization Science* (30:6), pp. 1232-1251.

Schilling, M. A. 2000. "Toward a General Modular Systems Theory and Its Application to Interfirm Product Modularity," *Academy of Management Review* (25:2), pp. 312-334.

Schmeiss, J., Hoelzle, K., and Tech, R. P. 2019. "Designing Governance Mechanisms in Platform Ecosystems: Addressing the Paradox of Openness through Blockchain Technology," *California Management Review* (62:1), pp. 121-143.

Setia, P., Rajagopalan, B., Sambamurthy, V., and Calantone, R. 2012. "How Peripheral Developers Contribute to Open-Source Software Development," *Information Systems Research* (23:1), pp. 144-163.

Sims, C. A. 1980. "Macroeconomics and Reality," *Econometrica* (48:1), pp. 1-48.

Song, P., Xue, L., Rai, A., and Zhang, C. 2018. "The Ecosystem of Software Platform: A Study of Asymmetric Cross-Side Network Effects and Platform Governance," *MIS Quarterly* (42:1), pp. 121-142.

Stabell, C. B., and Fjeldstad, Ø. D. 1998. "Configuring Value for Competitive Advantage: On Chains, Shops, and Networks," *Strategic Management Journal* (19:5), pp. 413-437.

Stewart, K. J., Ammeter, A. P., and Maruping, L. M. 2006. "Impacts of License Choice and Organizational Sponsorship on User Interest and Development Activity in Open Source Software Projects," *Information Systems Research* (17:2), pp. 126-144.

Stock, J. H., and Watson, M. W. 2001. "Vector Autoregressions," *Journal of Economic Perspectives* (15:4), pp. 101-115.

Syed, T. A., Alzahrani, A., Jan, S., Siddiqui, M. S., Nadeem, A., and Alghamdi, T. 2019. "A Comparative Analysis of Blockchain Architecture and Its Applications: Problems and Recommendations," *IEEE Access* (7), pp. 176838-176869.

Tiwana, A., Konsynski, B., and Bush, A. A. 2010. "Research Commentary—Platform Evolution: Coevolution of Platform Architecture, Governance, and Environmental Dynamics," *Information Systems Research* (21:4), pp. 675-687.

von Krogh, G., and von Hippel, E. 2006. "The Promise of Research on Open Source Software," *Management Science* (52:7), pp. 975-983.

Wang, P. 2021. "Connecting the Parts with the Whole: Toward an Information Ecology Theory of Digital Innovation Ecosystems," *MIS Quarterly* (45:1), pp. 397-422.

Wu, K., Peng, B., Xie, H., and Huang, Z. 2019. "An Information Entropy Method to Quantify the Degrees of Decentralization for Blockchain Systems," *IEEE 9th International Conference on Electronics Information and Emergency Communication (ICEIEC)*, pp. 1-6.

Yang, Y., and Boodraj, M. 2020. "Managing Code Debt in Open Source Software Development Projects: A Digital Options Perspective," *Americas Conference on Information Systems (AMCIS)*.

Yli-Huumo, J., Ko, D., Choi, S., Park, S., and Smolander, K. 2016. "Where Is Current Research on Blockchain Technology?— a Systematic Review," *PloS One* (11:10), p. e0163477.

Yoo, Y. J., Henfridsson, O., and Lyytinen, K. 2010. "The New Organizing Logic of Digital Innovation: An Agenda for Information Systems Research," *Information Systems Research* (21:4), pp. 724-735.

Zheng, Z., Xie, S., Dai, H., Chen, X., and Wang, H. 2017. "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends," *IEEE International Congress on Big Data (BigData Congress)*, pp. 557-564.

APPENDIX A

TABLE A
VARX Results

	Dependent Variables			
	CD	**MN**	**TXN**	**PD**
CD_{t-1}	0.561*** (0.100)	-0.447** (0.190)	-0.290 (0.211)	-1.624 (1.685)
CD_{t-2}	-0.164 (0.102)	0.502** (0.225)	0.552** (0.250)	1.626 (2.000)
CD_{t-3}	0.215* (0.129)	-0.171 (0.220)	-0.155 (0.245)	-5.348*** (1.957)
CD_{t-4}	0.084 (0.076)	0.181 (0.221)	0.057 (0.245)	5.295*** (1.961)
CD_{t-5}	-0.030 (0.072)	0.110 (0.193)	0.150 (0.215)	-0.178 (1.715)
MN_{t-1}	0.003 (0.068)	0.124 (0.117)	0.847*** (0.130)	-0.064 (1.041)
MN_{t-2}	-0.001 (0.038)	0.158 (0.136)	0.766*** (0.151)	-1.518 (1.207)
MN_{t-3}	0.117 (0.080)	0.012 (0.138)	0.530*** (0.154)	-2.093* (1.228)
MN_{t-4}	-0.006 (0.044)	0.105 (0.141)	0.498*** (0.156)	0.916 (1.250)
MN_{t-5}	0.048 (0.062)	-0.049 (0.130)	0.298** (0.145)	-0.150 (1.157)
TXN_{t-1}	-0.006 (0.029)	-0.249** (0.098)	-1.062*** (0.109)	1.549* (0.874)
TXN_{t-2}	-0.035 (0.046)	-0.252** (0.124)	-0.926*** (0.138)	0.488 (1.106)
TXN_{t-3}	-0.033 (0.049)	0.081 (0.128)	-0.636*** (0.143)	0.400 (1.140)
TXN_{t-4}	-0.009 (0.035)	-0.016 (0.121)	-0.497*** (0.135)	-0.420 (1.079)
TXN_{t-5}	0.007 (0.022)	0.097 (0.100)	-0.213* (0.111)	0.167 (0.885)
PD_{t-1}	0.006 (0.004)	0.002 (0.010)	-0.002 (0.011)	-0.652*** (0.086)
PD_{t-2}	0.003 (0.007)	0.024** (0.012)	-0.024* (0.014)	-0.460*** (0.108)
PD_{t-3}	-0.004 (0.007)	0.016 (0.013)	-0.013* (0.015)	-0.395*** (0.116)
PD_{t-4}	-0.012* (0.007)	0.001 (0.012)	-0.001 (0.013)	-0.203* (0.108)
PD_{t-5}	-0.007* (0.004)	-0.016 (0.010)	-0.017 (0.011)	-0.183** (0.090)
Control Variables	Y	Y	Y	Y
R square	0.498	0.273	0.456	0.506

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. Control variables include Ether Price, Mining Difficulty, Version Release, and Hard Fork. N = 199. Variables are logged. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

APPENDIX B

Robustness Check: Using New contracts as Contract Deployment

TABLE B1
Granger Causality Test (New Contracts as CD)

	Dependent Variables			
	CD	**MN**	**TXN**	**PD**
CD	–	4.415	10.570*	5.069
MN	1.642	–	62.439***	5.168
TXN	4.968	15.585***	–	3.879
PD	14.211**	9.349*	8.816	17.366

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

TABLE B2
Tests for Serial Correlation and Heteroskedasticity (New Contracts as CD)

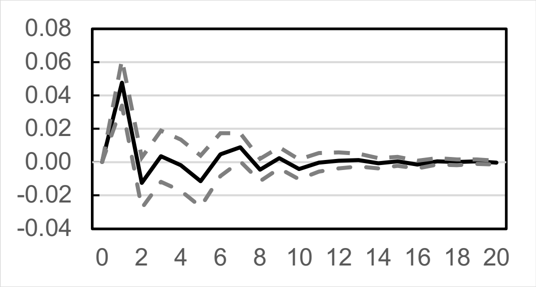
Dependent Variable	Breusch-Godfrey Test	Breusch-Pagan Test
Transaction	3.202 (0.669)	3.200 (0.074)
Contract Deployment	3.626 (0.605)	11.480 (0.001)
Mining	4.458 (0.486)	3.610 (0.058)
Protocol Development	13.117 (0.022)	1.380 (0.241)

Notes: The results show χ^2 values with p-values in parentheses.

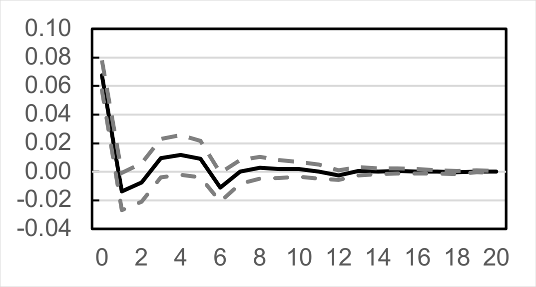
FIGURE B
Impulse Response Functions (New Contracts as CD)

Network Effects in Exchange Subsystem

Mining → Transaction

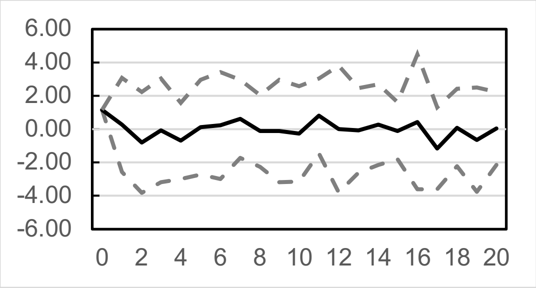


Transaction → Mining

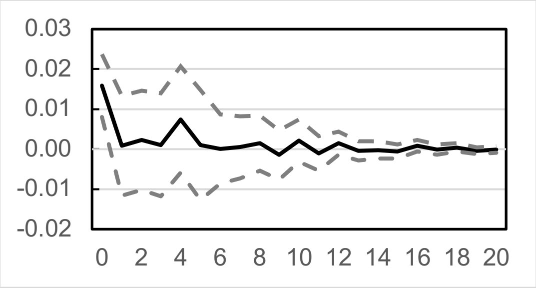


Network Effects in Contract Subsystem

Mining → Contract Deployment



Contract Deployment → Mining



Network Effects in Protocol Subsystem

Protocol Development → Protocol Development

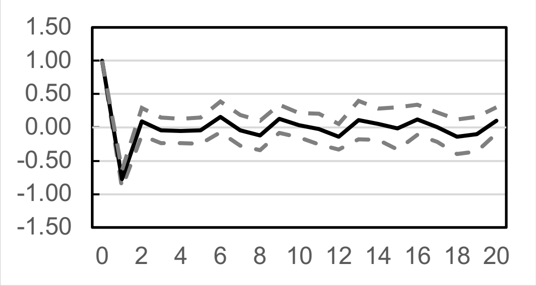
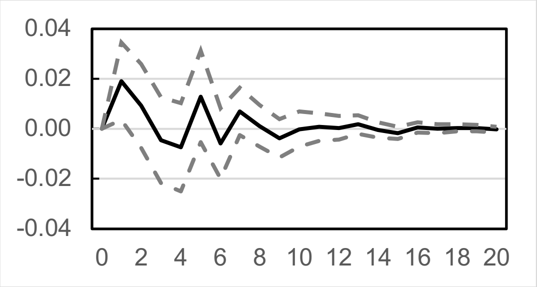


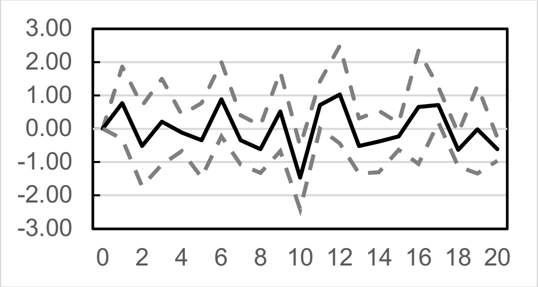
FIGURE B (Continued)
Impulse Response Functions (New Contracts as CD)

Network Effects between Exchange Subsystem and Contract Subsystem

Contract Deployment → Transaction

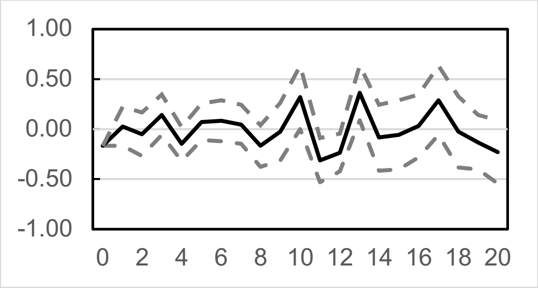


Transaction → Contract Deployment

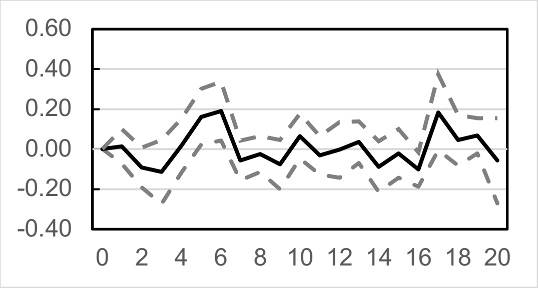


Network Effects between Contract Subsystem and Protocol Subsystem

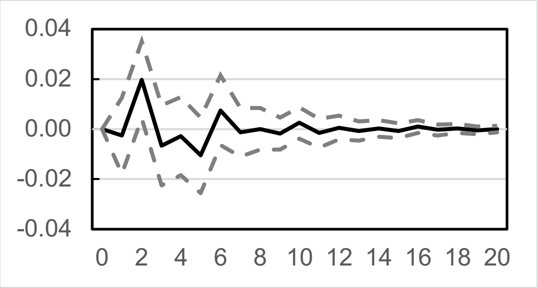
Contract Deployment → Protocol Development



Protocol Development → Contract Deployment

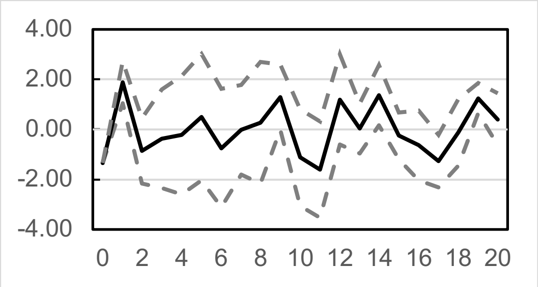


Protocol Development → Mining

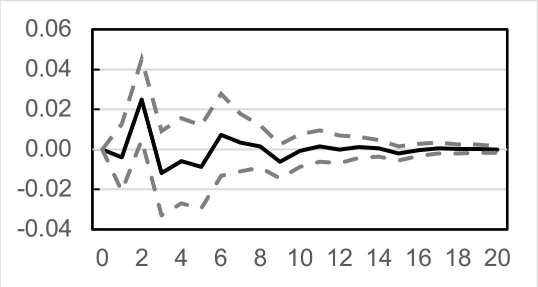


Network Effects between Exchange Subsystem and Protocol Subsystem

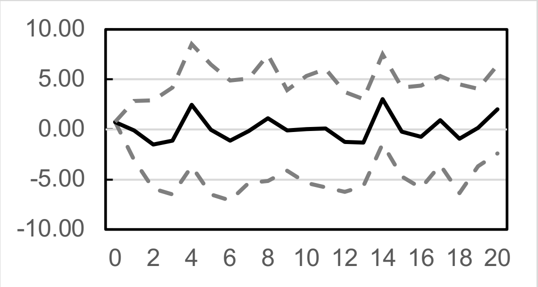
Transaction → Protocol Development



Protocol Development → Transaction



Mining → Protocol Development



APPENDIX C

Robustness Check: Using Code Changes as Protocol Development

TABLE C1
Granger Causality Test (Code Changes as PD)

	Dependent Variables			
	CD	**MN**	**TXN**	**PD**
CD	–	5.350	4.690	9.946*
MN	8.193	–	54.727***	4.428
TXN	0.886	11.280**	–	4.631
PD	7.303	2.665	2.145	17.061

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

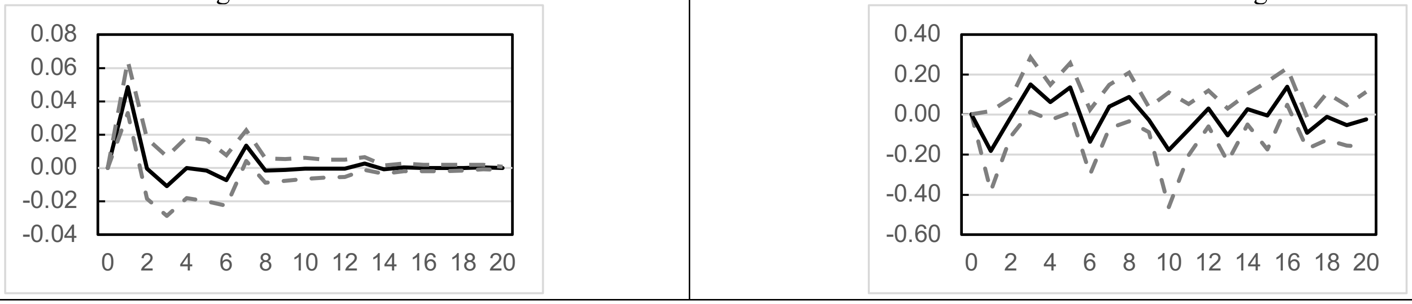
TABLE C2
Tests for Serial Correlation and Heteroskedasticity (Code Changes as PD)

Dependent Variable	**Breusch-Godfrey Test**	**Breusch-Pagan Test**
Transaction	2.836 (0.725)	3.190 (0.074)
Contract Deployment	3.691 (0.595)	4.660 (0.031)
Mining	2.889 (0.717)	19.160 (0.000)
Protocol Development	0.050 (0.830)	9.570 (0.088)

Notes: The results show χ^2 values with p-values in parentheses.

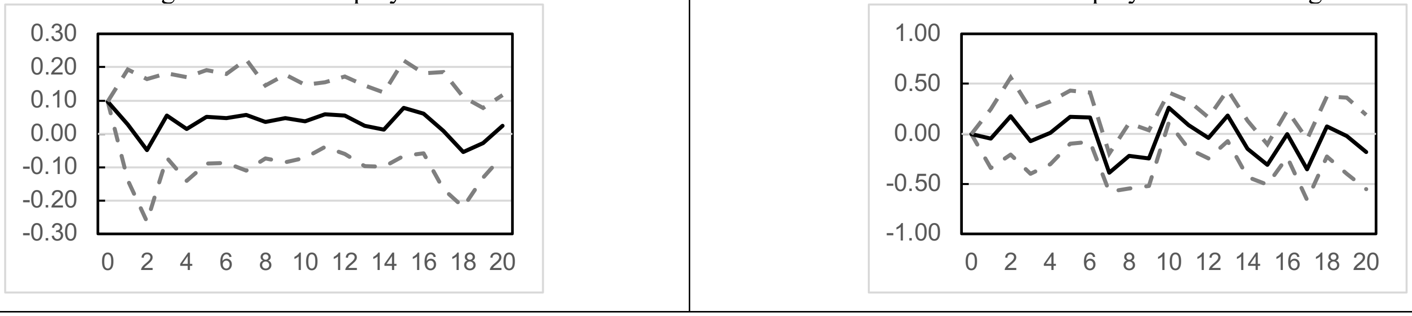
FIGURE C
Impulse Response Functions (Code Changes as PD)

Network Effects in Exchange Subsystem


Mining → Transaction

Transaction → Mining

Network Effects in Contract Subsystem


Mining → Contract Deployment

Contract Deployment → Mining

Network Effects in Protocol Subsystem

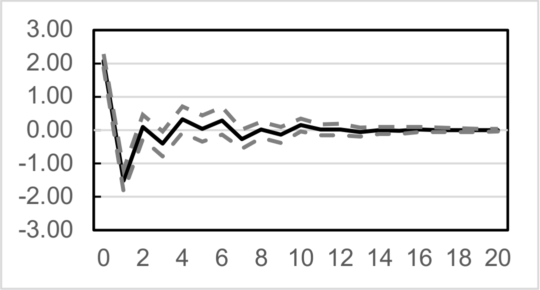
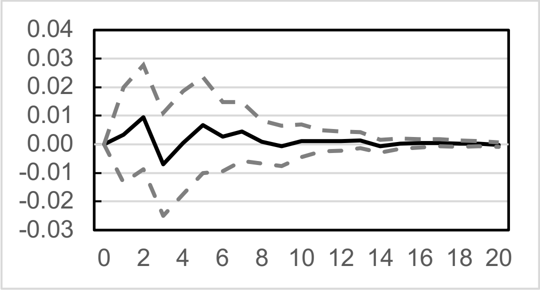
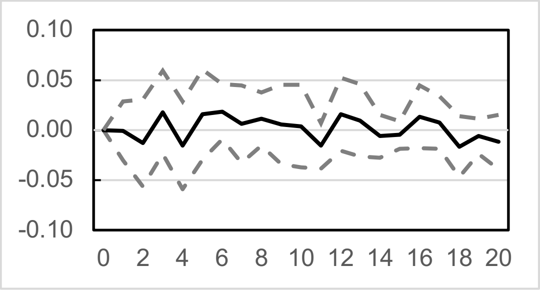

Protocol Development → Protocol Development

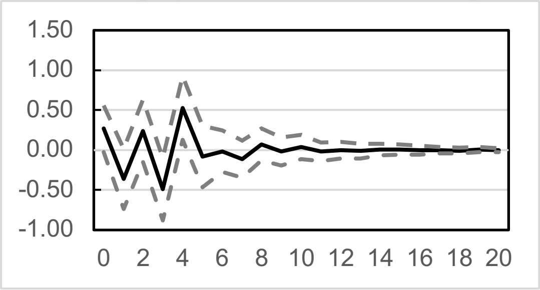
FIGURE C (Continued)
Impulse Response Functions (Code Changes as PD)

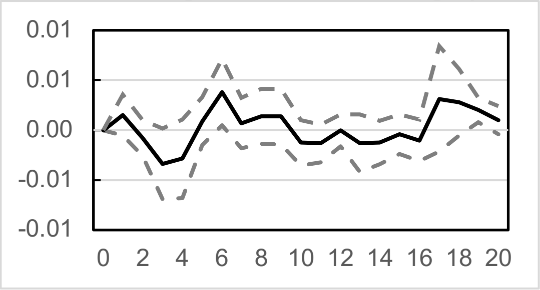
Network Effects between Exchange Subsystem and Contract Subsystem

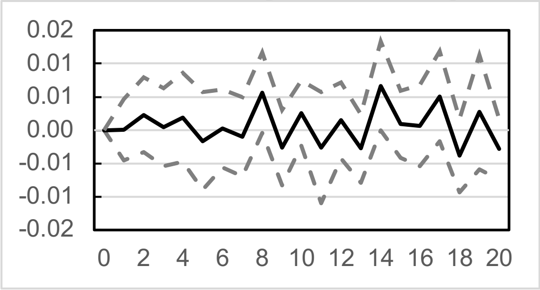

Contract Deployment → Transaction


Transaction → Contract Deployment

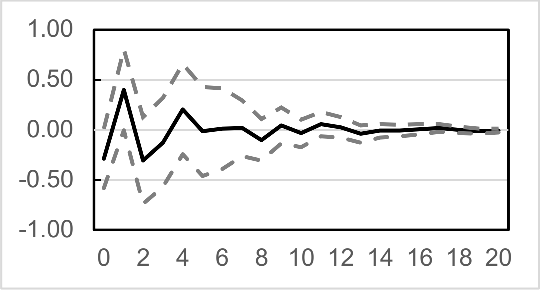
Network Effects between Contract Subsystem and Protocol Subsystem

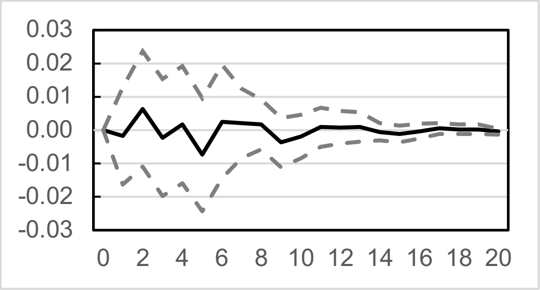

Contract Deployment → Protocol Development

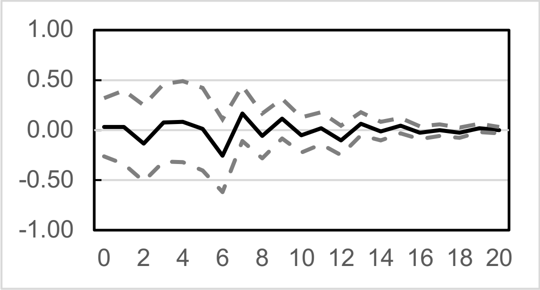

Protocol Development → Contract Deployment


Protocol Development → Mining

Network Effects between Exchange Subsystem and Protocol Subsystem


Transaction → Protocol Development


Protocol Development → Transaction


Mining → Protocol Development

CHAPTER 3. DECENTRALIZED GOVERNANCE IN A PUBLIC BLOCKCHAIN ECOSYSTEM

INTRODUCTION

Digital platform-enabled ecosystems play a dominant role in today's economy, and a suitable governance approach is key to orchestrating a successful platform-enabled ecosystem for all stakeholders (Schreieck et al. 2016). In a broad sense, governance of platform-enabled ecosystems can be defined as the structures that determine "how rigidly authority is exerted and who has authority to make decisions and craft rules for orchestrating key activities" (Maruping and Yang 2020, p. 1). Governance mechanisms are viewed as a means for orchestrators to solve challenges and exert influence over participants in the ecosystem (Schmeiss et al. 2019; Song et al. 2018; Tiwana et al. 2010). Although governance is a multifaceted concept with aspects such as decision rights, accountability, and incentives, the central element of governance is decision-making authority (Brown and Grant 2005; Chen et al. 2021; Tiwana 2009). Depending on whether decision-making authority is in the hands of a central party or distributed to participants, governance is characterized as centralized or decentralized (Brown and Grant 2005; Huber et al. 2017; Tiwana et al. 2010).

An ecosystem with centralized forms of governance usually consists of a platform leader (or owner, sponsor) that designs and governs the technical architecture and different groups of actors (such as complementors and users) that interact on the platform (Schmeiss et al. 2019). The primary purpose of governing typical digital platform-enabled ecosystems is for the platform owner to lead stakeholders to create value (Kyprianou 2018; Rietveld et al. 2019). For example, a platform sponsor can selectively promote individual complements to manage the value of the overall ecosystem (Rietveld et al. 2019). Despite the merits of centralized governance such as exclusive governance control for platform owners to shape innovation processes and outcomes, there are also issues inherent to centralized governance, such as a lack of transparency, corruption, coercion, censorship, and excessive market power (Atzori 2015; Chen et al. 2021)

In recent years, decentralized governance has been increasingly embraced to deal with centralized governance's issues (Atzori 2015; Pereira et al. 2019). An example is open-source software development platforms where multiple decentralized governance mechanisms are designed and enacted, such as self-assignment mechanism, monitoring and sanction mechanism, and reputation mechanism (Di Tullio and Staples 2013). The emergence of blockchain technology has promoted the emergence of a growing number of decentralized digital platform-enabled ecosystems that are governed by community efforts (Chen et al. 2021; Hsieh et al. 2018). Among all types of blockchain, public blockchain (e.g., Bitcoin and Ethereum) opens all transaction records to the public and allows everyone to participate in the process of block validation without restrictions. These ecosystems do not have a platform owner as the trusted third party who orchestrates the overall ecosystem, and the value creation in these ecosystems depends on the incentive alignment of multiple types of actors on different sides of interactions and their spontaneous participation.

The extant literature has tended to place a greater emphasis on centralized governance. Further, the platform literature on governance has tended to focus on centralized governance and has done so primarily in the context of the platform itself rather than the platform ecosystem. Less attention has been paid to platform-enabled ecosystems with highly decentralized governance. There are two plausible reasons for the lack of studies on this subject: First, an ecosystem involves multiple sides of actors on various platforms, making it much more complex than a study on two-sided digital platforms. Second, it is practically difficult for an ecosystem to achieve decentralized governance, since centralized governance allows platform owners to manage value co-creation and value capture processes within the ecosystem and acquire the most profit from the innovation process (Pereira et al. 2019; Rietveld et al. 2019).

Based on these observations and distinctive attributes of public blockchain ecosystems, I argue that there are limits to the lessons that can be drawn from the cumulative literature on governance of digital platform ecosystems. For one, as ecosystem participants may hold vastly diverse perspectives and interests, they may find it difficult to achieve consensus on a specific blockchain ecosystem governance mechanism (Chen et al. 2021). It is possible that a governance mechanism that is locally optimal may be globally suboptimal or even destructive. As such, decision makers need to observe and learn from other ecosystem participants' behaviors to guide their subsequent governance practices. This makes decentralized governance mechanisms more dynamic compared to centralized governance mechanisms.

I argue that the governance mechanisms of a blockchain ecosystem are critical for its sustainability as they enable stakeholders to discuss and make decisions on how the blockchain should evolve (van Pelt et al. 2021). Prior studies have conceptually discussed decentralized governance enabled by blockchain technologies (e.g., Atzori 2015; Beck et al. 2018; Glaser 2017; Pereira et al. 2019; van Pelt et al. 2021). Example topics include conceptualization of decentralized governance and its dimensions (e.g., Beck et al. 2018; van Pelt et al. 2021), fundamental principles and assumptions of blockchain-based governance (e.g., Atzori 2015), and a comparison of centralized governance and decentralized governance (e.g., Pereira et al. 2019). Little is known about what and how key decisions are made and enforced in blockchain ecosystems and more importantly, how they dynamically affect economic activities (Beck et al. 2018; Hsieh et al. 2018; van Pelt et al. 2021; Ziolkowski et al. 2020). Participants may find it difficult to understand the mechanisms of blockchain ecosystem governance. Some are not even aware that they are stakeholders themselves in the decisions made during blockchain governance (van Pelt et al. 2021). If participants do not know that they have a stake in decision making, they may not feel responsible for contributing to the blockchain ecosystem's development.

The objectives of this research are two-fold: (1) to identify the decentralized governance mechanisms and determine who has the governance power in terms of decision-making rights in platform-enabled ecosystems that are fundamentally decentralized in their composition, and (2) to understand the impacts of these decentralized governance mechanisms on ecosystem functioning. I conceptualize decision control and decision management mechanisms building on Fama and Jensen's (1983) framework of decision processes in organizations, and contextualize these mechanisms to the layered structure of the blockchain ecosystem. Then, I examine the dynamic influences of specific governance mechanisms on participants' activities within and across different layers and the interactions between different governance mechanisms.

I conduct a time-series analysis using weekly time-series data collected from Ethereum and its protocol repository on GitHub between January 2016 and October 2019. I utilize vector autoregression (VAR) to examine the hypotheses. My findings reveal dynamic effects of decision mechanisms on other economic activities at the application layer and at the architecture layer, respectively. The results also show the significant effect of the decision control mechanism on the decision management mechanism across layers.

This research presents three key contributions to the ecosystem governance and blockchain literatures. First, by decomposing the ecosystem into interrelated layers, my study sheds light on understanding decentralized ecosystem governance. Second, my study extends Fama and Jensen's (1983) two types of decision activities from a centralized organization context to the decentralized ecosystem context, providing a unique angle for understanding highly decentralized governance. Third, my study adds new insight to the blockchain literature by empirically examining the dynamic influences of decentralized governance mechanisms while the existing research mainly focuses on blockchain-enabled governance from a theoretical perspective (Constantinides et al. 2018; Risius and Spohrer 2017). These findings also generate important practical implications as to how the governance of public blockchain ecosystems can be improved.

THEORETICAL DEVELOPMENT

Layered Structure of a Public Blockchain Ecosystem

A public blockchain ecosystem usually consists of four types of participants: users, contract creators, miners, and protocol developers. Users engage in transaction activities or invoke smart contracts. I refer to these as *transaction* activities. A smart contract is a piece of self-executing code that defines the rules and penalties around an agreement and automatically executes and enforces the obligation (Janssen et al. 2020). Contract creators deploy new smart contracts on the blockchain platform, referred to as *contract deployment* activities. Miners verify the validity of transactions and smart contracts to ensure the consistency of the records by solving a cryptographic puzzle. Such activities are referred to as *mining* activities (Arnosti and Weinberg 2019). Protocol developers develop and improve the underlying blockchain protocol to support on-platform activities. I call these *protocol development* activities. A blockchain protocol defines the main rules that govern the platform's functioning and the data infrastructure (Buterin 2014). Table 1 summarizes different types of participants and the economic activities in which they engage.

TABLE 1
Participants and Activities in A Public Blockchain Ecosystem

Participant	Description	Economic Activity
Application Layer		
Miners	Participants who verify blocks of transactions and contracts and keep complete records of the transaction history.	Mining: a validation process to ensure a block of transactions is valid before adding it to the blockchain.
Contract creators	Participants who create smart contracts and deploy the smart contracts on a blockchain.	Smart contract deployment: a transaction that is sent from the contract creator with the purpose of deploying a new contract on the blockchain.
Users	Participants who transfer money (in cryptocurrencies) or invoke smart contracts.	Transaction: a signed data package that stores money or a message sent from one account to another. A transaction can be made from a user to another user, or from a user to a smart contract.
Architecture Layer		
Protocol developers	Participants who create and improve the underlying blockchain protocol.	Protocol development: code contributions from developers to develop and improve the blockchain protocol.

A layered structure is commonly seen in digital technology architecture, which enables separation between device and service and the separation between network and content (Adomavicius et al. 2008). A digital platform-enabled ecosystem can also be viewed as a multi-layer entity. The application layer is where business logic is developed and complementors provide services, and the infrastructure layer is where platform owners manage users and maintain the database (Glaser 2017). Yoo et al. (2010) proposed a layered modular architecture in which the layered architecture of digital technology enhances product functionality with software-based capabilities. In digital innovation ecosystems, the multiple layers of complementary products increase task interdependencies, making the ecosystem more complex and challenging to manage (Kapoor and Agarwal 2017; Wang 2021).

Based on prior literature on the layered structure of digital platform-enabled ecosystems and blockchain technology characteristics, I conceptually divide the blockchain ecosystem into *application layer* and *architecture layer* (Andersen and Bogusz 2017; Glaser 2017). The *application layer* of a blockchain ecosystem deals with application functionalities that directly serve participants as they exchange digital assets, implement smart contracts, and verify transactions on the blockchain platform (Glaser 2017). The *architecture layer* of a blockchain ecosystem includes activities that contribute to designing, developing, and implementing the underlying architecture of blockchain technologies, which is at the heart of value creation for participants on the *application layer* (Andersen and Bogusz 2017; Pereira et al. 2019; Stabell and Fjeldstad 1998).

Governance

Corporate governance is one of the dominant research areas in the finance and management literature. In the corporate context, governance mainly deals with the agency problem–the separation of management and finance (Shleifer and Vishny 1997; Williamson 1988). Corporate governance is understood as "structures and procedures that aim to ensure that (1) authority responsibility and control flows 'downwards' from the investors through a board of directors to management and finally, to the employees; and (2) accountability flows 'upwards'" (Fenwick et al. 2019, pp. 178-179). The fundamental question of corporate governance is how to assure investors that they get a return on their financial investment (Shleifer and Vishny 1997).

With the wide adoption of information technology (IT), IT governance has received a significant increase in attention from business management. IT governance is defined as "the framework for decision rights and accountability to encourage desirable behavior in the use of IT" (Weill 2004, p. 3). A substantial number of studies have discussed and theorized the virtues of prudent, practical, and well-aligned IT governance (Brown and Grant 2005; Tiwana 2009). Brown and Grant (2005) conducted a comprehensive review of IT governance literature and grouped them into two research streams: the research on IT governance forms regarding IT decision-making locus and structures and the research on IT governance contingency analysis for uniform and non-uniform governance frameworks.

The emergence of digital platforms opens a research branch of IT governance. Compared to corporate IT governance, digital platform governance is more open and community-driven as the platform leverages networked technologies to promote economic exchange, transfer information, and encourage collaboration among multiple stakeholders (Fenwick et al. 2019). Here, digital platform governance is defined as the partitioning of decision-making authority between platform owners and complementors (i.e., decision right), control mechanisms (i.e., control), and pie-sharing structures (i.e., pricing) (Tiwana et al. 2013). More topics in this area focus on the structuring of decision-making authority and control rights to ensure effective value creation and fair value distribution (Chen et al. 2021).

The context of exerting governance becomes more complex when there is more than one digital platform functioning altogether as an ecosystem. In a digital platform-enabled ecosystem, the alignment of multi-side participants' incentives becomes particularly important as it helps understand the relationship among participants and guides the design for appropriate governance mechanisms (Alves et al. 2017). Beck et al. (2018) describe ecosystem governance as the mechanism that determines who makes each type of decision (decision right), incentives for participants to engage in value creation in the ecosystem (incentive structure), and types of formal and informal control mechanisms used to ensure the alignment of participants' incentives (control mechanism). The existing governance literature has been centered on the ecosystems of two-sided digital platforms (e.g., Rietveld et al. 2020; Wareham et al. 2014). A salient feature of such ecosystems is the centralized decision-making authority of platform owners. As such, many studies focus on governance from the platform owners' perspective (Schreieck et al. 2016). In a high centralized governance ecosystem, platform owners enjoy exclusive governance control, which allows them to apply appropriate governance mechanisms to motivate third-party complementors (Rietveld et al. 2020), orchestrate the innovation process (Boudreau 2010; Wareham et al. 2014), regulate access and interactions among users and complementors, and enhance network effects and attract users (Pereira et al. 2019). However, platform owners with centralized decision-making authority may put the digital platform at risk in pursuing activities that benefit themselves at the expense of other stakeholders (Chen et al. 2021). For example, the platform owner can control downstream innovation by complementors, increasing profits through an optimal choice of platform openness but harming the interests of the complementors (Parker and Alstyne 2008).

Some studies have explored digital platform-enabled ecosystems where the platform owners distribute a degree of decision-making authority to participants. However, these studies still pay specific attention to platforms owned or sponsored by a third party. For example, Huber et al. (2017) identify two governance routes and develop a process theory to explain how different routes successfully navigate the governance tension between co-created value and governance costs. In this process, platform owners assign partnership managers to enact ecosystem-wide rules and values. Tiwana et al. (2010) discuss decision rights partitioning between the platform owner and module developers and explore its impact on the evolution of the overall ecosystem. Nevertheless, the governance of ecosystems with highly decentralized decision-making authority remains understudied. There is no platform owner in such an extreme form of governance, and platform participants collectively enjoy full governance control (Chen et al. 2021). Notably, an absence of the platform owner does not mean the absence of governance. Instead, highly decentralized governance emphasizes maximizing the overall welfare of all participants rather than the residual profits of the platform owner (Chen et al. 2021). It also allows platform participants to engage in decision-making and represent their perspectives and leverage their local information to improve the informational efficiency of platform governance processes (Chen et al. 2021).

I believe that a focus on governance in decentralized platform-enabled ecosystems is theoretically essential. A digital platform-enabled ecosystem is a loosely coupled set of autonomous participants who interact without hierarchical fiat. The more participants join the ecosystem with their skills and creativity, the more difficult it is for participants to integrate their efforts to sustain the ecosystem (Wang 2021). Such complexity of ecosystems requires that governance be more decentralized to support participants' interdependencies. The basic idea behind adopting decentralized governance is to provide a fault-tolerant distributed computing environment where the authority is distributed, ensuring trust, transparency, and data integrity (Syed et al. 2019). For ecosystem participants, the complexity, interdependencies, and uncertainties require them to collect relevant information to inform decision-making (Wang 2021). As there is no central authority to orchestrate the overall ecosystem, participants' decision-making process can be more sensitive to others' actions, making decentralized governance a dynamic and mutually reinforcing mechanism.

Decentralized Governance in the Public Blockchain Ecosystem

Blockchain technology creates an "architecture of trust" in which multi-side participants do not need to know or trust each other to interact safely under predetermined conditions defined by the blockchain protocol and smart contracts (Schmeiss et al. 2019). All interactions are transparently executed on a blockchain platform and stored in a distributed ledger that follows the rules defined by the blockchain protocol (Schmeiss et al. 2019). As I stated, in a centralized digital platform-enabled ecosystem, the platform owner proposes and nurtures the value creation mechanism and thus has the ultimate decision-making authority. In a public blockchain ecosystem, participants collectively define the value proposition of the ecosystem and enjoy complete governance control—referred to as highly decentralized governance (Chen et al. 2021). For example, in Ethereum, the blockchain network is neither owned nor controlled by any single entity (Atzori 2015). Developers who are active in code contribution gain decision-making power.

Nevertheless, not all participants have decision-making power. I argue that the decentralization of such decision-making power is reflected in two ways. In the subsections that follow, I discuss the decision process framework proposed by Fama and Jensen (1983) and extended by Tiwana (2009). Combining the framework with the layered structure of the blockchain ecosystem, I identify three decentralized decision-making mechanisms exerted in a public blockchain ecosystem (Table 2 compares decision activities in different research contexts).

Two Classes of Decision Activities. Fama and Jensen (1983) argue that allocating "ownership" and "control" to different agents is vital in explaining the survival of organizations, meaning that important decision makers do not hold a substantial share of the wealth effects of their decisions. Fama and Jensen (1983) identify four steps of activities in a decision process: ratification–choice and approval of the initiatives to be implemented, monitoring–specification and implementation of performance measurement criteria, initiation–generation of proposals for resource utilization of organizational contracts, and implementation–execution of ratified decisions. As ratification and monitoring of decisions are typically allocated to the same agent in the organization, they are combined as *decision control*. Similarly, the initiation and implementation of decisions are clustered as *decision management* (Fama and Jensen 1983). In entrepreneurial firms that are characterized by separation of decision management and residual risk bearing, decision management is allocated to internal managers, while decision control is delegated in a board of external directors (Fama and Jensen 1983). The key benefit of doing so is to decrease the possibility of collusion between top-level decision management and control agents.

Building on Fama and Jensen's (1983) work, Tiwana (2009) conceptualized decision rights in information systems development projects, where ratification and monitoring involves "establishing rewards and penalties for project outcomes, and implementing mechanisms to evaluate the project team's performance, specifying project milestones and deliverables, and monitoring project process" (Tiwana 2009, p. 182). Implementation and initiation involves activities such as "systems design, software architecture design, and the definition of application features/functionality" (Tiwana 2009, p. 182). Unlike the original definition, which emphasizes the exclusive allocation of decision management and decision control to different agents, Tiwana (2009) states that these two decision rights are usually shared to varying degrees by the IT and client departments in information system development practice.

I argue that the conceptualization of two decision classes fits in the context of decentralized platform-enabled ecosystems. First, the ecosystem's layered structure makes it convenient to partition decision-making activities into decision control and decision management and assign them to different groups of participants. Specifically, decision management activities happen at the architecture layer, where new features of the blockchain protocol are initiated and implemented. Decision control activities occur at the application layer, where economic activities such as transactions and contract deployment are regulated. Second, the conceptualization of the two decision classes of decisions can streamline my understanding of decentralized governance. The governance complexity of a multi-side ecosystem is high, and it is even higher when there is no central authority with ultimate control over the ecosystem (Wang 2021). Clustering decision activities into *decision control* and *decision management* provides a structure to understand the exercise of governance in the context of decentralized ecosystems. However, as decision rights are decentralized to participants (Pereira et al. 2019; van Pelt et al. 2021), the conceptualization of two decision classes needs to be revisited before translating into a decentralized ecosystem context.

As this research focuses on the mechanisms that participants utilize to govern the decentralized ecosystem, I conceptualize governance mechanisms in a public blockchain ecosystem as comprising two classes: the *decision control* mechanism at the application layer and the *decision management* mechanism at the architecture layer (Andersen and Bogusz 2017; van Pelt et al. 2021). In the following two subsections, I provide an in-depth discussion on the two decision classes in the public blockchain ecosystem and their most used mechanisms.

TABLE 2
Classes of Decision Activities in Different Research Contexts

Class of Decision Activities	**Research Context**		
	Entrepreneurial firms	**System development project**	**Blockchain ecosystem**
Decision Control	*Ratification*: choose decision initiatives to be implemented *Monitoring*: measure the performance of decision agents, and implement rewards	*Ratification*: specify project milestones and deliverables *Monitoring*: establish rewards and penalties for project outcomes, evaluate the project team's performance, and monitor project progress	*Ratification*: vote for core developers' decisions, and indicate interest in continuous participation *Monitoring*: select and verify pending transaction and contract deployment requests, and adjust the block gas limit
Decision Management	*Initiation*: generate proposals for resource utilization and structuring of contracts *Implementation*: execute ratified decisions	*Initiation*: design systems and software architecture, select a software platform, and define application functionality *Implementation*: develop methodology and programming language	*Initiation*: generate proposals related to blockchain protocol development *Implementation*: execute ratified changes to the blockchain protocol, and release new versions of client software
Relevant Literature	Fama and Jensen 1983	Tiwana 2009	Beck et al. 2018; van Pelt et al. 2021

Decision Control Mechanism at the Application Layer. According to Fama and Jensen (1983), *decision control* encompasses ratification and monitoring activities. In the blockchain ecosystems context, ratification involves voting for the proposal initiated by protocol developers and indicating interest in continuous participation. In blockchain ecosystems such as the Tezos ecosystem, participants who hold tokens have the right to vote for motions proposed by protocol developers. In some blockchain ecosystems, for example, the Ethereum ecosystem, the voting role is weakened. Another way to show participants' support for core developers' decisions is to indicate continuous participation (Pereira et al. 2019). In blockchain ecosystems, monitoring includes selecting and verifying pending transactions and contract deployment requests and adjusting the block gas limit. Unlike monitoring activities conceptualized by prior literature, there is no specific mechanism for participants to implement criteria of decision makers' performance in public blockchain ecosystems, which dampens its functionality in terms of performance evaluation. However, participants can exert their decision control power by monitoring all the exchange activities at the application layer. At the application layer, miners are the major decision makers as they play a critical role in examining the validity of transactions and smart contracts and maintain a digitally shared, distributed ledger recording their history (Hsieh et al. 2018; Pereira et al. 2019).

Notably, the authority for miners to exercise *decision control* is distributed across multiple participants rather than concentrating on a single entity. Distributing *decision control* across multiple participants usually incurs coordination costs as miners need to communicate and agree upon ratification decisions (Schmeiss et al. 2019). *Network capacity adjustment* is a commonly used decision control mechanism that adopts a market-based approach to this coordination. Network capacity is the blockchain's capability of verifying transactions and smart contracts in a given period (van Pelt et al. 2021). It can be captured by the average number of pending transactions and smart contracts that can be included in one block at a time. As the verification process usually consumes a large amount of computational power, a critical issue for miners is allocating their limited resources to gain as many rewards as possible. As suggested by Hayek (1945), price is an effective communication mechanism at scale. He pointed out that "in a system where the knowledge of the relevant facts is dispersed among many people, prices can act to coordinate the separate actions of different people in the same way as subjective values help the individual to coordinate the parts of his plan" (Hayek 1945, p. 526). Through this price mechanism, "the whole acts as one market, not because any of its members survey the whole field, but because their limited individual fields of vision sufficiently overlap so that through many intermediaries the relevant information is communicated to all" (Hayek 1945, p. 526). In the public blockchain ecosystem context, mining rewards are the "prices" to miners. The local rewards to each miner are connected in a manner determined by the block gas limit, which brings about the solution (increase or decrease the average block gas limit, i.e., network capacity) which might have been arrived at by one single mind possessing all the information which is in fact dispersed among all the miners at the application layer. An increase in the network capacity enables miners to include more transactions, thus gaining higher rewards. However, it slows down the block verification process as it requires more computational power to verify transactions. A decrease in the network capacity can speed up block verification but causes a drop in rewards for mining a block. Adjusting network capacity may also send out signals to both transaction senders and smart contract creators regarding the speed and cost of having their pending requests fulfilled, which can influence their subsequent participation (Beck et al. 2018).

As such, multiple miners can implicitly coordinate their exercise of *decision control* by adjusting network capacity.

Based on the discussion, I conceptually define *decision control mechanism* as the means by which miners select and verify transaction and contract deployment requests at the application layer. In this research, I specifically focus on *network capacity adjustment* as the decision control mechanism.

Decision Management Mechanisms at the Architecture Layer. According to Fama and Jensen (1983), *decision management* includes initiation and implementation activities. In public blockchain ecosystems, initiation and implementation involve generating proposals related to blockchain protocol development, executing ratified changes to the blockchain protocol, and releasing new versions of client software. Most blockchain platforms rely on open-source communities for continued protocol development (Chen et al. 2021; Ziolkowski et al. 2020). Because of the complexity of digital infrastructures at a large scale (such as blockchain), distributed forms of control are often the only way to organize digital infrastructure (Andersen and Bogusz 2017). In the public blockchain ecosystem context, *decision management* rights are distributed to core developers (van Pelt et al. 2021). Just like the flexibility of being a miner, any protocol developer can become a core developer, and membership in the core developer team is not fixed (Hsieh et al. 2018). However, the difference is that the core developer team's size is much smaller than the size of the group of miners, meaning that it would be relatively easier for core developers to reach a consensus upon a decision.

In general, core developers exercise two *decision management* via two mechanisms: first, core developers review, accept or decline pull requests and implement the changes in the next version of the blockchain client software. I refer to these kinds of decisions as *client update*.

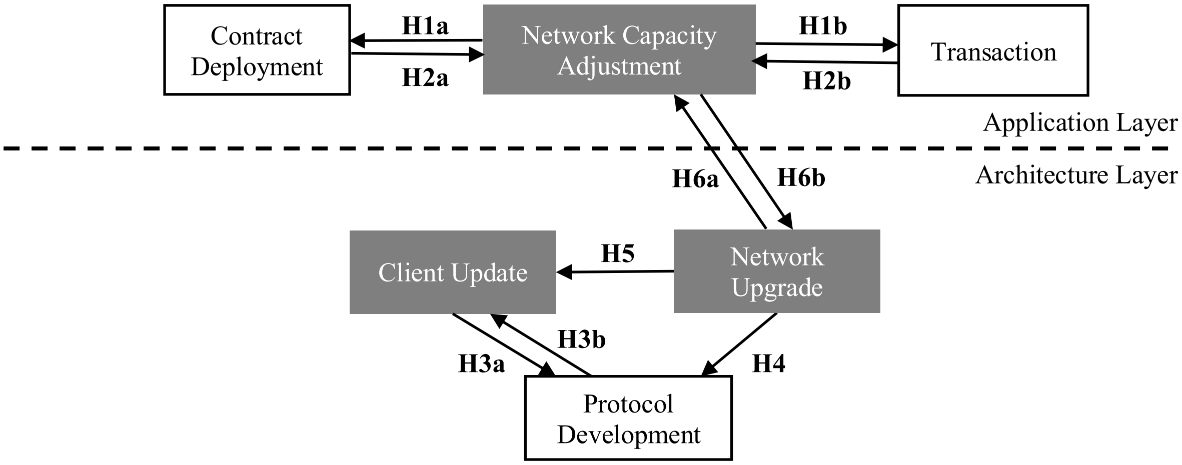
Updates to the client software are an important way to address governance by improving the blockchain platform's design and architecture (Tiwana 2014). Frequent changes to the client software may generate both benefits and counterproductive effects (Song et al. 2018). On the one hand, frequent updates suggest that the platform is constantly improved, boosting developers' confidence (Arora et al. 2006). On the other hand, frequent updates may increase developers' pressure to adapt to new functionalities (Boudreau 2010) and dealing with uncertainties (Kapoor and Agarwal 2017) and more technical debt (Ramasubbu and Kemerer 2016). As such, core developers can exercise *decision management* by deliberately scheduling client updates.

Second, core developers can initiate a code fork when miners' interests diverge (Gervais et al. 2014; Ziolkowski et al. 2020). I refer to the decisions on releasing a new code fork as *network upgrade*. Different from *client update* that incorporates new features into the blockchain protocol, a code fork enables fundamental changes in the underlying protocol code such that the new version and the old version of the code are forward incompatible. From this perspective, a code fork usually represents a radical change in the organizational structure (Andersen and Bogusz 2017). For example, a code fork may include adjusting the amount of rewards to miners (Gervais et al. 2014; Ziolkowski et al. 2020). The influence of code forks is also multifaceted. For one, code forks may change power dynamics and make decision-making controlled by fewer people (Andersen and Bogusz 2017). However, adapting to the changing environment through code forks may also attract new users to the community (Andersen and Bogusz 2017). The community may become more homogeneous due to the departure of participants with dissenting opinions (Pereira et al. 2019). As such, core developers need to plan code forks as an exercise of *decision management* subtly.

In sum, I conceptually define *decision management* mechanism as the means by which core developers generate and execute proposals for improving the blockchain protocol. In this research, I specifically focus on *client update* and *network upgrade* as two decision management mechanisms. Exercising different decision management mechanisms may signal unobservable protocol quality and the core developer team's commitment level, affecting protocol developers' subsequent contributions.

Connection between Decision Control Mechanism and Decision Management Mechanism. It is noteworthy that the dual role of miners is a critical characteristic that distinguishes the governance of public blockchain ecosystems from the governance in centralized organizations. On the one hand, miners are the decision-makers at the application layer whose exercise of decision control mechanisms can affect the behaviors of other participants. On the other hand, miners also follow the predefined rules in the blockchain protocol, making them users for protocol developers on the architecture. Miners' dual identities imply a potential relationship between exercising the decision control mechanism and decision management mechanisms, which I will discuss in the next section. Figure 1 illustrates the research model.

FIGURE 1
Research Model



HYPOTHESIS DEVELOPMENT

Effects of Decision Control Mechanism at the Application Layer

Network capacity is the primary means by which miners exercise decision control. The average block gas limit can be used to understand the network capacity of a blockchain. Block gas limit determines the maximum gas of a block, which indicates the approximate number of transactions or smart contracts that can be included in a block. Miners' decision control governs the activity of users and contract creators. Specifically, enhanced network capacity enables miners to include more pending transactions and smart contracts in one block, which requires more computational power to verify and slows down solving the cryptographic puzzle (Seifelnasr et al. 2020). Users and contract creators need to wait for a longer time to get their pending exchanges verified. However, fitting more exchanges into one block can decrease the transaction fee that users and contract creators pay to fulfill their requests promptly. As such, whether to use the blockchain depends on how users and contract creators evaluate the trade-offs between waiting time and transaction fees. As contract deployment is a one-time activity for contract creators, saving on transaction fees is less likely to affect them much. In contrast, a longer waiting time may reduce prospective users as it affects the user experience on invoking their smart contract. Therefore, I expect that an upward adjustment on network capacity will negatively affect contract deployment in subsequent periods. Compared to contract deployment activities, transaction activities occur more frequently. As such, users may be more sensitive to both time and monetary costs spent on transaction verification. An increase in network capacity leads to an immediate verification delay, while a reduced transaction fee encourages user participation. In the short term, these two effects may cancel each other out. In the long term, as miners continuously invest in infrastructure to gain greater mining power, the verification delay can be improved gradually. A higher network capacity indicates that miners can handle more verification requests. Users will benefit more from the reduced transaction fee, which boosts users' confidence in participating in the ecosystem. In sum, I hypothesize that,

Hypothesis 1a. Network capacity adjustment has a short-term negative effect on subsequent contract deployment, such that an increase shock to block gas limit will lead to a decrease in the deployment activities of new smart contracts in the short term.

Hypothesis 1b. Network capacity adjustment has a long-term positive effect on subsequent transactions, such that an increase shock to block gas limit will lead to an increase in transaction activities in the long term.

Users' and contract creators' participation shapes how miners exercise decision control as reflected in adjusting network capacity. As stated, without a central authority, decision-makers in a highly decentralized ecosystem frequently observe and learn from other participants' behaviors to guide their subsequent governance activities. I expect feedback effects from activities to governance mechanisms. When transactions and contract deployment activities increase at the application layer, miners have more pending requests to select. However, miners are restricted by the network capacity. They cannot verify as many exchanges as they want. In order to gain higher rewards, miners are more likely to lift the network capacity. On the contrary, when the number of transactions and new smart contracts decreases, miners will perceive it as a signal that their strategy of increasing network capacity does not work well. They may consider decreasing the network capacity to speed up the verification process to attract more transactions and contract deployment activities. In sum, I hypothesize that,

> *Hypothesis 2a. Contract deployment has a short-term positive effect on subsequent network capacity adjustment, such that an increase shock to deployment activities will lead to an increase in block gas limit in the short term.*
>
> *Hypothesis 2b. Transaction has a short-term positive effect on subsequent network capacity adjustment, such that an increase shock to transaction activities will lead to an increase in block gas limit in the short term.*

Effects of Decision Management Mechanisms at the Architecture Layer

Client update and *network upgrade* are the two main decision management mechanisms exerted by core developers. Updating the client software to improve a centralized platform's design and architecture has been proved as a necessary means for platform owners to address governance (Song et al. 2018; Tiwana et al. 2010). On a two-sided digital platform, updates often need both complementors and users to make adaptive actions. For example, application complementors may need to address compatibility issues with the new version, and users need to adopt the new version to use the new functions. In an open-source development context, both changing and maintaining the source code is done jointly by contributors and core developers (Pereira et al. 2019). Both bugs within the code and threats to the infrastructure are dealt with collectively by community members (Andersen and Bogusz 2017). Although the core developer team decides whether and when they release a new version of the client software, their decisions are largely based on the community's feedback and will influence the community's behaviors.

Most blockchain platforms rely on open-source communities as a primary source of protocol development (Chen et al. 2021). Community developers may evaluate the protocol quality and decide whether to engage in the protocol development by observing core developers' performance in handling feature requests. The signals associated with client updates provide additional information about the protocol quality. Frequent updates of the blockchain client software indicate a continuous commitment of core developers. It also suggests that the protocol is constantly improved and adapted to the changing environment by incorporating advanced features (Arora et al. 2006). When the perceived protocol quality is high, community contributors will consider the chance of producing a good client software to be high and are attracted to participate in the project (Ho and Rai 2017).

Nevertheless, it often takes time for the community developers to develop new feature suggestions and modify the source code after each new version of the client software. As such, I expect that a growth shock to client update will lead to increased protocol development in the long term. In the short term, as significant revision requests have been handled in the most up-to-date version, I would expect an immediate drop in the protocol development right after a client update. In sum, I hypothesize that,

Hypothesis 3a. Client update has a negative short-term effect and a positive long-term effect on subsequent protocol development, such that an increase shock to the release of a new version of client software will lead to a decrease in protocol development activities in the short term but an increase in protocol development activities in the long term.

The increasing protocol development activities reveal the community's growing interest in developing the blockchain protocol. The increasing revisions and new feature suggestions also remind the core developer team that the current version of the blockchain client software cannot meet the community's demand (Spaeth et al. 2015). As a response to the growing community demand, the core developer team will be more involved in scrutinizing pull requests and update the client software. Therefore, I expect that a client update is more likely to happen due to a growth shock to protocol development. I also expect this feedback effect will take time to manifest as core developers need to discuss the changes on forums or through online meetings and arrange the new version release. However, an increase in protocol development may not directly affect network upgrades because a code fork is more about dramatic changes in the fundamental rules of the blockchain protocol than minor revisions to the client software (Pereira et al. 2019).

Hypothesis 3b. Protocol development has a long-term positive effect on subsequent client update, such that an increase shock to protocol development activities will lead to an increase in new version release in the long term.

Network upgrade is another decision management mechanism leveraged by core developers. It is completed by initiating a code fork. A code fork happens when irreconcilable divergent opinions exist among blockchain's key stakeholders (i.e.., miners, protocol developers). A complete upgrade of the whole blockchain network makes the new and the old versions of the underlying source code forward incompatible (Andersen and Bogusz 2017). Such a network upgrade shows different impacts in a public blockchain ecosystem. On the one hand, a network upgrade indicates a substantial improvement in the underlying critical rules or functions, portraying an active and promising protocol development community. On the other hand, network upgrades may raise concerns regarding the hindered progress and wasted resources due to the incompatible versions of a blockchain network, thus discouraging related future developments (Nyman and Lindman 2013).

Network upgrades may send out an immediate negative signal to peripheral developers interested in blockchain protocol development. One reason is that the dramatic change in the source code may require developers to learn and adapt to the new source code before revising it. Additionally, as the network upgrade originates from a divergence of opinions in the blockchain development, the network version to which a developer contributes may be abandoned (if most miners select the other network version after forking), which wastes the developer's contribution (Gervais et al. 2014). As such, developers may suspend their engagement after a code fork. I expect that a network upgrade will lead to an instant drop in subsequent protocol development. Despite the negative tones about network upgrades, developers may view the network upgrade as an opportunity to make significant contributions to the new version of the blockchain network to establish an individual reputation and hone protocol development skills. Further, the network upgrade signals that the core developer team intends to improve the fundamental rules of the blockchain protocol, which supports peripheral developers' contributions. As such, I expect a positive effect of network upgrades on protocol development in the long term.

Hypothesis 4. Network upgrade has a short-term negative effect and a long-term positive effect on subsequent protocol development, such that a code fork will lead to a decrease in protocol development activities in the short term but an increase in protocol development activities in the long term.

As a code fork represents fundamental changes to the blockchain protocol, it often requires follow-up updates of the client software to provide compatible support to the new version of the blockchain network. Code forks also require most miners' adoption to be effective (Andersen and Bogusz 2017; Eyal and Sirer 2014). The chain that achieves greater adoption will remain as the main chain (Andersen and Bogusz 2017). As both development activities and version release take time to happen, I expect the positive effect of the network upgrade on client update to be long-term. For example, the Istanbul fork of Ethereum allows smart contracts to introduce more creative functions, which requires new features in the client software to support this change in the protocol. As such, I expect that there will be an increase in client update as a response to the network update in the long term.

> *Hypothesis 5. Network upgrade has a long-term positive effect on subsequent client update, such that a code fork will lead to an increase in the new version release in the long term.*

Interaction between Decision Mechanisms across Layers

I argue that the two decision mechanisms across layers also influence each other. By definition, *decision management* activities relate to initiating and executing ratified decisions, while *decision control* activities relate to monitoring and ratifying the upper management initiatives (Fama and Jensen 1983). In the context of public blockchain ecosystems, miners exert *decision control* rights by adjusting network capacity at the application layer, while the core developer team exerts decision management rights by updating the client software and upgrading the whole blockchain network. As miners' behaviors comply with the rules specified in the blockchain protocol, the decision control mechanism used by miners is likely to be affected by the decision management mechanisms used by the core developer team. However, I do not expect significant effects between network capacity adjustment and client update for two reasons. First, adjusting the block gas limit does not necessarily require support in the form of new features. Second, as a new client version release only includes minor revisions to the client software, miners may not be aware of these changes that may not directly relate to their own interests. I argue that the interactions between governance mechanisms across layers concentrate on the relationship between network capacity adjustment and network upgrade. I will explain these interactions in detail below.

Network upgrade represents a radical change in the organizational structure of the blockchain ecosystem and requires adoption by the majority of miners in order to take effect (Andersen and Bogusz 2017; Eyal and Sirer 2014). Miners view a network upgrade as an opportunity to gain a first-mover advantage. As the network upgrade will separate the blockchain into two chains, the market will also split into two segments. After deciding to favor one chain over the other, miners may take the chance to earn a greater share of verification activity (i.e., verifying more transactions and smart contracts) as there are fewer competitors right after a network upgrade (Andersen and Bogusz 2017). However, the current block gas limit constrains miners from doing so. Therefore, after the network is upgraded, miners are more likely to lift the block gas limit to include more pending transactions and contract deployment requests into one block to gain more monetary rewards.

> *Hypothesis 6a. Network upgrade has a short-term positive effect on subsequent network capacity adjustment, such that a code fork will lead to an increase in block gas limit in the short term.*

Miners' goal is to pursue the highest profits by being the first to solve the cryptographic puzzle. At the same time, core developers aim to improve the blockchain protocol to increase its competitiveness and persistence (Pereira et al. 2019). The misaligned motivations of the two decision-making parties may result in a conflict of decisions. For one, lifting the block gas limit can enhance miners' monetary rewards and broaden the use of blockchain (Andersen and Bogusz 2017). However, it also slows down the overall verification speed and makes it more challenging to keep a copy of the expanding exchange history. Lifting the gas limit indicates that miners are eager to reap profits at the expense of the health of the overall blockchain network, which arouses developers' responsibility to protect the healthy development of blockchain. As such, a growth shock to adjusting the block gas limit upward is likely to lead to divergent opinions regarding future blockchain development, resulting in a code fork.

Hypothesis 6b. Network capacity adjustment has a positive short-term effect on subsequent network upgrade, such that an increase shock to block gas limit will lead to a code fork in the short term.

RESEARCH DESIGN AND METHODOLOGY

Research Context and Data

I continue using Ethereum as my empirical setting and using the same dataset as my study in Chapter 2. To be more specific, I collected the data to evaluate application layer activities from an open dataset maintained by Google BigQuery. I also collected the data to evaluate architecture layer activities from Ethereum's repository on GitHub. The time span for the data is from Week 1 in 2016 to Week 43 in 2019 (199 weeks). Consistent with the data processing method in Chapter 2, I aggregate data at the weekly level.

Operationalization of Economic Activities. *Transaction (TXN), contract deployment (CD), mining (MN),* and *protocol development (PD)* are measured in the same way as in the study in Chapter 2. I measure *transaction (TXN)* as the total number of user-to-user transactions and user-to-contract transactions that occur in a particular week. To measure *contract deployment (CD)*, I count the accumulated number of smart contracts that have been successfully deployed on the Ethereum blockchain in a particular week. I measure *mining (MN)* as the total number of mining activities in terms of the transactions and smart contracts that are verified by miners successfully (in real blocks) and unsuccessfully (in uncle blocks) in a particular week. I measure *protocol development (PD)* as the total number of commits, which includes the contributions by core developers and admitted pull requests from peripheral developers in a particular week.

Operationalization of Governance Mechanisms. To examine governance mechanisms on the two layers, I measure *network capacity adjustment (NCA)* using the average block gas limit in a particular week. I measure *client update (CU)* using the number of client software releases in a particular week. I use a binary indicator as the measure of *network upgrade (NU)*, with a value of 1 for weeks that has a code fork, and value of 0 for weeks that do not have code forks. To address skewness in the distribution, I took the natural log of each of non-binary endogenous variables adjusted by adding 1. Table 3 shows the definitions and summary statistics of key variables. The average values over the observation period for network capacity adjustment, client update, and network upgrade are 6,324,141 (unlogged), 0.4221 (unlogged), and 0.03015, respectively.

TABLE 3
Constructs, Measures, and Descriptive Statistics

Variables	Measurement	Mean	S.D.	Min	Max
Transaction (TXN)	Number of user-to-user transactions and user-to-contract transactions in week t (log)	14.27	1.34	11.29	15.93
Contract Deployment (CD)	Accumulated number of smart contracts deployed on Ethereum by week t (log)	14.11	2.33	8.80	16.78
Mining (MINE)	Number of mining activities on Ethereum in week t (log)	14.38	1.34	11.40	16.23
Protocol Development (PD)	Number of code contributions to Ethereum protocol on GitHub in week t (log)	3.77	0.88	0.00	5.62

Network Capacity Adjustment (NCA)	Average value of block gas limit in week t (log)	15.59	0.41	13.97	16.11
Client Update (CU)	Number of version release of the client software in week t (log)	0.25	0.37	0.00	1.39
Network Upgrade (NU)	Whether a code fork is conducted in week t	0.03	0.17	0.00	1.00

Notes: N = 199. Non-binary variables are logged.

Model Specification and Estimation

As the data is time-series in nature, I employ *vector autoregression* (VAR) in my model estimation. This method allows us to capture both the short-term and long-term dynamic interdependent relationships of different activities in a blockchain ecosystem (Song et al. 2018). Consistent with prior research and the study in Chapter 2, I adopt a standard VAR procedure (e.g., Dekimpe and Hanssens 1999).

I use an augmented Dicky-Fuller (ADF) test to determine whether endogenous variables are evolving or stationary. Stationarity of endogenous variables implies that the fluctuation of the variables caused by any unexpected changes will eventually dissipate, and these variables will revert to their deterministic patterns without a permanent regime shift (Song et al. 2018). If the process is not stationary, de-trending of the data can be performed in several ways, among which differencing the data is a commonly used method (Enders 1995; Lütkepohl 2013). The ADF tests of all endogenous variables reject the null hypothesis of a unit root and suggest stationarity after taking the first difference (as shown in Table 4). Therefore, I examine my models using the first-difference values of variables. In the model specification, I need to determine the appropriate number of lags used for endogenous variables. The Akaike information criterion (AIC = -1.605) and final prediction error (FPE = 4.8e-10) suggest that a lag of three periods (weeks) is the optimal choice. My VAR model, therefore, includes lags of up to three weeks.

TABLE 4
Unit Root Test Results after First Differences

Variables	**Test Statistic**	***p*-value**

Transaction	-16.909	< 0.001
Contract Deployment	-15.234	< 0.001
Mining	-12.969	< 0.001
Protocol Development	-22.474	< 0.001
Network Capacity Adjustment	-5.2756	< 0.001
Client Update	-11.068	< 0.001
Network Upgrade	-5.7042	< 0.001

The general standard reduced-form VAR(p) model with lag order p is

$$Y_t = C + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + \varepsilon_t, t = 1, \dots, T \tag{1}$$

where $Y_t = (y_{1t}, y_{2t}, \dots, y_{nt})'$ denotes an $(n \times 1)$ vector of time series variables, including economic activities such as *transaction* (TXN_t), *contract deployment* (CD_t), *mining* (MN_t)[3], and *protocol development* (PD_t), and decision activities such as *network capacity adjustment* (NCA_t), *client update* (CU_t), and *network upgrade* (NU_t). C is an $(n \times 1)$ vector of constant terms, A_i are $(n \times n)$ coefficient matrices, and ε_t is an $(n \times 1)$ vector of white-noise disturbances with a normal distribution of $\mathrm{N}(0, \Sigma)$. The VAR specification given in Model (1) is used to capture the dynamic effects of governance mechanisms in the public blockchain ecosystem. At the application layer, the effects of decision control mechanism are reflected in how *transaction* (TXN_t), *contract deployment* (CD_t), and *mining* (MN_t) changes over time following a change in *network capacity adjustment* (NCA_t). At the architecture layer, the effects of decision management mechanisms are reflected in how *protocol development* (PD_t) changes over time following a change in *client update* (CU_t) or *network upgrade* (NU_t). The interactions between governance mechanisms across layers are reflected in how *network capacity adjustment*

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[3] Although I do not hypothesize relationships between *mining* and *network capacity adjustment*, as I expect *mining* would influence and be influenced by other economic activities, I include it to my VAR model and report the results.

(NCA_t) changes over time following a change in *network upgrade* (NU_t), and how *network upgrade* (NU_t) changes over time following a change in *network capacity adjustment* (NCA_t).

I determine the appropriateness of using VAR based on Granger causality tests (Granger 1969). Granger causality is typically tested using Wald tests of the null hypothesis that all coefficients of the corresponding lags are equal to zero (Enders 1995). The results in Table 5 show that there are several significant Granger-causal relationships in the estimated model that reject the null hypothesis. Notably, for equations that have serial autocorrelation or heteroscedasticity issues the Granger test results may not capture the potential causal relationships accurately. As such, I also test the existence of serial correlation using Breusch-Godfrey Test and heteroskedasticity using the Breusch-Pagan Test (as shown in Table 6). For equations that have these two concerns, I refer to impulse response functions (IRFs) for more robust results.

Impulse response functions plot the response of current and future values of variables in the VAR model to a one-unit increase in the current value of one of the VAR error terms (Adomavicius et al. 2012; Enders 1995). The VAR estimated coefficients are not usually directly interpretable due to general multicollinearity issues associated with including lagged terms (Sims 1980). Therefore, I report the IRFs results in Figure 2 and use them as the basis for interpreting the results of the model estimation.

TABLE 5
Granger Causality Test (F Statistic)

	Dependent Variables						
	CD	**MN**	**TXN**	**PD**	**NCA**	**CU**	**NU**
CD	–	0.298	5.803	4.477	2.042	7.714*	0.822
MN	1.202	–	42.411***	5.019	1.820	8.360**	0.536
TXN	0.443	2.345	–	6.067	0.244	8.220**	0.492
PD	0.136	3.652	3.705	–	5.536	7.227*	1.561
NCA	18.756***	6.582*	7.492*	5.849	–	11.103**	37.464***
CU	3.372	2.039	7.446*	5.262	5.537	–	5.506

NU	3.650	6.300*	5.440	5.860	2.003	8.537**	–

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

TABLE 6
Tests for Serial Correlation and Heteroskedasticity

Dependent Variable	Breusch-Godfrey Test	Breusch-Pagan Test
Transaction	3.006 (0.391)	0.020 (0.900)
Contract Deployment	4.499 (0.212)	1.670 (0.197)
Mining	1.523 (0.667)	4.620 (0.032)
Protocol Development	17.238 (0.001)	4.760 (0.029)
Network Capacity Adjustment	3.234 (0.357)	331.670 (0.000)
Client Update	12.951 (0.005)	4.130 (0.042)
Network Upgrade	3.063 (0.382)	116.350 (0.000)

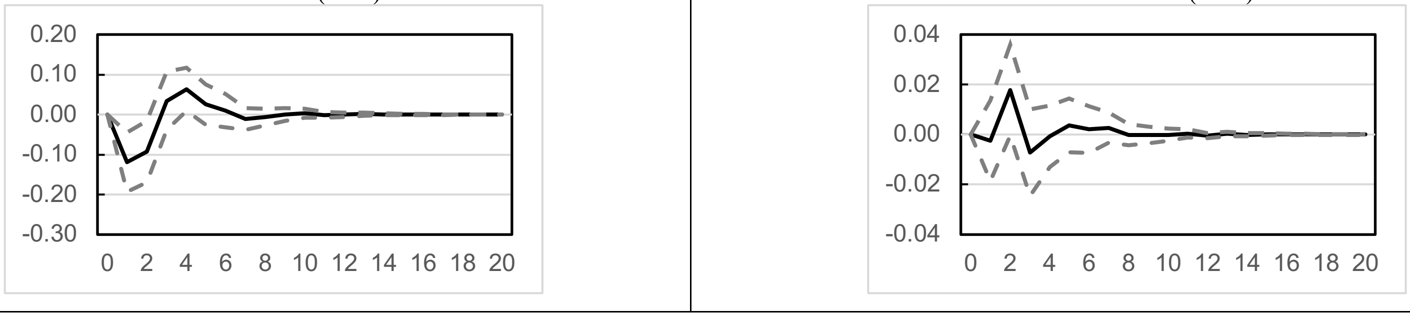
Notes: The results show χ^2 values with p-values in parentheses.

FIGURE 2
Main Results—Impulse Response Functions

Effects of Network Capacity Adjustment at the Application Layer

NCA → CD (H1a)

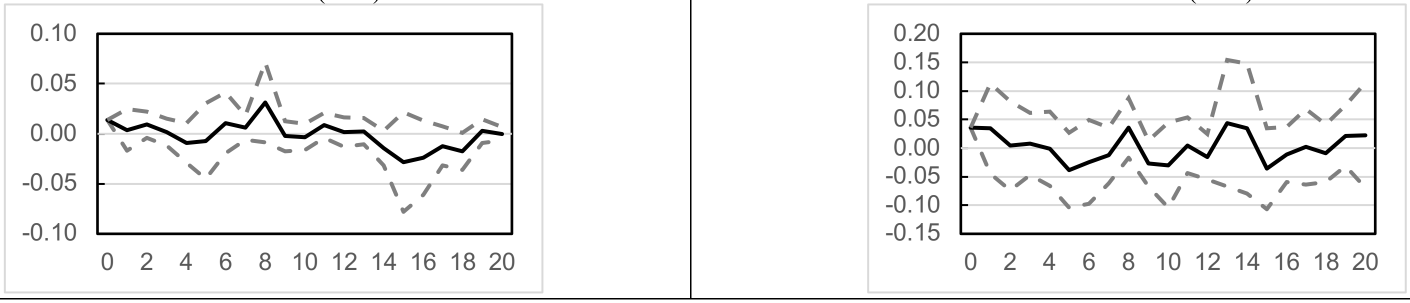
NCA → TXN (H1b)



Feedback Effects on Network Capacity Adjustment at the Application Layer

CD → NCA (H2a)

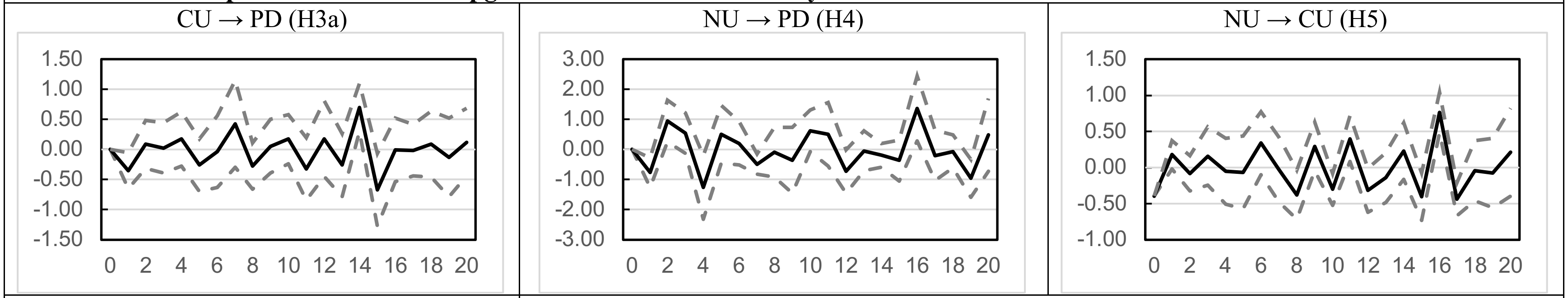
TXN → NCA (H2b)



Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

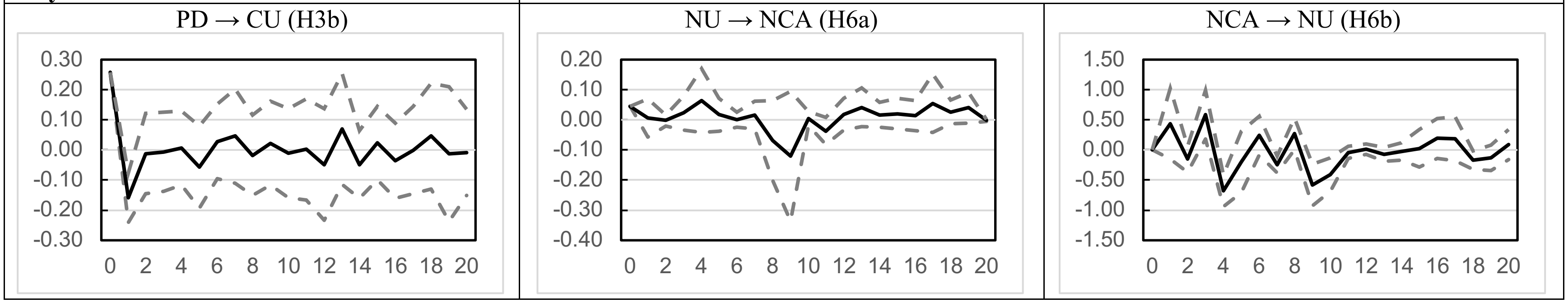
FIGURE 2
Main Results—Impulse Response Functions (continued)

Effects of Client Update and Network Upgrade at the Architecture Layer



Feedback Effects at the Architecture Layer

Effects Across Layers

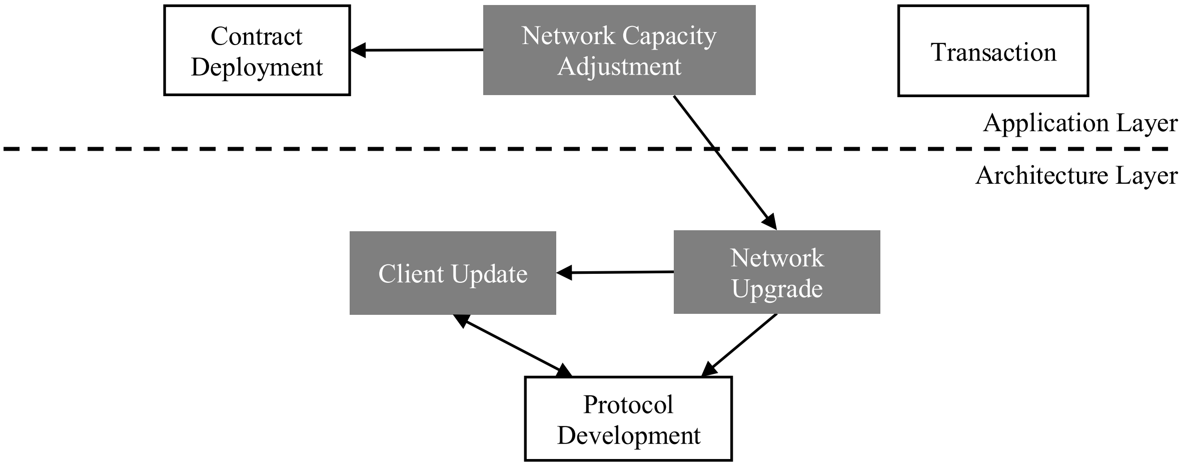


Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

RESULTS

My goal in this study is to (1) identify three governance mechanisms in a public blockchain ecosystem, and (2) examine how each mechanism influences other economic activities at two ecosystem layers. I also explore the interaction between mechanisms. This study considers a short-term effect as the response in growth of one type of activity (decision activity or economic activity) within the first four weeks after a growth shock to another type of activity. Likewise, I consider a long-term effect as the growth of one type of activity to the growth of another type of activity after four weeks. The estimated model coefficients can be found in Appendix A. Figure 3 provides a reduced form of the research model as uncovered by Granger causality analysis and IRFs analysis.

FIGURE 3
Reduced Form of Research Model



Main Results

Effects of decision control mechanism at the application layer. The Granger causality results in Table 5 indicate significant effects of *network capacity adjustment* on *contract deployment* and *transaction*, respectively. Figure 2 corroborates the results and shows that *network capacity adjustment* has a short-term negative effect on *contract deployment* (in week 2 and week 3), supporting Hypothesis 1a. I also find a positive influence of *network capacity adjustment* on *contract deployment* at week 4. It is possible that when miners' ability to verify more pending requests is increased by upgrading their mining facilities, contract creators are motivated to participate as they would expect growth of transactions along with the increased network capacity. According to the IRF graph, *network capacity adjustment* does not significantly affect *transaction*. Hypothesis 1b is not supported. This result suggests that users may care less about miners' decision control behaviors. One reason could be that the benefits incurred by increased network capacity (e.g., reduced transaction fee) is not attractive enough to encourage user participation. Users' transaction behaviors may be tied to other factors. For example, when the blockchain ecosystem has accumulated a large user base and built strong network effects, users may find it challenging to find alternative blockchain platforms.

Contrary to my Hypotheses 2a and 2b, the IRF graphs do not show significant feedback effects from *contract deployment* or *transaction* to *network capacity adjustment*. Therefore, Hypothesis 2a and Hypothesis 2b are not supported. The results suggest that miners' decision control activities are not shaped by users' and contract creators' activities.

Effects of decision management mechanisms at the architecture layer. Although the Granger test results indicate that neither *client update* nor *network upgrade* has causal relationships with *protocol development*, the IRF graphs reveal significant effects after correcting for issues with serial correlation and heteroskedasticity. Specifically, the IRF graph in Figure 2 shows that client update has a negative short-term effect on protocol development (at week 1) and a positive long-term effect on protocol development (at week 14). Hypothesis 3a is supported. The results suggest that updates of the client software help to attract code commits in the long term. A similar pattern is shown in the relationship between *network upgrade* and *protocol development*. However, the influence of *network upgrade* on *protocol development* is more dynamic than theorized. *Network upgrade* affects *protocol development* negatively at weeks 1, 4, 7, and 19, while the effects turn positive at weeks 2 and 16. As such, Hypothesis 4 is partially supported. The results suggest that the effects of the *decision management* mechanism in terms of *network upgrade* are complex. It may be because the aspects of the blockchain protocol that are fundamentally changed require a different amount of code contribution at a later stage. Compared to the changes that are proposed the first time, the ones that were previously undertaken may require less effort in protocol development.

As a feedback effect, the influence of *protocol development* on *client update* is immediate and negative, which contradicts the long-term positive effect in Hypothesis 3b. A plausible reason for the short-term negative effect is that a growth shock to protocol development may suggest the core developers postpone the release and reconsider which new features should be included in the next version. The non-significant effect reveals that core developers' decisions on new version release in the long term do not rely on the number of protocol development activities in previous periods.

Network upgrade shows dynamic effects on *client update*. The effects are positive at weeks 11 and 16 but negative at weeks 10, 15, and 17. As such, Hypothesis 5 is not supported.

Interaction between of governance mechanisms across layers. The IRF graphs in Figure 2 indicate that the effect of *network upgrade* on *network capacity adjustment* is non-significant (Row 4, Column 2). Thus, Hypothesis 6a is not supported. It means that the miners' *decision control* activities are not affected by core developers' *decision management* activities. However, the *decision control* activities dynamically influence *decision management* activities.

Specifically, *network capacity adjustment* affects *network upgrade* positively at week 3. Then the effects become negative at weeks 4, 7, and 9 (Row 4, Column 3). Hypothesis 6b is supported.

Robustness Checks and Additional Analyses

I conduct two additional analyses to verify the robustness of my results. First, I use the drastic change in the average block gas limit to measure *network capacity adjustment (NCA)*. An alternative explanation for the insignificant relationship between *NCA* and *transaction* could be that users are not aware of the gas limit change within a relatively small range. Increasing or decreasing the average block limit to another level (i.e., the change >= 1 million in Ethereum) may attract users' attention. To test the influence of *NCA* using the alternative measurement, I calculate the change in average block gas limit and assign a value of 1 for weeks that have a drastic change in the average block gas limit and a value of 0 for weeks that do not. I rerun the VAR model. The results are summarized in Appendix B. Interestingly, according to the IRF graph in Figure B, I find that the drastic change of *network capacity adjustment* has a positive short-term effect on *contract deployment*, which is contrary to my main results. A plausible explanation is that compared to granular changes in the network capacity, a significant change may boost contract creators' confidence in the ecosystem's capability of handling more exchanges and attracting more users. A drastic change of the network capacity also negatively affects transactions in the short term. This result suggests that users worry more about the extended waiting time that would affect their transactions than the saved transaction fees when there is a drastic change in network capacity. I also find significant and negative long-term effects of *network upgrade* on *network capacity adjustment*, while there is no significant effect in return. The results are reasonable if I think of it from the objective of *network upgrade* in terms of resolving divergent opinions. After each network upgrade, miners who hold the same opinions will stay on the same chain. In the long term, they may feel less necessary to change the average gas limit dramatically.

Second, I try alternative measures that characterize the participant engagement at two layers. I collect additional data on unique number of users, miners, contract creators, and protocol developers, respectively. Specifically, I use *unique user* (UU) as an alternative measure for *transaction*, *unique contract creator* (UC) as an alternative measure for *contract deployment*, *unique miner* (UM) as an alternative measure for *mining*, and *unique developer* (UD) as an alternative measure for *protocol development*. I rerun the VAR model with these new measures. The results, as summarized in Appendix C, are qualitatively consistent with the main results. I find that although *network capacity adjustment* has a short-term negative effect on *contract deployment*, its impacts on *unique contract creator* are long-term and tend to be negative (at Weeks 6, 8, 13, and 15). The results suggest that an increase in network capacity adjustment leads to a drop in contract deployment activities shortly and gradually turns out to decrease the number of distinct contract creators. I also find long-term positive effects of *network capacity adjustment* on *unique user* at Week 7 and Week 10, which supports Hypothesis 1b.

DISCUSSION

In this research, I sought to understand the specific decentralized governance mechanisms exerted by different parties of participants in a public blockchain ecosystem. Drawing on the ecosystem's layered structure and Fama and Jensen's (1983) framework of decision processes, I conceptualized *network capacity adjustment* as the decision control mechanism at the application layer and *client update* and *network upgrade* as decision management mechanisms at the architecture layer. Then, I examined the dynamic effects of these governance mechanisms on economic activities and the interactions between mechanisms.

The longitudinal empirical study provides unique insights into the governance of a highly decentralized platform-enabled ecosystem. At the application layer, the results show that a lift of network capacity affects contract deployment activities but does not influence transaction activities. I also find that miners do not rely on economic activities at the application layer to exert the *decision control* mechanism. At the architecture layer, my results indicate that both *decision management* mechanisms significantly affect *protocol development*. *Network upgrade* also influences *client update*, while no feedback effect is found on *network upgrade*. The cross-layer results indicate that although miners follow the rules defined in the blockchain protocol, the *decision control* mechanism is not affected by *decision management* mechanisms. Instead, core developers would reflect on the feedback of the *decision control* mechanism to exert the *decision management* mechanism.

Theoretical Implications

This research makes several research contributions. First, my research contributes to the platform-enabled ecosystem literature by focusing on decentralized governance that has been previously understudied. The extant studies have concentrated on the governance of centralized ecosystems while paying less attention to highly decentralized ecosystems (Chen et al. 2021). Compared to centralized ecosystem governance, the lack of a central authority increases the difficulty of reaching consensus in highly decentralized ecosystems. Residing in the context of public blockchain ecosystems, I introduce a two-layer structure that decomposes a complex ecosystem into self-contained yet interdependent layers. The layered structure of ecosystems set a basis for understanding decentralized forms of governance in a multi-side and cross-platform ecosystem.

Second, I extend Fama and Jensen’s (1983) two types of decision activities and conceptualize *decision control* mechanism and *decision management* mechanism in the context of public blockchain ecosystems. Prior literature has investigated how centralized organizations exert *decision control* and *decision management* activities. My study extends the prior literature by investigating decision mechanisms in a highly decentralized ecosystem and how these mechanisms influence other economic activities. As decision-making authority is distributed to a wide range of participants, the mechanisms that decision-makers carry out to govern a decentralized ecosystem can be fundamentally different from those in a centralized organization. First, exercising the *decision control* mechanism is an individual miner’s behavior rather than a collective behavior. However, individual miners’ common vision about acquiring mining rewards brings about the same solution (exercise of decision control mechanism) with other miners (Hayek 1945). My conceptualization of decision control in decentralized ecosystems offers a unique angle for understanding highly decentralized governance. Second, the impacts of decision mechanisms in the public blockchain ecosystem are dynamic due to highly decentralized governance. My results show that different parties of participants respond to decision mechanisms differently in different time periods, which provides insight for understanding the influence of decentralized governance at a more granular level.

Finally, my research contributes to the blockchain literature by empirically examining the influence of three decision mechanisms, while previous literature studies blockchain governance from a theoretical perspective (Chen et al. 2021). My research also responds to previous literature’s call for research on allocating decision rights in the blockchain economy (Beck et al. 2018). Specifically, I identify three specific decision mechanisms that govern the public blockchain at different layers and examine the influences of each mechanism on other economic activities. I also explore the interaction between decision mechanisms across layers. The results provide insights for future studies on blockchain governance design.

Practical Implications

I suggest that core developers should be cautious of using *network upgrade*. According to my results, *network upgrade* has significant relationships with *protocol development* and other decision mechanisms such as *client update* and *network capacity adjustment*. However, the valence of these relationships fluctuates over time, which means the influence of enacting *network upgrade* remains unclear. On the one hand, initiating a network upgrade can revise the underlying rules in the blockchain protocol and resolve stakeholders' divergent opinions. On the other hand, network upgrades can cause a decrease in the community size, which may negatively impact the token valuation and the reputation (Pereira et al. 2019).

My results also provide insights to organizations that are interested in adopting a decentralized form of governance supported by blockchain technologies. The three decision mechanisms I identify at the two layers of the blockchain ecosystem is a good starting point for organizations to consider their governance design. For example, as increasing the network capacity shows long-term positive effects on contract deployment, blockchain ecosystems whose priority is to scale the base of complementors may consider providing miners more flexibility in exerting the decision control mechanism.

Limitation and Future Research

This research has some limitations and creates potential directions for future research. First, this research focuses on the public blockchain in a specific empirical setting. My decision to focus on a public blockchain ecosystem was informed by the research objective of investigating the highly decentralized governance of an ecosystem. Future studies may consider expanding insights by examining other blockchain ecosystems, such as private blockchain ecosystems and consortium blockchain ecosystems.

Second, this research focuses on a specific blockchain ecosystem to understand the dynamic influences of different decentralized governance mechanisms on other activities in the ecosystem. Another pertinent and exciting topic is exploring how various degrees of decentralization of decision-making power would affect an ecosystem's functioning. Future studies may collect data about multiple blockchain ecosystems to examine the role of decentralization degree.

Finally, although my research pinpoints the fluctuating influences of *decision management* mechanisms on the *decision control* mechanism and other economic activities, I are unable to explore specific mechanism features that might cause such differentiation due to the restriction of the dataset. Future studies may consider collecting data from multiple blockchain ecosystems and using the panel vector autoregression (PVAR) method to conduct a more in-depth analysis.

CONCLUSION

To summarize, I report the public blockchain ecosystem governance as consisting of three decision mechanisms: *network capacity adjustment* as the *decision control* mechanism at the application layer, and *client update* and *network upgrade* as *decision management* mechanisms at the architecture layer. My results demonstrate the dynamic effects of decision mechanisms on other activities in the ecosystem. The results also reveal interaction effects between mechanisms. Overall, my findings provide empirical evidence of how decentralized governance is enacted in a digital platform-enabled ecosystem.

REFERENCES

Adomavicius, G., Bockstedt, J., and Gupta, A. 2012. "Modeling Supply-Side Dynamics of It Components, Products, and Infrastructure: An Empirical Analysis Using Vector Autoregression," *Information Systems Research* (23:2), pp. 397-417.

Adomavicius, G., Bockstedt, J. C., Gupta, A., and Kauffman, R. J. 2008. "Making Sense of Technology Trends in the Information Technology Landscape: A Design Science Approach," *MIS Quarterly* (32:4), pp. 779-809.

Alves, C., de Oliveira, J. A. P., and Jansen, S. 2017. "Software Ecosystems Governance-a Systematic Literature Review and Research Agenda," *ICEIS (3)*, pp. 215-226.

Andersen, J. V., and Bogusz, C. I. 2017. "Patterns of Self-Organising in the Bitcoin Online Community: Code Forking as Organising in Digital Infrastructure," *ICIS 2017 Proceedings*.

Arnosti, N., and Weinberg, S. M. 2019. "Bitcoin: A Natural Oligopoly," in *Innovations in Theoretical Computer Science*.

Arora, A., Caulkins, J. P., and Telang, R. 2006. "Sell First, Fix Later: Impact of Patching on Software Quality," *Management Science* (52:3), pp. 465-471.

Atzori, M. 2015. "Blockchain Technology and Decentralized Governance: Is the State Still Necessary?." Available at https://ssrn.com/abstract=2709713.

Beck, R., Müller-Bloch, C., and King, J. L. 2018. "Governance in the Blockchain Economy: A Framework and Research Agenda," *Journal of the Association for Information Systems* (19:10), pp. 1020-1034.

Boudreau, K. 2010. "Open Platform Strategies and Innovation: Granting Access Vs. Devolving Control," *Management Science* (56:10), pp. 1849-1872.

Brown, A. E., and Grant, G. G. 2005. "Framing the Frameworks: A Review of It Governance Research," *Communications of the Association for Information Systems* (15:1), pp. 696-712.

Buterin, V. 2014. "A Next-Generation Smart Contract and Decentralized Application Platform." White Paper.

Chen, Y., Pereira, I., and Patel, P. C. 2021. "Decentralized Governance of Digital Platforms," *Journal of Management* (47:5), pp. 1305-1337.

Constantinides, P., Henfridsson, O., and Parker, G. G. 2018. "Introduction—Platforms and Infrastructures in the Digital Age," *Information Systems Research* (29:2), pp. 381-400.

Dekimpe, M. G., and Hanssens, D. M. 1999. "Sustained Spending and Persistent Response: A New Look at Long-Term Marketing Profitability," *Journal of Marketing Research* (36:4), pp. 397-412.

Di Tullio, D., and Staples, D. S. 2013. "The Governance and Control of Open Source Software Projects," *Journal of Management Information Systems* (30:3), pp. 49-80.

Enders, W. 1995. *Applied Econometric Time Series*. Wiley, New York.

Eyal, I., and Sirer, E. G. 2014. "Majority Is Not Enough: Bitcoin Mining Is Vulnerable," *International Conference on Financial Cryptography and Data Security*: Springer, pp. 436-454.

Fama, E. F., and Jensen, M. C. 1983. "Separation of Ownership and Control," *The Journal of Law and Economics* (26:2), pp. 301-325.

Fenwick, M., McCahery, J. A., and Vermeulen, E. P. 2019. "The End of ‘Corporate’governance: Hello ‘Platform’governance," *European Business Organization Law Review* (20:1), pp. 171-199.

Gervais, A., Karame, G. O., Capkun, V., and Capkun, S. 2014. "Is Bitcoin a Decentralized Currency?," *IEEE Security & Privacy* (12:3), pp. 54-60.

Glaser, F. 2017. "Pervasive Decentralisation of Digital Infrastructures: A Framework for Blockchain Enabled System and Use Case Analysis," *Proceedings of the 50th Hawaii International Conference on System Sciences*.

Hayek, F. A. 1945. "The Use of Knowledge in Society," *The American Economic Review* (35:4), pp. 519-530.

Ho, S. Y., and Rai, A. 2017. "Continued Voluntary Participation Intention in Firm-Participating Open Source Software Projects," *Information Systems Research* (28:3), pp. 603-625.

Hsieh, Y.-Y., Vergne, J.-P., and Wang, S. 2018. "The Internal and External Governance of Blockchain-Based Organizations: Evidence from Cryptocurrencies," in *Bitcoin and Beyond: Blockchains and Global Governance*.

Huber, T. L., Kude, T., and Dibbern, J. 2017. "Governance Practices in Platform Ecosystems: Navigating Tensions between Cocreated Value and Governance Costs," *Information Systems Research* (28:3), pp. 563-584.

Janssen, M., Weerakkody, V., Ismagilova, E., Sivarajah, U., and Irani, Z. 2020. "A Framework for Analysing Blockchain Technology Adoption: Integrating Institutional, Market and Technical Factors," *International Journal of Information Management* (50), pp. 302-309.

Kapoor, R., and Agarwal, S. 2017. "Sustaining Superior Performance in Business Ecosystems: Evidence from Application Software Developers in the Ios and Android Smartphone Ecosystems," *Organization Science* (28:3), pp. 531-551.

Kyprianou, C. 2018. "Creating Value from the Outside in or the inside Out: How Nascent Intermediaries Build Peer-to-Peer Marketplaces," *Academy of Management Discoveries* (4:3), pp. 336-370.

Lütkepohl, H. 2013. *Introduction to Multiple Time Series Analysis*. Springer Science & Business Media.

Maruping, L., and Yang, Y. 2020. "Governance in Digital Open Innovation Platforms," in *Oxford Research Encyclopedia of Business and Management*.

Nyman, L., and Lindman, J. 2013. "Code Forking, Governance, and Sustainability in Open Source Software," *Technology Innovation Management Review* (3:1), pp. 7-12.

Parker, G., and Alstyne, M. V. 2008. "Managing Platform Ecosystems," *ICIS 2008 Proceedings*, p. 53.

Pereira, J., Tavalaei, M. M., and Ozalp, H. 2019. "Blockchain-Based Platforms: Decentralized Infrastructures and Its Boundary Conditions," *Technological Forecasting and Social Change* (146), pp. 94-102.

Ramasubbu, N., and Kemerer, C. F. 2016. "Technical Debt and the Reliability of Enterprise Software Systems: A Competing Risks Analysis," *Management Science* (62:5), pp. 1487-1510.

Rietveld, J., Ploog, J. N., and Nieborg, D. B. 2020. "Coevolution of Platform Dominance and Governance Strategies: Effects on Complementor Performance Outcomes," *Academy of Management Discoveries* (6:3), pp. 488-513.

Rietveld, J., Schilling, M. A., and Bellavitis, C. 2019. "Platform Strategy: Managing Ecosystem Value through Selective Promotion of Complements," *Organization Science* (30:6), pp. 1232-1251.

Risius, M., and Spohrer, K. 2017. "A Blockchain Research Framework," *Business & Information Systems Engineering* (59:6), pp. 385-409.

Schmeiss, J., Hoelzle, K., and Tech, R. P. 2019. "Designing Governance Mechanisms in Platform Ecosystems: Addressing the Paradox of Openness through Blockchain Technology," *California Management Review* (62:1), pp. 121-143.

Schreieck, M., Wiesche, M., and Krcmar, H. 2016. "Design and Governance of Platform Ecosystems–Key Concepts and Issues for Future Research," in: *European Conference on Information Systems (ECIS)*.

Seifelnasr, M., Galal, H. S., and Youssef, A. M. 2020. "Scalable Open-Vote Network on Ethereum," *International Conference on Financial Cryptography and Data Security*: Springer, pp. 436-450.

Shleifer, A., and Vishny, R. W. 1997. "A Survey of Corporate Governance," *The Journal of Finance* (52:2), pp. 737-783.

Sims, C. A. 1980. "Macroeconomics and Reality," *Econometrica* (48:1), pp. 1-48.

Song, P., Xue, L., Rai, A., and Zhang, C. 2018. "The Ecosystem of Software Platform: A Study of Asymmetric Cross-Side Network Effects and Platform Governance," *MIS Quarterly* (42:1), pp. 121-142.

Spaeth, S., von Krogh, G., and He, F. 2015. "Research Note—Perceived Firm Attributes and Intrinsic Motivation in Sponsored Open Source Software Projects," *Information Systems Research* (26:1), pp. 224-237.

Stabell, C. B., and Fjeldstad, Ø. D. 1998. "Configuring Value for Competitive Advantage: On Chains, Shops, and Networks," *Strategic Management Journal* (19:5), pp. 413-437.

Syed, T. A., Alzahrani, A., Jan, S., Siddiqui, M. S., Nadeem, A., and Alghamdi, T. 2019. "A Comparative Analysis of Blockchain Architecture and Its Applications: Problems and Recommendations," *IEEE Access* (7), pp. 176838-176869.

Tiwana, A. 2009. "Governance-Knowledge Fit in Systems Development Projects," *Information Systems Research* (20:2), pp. 180-197.

Tiwana, A. 2014. *Platform Ecosystems: Aligning Architecture, Governance, and Strategy*. New York: Elsevier, Inc.

Tiwana, A., Konsynski, B., and Bush, A. A. 2010. "Platform Evolution: Coevolution of Platform Architecture, Governance, and Environmental Dynamics," *Information Systems Research* (21:4), pp. 675-687.

Tiwana, A., Konsynski, B., and Venkatraman, N. 2013. "Information Technology and Organizational Governance: The It Governance Cube," *Journal of Management Information Systems* (30:3), pp. 7-12.

van Pelt, R., Jansen, S., Baars, D., and Overbeek, S. 2021. "Defining Blockchain Governance: A Framework for Analysis and Comparison," *Information Systems Management* (38:1), pp. 21-41.

Wang, P. 2021. "Connecting the Parts with the Whole: Toward an Information Ecology Theory of Digital Innovation Ecosystems," *MIS Quarterly* (45:1), pp. 397-422.

Wareham, J., Fox, P. B., and Cano Giner, J. L. 2014. "Technology Ecosystem Governance," *Organization Science* (25:4), pp. 1195-1215.

Weill, P. 2004. "Don't Just Lead, Govern: How Top-Performing Firms Govern It," *MIS Quarterly Executive* (3:1), pp. 1-17.

Williamson, O. E. 1988. "Corporate Finance and Corporate Governance," *The Journal of Finance* (43:3), pp. 567-591.

Yoo, Y. J., Henfridsson, O., and Lyytinen, K. 2010. "The New Organizing Logic of Digital Innovation: An Agenda for Information Systems Research," *Information Systems Research* (21:4), pp. 724-735.

Ziolkowski, R., Miscione, G., and Schwabe, G. 2020. "Decision Problems in Blockchain Governance: Old Wine in New Bottles or Walking in Someone Else's Shoes?," *Journal of Management Information Systems* (37:2), pp. 316-348.

APPENDIX A

TABLE A1
VAR Results – Application Layer

	Dependent Variables			
	CD	**MN**	**TXN**	**NCA**
CD_{t-1}	-0.174** (0.072)	0.002 (0.140)	0.015 (0.016)	-0.002 (0.010)
CD_{t-2}	-0.208*** (0.070)	0.007 (0.136)	0.034** (0.015)	0.009 (0.010)
CD_{t-3}	-0.209*** (0.071)	0.001 (0.014)	0.017 (0.016)	0.010 (0.010)
MN_{t-1}	-0.073 (0.603)	0.235** (0.118)	0.846*** (0.133)	0.007 (0.082)
MN_{t-2}	0.247 (0.663)	0.126 (0.129)	0.409*** (0.146)	-0.052 (0.090)
MN_{t-3}	0.668 (0.620)	0.027 (0.121)	0.202 (0.136)	0.085 (0.084)
TXN_{t-1}	0.259 (0.509)	-0.145 (0.099)	-0.799*** (0.112)	0.019 (0.069)
TXN_{t-2}	-0.049 (0.581)	-0.062 (0.113)	-0.432*** (0.128)	0.001 (0.079)
TXN_{t-3}	-0.003 (0.502)	0.009 (0.098)	-0.168 (0.110)	-0.023 (0.069)
PD_{t-1}	0.011 (0.050)	0.003 (0.010)	-0.001 (0.011)	0.008 (0.007)
PD_{t-2}	0.014 (0.057)	0.019* (0.011)	0.019 (0.013)	0.018** (0.008)
PD_{t-3}	-0.005 (0.052)	0.008 (0.010)	0.004 (0.011)	0.008 (0.007)
NCA_{t-1}	-1.718*** (0.539)	-0.110 (0.105)	-0.034 (0.119)	0.381*** (0.073)
NCA_{t-2}	-0.872 (0.591)	0.295*** (0.115)	0.338*** (0.130)	0.050 (0.080)
NCA_{t-3}	0.779 (0.554)	-0.813 (0.108)	-0.164 (0.122)	-0.103 (0.075)

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. N = 199. Variables are logged. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

TABLE A2
VAR Results – Architecture Layer

	Dependent Variables		
	PD	**CU**	**NU**
PD_{t-1}	-0.631*** (0.083)	0.087** (0.036)	0.012 (0.014)
PD_{t-2}	-0.394*** (0.095)	0.031 (0.042)	0.001 (0.017)
PD_{t-3}	-0.214** (0.087)	-0.015 (0.038)	0.011 (0.015)
CU_{t-1}	-0.394** (0.189)	-0.973*** (0.083)	0.058* (0.033)
CU_{t-2}	-0.401* (0.236)	-0.553*** (0.104)	0.078* (0.041)
CU_{t-3}	-0.297 (0.192)	-0.219** (0.084)	0.008 (0.033)
NU_{t-1}	-0.445 (0.408)	-0.500*** (0.179)	0.051 (0.071)
NU_{t-2}	-0.806* (0.413)	-0.165 (0.181)	-0.041 (0.072)
NU_{t-3}	0.362 (0.412)	-0.024 (0.181)	0.044 (0.072)

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. N = 199. Variables are logged. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

TABLE A3
VAR Results – Cross Layers

	Dependent Variables	
	NCA	**NU**
NCA_{t-1}	0.381*** (0.073)	-0.177 (0.156)
NCA_{t-2}	0.050 (0.080)	0.700*** (0.172)
NCA_{t-3}	-0.103 (0.075)	-0.908*** (0.161)
NU_{t-1}	0.045 (0.033)	0.051 (0.071)
NU_{t-2}	-0.010 (0.034)	-0.041 (0.072)
NU_{t-3}	-0.011 (0.034)	0.044 (0.072)

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. N = 199. Variables are logged. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

TABLE A4
Model Fitness

Equation	**R square**
Contract Deployment (CD)	0.2354
Mining (MN)	0.0927
Transaction (TXN)	0.3013
Protocol Development (PD)	0.4283
Network Capacity Adjustment (NCA)	0.2238
Client Update (CU)	0.5474
Network Upgrade (NU)	0.2170

APPENDIX B

Robustness Check: Using Drastic Change as Network Capacity Adjustment

TABLE B1
Granger Causality Test (Drastic Change as NCA)

	Dependent Variables						
	CD	**MN**	**TXN**	**PD**	**NCA**	**CU**	**NU**
CD	–	0.595	6.262	4.799	2.212	11.458***	1.645
MN	1.888	–	40.682***	5.625	1.692	7.557*	0.479
TXN	1.149	2.395	–	5.365	0.838	7.591*	0.275
PD	0.651	2.837	2.843	–	3.560	7.819**	2.809
NCA	37.301***	7.680*	8.799**	7.455*	–	5.620	6.945*
CU	2.911	1.789	6.909*	4.958	7.304*	–	4.940
NU	4.084	5.509	4.071	7.680*	0.380	10.300**	–

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

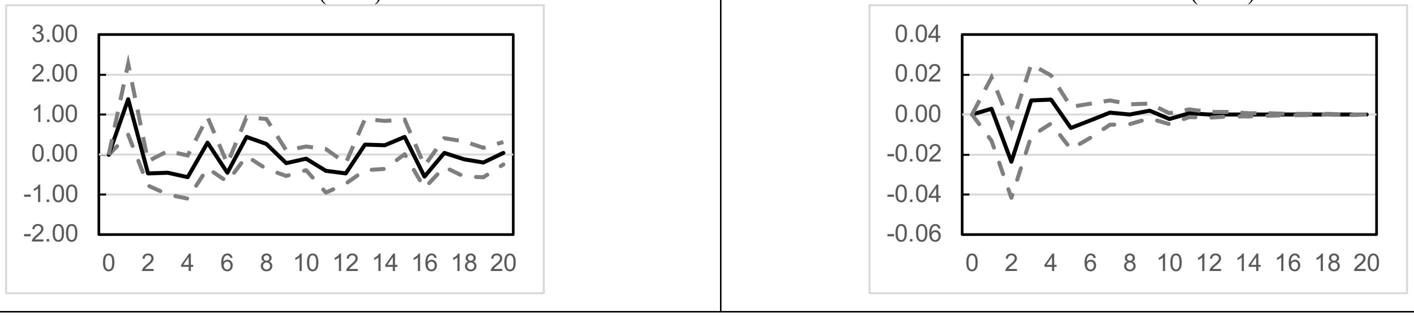
TABLE B2
Tests for Serial Correlation and Heteroskedasticity

Dependent Variable	Breusch-Godfrey Test	Breusch-Pagan Test
Transaction	3.206 (0.361)	0.020 (0.897)
Contract Deployment	3.386 (0.336)	17.430 (0.000)
Mining	4.348 (0.226)	4.770 (0.029)
Protocol Development	10.494 (0.015)	3.600 (0.058)
Network Capacity Adjustment	2.608 (0.456)	213.120 (0.000)
Client Update	16.849 (0.001)	2.870 (0.090)
Network Upgrade	14.028 (0.003)	252.170 (0.000)

Notes: The results show χ^2 values with p-values in parentheses.

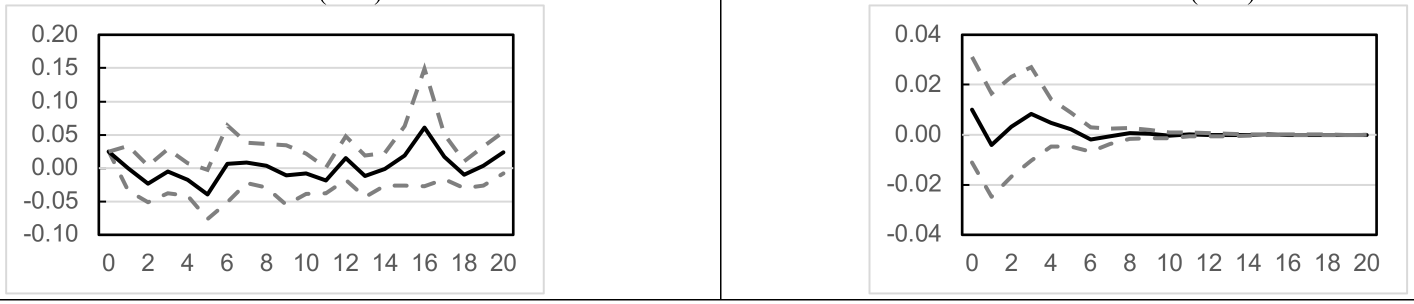
FIGURE B
Impulse Response Functions (Drastic Change as NCA)

Effects of Network Capacity Adjustment on the Application Layer


NCA → CD (H1a)

NCA → TXN (H1b)

Feedback Effects on Network Capacity Adjustment on the Application Layer


CD → NCA (H2a)

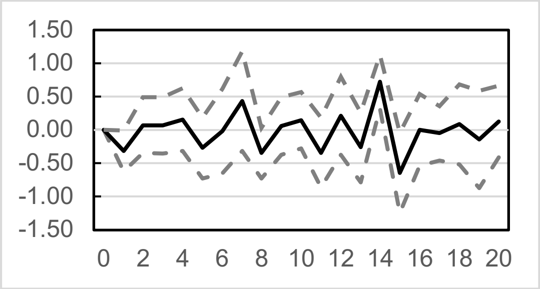
TXN → NCA (H2b)

Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

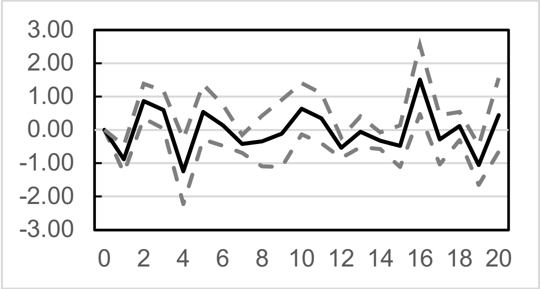
FIGURE B (Continued)
Impulse Response Functions (Drastic Change as NCA)

Effects of Client Update and Network Upgrade on the Architecture Layer

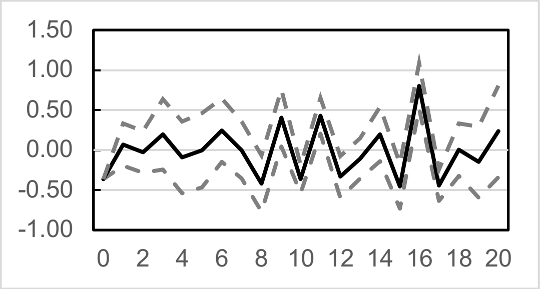
CU → PD (H3a)



NU → PD (H4)

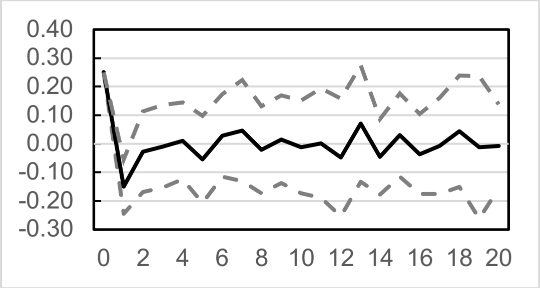


NU → CU (H5)



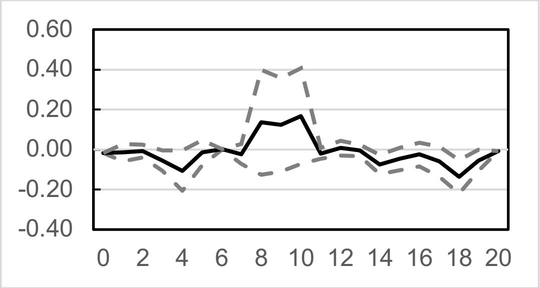
Feedback Effects on Client Update on the Architecture Layer

PD → CU (H3b)

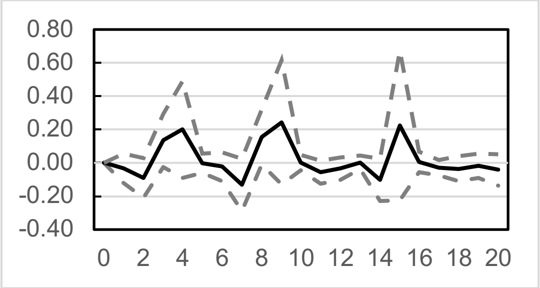


Effects Across Layers

NU → NCA (H6a)



NCA → NU (H6b)



Notes: CD, MN, TXN, and PD stand for Contract Deployment, Mining, Transaction, and Protocol Development, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

APPENDIX C

Robustness Check: Using Unique Number of Participants

TABLE C1
Granger Causality Test (Unique Number of Participants)

	Dependent Variables						
	UC	**UM**	**UU**	**UD**	**NCA**	**CU**	**NU**
UC	–	2.308	3.606	7.354*	2.842	12.027***	2.088
UM	2.279	–	2.018	6.691*	1.396	1.598	1.207
UU	7.383*	3.824	–	4.640	2.194	3.205	0.875
UD	0.764	2.773	3.101	–	3.610	3.386	0.963
NCA	0.829	0.573	3.095	5.925	–	17.419***	32.77***
CU	5.040	2.100	4.096	3.812	4.984	–	6.794*
NU	3.876	3.181	5.394	2.396	2.476	9.153**	–

Notes: UC, UM, UU, and UD stand for Unique Contract Creator, Unique Miner, Unique User, and Unique Developer, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively. ***, **, * denote significance at 1%, 5%, and 10%, respectively.

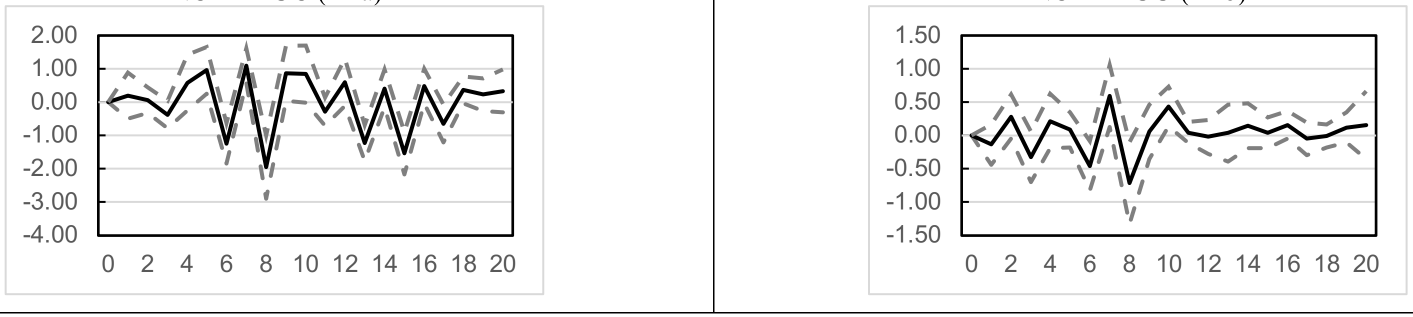
TABLE C2
Tests for Serial Correlation and Heteroskedasticity

Dependent Variable	Breusch-Godfrey Test	Breusch-Pagan Test
Unique User	4.660 (0.199)	4.820 (0.028)
Unique Creator	5.092 (0.165)	0.180 (0.668)
Unique Miner	1.352 (0.717)	1.290 (0.255)
Unique Developer	20.675 (0.000)	2.05 (0.153)
Network Capacity Adjustment	5.381 (0.146)	309.410 (0.000)
Client Update	13.911 (0.003)	3.710 (0.054)
Network Upgrade	3.269 (0.352)	119.39 (0.000)

Notes: The results show χ^2 values with p-values in parentheses.

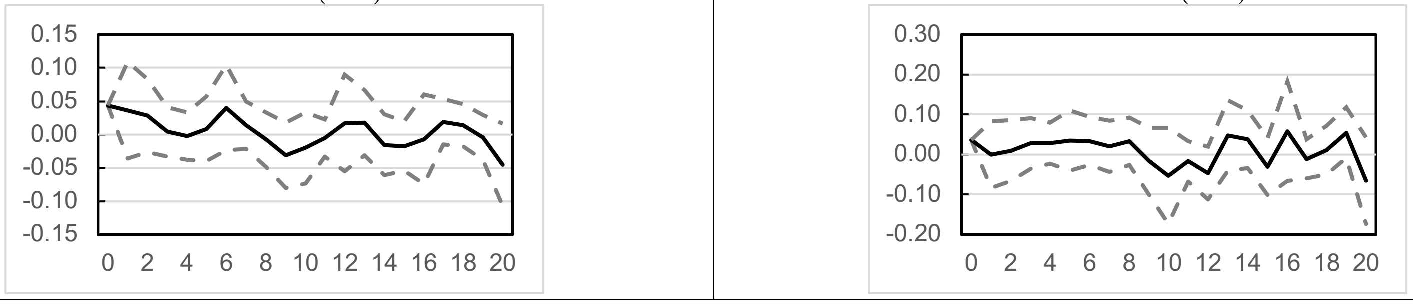
FIGURE C
Impulse Response Functions (Unique Number of Participants)

Effects of Network Capacity Adjustment on the Application Layer


NCA → UC (H1a)

NCA → UU (H1b)

Feedback Effects on Network Capacity Adjustment on the Application Layer

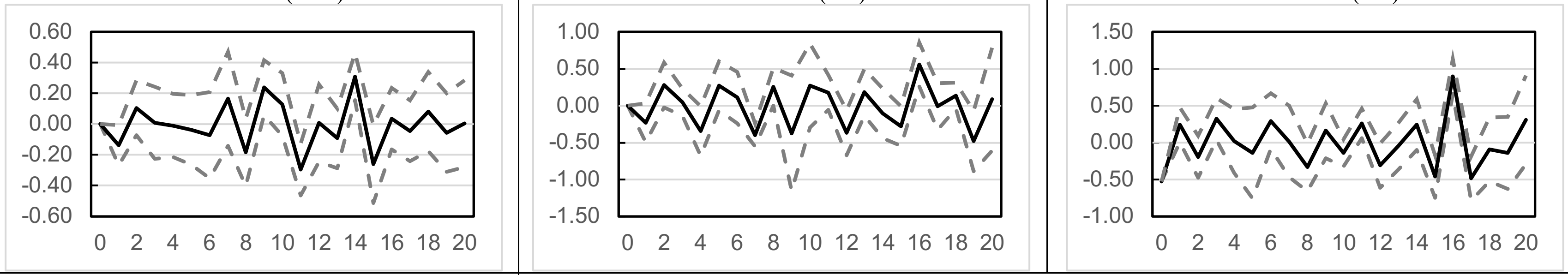

UC → NCA (H2a)

UU → NCA (H2b)

Notes: UC, UM, UU, and UD stand for Unique Contract Creator, Unique Miner, Unique User, and Unique Developer, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

FIGURE C (Continued)
Impulse Response Functions (Unique Number of Participants)

Effects of Client Update and Network Upgrade on the Architecture Layer



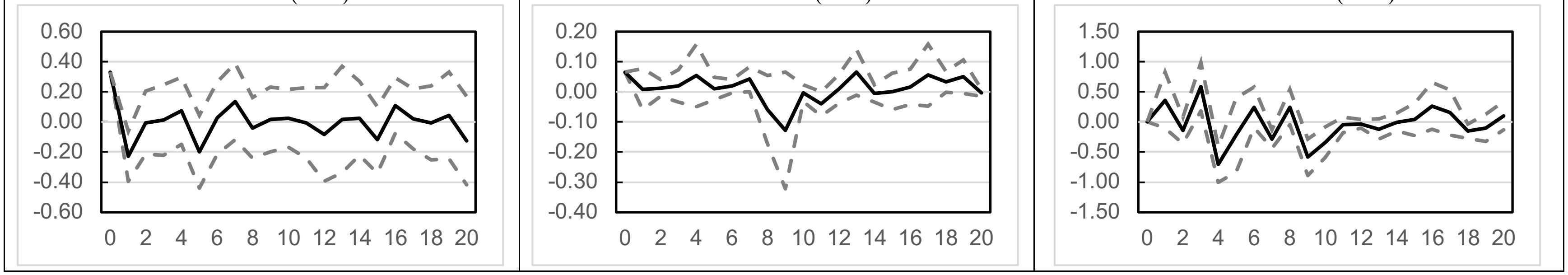
CU → UD (H3a)

NU → UD (H4)

NU → CU (H5)

Feedback Effects on Client Update on the Architecture Layer

Effects Across Layers



UD → CU (H3b)

NU → NCA (H6a)

NCA → NU (H6b)

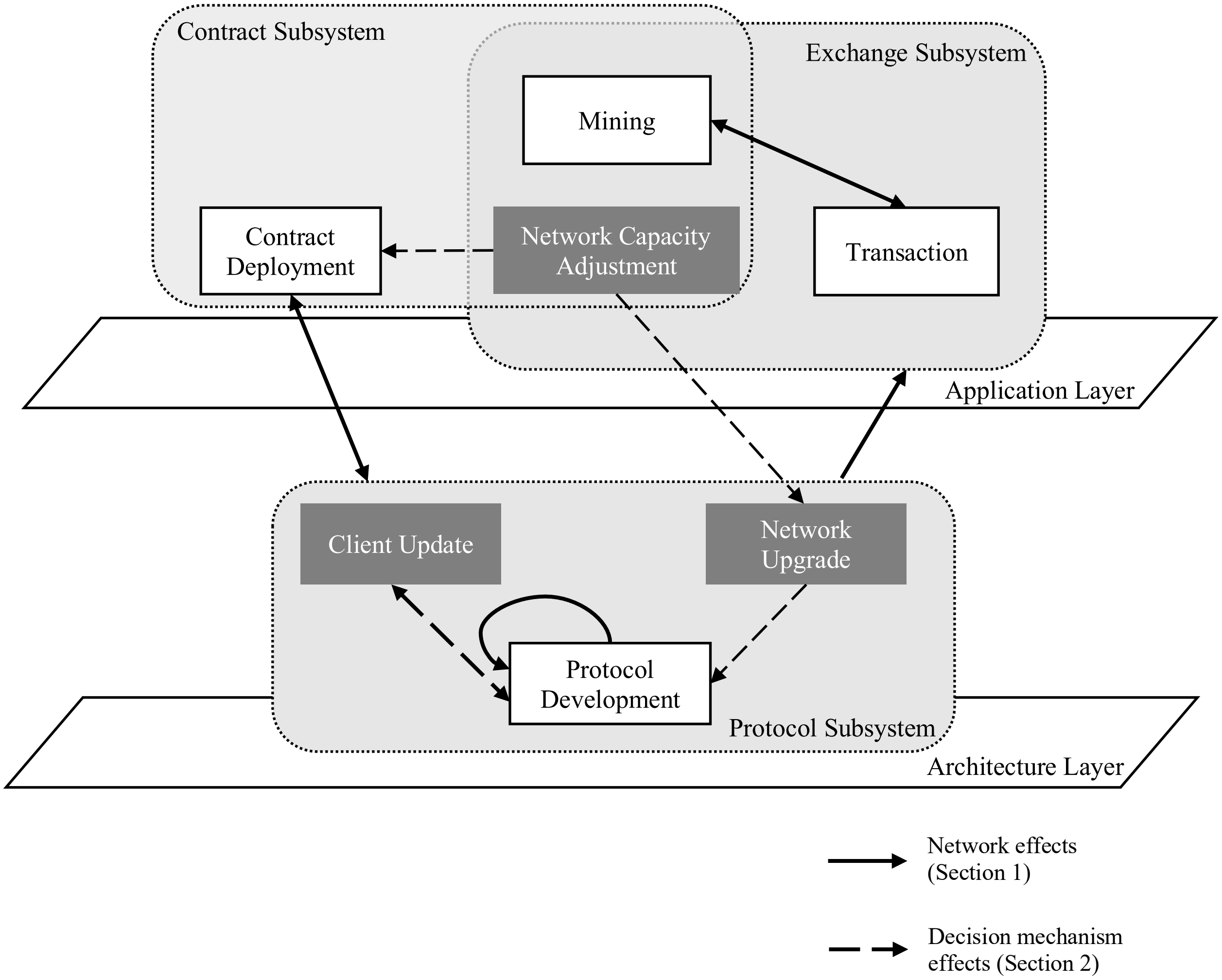
Notes: UC, UM, UU, and UD stand for Unique Contract Creator, Unique Miner, Unique User, and Unique Developer, respectively. NCA, CU, and NU stand for Network Capacity Adjustment, Client Update, and Network Upgrade, respectively.

CHAPTER 4. CONCLUSION

The objective of this dissertation was to understand decentralized platform-enabled ecosystems from two perspectives. From the value co-creation perspective, this dissertation investigates how interdependent activities facilitate network effects in public blockchain ecosystems. From the governance perspective, this dissertation explores how decentralized governance mechanisms influence these activities. This dissertation was motivated by the newly emergent form of highly decentralized ecosystems and the lack of knowledge about the mechanisms through which decentralized governance is enacted. I proposed a layer-subsystem structure to decompose a complex ecosystem with multiple sides of participants into two layers and three subsystems: the contract subsystem and exchange subsystem at the application layer and protocol subsystem at the architecture layer. Drawing on the theoretical lens of value co-creation, I found that network effects within subsystems are direct and can manifest immediately. In contrast, the network effects between subsystems are indirect and can be short-term or long-term at a layer but are more likely to be long-term across layers.

Enlightened by the findings, I took a step further to explore the decentralized governance mechanisms in the public blockchain ecosystem and how they impact the activities at each layer. I extended the two types of decision activities to the public blockchain ecosystem context and conceptualized two decision mechanisms. Specifically, I identified network capacity adjustment as the decision control mechanism at the application layer and client update and network upgrade as two decision management mechanisms at the architecture layer. I empirically examined my research model and found significant influences of each decision mechanism on other activities at the same layer. My results also identified a feedback effect from activities to client update at the architecture layer. In addition, I found that the decision control mechanism has a cross-layer impact on the decision management mechanism. Figure 1 provides a summary of findings.

FIGURE 1
Conceptual Framework



This dissertation makes critical theoretical implications that can guide future research on platform-enabled ecosystems and decentralized governance. First, this dissertation contributes to the literature on platform-enabled ecosystems with a specific focus on decentralized ecosystems underexplored by prior literature. I identify the distinctiveness of decentralized ecosystems and stress the importance of understanding how network effects are generated in such ecosystems.

Future research can continue to study topics in this research stream, such as investigating various decentralization degrees of governance on network effects in the ecosystem. Second, the layer-subsystem structure decomposes a complex platform-enabled ecosystem into self-contained but interrelated components. It provides insights into how value co-creation activities generate network effects in the ecosystem. Future studies can build on this structure and extend it into other types of platform-enabled ecosystems. Third, the two classes of decision mechanisms provide a framework for understanding the decentralized governance of a complex ecosystem. Future studies may continue to identify and examine other mechanisms that fall into these two classes. Finally, this dissertation contributes to the blockchain literature by studying blockchain ecosystems from a managerial perspective and empirically examining the influence of decentralized governance mechanisms. Future studies could invest in the overall governance design or improving the existing governance mechanisms to make the blockchain ecosystem more synergistic and self-organized.

I believe that the research streams on decentralized governance and decentralized ecosystems are very promising, especially considering that many people’s work has permanently transformed into a remote mode due to the global pandemic caused by Covid-19. Despite the excitement about decentralized governance supported by blockchain technologies, I should acknowledge that decentralized ecosystems and their governance are still at an early stage of exploration. Governance mechanisms need to be well designed to fit into specific organizational contexts. The impacts of these mechanisms also need to be carefully evaluated before an organization decides to adopt blockchain technologies.