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Network effects in blockchain and supply chain: a theoretical research synthesis

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Abstract

Purpose – This paper addresses a gap in research literature in the fields of blockchain technology (BC), supply chain network dynamics (SC) and network effect phenomena (NE). Extant BC and SC literature describes the potential benefits to be reaped through the adoption of BC technology. While BC technology does not yet meet the researched expectations of adoption, performance and efficacy, the authors analyze the three inter-related fields (BC, SC and NE) to bridge this gap in theory.
Design/methodology/approach – This paper begins with a research review correlating the technological fundamentals of BC technology into fundamental value propositions for SC logistics contexts. The authors review the gap between these theoretical technological functions and the current ecosystem of BC applications. With an overarching understanding of BC in SC contexts, this paper then explores the phenomena of NE and attempts to synthesize various interrelated aspects of the three fields (BC, SC and NE). Research frameworks from extant literature are used for cross-comparing legacy software/information system solutions with potential and existing BC-based solutions. Case studies are utilized to support this analysis.
Findings – Several key considerations and themes are identified to better inform practitioner and researcher decision-making. Novel insights pertain to BC platform architecture and application modularity, integrated governance and decision-making capabilities, and the automation capabilities that arise from a healthy application and smart contract ecosystem.
Originality/value – The core contribution is the synthesis of network effect theory with SC phenomena and BC theory and the exploration of how these three fields are inter-related in the maturation of BC technology. Specifically, the authors deepen insights from extant literature by contextualizing findings with relevant interdisciplinary theoretical frameworks.

Keywords Blockchain, Supply chain, Network effects, Software platform, Automation, Information systems
Paper type Research paper

1. Introduction

Today's digital era has reshaped supply chain management (SCM) at various levels. New digital platforms have provided managers improved visibility and integration performance. Data management challenges in SC have also evolved from data availability to data usefulness (in terms of information and knowledge) to data integrity. During this evolution, different enabling technologies have been developed to manage the challenges. These include Internet of things (IoT) which enhances data gathering along the SC, artificial intelligence (AI) that improves decision-making and optimization among SC echelons, and more recently blockchain (BC) with high potential to integrate and automate many business processes.

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BC technology is a distributed database of records or shared public/private ledgers of all digital events that have been executed and shared among BC participating agents (Nakamoto, 2008). In BC, an agent creates a new transaction to be added to the BC. This new transaction is broadcasted to the network for verification and auditing by nodes called validators. Once this transaction is approved by the majority of nodes in the chain, according to the pre-specified rules inherent to the BC protocol, it will be added to the chain as a new block. A record of that transaction is saved in a network of nodes for security (Saberi *et al.*, 2019). Hashing is one of the main concepts used in BC solutions to secure these developed blocks. Hashing can be explained as an "arithmetically produced code that is generated from the data contained within the block" (White, 2017, p. 440). That means that each hash is a unique digital fingerprint of the transactions in a block. To mitigate the possibility of manipulation of blocks, "proof of work" is a security mechanism utilized by Bitcoin's BC protocol. This mechanism slows down the process of creating blocks by increasing computational difficulty and incentivizing the distribution of computational effort across the network to prevent manipulation of the shared ledger. This process of incentivizing network participation and the ongoing proposal of new blocks is called "mining". Through this system, "miners" or groups of miners may earn the native currency of a BC when they successfully compute the hash of a given block. Simply put, hashes, proof of work and a distributed network of nodes are the reasons behind the high level of the BC technology's security and the network's ability to have consensus over the state of the network (Nakamoto, 2008).

Ethereum is a public BC, similar to Bitcoin, that provisions an additional computational protocol called the Ethereum virtual machine (EVM) that is secured by the same programmatic rules that secure the BC digital ledger. This computational layer allows for the execution of smart contracts, "a computerized transaction protocol that executes the terms of a contract" (Szabo, 1996). Network-wide updates on December 1, 2020, and September 15, 2022, progressed the Ethereum BC from the above-mentioned, computationally secured, "proof of work" mechanism towards a financially secured mechanism called "proof of stake" "Proof of stake" randomizes the selection process for each block proposal. The block-proposing agent is randomly selected from the network of nodes with a sufficient "stake" or quantity of the native Ethereum token, Ether, secured as collateral. This protocol provides a backbone for the expansion of the network without a parallel increase in the computing power, electricity and hardware necessitated by "proof of work." Ethereum developers plan to enable this expansion through the development of two scalability features on the Ethereum network: rollups and sharding (Buterin, 2020, 2021). Concretely, the September 15 update reduced Ethereum network energy consumption by 99.95% (The Merge, 2022). This technological progress is often overlooked in existing research, but is a vital component in considering and contextualizing the existing limitations of the technology. It is likely overlooked due to its constantly fluctuating nature as developers ideate and progress in their efforts to resolve issues of scalability, security and decentralization (Buterin, 2021).

The native computational protocol, the EVM, allows for seamless integration of other novel scalability solutions called Layer 2 (L2) solutions. These L2 solutions use the Ethereum protocol as a secure backbone for building out a variety of additional functionalities in addition to scalability capabilities. This is another, often overlooked, aspect of BC development. The EVM and other virtual machine protocols also provision a financial and computational ecosystem for token-based projects in addition to smart contracts and L2 solutions. "Token-omics," short for crypto-token economics, is a less explored topic in the field of BC and SC. Crypto-tokens are units of account or utility that exist on and are secured by an underlying BC. For example, an entrepreneur may develop some application using smart contracts that provides value to an end user. Instead of using the BC's native currency to transact, the entrepreneur may issue a token that may be redeemed for some utility or used in such a way as to bolster the value of the entrepreneur's application. Essentially, entrepreneurs can create micro-economic conditions to incentivize certain behaviors or outcomes with regard to their application. The application and its micro-economic conditions inherit the features of immutability, transparency and security from the BC protocol on which it exists. Tokens, may enable the capitalization of future platform growth, accelerate adoption and reduce user-based volatility (Cong *et al.*, 2021).

The BC capability of ensuring data immutability, public accessibility of data-streams and executing specified business processes within an immutable and transparent framework makes the disruptive innovation a good candidate for visibility improvements across many industries. Specifically, with regard to SCM and logistics, BC's decentralized and distributed infrastructure serves to enhance SC integration. Optimized SC integration can be achieved through preventing the problems of the current centralized approaches, including trust issues, such as fraud, corruption, tampering and falsified information, and their limited resiliency. In parallel, smart contracts, a critical feature of BC technology, allow the performance of credible transactions without third parties' involvement thereby reducing both networking and verification costs while optimizing business processes execution and aligning stakeholder incentives (Chang and Chen, 2020).

The above-mentioned advantages of employing BC-based solutions come with challenges. Among the widely discussed challenges are the scalability issues with the increasing number of echelons and their transaction across a global distributed network. The complexity of digitization, digitalization and interoperability infrastructure are also big hurdles for BC implementation in SCs. In addition, since the global SC requires various parties to comply with diverse laws, regulations and institutions, aligning these requirements while developing BC-based solutions is not an easy task. Other challenges include the usability of the existing BC-based solutions as well as the last mile problem linking off-chain activities (which are highly diverse and distributed) to the on-chain digital network.

This paper focuses on the ascribed benefits of BC technology and offers insight about the role of network effects (NE) in achieving those benefits – in this way, we address a gap in understanding how BC may deliver the big efficiency improvements associated with the technology. We focus on the SCM and logistics field as a representative industry for exploring these broad theoretical relationships. SCM is selected for two reasons. (1) Many research studies describe BC's potential in disrupting existing SCM software solutions. (2) The phenomena of SC networks and the suite or network of software solutions they use are analogous to BC networks and the network of applications built upon the BC infrastructure. Namely, we identify and review existing literature describing the value propositions of BC technology across a wide variety of SC business processes. The value propositions are contextualized by reviewing literature on the developmental stages of BC application development, adoption and use cases.

Our contribution is the synthesis of these perspectives with the phenomena of NE. Until now, NE have not been a topic of interest for academic papers. Extant literature focuses on NE in cryptocurrency valuation, but this research is shallow and does not adequately explore NE as a phenomena leading to value creation in the BC space. To address this gap, we review theoretical research on NE, applied research on NE in software markets, and apply these frameworks in the context of BC's technological fundamentals and value propositions for business process improvement in an SCM context. Developmental hurdles for BC adoption and ecosystem development are also discussed in the context of NE.

Specifically, we define our research scope by addressing the following questions: What are the qualitative aspects of BC technology that would bring value to a SC? How do those aspects relate to the existing ecosystem of BC networks and applications? How do BC technological fundamentals pertain to the application of network effect theory? What are the main considerations in attributing the disruptive potential of BC technology to these NE phenomena? Through our research analysis and synthesis, we hope to answer these questions and contribute actionable insights in the areas of managerial decision-making, BC application architecture and further research on NE in BC application ecosystems.

2. Methodology

The structure of this paper is sequenced with the intention of laying a foundation of BC and SC interdependencies, then contextualizing those interdependencies by applying network effect theory to extant BC and SC literature, and finally utilizing brief case studies to further illustrate this broadened perspective on NE impacting BC development, adoption and maturation in the field of SC logistics.

Specifically, the BC and SC literature review cites many examples of how BC stands to impact the field of SC (3.1). We discuss the core technological features of BC, namely smart contracts that underlie many of the discussed improvements BC stands to offer SC industry (3.2). Case study literature is reviewed to further illustrate how these BC features have been implemented in SC (3.3). Literature review sections (3.1)–(3.3) provide a clear picture of the academic and industry expectations surrounding BC in SC but do not propose any theory for how these improvements stand to proliferate. In section (3.4), we introduce theoretical literature about BC development, maturation and adoption. Overall, Section 3 illustrates the current state of BC in SC from a practitioner and academic perspective.

In Section 4, we introduce NE theory that contextualizes Section 3 literature review. Section 4 begins with an overview of NE typologies and applies these typologies to BC (4.1). Important pre-requisites for NE phenomena are reviewed and applied to BC as well. We identify that most existing BC research only mentions NE in the context of BC network valuation, then we discuss why NE merits much deeper analysis in BC and SC (4.2). Network governance is identified as an important consideration in NE phenomena – we then discuss novel governance mechanisms enabled by BC (4.3). Lastly, we discuss the "software platform" architecture of BC networks and the importance of "application network effects" in understanding how the software platform ecosystem may develop (4.4).

Following this section, the above-mentioned literature is synthesized in order to cross-analyze existing legacy software solutions with possible BC-based solutions. Both scenarios are explored utilizing the lens provided by NE theoretical frameworks. In summary, we utilize NE theory to explore and analyze how BC benefits in SC may proliferate, understand the intertwined nature of BC technological features with NE and how BC application ecosystem matures. This interdisciplinary synthesis is the core contribution of our research in the fields of BC, SC and NE.

In order to validate the hypotheses, we set forth in the Synthesis section, we utilize novel case studies that illustrate how NE relationships currently manifest itself in some BC and SC industrial applications. These examples represent a primitive or "early-stage" NE dynamic that practitioners and researchers should look to for deeper insight into the development of BC in SC.

In the discussion section, we revisit the practical implications and theoretical contribution of the paper. The discussion focuses on clarifying the relationship between extant BC and SC literature and the results of our NE framework analysis.

Finally, we conclude with summary responses to the guiding research questions set forth in the introduction. These questions distill the essence of our contribution, the analysis and synthesis of BC, SC and NE literature into several core insights.

3. Blockchain and supply chain literature review

3.1 Blockchain and supply chain overview

The literature for BC implementation in SC is still in its early development phase relative to other established fields of SC. Many literature studies focus on exploring the potential benefits BC technology will bring to SCM. This includes the work of Dong *et al.* (2017) that shows how BC technology exhibits multiple advantages over existing SCM systems because it is not susceptible to single point of failure vulnerabilities from error, hacking, corruption or other attacks. Swan (2015) claims that BC-based solutions make SC transparency, security, durability and process integrity more organizationally, technologically and economically feasible. Abeyratne and Monfared (2016) argue that data collection, storage and management on open, neutral, reliable and secure BC networks result in these desirable outcomes. This, in part, is a function of the disintermediation of payment networks, stock exchanges and money transfer services as demonstrated by Tapscott and Tapscott (2017). Tönnissen and Teuteberg (2020) explain that, up to this point, BC has only led to re-intermediation through the new technological capacities it offers. The above research points towards the technical capacity of BC in information sharing, value/property transfer and trust provision – foundational attributes of SC information systems (SCIS) (Saberi *et al.*, 2019).

Existing research describes how collaboration and information sharing in SC leads to improved trust which, in turn, can positively reinforce collaboration levels (de Almeida *et al.*, 2015). Ko *et al.* (2018) state that these effects also arise from BC technology because of this its ability to enable transparency, thus allowing firms to reduce verification and surveillance costs. Catalini and Gans (2018) mention that implementing BC technology can structure confident relationships with their counterparts, thereby reducing costs associated with low-trust relationships. In their research, Kouhizadeh *et al.* (2021) conclude that a leading barrier to BC adoption is this lack of trusted network constituents willing to implement new joint systems. Overall, the above BC and SC research points towards the technological features of BC and the corresponding SCM processes they positively impact.

3.2 Blockchain smart contracts and supply chain processes

Smart contracts and their potential benefits for SC were also part of this growing line of research. Hofmann *et al.* (2018) discussed how these organized, self-enforcing and self-executing financial arrangements can ensure timely and automated payments leading to a more streamlined SC. Two core functions of smart contracts enable this streamlining: the *active mediation* of business processes and the *choreography monitoring* of those actively mediated processes (Weber *et al.*, 2016). More recent research elaborates on implementations of the active mediation and choreography monitoring functions in BC-based business processes (Guerreiro *et al.*, 2020; Klinger and Bodendorf, 2020; Evermann and Kim, 2020; Omar *et al.*, 2021). Eggers *et al.* (2021) explore smart contract value propositions through case analyses of multiple companies utilizing key smart contract features. One company they cite provides additional customer value through the automation of both front-facing and back-facing processes in order to reduce turn-around time and ensure timely insurance pay-outs. Another company re-intermediates the anti-malware market, offering a smart-contract platform for securely exchanging documents, information and assets between clients and service providers. A third company provides value in the transportation and logistics industry: securely measuring and communicating shipment temperature data for pharmaceuticals. These capacities are achieved through the features of choreography monitoring and automatic active mediation offered by smart contracts. Eggers *et al.* (2021) conclude that smart contracts provide distinct value to corporations as automation infrastructure that is maintained by collaboration rather than a third party. It is worth noting that the domains of insurance, logistics and even network security are pertinent throughout SCs.

Figure 1 below illustrates the phenomena of smart contracts with their two core functions: active mediation and choreography monitoring. Through active mediation, a wide variety of business process objectives can be automated with smart contract execution. These business processes vary as described in extant literature. The ability to programmatically manage information and assets are another core component of this active mediation capability. These two functions essentially enable lead time improvements, novel organizational competencies like decision-making and governance, and automation of administrative functions. The tangential choreography monitoring function of smart contracts enables the integrated, efficient and secure record keeping of these various processes.

3.3 Supply chain blockchain implementation case studies

More research highlighted BC-based solutions in SC networks. Examples include Perboli *et al.* (2018) who propose a BC implementation framework and demonstrated it in the fresh food delivery industry showing how BC helped in reducing the logistics costs and in optimizing the operations. Pour *et al.* (2018) demonstrate how BC with integrated agent-based AI technology could improve the mining industry. Tian (2016) shows how BC with Radio-frequency identification (RFID) had improved traceability in Chinese agri-food SC. Another study cites the positive impact of BC solutions on the SC of eleven different industries (Kshetri, 2018). These industries included logistics, manufacturing, retail and finance to name some.

Lim *et al.* (2021) offer a comprehensive literature review detailing the themes and potential of BC technology specifically in SC contexts. They reiterate the technology's potential for streamlining information flows, capital flows and logistics flows to enable dynamic and efficient SCs. More real world examples are cited: Walmart's reduction of mango traceability time from seven days to just two seconds (Wong *et al.*, 2020) as well as Maersk's and IBM's increase of cross-border SC transparency and information sharing (Chang *et al.*, 2020). Their literature review specifies themes consistent across BC research: "impact," "function" and "configuration" along with subthemes like product traceability, information sharing, trust systems, that touch on the various above-mentioned aspects of BC technology that lead to improved order management, production, workflow and logistics (Chang *et al.*, 2020).

Wamba *et al.* (2020) empirically examine the antecedents of BC adoption in the United States and India. Their results verify the impact of transparency and knowledge sharing in improving SC performance. Dutta *et al.* (2020) summarize extant literature, describing the various dimensions of BC's potential applications in SC: data management, inter-organizational transparency, response time, operational efficiency, disintermediation, immutability and intellectual property management. Their review specifies how these dimensions stand to positively impact SC resilience, SC provenance, SC reengineering, security enhancement, business process management and product management. Specific sectors with real world applications of BC are also described: energy, financial services, healthcare, technology, manufacturing, shipping, automotive, agriculture, aviation, governments, education, e-commerce, entertainment, fashion and construction. Core challenges from their review include scalability, privacy, interoperability, product

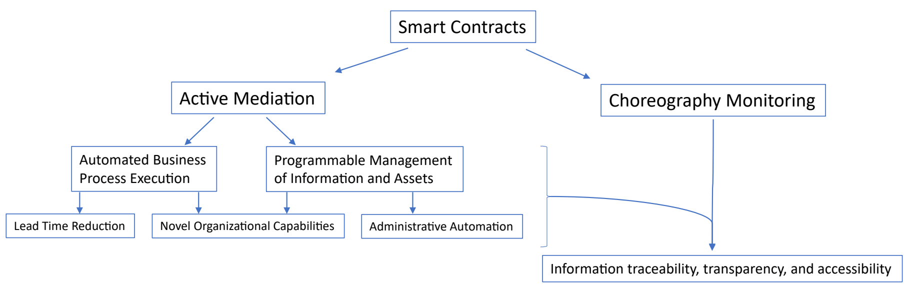

Figure 1.
Diagram of functionalities stemming from BC-based smart contracts

provenance and latency. The above case study literature describes the existing implementations of BC technology as well as its disruptive potential across many sectors and business functions. Through the exploration of BC and NE theory below, we hope to gain insight into the underlying dynamics behind this often-cited disruptive potential.

3.4 Blockchain theory

Other research studies refocus the conceptualization of BC networks as a platform (BNaaP) (Shi, 2021). Specifically, Shi highlights that the ascribed benefits of BC do not arise directly from the various technological features described in other literature studies – rather these benefits and the value it stands to create arises from BC as an architectural design and organization logic. Similarly, Xu *et al.* (2016) describes the software-connecting capacity of BC technology as an important consideration in distributed software architecture design. This research represents an important reframing of BC as a multi-layered platform for securely connecting otherwise separate software functions and provides a theoretical basis for better investigating NE and how the ascribed benefits of BC may come to fruition.

While missing from most extant academic literature, network effect theory is not entirely missing from BC literature in general. One of the earlier expressions of NE in BC was by Vitalik Buterin in a blog post that provided an initial typology of NE effects across multiple facets of BC technology. He describes BC-specific NE that give rise to higher security levels, platform-specific NE pertaining to development and adoption, currency-specific NE regarding the economics and psychology of digital currency adoption and general NE phenomena relevant to technology adoption (Buterin, 2014).

Lakhani and Iansiti (2017) present four stages of BC functionality that can be expected to develop as the technology matures: *single-use, localization, substitution* and *transformation*. Dobrovnik *et al.* (2018) elaborate the nature of these four levels: *single-use* represents the automation of a single business process. *Localization* extends the scope of the automation to closely adjacent business processes that may execute in tandem with the first single-use application. *Substitution* occurs when even larger segments of business processes are executed together, streamlined through networks of smart contracts that define the business logic. At this stage, a network of smart contracts or decentralized applications may enable some BC-based interorganizational enterprise resource planning (ERP), customer relationship management (CRM) or electronic data interchange (EDI) system. *Transformation* occurs at a point when entire business segment functions may be executed through BC. At this stage, larger scale operations execute according to a cascade of business logic that would be enabled by multiple interconnected BC applications and software solutions. Transformational applications reflect a future state of the BC ecosystem where, not only it will have scalability barriers been solved, but the ecosystem of applications will also be matured to a point where SC functions are mediated by BC and are widely available and cross compatible or modular between many use cases. Table 1 below organizes this theoretical framework into a visual matrix. In the context of this framework, BC's current uses trend towards the *single-use* and *localized* stages of maturation. In particular, research shows that the most widely and frequently used decentralized applications are financial exchanges and financial instruments (Min and Cai, 2022). In terms of ecosystem maturation, this statistic points towards these early decentralized finance applications as a foundational competency of BC technology. At the same time, the statistic is evidence of the lack of widespread adoption and a prompt for inquiring into the nature of ecosystem maturation and adoption.

To summarize extant literature, there is a large body of work pointing towards BC technology as a strong technological foundation for Industry 4.0 and for the improvement of a wide variety of SC processes. Many literature studies describe real world examples of BC being used with narrow scope to improve specific SC pain points. These real world examples

Stages of maturation	Application scope	Real world examples	Significance
Single-Use (1)	Singular function (very limited scope)	Cryptocurrency as a unit of exchange, financial instruments and crypto-asset exchanges	Foundational competencies are designed and honed to efficiently enable more complex applications
Localization (2)	Narrow clusters of interrelated functions	1. Remediation of real-world goods/services with the exchange of cryptocurrency. 2. Regulatory compliance with international paperwork	Specialized single-use functions are called to complete simple tasks – localized applications leverage these functions to enable new efficiencies/automation
Substitution (3)	Widening clusters of functions that inform or trigger one another	Integration sales or SC pipeline with BC based ERP, EDI or CRM type systems with potential for regulatory compliance integrations	A small network of interrelated and modular applications enable integration of new functions and shared BC-based platform for interdepartmental information transfer
Transformational (4)	Competitive and diverse network of modular applications and automated processes across multiple industries or business departments	Inter-organizational and modular BC applications that automate the flow of products, processes, information and assets while also enabling decision-making and dispute resolution amongst stakeholders	A wider network of BCs and BC-based applications leverage one another to offer customizable and powerful automation, information system and governance integrations

Table 1.
Stages of BC maturation with examples and analysis

lack the high level of integration, automation and comprehensiveness associated with Industry 4.0. While many literature studies points towards the regulatory, cultural and technological hurdles standing in the way of adoption, very little research discusses the theoretical basis for understanding how BC technology stands to mature and develop in such a way that transformative capacity of the technology may be realized. Lakhani and Iansiti's (2017) research presents a useful framework for understanding the developmental stages of BC ecosystem maturation but does not quite fill the gap in explaining the phenomena driving that developmental trajectory. Below we address this gap by exploring the phenomena of NE as an important consideration in the understanding the dynamic nature of BC technology, its maturation and adoption.

4. Blockchain and network effects: literature review and cross-analysis

4.1 Network effect typology

"Network effects are defined as the changes in decision variables of an economic agent, such as benefits, are based on choices of other agents consuming similar goods (Liebowitz and Margolis, 1994)" (Kemper, 2009). Various typologies of NE can be categorized into *application effects, user effects and system effects* (Gröhn, 1999) as well as *direct* or *indirect* NE (Ichbiah and Knepper, 1991). *Application effects* pertain to the utility derived from compatible applications, user effects align with the number of network participants, and system effects result from software and hardware interdependency. *Horizontal direct network effects*

(*HDNE*) are a type of direct network effect that arises from the additional utility gained through additional network participants. *Application effects* are characterized by the increase in utility gained through compatibility with other applications (Kemper, 2009). At their most fundamental level, *HDNE, application effects and user effects* represent increases in network interconnectivity through additional nodes: whether those nodes are users/network participants or specific application functions. On the other hand, *indirect NE* arise from the benefits in the form of complementary goods and services (Economides, 1996).

Applying this to BC, network participants, the users themselves, represent the *user effect* and the *HDNE* of gaining utility through the ability to interact with more users. *Application effects* arise as more applications are developed on a given network and as those applications gain functionality through their interconnectivity. *Indirect NE* arise from the user-base of the network, which in turn incentivizes the application development on that network, thus attracting more users to the network. *System NE* may translate to the interdependency between the network protocol itself, including the cost of executing smart contracts on the network and the applications that are built on that platform. Table 2 above organizes the various network effect typologies into a matrix outlining various pertinent and theoretical examples.

Compatibility is a crucial pre-requisite for the manifestation of NE in software and platform markets (Katz and Shapiro, 1985; Wiese, 1991; Kemper, 2009). This compatibility spans three categories: physical, communication and contractual compatibilities. BC technology presents novel capabilities in terms of communication and contractual compatibilities. That is, BC-based applications share an underlying BC protocol and consensus infrastructure that facilitates the seamless interface between applications. Contractual communications are methods of interfacing between systems or applications that enable the execution of some agreement or shared process between the systems. Through its protocol and the smart contract functionality it provisions, BC presents unprecedented opportunity for interconnectivity and compatibility in this regard.

4.2 Blockchain valuation from network effect theory

Extant literature has been limited in scope in the exploring of NE theory as it pertains to BC, primarily focusing on network and asset valuation (Alabi, 2017, 2020; Zalan, 2018; Catalini and Gans, 2020; Stylianou *et al.*, 2021). NE are a multidimensional phenomenon and framework for better understanding how novel BC ecosystems of platforms, applications and users develop and mature. NE phenomena merit deeper consideration for the same reasons BC has gained attention in the field of SCIS and management, namely, BC functionalities stemming from trust, automation and disintermediation offer novel possibilities for how network constituents interact. These may enable more dramatic NE phenomena among network constituents or enable entirely new programmatic and economic possibilities for NE markets. The new opportunities for NE correspond with the novel technological capacities offered by BC, namely, BC provides a digital, secure, transparent and immutable business-process execution environment that enables many features cited by extant literature in section 3. At the same time, negative NE should also be accounted for: namely the negative impact on BC utility that accompanies network congestion.

New technological features of BC technology also parallel the novel information and value channels that grew from the simple TCP/IP protocol underlying the Internet. As the Internet and its associated architecture and applications matured, it became a key component of SC and industry infrastructure. Since the Web 1.0 paradigm, the technology's maturation into Web 2.0 has trended towards centralized services but has enabled unprecedented network interconnectivity surrounding those centralized entities: Amazon being a common platform for over six million "third-party sellers" globally for example. The features and architecture of

Table 2. Network effect typology matrix with clarifying examples across multiple fields

Network effect (NE) typology	Definition	Real world example	Blockchain example	SC network example
Direct NE	Increases in platform utility from increased platform participation	Keyboard QWERTY layout standardized → adoption of standard yields improved product experience (Kemper, 2009)	Growth of cryptocurrency platform → increase in possible interactions for asset transfer	A SC network inherits utility through its constituents, their competencies, and through the logistical systems that interconnect them
Indirect (Market-mediated) NE	Increases in platform demand resulting from complementary products/ services	Development of software on operating system platform → increase in demand for operating system (Kemper, 2009)	Increase in custodial and asset exchange services like Coinbase → increased demand for cryptocurrencies	A SC network may experience increased demand and participation resulting from a wide variety of market mediated factors (Regulation, international relations, competitor competencies, etc)
Application NE	Increases in platform utility from compatible applications/services	Additional websites accept Google's Gmail single sign-on option for account creation → Gmail account holders gains utility through novel compatibility	Decentralized exchange facilitates seamless conversion between cryptocurrencies → novel BC-backed marketplace can leverage existing application to enable transactions across many cryptocurrencies	A SC network may gain utility through its ability to seamlessly integrate new constituents, business processes, and competencies. For example, a network's ability to leverage digitalization to streamline trade-document processing
User NE	Increases in platform utility from additional network constituents	Increase in social network userbases (Instagram, AirBnB, and Uber) → network gains specified functionality (social communication, BnB locations, transportation options)	Golem Network – a BC application on the Ethereum network for purchasing and selling computational power – increases its utility through additional network constituents and the computational power they buy or sell on the network	A SC network may gain utility through additional constituents – for example, through a new "last-mile" service partner for some geographical region
System NE	Increases in platform utility or demand from interdependency between software, hardware, and platform functionality	Apple's product integrations that increase the utility of a given product (i.e. Airpod functionalities only accessible through iPhone) and thereby also drive demand	Ethereum BC – through provisioning a platform for smart contract applications – inherits some utility and demand from those applications	A SC network may gain utility and demand through interdependency or efficient configuration of constituents, their competencies, and the logistical systems that interconnect them

BC protocols enables network constituents to interact, transact and organize into decentralized digital institutions that are expected to characterize Web 3.0. Below, we explore the theoretical implications of this network structure in the context of the technological fundamentals of the BC protocol architecture.

4.3 Network self-governance

Network effect literature points to the importance of governance in effectively moderating interdependent constituents, especially in a software platform context (Song *et al.*, 2018). It is established that BC technology provides novel distributed governance capacities amongst stakeholders (Lumineau *et al.*, 2021; Pelt *et al.*, 2021). These governance mechanisms exist on multiple layers of the BC ecosystem. The BC protocol itself, "proof of work" or "proof of stake", is a governance mechanism by which network participants agree upon the state of the ledger. Crypto-tokens are another governance mechanism whereby entrepreneurs or a firm may create some micro-economic conditions or incentive structure to guide stakeholder decision-making surrounding their token.

Decentralized autonomous organizations (DAOs) are another layer of governance capacities that exist alongside token governance. DAOs are a novel organizational construct based upon protocols and functions that allow stakeholders to decide upon and take collective action that is subsequently enforced by the smart contract protocols. These actions may range from contracting freelance computer scientists for specific tasks to coordinating with other DAOs in order to achieve a common goal (Murray *et al.*, 2021).

These integrated governance mechanisms allow for the phenomena of "platform cooperativism" by which network participants may act as both shareholders and users (De Filippi, 2017). Users' dual status as decentralized administrators and users of the BC applications allows for the creation of self-regulating and self-controlling markets (Babkin *et al.*, 2018; Catalini and Gans, 2018). Specifically, these capacities allow for the integration of platform management and governance as a native network function for a given application or BC platform. "From a complex adaptive business systems (CABS) theoretical perspective (Varga *et al.*, 2009; Benbya and McKelvey, 2006; Tanriverdi *et al.*, 2010), effective platform governance is about establishing mechanisms that enable adaptiveness of the ecosystem and requires understanding the nature of interdependencies between two sides of the market" (Song *et al.*, 2018). BC and SC literature likewise points to the importance of collaboration and joint participation in improving both platform functionality and SC performance (Kamble *et al.*, 2020; Hald and Kinra, 2019). Other research studies point to BC's ability to enable large-scale collaboration and reduce SC friction (Sharma *et al.*, 2018). Integrated BC governance mechanisms enable new features by which users, administrators and platforms may interact. The new features also stand to enable new markets and services that correspond with the researched promises of large-scale collaboration, reduced SC friction and joint SC participation. Through the incentive structures and architecture of those platforms and applications, these markets may have the potential to exhibit more potent or novel NE by more effectively or efficiently distributing services and resources to the network participants.

4.4 Blockchain application effects – platform, software and open source development

Song *et al.* (2018) also empirically investigate the differences between two main types of NE that exist in software platform contexts: user-to-application and application-to-user cross-side network effects (CNEs). In this context, CNEs are NE that result from users incentivizing new application development and new applications attracting new users to a software platform – that is, CNEs are another way to describe *indirect* NE. Their findings show that in general the NE of a large platform userbase are long-term compared to the NE of additional applications on the platform. These findings remain to be validated in a BC context but are an important consideration for software platforms in general. Native platform governance may play a role in how these NE manifest. Most specifically, application-to-application CNEs or just *application effects* merit deeper investigation in BC platform and software ecosystems. Research describes BC's software-connecting capabilities and conclude that BC may connect ecosystems of software by providing "communication and coordination services through transactions, validation oracles and smart contracts, and specific facilitation services, including permission management, cryptography-based secure payment, transaction validation, mining and incentives" (Xu *et al.*, 2016). These attributes stand to facilitate existing *application NE* phenomena and are associated with many of the BC security features cited in the extant literature, namely, BC can act as a secure and transparent type of digital connective tissue between business process execution on separate systems or applications.

Looking at BC as a software platform, extant literature in the field of software development should be re-evaluated in the novel context of open source BC application development. We expect that ecosystem of BC-based open source software development would exhibit unique attributes compared to general open source software development. Two specific areas are identified as being particularly relevant to this uniqueness: the paradigm of network social capital, 'the benefits open source developers secure from their membership in developer collaboration networks," and external versus internal cohesion paradigm (Singh *et al.*, 2011) in BC-based open source software development. The nascency of BC also precipitates an environment with limited quantities of developers. Accordingly, it is worth exploring the network effect outcomes associated with a platform's developer population. This "developer network effect' is conceptualized as when "more people interested in writing tools that work with platforms that are widely adopted, and the greater number of these tools will make the platform easier to use" (Buterin, 2014).

BC interoperability is a highly researched issue in the field with significant implications in possible NE. Specifically, research focuses on the interoperability of multiple BCs with an emergent view that each BC in the ecosystem will specialize in particular functions and be interconnected through means of smart contracts, while another BC will be dedicated to managing interoperability, or enabled by a software service (Belchior *et al.*, 2021). This BC interoperability perspective calls for a shift in the understanding of possible NE in a boundary-less ecosystem of BC platforms where applications on one BC may interact with those on another BC. This level of interoperability between BCs would likely fall into the above-mentioned fourth, most advanced, "transformational" category of disruption (Lakhani and Iansiti, 2017). From a theoretical standpoint, this research points to a future state of BC technology wherein BCs or specific BC applications must conform to a set of parameters to gain access to an interoperability network. It follows that NE may be an important consideration in understanding this developmental trajectory.

The above literature points towards the modular nature of BC and BC applications. Literature indicates that platform governance and software interconnectivity are important components in network effect outcomes resulting from this modularity (Hein *et al.*, 2020). Platform cooperativism, enabled by native platform governance, remains to be explored in this context of modular software and platform ecosystems.

5. Synthesis: Blockchain, supply chain and network effects

Various business models arise from the phenomena of NE: data networks that allow for the improvement of product value using large quantities of data, interaction networks that enable direct interactions between users, marketplaces that connect buyers and sellers and platforms that provide developers a way to integrate applications on top of a product (Singh, 2020). BCs are an unprecedented development in this broad framework of NE and platform technology. They provision a platform ecosystem with a fully integrated financial, computational and governance backbone. Through these financial, computational and governance integrations, BC's software-connecting functionality, described by Xu *et al.* (2016), and multi-layered architecture, presented by Shi (2021), inherits multiple echelons of possible NE.

A key attribute that arises from these financial, computational and governance integrations is the often-mentioned gain in efficiency and automation cited by many research studies. The practical implication of this efficiency and automation improvement is the possibility of new value channels for economic interactions. That is, economic interactions that were previously infeasible due to administrative, financial or technological limitations become possible through the efficiencies of BC. The effect of this is two-sided – that new markets and services are born from this capacity but also that new population segments and underserved industries may gain access to markets that previously had a higher economic barrier to entry. Decentralized computing is one such industry that began as a charitable endeavor but gained economic feasibility through BC technology (Kondru *et al.*, 2021). A well-known example of lowering the barrier to entry is decentralized-finance and the offering of financial services to previously un-banked segments of the population (Schuetz and Venkatesh, 2020). These developments represent growth in possible economic interactions and in the number of possible participating economic entities. In terms of network effect theory, these effects correspond with opportunities to further leverage *user* NE, *application effects* and *indirect* NE. From an SCM perspective, these efficiencies may be associated with growth in SC network constituents, total addressable markets and organizational competencies.

Shi (2021) differentiates between three core architectural layers of BC technology: the *foundational* layer with its technological, functional and operational aspects; the *interaction* layer by which users participate in the network; and the *application* layer of software services. These multiple architectural layers each have respective opportunities for how NE may manifest. Each architectural layer corresponds with its respective governance mechanisms: the foundational layer with its cryptographic protocol, the interaction layer with capacities for decentralized autonomous organizational (DAO) governance mechanisms, and the application layer with "tokenomic" incentivization governance that applications use to structure shareholder decision-making. Until now, the interaction layer has been the focus of research exploring these potential NE, namely, through analysis of active network wallets and asset valuation. Still, Industry 4.0 will likely necessitate the paradigm shifting outcomes associated with the NE at all three layers. Below we apply this architectural layer framework to hypothetical BC-based SCIS as well as legacy systems. Table 3 below organizes this information into a matrix for easy visualization.

At the *foundational* layer, BC technology gains efficacy through the participation of network members in running the BC protocol. Ultimately, the protocol itself determines the nature of possible NE: governing the hosting of network data, the economic incentives and disincentives of network participation, and the technological capacities associated with the platform. In legacy SCIS, ERP and EDI software solutions, there is no common foundational protocol like with BC. Rather, each software solution itself is the foundational architectural layer that underlies SC network business processes and data management. In this legacy paradigm, these foundational software solutions generally have a centralized intermediating entity that arbitrates and governs the foundational, interaction and application layers of SC network software systems.

The functions on the *interaction* layer of BC networks arise from the foundational protocol that is being run by the network constituents. It inherits the attributes determined by the *foundational* layer. That is, in BC, the *interaction* layer generally inherits the protocol's distributed governance mechanism with integrated financial and computational functionalities. As described above, these financial and computational functionalities offer

Architecture layers	System of governance	Functionalities	Current SC paradigm	Theoretical BC-based solution
Foundational Layer	Consensus protocol (PoW or PoS) enables agreement upon state of blockchain network	Ledger capabilities for crypto-assets and hosting data – incentives yield immutable and unstoppable system for publishing and executing smart contracts	No shared foundational layer infrastructure – SCM solutions are often software based with web integrations	Foundational BC protocol underlies mature ecosystem of applications across a wide variety of industries. Trilemma of scalability, decentralization and security has been improved
Interaction Layer	Smart contract code and DAOs enabling collaboration and decision-making	Active mediation (automation), choreography monitoring (information visibility), and joint decision-making through smart contracts	SC network interactions are mediated by centralized software/ service provider. Little standardization or interoperability between organizations and industries leads to SC pain points	SC network constituents configure DAO for decision-making needs. Network agrees upon areas for automation/active mediation – adopts modular applications from ecosystem based on network needs
Application Layer	Application "tokenomics" enabling configurable incentives and micro-economic conditions	A system of smart contracts and crypto-assets, normally with a software back end, enables a wider range of incentive and automation configuration	SC network selects centralized SCM software providers. Lacking interoperability and coordinated incentive structure, software providers and network constituents have competing interests leading to inefficiencies	Shared foundational layer with contractual execution allows for seamless data, asset, and process flow. Shared interaction layer allows for coordination and agreement upon specific configurations of applications and incentive structures. Modular interoperable applications facilitate operational efficiency

Table 3. Blockchain architectural layers with their respective governance mechanisms, explanations and examples

opportunities for business process streamlining and automation infrastructure that may enable SC network growth, participation, and facilitate entity interaction. At this layer, DAOs may also facilitate coordination amongst network constituents to enable joint decision-making. Legacy SCIS solutions can be expected to inherit the foundational layer attributes of their centralized service provider. For example, interactions between constituents on the legacy *interaction* layer are mediated by a centralized service provider. In general, the centralized intermediator does not operate through a system of administrative automation and integrated governance – accordingly it often requires additional economic resources to fulfill its intermediation services between network constituents on the *interaction* layer. Coordination and decision-making amongst the software provider and network constituents are also resource intensive business functions. While legacy organizational structure requires these investments, the proliferation and maturation of BC-based decision-making and coordination capabilities may stand to supplement or streamline these governance processes.

The *application* layer also inherits functional attributes of the *foundational* protocol and *interaction* layer. In BC-based applications, that means that the integrated governance, computational, and financial capacities are retained along with the administrative and business process efficiencies that may exist on the *interaction* layer. Accordingly, the possibility for additional network constituents to participate remains due to lower economic barrier to entry. At this *application* layer, the open source platform architecture allows for applications to interact: securely sending data and assets or executing contingent contractual business processes according to programmatic definition. All of this is secured by an immutable BC protocol backbone from which authority and security is derived. Potential NE on this layer arises from this application modularity: the secure and transparent execution of interorganizational business processes with the capacity for multiple application or software functions to execute in tandem with one another. The software connecting functionality of BC technology, described by Xu *et al.* (2016) is especially relevant at this layer. Platform cooperativism and the associated benefits of coordinated incentives may arise at this layer through the structuring of behavioral or economic incentives by a given application.

Interoperability is a key issue facing legacy SCIS. This can be attributed to differences at the *foundational* layer of each respective ERP, EDI or CRM software solution. The *interaction* and *application* layers of legacy software architecture inherit these differences but lack the immutable and transparent automation infrastructure that enables interoperability on a BC-based platform. Based upon a synthesis of empirical studies on NE in software markets, Kemper (2009) concludes that software incompatibility is a leading consideration in corporate decision-making, and thus he highlights the importance of NE that may arise from software compatibility. Specifically, ERP and EDI platforms are identified by Kemper as markets where NE are likely to become important. He bases this conclusion on von Westarp's (2003) research that business leaders are becoming increasingly concerned with system standardization and external-facing interoperability, especially regarding ERP and EDI software.

6. Network effects in BC and SC: case studies

In what follows, we utilize the theoretical groundwork laid out above to discuss the current BC ecosystem, SC pain points and use case studies to explore actionable industry insights about BC-enabled NE in the field of SC logistics. We consider the broader implications for BC developers and the BC application ecosystem in the context of this network effect framework.

To do this, we review real-world case studies that support and clarify the academic literature and theory described above. First, we discuss ConsenSys, a BC company that incubates Ethereum-based projects that contribute to the BC ecosystem's foundational infrastructure. This business model, centered around application effects on the Ethereum platform, has been adopted in a SC context by agri-business company Covantis. The Covantis case study illustrates the parallel nature of SC network business processes and application networks that offer automation capacities for those business processes. Last we mention an IBM and Maersk case study to provide additional supporting evidence of SC pain points and BC's theoretical ability to address them.

6.1 ConsenSys case study

In today's BC development ecosystem, much focus is allocated towards the development of foundational single-use and localized applications. The leading BC technology company, ConsenSys, is oriented around this maturation of the BC ecosystem – creating infrastructural

BC applications on the Ethereum network that stand to provide a secure foundation for other novel applications and use cases. The ConsenSys product suite spans several core competencies that the organization has deemed foundational for the development of "next generation' applications, launching modern financial infrastructure, and accessing the decentralized web" (ConsenSys, 2022a). Most relevant to this research is the CodeFi suite of finance and commerce applications. This suite is its own small ecosystem of interoperable applications for business process automation, asset digitization, tokenization, currency exchange, compliance, data and risk analytics. ConsenSys's other contributions to the BC ecosystem include tools for smart contract security auditing, developer tools like web APIs for BC services, and an open source platform for configuring new foundational layer protocols to customize permissions, privacy and transaction parameters amongst other variables (ConsenSys, 2022b).

ConsenSys's actions and selection of infrastructural applications has been a reflection of the process of BC ecosystem maturation discussed above: with foundational elements that are leveraged by novel applications. The original ConsenSys approach to this infrastructure development was dubbed the "hub and spoke" model, as seen in Figure 2 (ConsenSys, 2017). This model of application development centered around the same premise of building out a powerful foundation of infrastructure elements, ones that make up their core product suite today and incubating an ecosystem of other "spoke" applications. Many of these spokes shown in Figure 2 have been spun out into their own respective and independent teams since then. Despite ConsenSys's contributions towards the overarching interaction and application layers, foundational protocol layer problems like the scalability, security and decentralization trilemma are being addressed in an open source fashion. ConsenSys's "Quorum" toolset allows for the configuration of BC protocols in ways that overcome only selected elements of the trilemma.

Figure 2.
ConsenSys "Hub and Spoke" business model to create an ecosystem of modular and interrelated BC infrastructure (ConsenSys, 2017)

ConsenSys serves as a real world example of the importance of application architecture as described by Xu *et al.* (2016) and Shi (2021). The application effects that may arise from the modular application design seems to be understood at least implicitly by ConsenSys professionals. Similarly, this developmental trajectory follows Lakhani and Iansiti's (2017) framework for the stages of BC development, namely, ConsenSys' foundational "single-use" and "localized" applications may provide a basis for product suites that eventually "substitute" or entirely "transform" business sectors. Our research calls out this relationship and provides an academic foundation for a more detailed investigation of NE dynamics in this context.

6.2 Covantis case study

Quorum, along with CodeFi and a couple other products in their suite have been adopted by Covantis: a SC information technology company that focuses on the execution of bulk agri commodity trade processes. The Covantis initiative is to facilitate the digitization of global SC processes in the agricultural trading and shipping industries. Within their agricultural niche, Covantis estimates that their BC platform allows for the automation of 60% business process execution tasks, a 70% increase in transaction speeds, 90% reduction in re-keyed entries, and 80% decrease in error rates and inconsistencies. Furthermore, by leveraging the application ecosystem offered by ConsenSys and within months of the project going live in February 2021, Covantis has streamlined operations amongst a network of 16 agri-groups comprised of 45 legal entities with 500 users. Their goal is to continue the expansion of their SC network and the integrated services/applications on the platform. Implicitly this means utilizing the trustful, transparent and collaborative efficiencies of their automation and choreography monitoring platform in order to attract, integrate and create value for all SC partners involved (ConsenSys, 2022c).

This Covantis case study serves as a concrete example of the value BC application ecosystems stand to offer in the SC contexts. Here. we abstract the case study using the theoretical framework presented in this paper. Simply put, the growth of a SC network represents increases in the number of connections amongst network nodes. Each connection or interaction requires some business process execution to facilitate the flow of information, assets or subsequent downstream processes. Utilizing legacy software or physical documentation systems pose challenges with key operational performance factors like lead time, traceability, dispute resolution, compliance, information delays and logistics. On the other hand, utilizing BC-based applications with the features of active mediation and choreography monitoring allows for the streamlining of information, asset and process flows as the network of constituents and contingent business processes grow. In this scenario, Covantis's ability to attract, integrate and create value for SC partners directly corresponds with the functions enabled by the ecosystem of applications they utilize. As their network grows, existing SC partners benefit from the addition of new service providers to the network. Similarly, as new applications and digital competencies are integrated into the BC application ecosystem, existing network members may benefit from an expanded range of business process intermediation with increased efficiency, savings or security.

6.3 Maersk case study

Maersk's 2014 investigation into their SC found that one shipment of refrigerated goods from Mombasa to Europe generated over 200 documents amongst 30 unique members of its SC (Haswell and Storgaard, 2017). The schematic diagram in Figure 3 illustrates the disjointed SCIS and physical process flow through a legacy SC network like this, although on a significantly reduced scale.

Schematic diagrams in Figures 3 and 4 are simplified visual representations of the Maersk study. Figure 3 shows how a disjointed network of software and physical processes results in many tangential or parallel processes in the flow of assets, verifications, documents, etc. through a SC network. Due to the lack of shared platform infrastructure, processes and attestations may require additional time and resources in order to execute, trace, ensure compliance, and verify or aggregate information. Figure 4 below illustrates a hypothetical visual representation of an alternative SC network interacting on a unified BC-based platform. It shows the SC's flow of assets, verifications, documents via an interoperable suite of BC applications whereby a single digitized record of the asset accrues the various requisite attestations as it flows through fulfillment process on a common BC platform. Through flexible and modular application architecture, process execution may be automated with associated information easily traced, verified and aggregated. In this scenario, the shared foundational BC platform infrastructure amongst constituents and their applications allow for automation such that information, asset and process flows may be integrated and seamless. In practice, this would have the potential to reduce those 200 documents to a single digital record flowing through the network's interconnected applications and receiving its respective attestations for digital bills of lading, packing lists, letters of credit, insurance policies, etc. At the same time, by reducing the financial and administrative costs associated with these documentation processes, the economic barrier to participation in this SC network is lowered, allowing for more potential constituents and competencies. As new constituents join these networks, they may participate in any collaborative or joint decisions amongst their SC network.

Through this case study and its exemplification of the development, adoption and expansion of the BC and SC ecosystems, we see many of the phenomena described in the literature. The case study is a primitive example of substitution level digitization from Iansiti and Lakhani's stages of BC ecosystem maturation (2017). This substitution level digitization occurs primarily at the interaction layer of BC architecture. In considering the value propositions and structure of the platform and its network constituents, elements of all network effect typologies are present in some capacity and are foundational in a cost–benefit analysis of SC network participation and platform adoption.

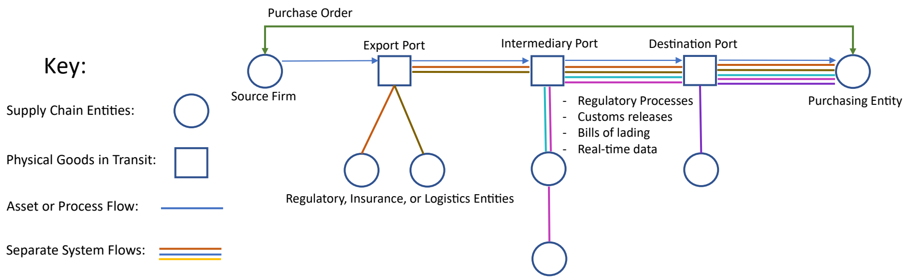

Figure 3.
Disjointed and cumulative process/ document flows through SC

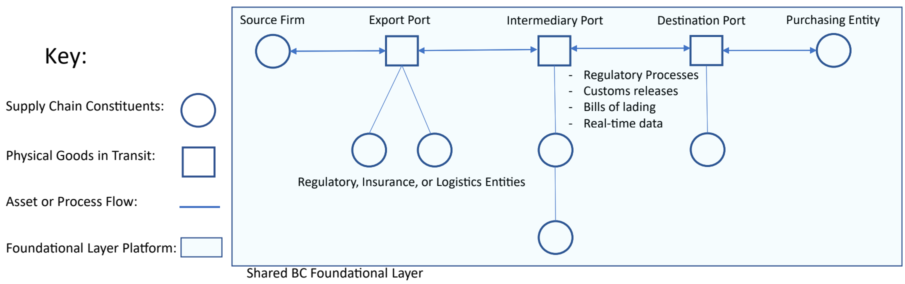

Figure 4.
Unified back-end platform for seamless business process execution and configurable bi-directional data transfer

Accordingly, business process scope and execution frequency are important factors in understanding the possible benefits of BC adoption. Specifically, as BC technology develops from the single-use stage to localized to the substitution stages of maturation, individual industries and processes will outpace others as the focus of these developments. With the high level of inter-organizational business process execution in SC logistics, developers and managers alike should consider the cost, frequency and scope of these processes while deliberating over the adoption of a BC platform or considering potential application development opportunities to address the "low hanging fruit" of SC inefficiencies.

7. Discussion

The above research analyzes previously unexplored relationships across the fields of SC, BC and NE. Here, we discuss the practical implications of this synthesis in the context of existing SC and BC research reviewed in Section 3. Extant literature promises improvements across a wide range of SC processes that may result from BC but fails to elaborate how those benefits may come to fruition. Accordingly, we discuss the practical implications of relevant NE theory on extant literature. We utilize Shi's (2021) BC architectural layer framework, Xu *et al.*'s (2016) BC software connecting capacity research and Lakhani and Iansiti's (2017) stages of BC development framework to clearly define and contextualize the discussion.

Section 3.1 literature reviews BC benefits relating to security: resilience to error, hacking and corruption; improvements to SC transparency, durability and process integrity; and novel data collection, storage and management capacities (Dong *et al.*, 2017; Swan, 2015; Abeyratne and Monfared, 2016). BC security benefits arise primarily from the *foundational* protocol layer and from its provisioning of a secure environment for process execution at the *interaction* and *application* layers. This security can be traced back to the governing consensus mechanism and its configuration of security, scalability and decentralization settings. Because the *interaction* layer inherits the secure computational environment provisioned by its *foundation* protocol, the cited security benefits also arise as a function of the number of interconnected SC constituents – nodes and users – at the *interaction* layer of the network. Similarly, cited security benefits arise as a function interconnected SC processes or applications that are interconnected at the *application* layer. Security benefits at the *application* layer are associated with BC's unique software connecting capacity through the common *foundation* layer. Practitioners and researchers should consider the number of interconnected network nodes at all BC architectural layers when considering the benefits of BC adoption for security improvements.

Section 3.2 reviews smart contract literature and its implications for SC automation infrastructure. Case study literature in 3.2 and 3.3 discuss many *single-use* and some *localized* implementations of BC smart contracts for process improvement and reintermediation. Smart contracts are automation infrastructure that exist at the *interaction* and *application* layers of BC. Each *single-use* smart contract process improvement can be thought of as an individual node at the *application* layer. At the *interaction* layer, network constituents may utilize the individual smart contract node to mediate an interaction with another network constituent. *User NE* may create additional value for network participants seeking to execute that smart contract business process with additional constituents. As the BC ecosystem matures, the *single-use* smart contract node on the *application* layer may be called on by another process or application node. In this way, *application NE* begins to manifest through process interconnectivity. Practically speaking, practitioners and researchers alike should pay close attention to developments that increase process interconnectivity. For example, Eggers *et al.* (2021) review case studies across the domains of insurance, logistics and network security. The smart contract automation in these examples is either *single-use* or *localized* and requires additional automation infrastructure to interconnect the insurance, logistics and security features mentioned. This process interconnectivity may yield *application* NE that are associated with the *substitution* tier of BC development. Similarly, practitioners and researchers should consider the importance of native governance mechanisms (at both *interaction* and *application* layers) that allow for the collaborative maintenance and governance over *application* layer features.

Section 3.3 reiterates BC potential for streamlining information flows, capital flows and logistics flows to enable dynamic and efficient SCs. As discussed above, these flows are contingent upon *interaction* and *application* layer interconnectivity. The Covantis case study illustrates this issue through their adoption of ConsenSys' BC application suite. As the BC application ecosystem continues to mature, application interoperability will be a key consideration for developers, adopters and investors alike. As discussed, BC core value proposition for SC is providing a secure environment for inter and intra organizational automation infrastructure. Researchers and practitioners can expect novel markets and services to arise from lowered economic barriers to entry, new measurement and payment capabilities, and the integrated governance functions that would allow these markets to self-govern. Novel markets, like the above-mentioned Golem Network market for computational power, are especially important for BC and SC professionals. In particular, as novel markets mature, industry professionals should analyze potential integration opportunities to enhance application interconnectivity. Novel markets represent previously economically infeasible business processes that most directly benefit from BC automation infrastructure. Integration of the newly feasible processes into a wider ecosystem of applications can be expected to drive value for all interconnected processes. Software platform dynamics are another key consideration in this regard. BCs with the highest application development activity and best development tools will naturally attract more developers, more applications and new market opportunities. We recommend more comprehensive analysis of "BC ecosystem health" to cross-compare different BC platforms and better understand the importance of variables like "developer network effect", "developer collaboration networks", application development activity and available development toolkits.

8. Conclusion

This research is a unique contribution at the intersection of BC, SC and NE literature. Research studies across these three fields are synthesized in order to better understand the disruptive and revolutionary potential attributed to BC. The fundamental value propositions and novel technological capacities stemming from BC technology are analyzed in the context of SC networks and the overarching technological trend of NE.

To review the questions set forth in the introduction:

(1) What are the qualitative aspects of BC technology that would bring value to a SC? The main qualitative aspect of BC that stands to impact industry is its ability to multi-laterally align incentives between network members through an integrated computational and financial backbone. This is accomplished through automation infrastructure, or applications, that are built with features of a secure *foundational* network protocol, active mediation, choreography monitoring and integrated governance. Another qualitative feature of BC that amplifies the impact of incentive alignment, automation infrastructure and governance would be its software-connecting capacity that enables secure interoperability between applications.

(2) How do those aspects relate to the existing ecosystem of BC networks and applications? In terms of the current developmental state of BC, these features are not yet fully mature and are dependent on technological progress at the foundational protocol layer (L1), interaction layer and application layer (L2). Through this progress, the process of BC application ecosystem maturation will occur and facilitate the transition from *single-use* cases, to *localized, substitution* and eventually *transformational* capacities. Explicitly, extant case study literature illustrates many *single-use* and *localized* BC applications in SC. As *single-use* and *localized* applications develop and become more versatile across SC use cases, new automation infrastructure can enable interoperability between those applications and create additional value for SC networks by streamlining business process execution across departments, organizations and even industries.

(3) How do BC technological fundamentals pertain to the application of network effect theory? BC technology merits additional research as it pertains to NE because of the novel integrations of asset transfer, transparency, platform cooperativism, trustfulness and automation. The novel feature integrations are especially important in considering BC as a new type of software platform – software platforms being a category of technology with proven network effect dynamics. BC theoretical frameworks presented by Shi (2021) and Xu *et al.* (2016) contextualize a new understanding of NE as it applies to the various architectural layers of a BC platform and as it applies to BC's software connecting capacity. BC also represents a development in information technology features that satisfies Kemper (2009) and von Westarp's (2003) descriptions of NE relevance for industries where software incompatibility, external-facing interoperability and system standardization are of concern.

(4) What are the main considerations in attributing the disruptive potential of BC technology to these NE? The main considerations in attributing BC disruptive potential to NE phenomena are the technology's software-connecting capacity and how that capacity manifests as the ecosystem matures. This software-connecting capacity parallels the flow of processes and information through a SC. Increasing efficiency in process and information flow may be achieved in parallel with the increases in software interconnectivity within the BC application ecosystem. Trends in this direction can be expected to follow the stages of BC development: *single-use*, *local*, *substitution* and *transformation*. By keeping these trends and phenomena in mind, BC developers and SCM practitioners alike may make more informed decisions in BC application ideation and development as well as SCM adoption.

This research does not cover the regulatory uncertainty, implementation hurdles, nor rate of technological adoption that are main considerations in the likelihood of this disruptive potential manifesting. Accordingly, these factors and many more demand further attention in understanding the likelihood and nature of this disruptive network effect potential.

This research serves as a broad framework for the potential NE that may arise from the maturation of the BC ecosystem. It also provides an analysis of how this maturation corresponds with the ascribed impact of BC technology in the SCM field.

Future research work attempting to understand the interrelation between the fields of SCM, BC and NE research has many opportunities and potential directions, some of which we list below:

(1) Validation of network effect typologies in BC platform contexts

(2) Empirical investigation of NE, specifically application effects, in the context of BC's software connecting capacity

(3) Quantitative research on business process interconnectivity and software process modularity

(4) Impact of integrated governance mechanisms on constituent joint decision-making, platform cooperativism and trustfulness between constituents

(5) Applied research to identify and understand potential business processes for BC-based automation through the framework of business process scope, interconnectivity, cost-efficiency and frequency

(6) Organizational research into the open source nature of BC protocol development and its downstream impacts on outcomes

(7) Deeper research into the nature of incentive alignment amongst competitive firms in a common network

This synthesis of existing BC, SC and NE research serves as a theoretical perspective to better understand the gap between reality and the "hype" underlying this new field. These theoretical perspectives stand to be validated empirically. The relationships identified in this research also stand to be explored in more depth and narrowed scope.

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