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An Attempt to Model Blockchain Implementation Cost Dynamics in Supply Chains

Ahmed M Deif
Industrial Technology and Packaging Dept., OCOB
California Polytechnic State University, CA, USA
Email: adeif@calpoly.edu (*corresponding author*)

Lorenzo Lynberg
Industrial Technology and Packaging Dept., OCOB
California Polytechnic State University, CA, USA
Email: lorenzo.lee.l96@gmail.com

ABSTRACT

This paper is an early attempt to explore the cost dynamics associated with blockchain implementation in supply chain. A system dynamic model is developed for that purpose that captures the theoretical value of blockchain implementation resulting from the accumulated costs and benefits encountered by supply chains over time. This model explores the promise of blockchain technology in supply chain logistics by synthesizing research from both fields to build a theoretical framework for understanding what factors drive costs and benefits of blockchain implementation. The main input elements in this model are the supply chain network size, the size of the supply chain entity seeking to implement blockchain information systems, and the level of process digitization desired. These inputs proliferate into qualitative cost and benefit relationships supported by existing research. These individual relationships are extrapolated into a quantitative format for modeling and synthesis. Results show that, the theoretical benefits of blockchain implementation generally grow in accordance with increases in digitization levels, firm size or network size. Network effects are identified as an underlying phenomenon in this relationship. The paper presents a novel framework for considering the relationships that underlie cost and benefit opportunities and challenges of blockchain in supply chains. Furthermore, important practical recommendations are proposed to help supply chain managers in some critical decisions necessary for successful and feasible blockchain implementation. The primary contribution of this work is a broad framework for understanding the functions underlying the often-touted benefits of blockchain technology in supply chains. These findings and synthesis serve to inform design and implementation considerations from a cost/benefit perspective and as a starting point for additional research.

Keywords*:* *blockchain implementation, cost dynamics, supply chain*

1. INTRODUCTION

The call for resilient supply chains in today's disruptive environment had increased the demand for digitization and digitalization of the different echelons of these chains. For this to happen, different technologies have been developed and implemented in the field of supply chain management. This includes artificial intelligence (AI), internet of things (IoT), cloud computing and blockchain (BC) (Haartman *et al.* 2025).

Blockchain acts as a distributed database that is shared amongst a large network. Blockchain serves to save this database as a digital format. From this digital format, blockchain can guarantee fidelity for authenticated users and a detailed record of data that ensures no need for a 3rd party regulator. Yaga *et al.* (2018) discusses the difference between blockchain and databases, as they appear to be very similar on the surface. The key difference between the two is how the data is structured. In a blockchain, the data and information are collected in groups known as blocks. These blocks have certain storage capacities and hold sets of information. When these blocks are filled, they are closed then linked to the previous block. From there, new data is added to a new block and is compiled as a chain. This allows blockchain to create a chain of encrypted and secure data that establishes an accurate timeline agreed upon by all constituents. This differs from the normal databases as these operate by structuring data into a table that can be manipulated once information is entered. Once a block is filled within the blockchain, it is given a time stamp and permanently becomes part of the blockchains timeline.

Blockchain produces improved accuracy by reducing or removing human involvement in the verification processes during data entry and retrieval. It can also greatly reduce overall costs as it eliminates the need for third-party verification (Enayati *et al.* 2024). Decentralization means that the data is nearly impossible to tamper with making transactions efficient, secure, and private. Similarly, blockchain promotes a completely transparent chain that further reinforces security. Milani *et al.* (2016) divide blockchain technology potential into seven categories, those being: transparency, quality, efficiency, compliance, agility, integration, and networking. With transparency at the center point, we can further categorize these values in to three pairs, quality and efficiency, compliance and agility, and integration and networking.

Despite the above-mentioned advantages and novel features of blockchain-based solutions in supply chain, challenges remain to be addressed to realize their potential. Scalability limitations are a foremost issue in addressing cost and security challenges that come with growth in network sizes. There is significant complexity associated with this growth. Namely, issues of network interoperability, business-process interoperability, as well as digitization and digitalization infrastructure requirements are all hurdles in real world blockchain implementations. Foundational technological progress and development in blockchain technology are required to address these technical issues. Still, other categories of external real-world hurdles must be addressed before the theoretical potential of blockchain technology can be realized. These include compliance with diverse laws and regulations, inter-organizational negotiations to establish shared blockchain application framework, and the issue of reconfiguring legacy information systems. In addition, with blockchain's technological immaturity, issues of user friendliness and usability are common as well as hardware capacities to bridge off-chain capacities with on-chain processes.

This paper focuses on blockchain implementation costs in supply chain contexts. Implementation cost reflects many of the above-mentioned challenges as well as other aspects related to initial setup and ongoing maintenance. This cost/benefit analysis is done through proposing a new dynamic model that captures many of the previously mentioned elements and exploring the overall generated value under different internal and external related parameters.

Naturally, an analysis of costs and benefits will be relative to current industry standards but also dependent upon the technological progress at the time of analysis. That is, any cost benefit analysis will change based on technological progress or the competitive environment. To mitigate this issue and circumvent the lack of real-world data, this paper reviews academic literature regarding theoretical benefits of Blockchain technology, analyzes the basis for these potential benefits, maps and assigns relationships between these technical features and supply chain benefits, and then synthesizes them with the costs of implementing a novel information technology. This research addresses a gap between the above-mentioned Blockchain capabilities and the lack of quantitative data in real-world examples of their implementation. To do so, theoretical research on these capabilities is synthesized with established supply chain phenomena to extrapolate an actionable understanding of the cost benefit dynamic across different Blockchain implementation scenarios.

Through this quantitative extrapolation of theoretical and qualitative relationships, we seek to answer the following questions. What are the attributes of blockchain technology that stand to impact business processes? How do those attributes relate to the larger question of theoretical cost-benefit expectations for a given firm? What are the main considerations in understanding whether a firm or supply chain stands to profit from blockchain adoption and what features are most important for maximizing profit?

2. LITERATURE REVIEW

A clear theme in the blockchain literature focuses on exploring the potential benefits that blockchain technology will bring to supply chain management. Dong *et al.* (2017) shows how blockchain technology exhibits information security advantages over existing supply chain management systems. These advantages result from blockchain network resilience that minimize single point of failure vulnerabilities from error, hacking, corruption, or other attack. Swan (2015) discusses the organizational, technological, and economic benefits that arise from blockchain's features of transparency, security, durability, and process integrity. Abeyratne and Monfared (2016) review how blockchain networks provide a novel means for data collection, storage, and management on open, neutral, reliable, and secure blockchain platforms. Tapscott and Tapscott (2017) show how blockchain's potential for disintermediation of payment networks, stock exchanges, and money transfer services contributes to the desirable organizational outcomes mentioned by much of the literature. Ward (2017) elaborates on blockchain-based disintermediation and how supply chain non-value-added activities would be reduced because of reduced transaction costs and time. Tönnissen and Teuteberg (2020) ground these expectations, explaining that blockchain has only led to re-intermediation at its current stage of technological development.

Smart contracts and their potential benefits for the supply chain were also part of this growing line of research. Hofmann *et al.* (2017) reviews how smart contracts are organized, self-enforcing, and self-executing financial arrangements and can ensure timely and automated payments to streamline supply chains. Weber *et al.* (2016) specifically identify two aspects of blockchain based smart contracts that enable execution and monitoring of business process on an untrusted network. These two aspects are the *active mediation* of business processes and the *choreography monitoring* of those actively mediated processes. Weber *et al.* (2016) add that smart contracts enable significant visibility and serve to enable information processing technology: a key factor in operational performance and organizational flexibility. More recent research elaborates on implementations of the active mediation and choreography monitoring functions blockchain based business properties (Guerreiro *et al.* 2020; Klinger *et al.* 2020; Evermann *et al.* 2020). Eggers *et al.* (2021) explore smart contract value propositions through case analyses of multiple companies utilizing these key smart contract features. They cite one company that provides additional customer value by automating front-facing and back-facing processes - this reduces turn-around time and ensures timely insurance pay-outs. Another company uses blockchain technology to re-intermediate the anti-malware market, offering a smart-contract platform for securely exchanging documents, information, and assets between clients and service providers.

A third company in the transportation and logistics industry securely measures and communicates shipment temperature data for pharmaceuticals. These novel organizational capacities are realized through choreography monitoring and automatic mediation offered by smart contracts. Eggers *et al.* (2020) 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 reviewed in their study - insurance, logistics, and even network security - are pertinent throughout supply chains.

Other literature focuses more narrowly on blockchain implementations in supply chains. For example, Ghosh and Tan (2018) offer a simple framework for blockchain implementation ito enhance supply chain information sharing. Perboli *et al.* (2018) propose a blockchain implementation framework to optimize fresh food delivery. They demonstrate how blockchain helps in reducing the logistics costs and in optimizing the operations. Pour *et al.* (2018) demonstrates how blockchain with integrated agent based AI technology could improve the mining industry. Tian (2016) shows how blockchain with RFID had improved traceability in Chinese agri-food supply chain. Additionally, Kshetri (2018) cites the positive impact of blockchain solutions on supply chains across eleven different industries including logistics, manufacturing, retail and finance to name some.

Lim *et al.* (2021) offer a comprehensive literature review detailing the themes and potential of blockchain technology specifically in supply chain contexts. They reiterate extant literature and summarize the technology's potential for streamlining information flows, capital flows, and logistics flows to enable dynamic and efficient supply chains. They cite real world examples: 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 supply chain transparency and information sharing (Chang *et al.* 2020). Their literature review specifies themes consistent across blockchain research: "impact," "function," and "configuration" along with subthemes like product traceability, information sharing, trust systems, that touch on the various above-mentioned aspects of blockchain technology that lead to improved order management, production, workflow, and logistics. Other work extended this to different types of supply chain including humanitarian supply chain (Ariningsih and Sundara 2019).

A much smaller portion of extant literature discusses the technical and organizational hurdles facing blockchain implementation in supply chain. Koteska *et al.* (2017) reviews the challenges facing blockchain implementation from a quality (specifically operation quality) perspective. They conclude that the research in this direction is immature and requires more effort. Rimba et al (2017) points to the importance of attending to the cost *and scalability* challenge when implementing blockchain. They compare the cost for computation and storage of business process execution on blockchain vs. a popular cloud service. Results show that in its current technological infancy, cloud services still outperform blockchains in this regard. Galvez *et al.* (2018) focus on the challenges facing blockchain implementation in the agriculture supply chain, specifically to improve traceability. Their outlined challenges included complexity of the supply chain, lack of records, lack of unification and conflicting demand. Wamba *et al.* (2020) conclude that blockchain in its current state of development requires significant computation power, IT infrastructure, and regulatory uncertainty that all add to costs. The authors also identify predictive and explanatory modeling as a direction for future research (Wamba *et al.* 2020). In the context of this proposed model, certain technological costs of computational power and IT infrastructure can be expected to follow Moore's Law – doubling in capacity every year or two. This correlates to a rapid reduction in associated costs of hardware.

The above brief review suggests that most of the research focused on the value generated by blockchain within supply chains with special emphasis on improved information sharing forms and capabilities. Less work discussed detailed implementation challenges especially from a cost perspective. This gap is even more evident if we seek quantitative approaches or models for either cost implementation challenges or potential benefit. The proposed model in this paper attempts to fill part of this gap through offering a dynamic theoretical perspective on the cost/benefit analysis of implementing blockchain-based solutions in supply chains.

3. BLOCKCHAIN IMPLEMENTATION COST MODEL

A system dynamics model is proposed to explore the cost/benefit interactions of blockchain implementation to create value in supply chain. The system dynamics approach is an effective means for assessing causal relations between strategic decisions and their outcomes. In this regard, it is useful for ascertaining the relationship between system structure and the dynamic behavior that results from variables in that system. Therefore, we believe that this approach would be useful in evaluating the potential outcomes of investment in blockchain technology against the associated costs within interconnected systems like supply chains. Furthermore, system dynamics serves to establish an effective viewpoint on how related implementation factors like trust, collaboration, supply chain digitization and a variety of other relevant factors play out together to structure decision making based on a system of causal relations (Feng 2012).

It is important to note that due to the early stage of full blockchain implementation in supply chains, we acknowledge that the proposed model will lack some degree of quantitative accuracy, especially in capturing non-linear relationships. However, utilizing the qualitative causal framework that this approach establishes may serve to structure decisions and analysis regarding important management practices related to blockchain implementation in supply chain systems. We also understand that the essential viewpoint taken by the proposed system dynamics model is that dynamic behavior is a consequence of the suggested blockchain costs and benefits' system structure as well as the selected input settings (the two factors are not all-inclusive). Nevertheless, the purpose of this attempt is to learn about the general blockchain implementation cost/benefit modes of behavior and to thus suggest policies and considerations that guide this implementation within supply chain.

Figure 1 below (Appendix 1) displays the proposed dynamic model for blockchain implementation cost/benefit analysis. The following sections will discuss the modeled variables and the underpinning logic of their modeling, followed by the suggested quantitative relationships that capture their dynamic interactions. The discussion will start first by the costs associated with blockchain implementation and then will move on to the selected benefits expected by such implementation. Readers are advised to refer to the diagram below for visual reference to all relationships described below.

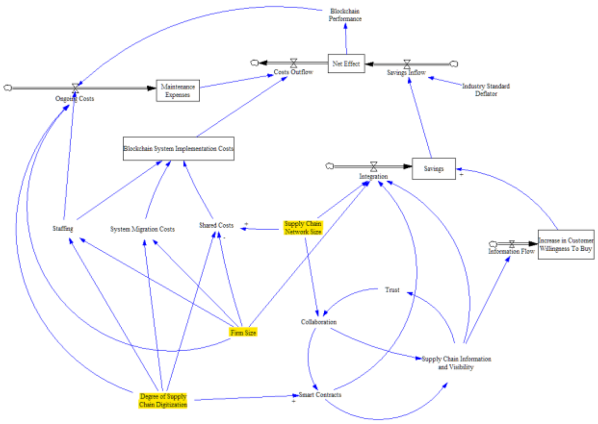


Figure 1 Dynamic model for blockchain implementation cost/benefit analysis. Created with Vensim system dynamics modeling software.

3.1 Blockchain Implementation Input Elements (Highlighted Fig. 1)

In this section, we discuss the three main blockchain implementation inputs (highlighted above in Figure 1) as they play a critical role in governing the cost/benefit dynamics sought in this research. Accordingly, the dynamic flow of the model's relationships begins with these inputs and proliferates into cost and benefit relationships. A practical explanation for these inputs is presented.

The implementation of blockchain technology is fundamentally related to both the digitization and digitalization infrastructure and the objective of supply chain network. This is why the model centers on an important first input variable called the Degree of Supply Chain Digitization (DoSCD). This variable represents the scope and depth of the blockchain capacities that the firm or network of firms desire to implement. In this model, we follow along the proposed four different levels of digitization by Iansiti and Lakhani (2018) namely: *single-use, localization, substitution,* and *transformation* that capture the four possible input values of DoSCD. To further explain the practical meaning of each of level, we follow the interpretation of Dobrovnic *et al.* (2018) for these four levels. The first level, which is the *single-use* scenario (DoSCD = 1), is the equivalent to modeling the implementation of a blockchain solution with one highly specific purpose. This is the typical case for a private blockchain with exclusive read and write capabilities for asset management, internal transactions, identity verification, or a range of other specific use cases. More robust and inclusive private network applications blur the spectrum as they transition into the *localization* level (DoSCD = 2), which is the second level of supply chain digitization. This level represents a blockchain application designed to fill in some localized process within a larger scheme. This scenario is similar to the single-use outcome but extends the scope of the automation to closely adjacent business processes that may execute in tandem with the first single-use application. The next level of digitization, *substitution* systems (DoSCD = 3), build on existing single-use and localized applications, but are high in coordination needs because they involve broader and increasingly public use cases. The processes that the supply chain partners hope to replace in this stage may be full-blown and deeply embedded within organizations and institutions. For example, supply chain tracking and payment system from raw materials to end user is at this level of digitization. A blockchain-based inter-organizational ERP or CRM system would also fall into this category. It can be argued that this is the highest degree of digitization that is currently feasible with existing supply chain networks infrastructure. As blockchain technology continues to progress in development, scalability, and maturity *transformational* (DoSCD = 4) applications will become viable. Transformational applications reflect a future state of the blockchain ecosystem where, not only have scalability barriers been solved, but the ecosystem of applications has matured to a point where supply chain functions are mediated by blockchain and are widely available and cross compatible or modular between many use-cases.

To quantitatively capture the different levels of DoSCD, research supports the notion that there is a power law distribution to the functionality these levels represent. That is, DoSCD = 2 represents an order of magnitude increase in the functionality and scope of a blockchain at DoSCD = 1. Specifically, this is based on Metcalfe's Law of network value, which correlates the value of the network with the square of its number of active users. Alabi (2017) showed that blockchain networks follow that law in their digital transformation. This power-law network effect behavior requires further elaboration as it represents the crux of the value that blockchains offer.

Most fundamentally, the price of blockchain-secured cryptocurrency assets has followed this power law behavior over the past 13 years since Bitcoin's start. This reflects that the technology and currencies gain utility through adoption and the number of interconnected nodes: a positive feedback loop that has yielded consistent exponential growth. Pictured in Figure 2 is a logarithmically scaled chart of the total market capitalization of blockchain-backed crypto assets (Coinmarketcap.com 2021). In Figure 3 a linearly scaled graph displays the exponential growth in blockchain wallet users over the same timeframe (Best 2021). This correlation supports the notion that blockchain value is associated with the number of interconnected nodes, in this case wallet users, in the network.

Figure 2 Logarithmically scaled graph of the total sum of cryptocurrency market capitalizations.

Kemper (2009) brings clarity to the nature of network effects themselves. He cites, "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 distinguishes between multiple types of network effects. Most relevant are *horizontal direct network effects* that arise from the additional utility gained through additional network participants. A second order of network effects are *application effects* that are characterized by the increase in utility gained through compatibility with other applications. At their most fundamental level, both represent increases in network interconnectivity through additional nodes: whether those nodes are users/network participants or specific application functions. *Increases* in DoSCD represent increases in possible application effects at multiple levels.

In the context of modeling the digitization of supply chain networks through Blockchain, there are multiple echelons of possible *horizontal* and *application* network effects. To better understand these potential network effects we introduce the second and third input variables: supply chain network size and firm size.

The second input variable that the cost/benefit dynamics relies on is the Supply Chain Network Size (SCNS). SCNS represents the relative size of the supply chain network a firm is participating in. It is also associated with the variety of external-facing processes between supply chain constituents. In the context of this analysis, the value of supply chain digitization lies in the network effect between constituents (Korpela *et al.* 2017). DHL Trend Research's 'Blockchain in Logistics' report, Kückelhaus (2018) also confirms this notion of how additional participants in the network increase value for all constituents. This can be attributed to the trustful common platform that blockchains stand to provision amongst untrusted network constituents.

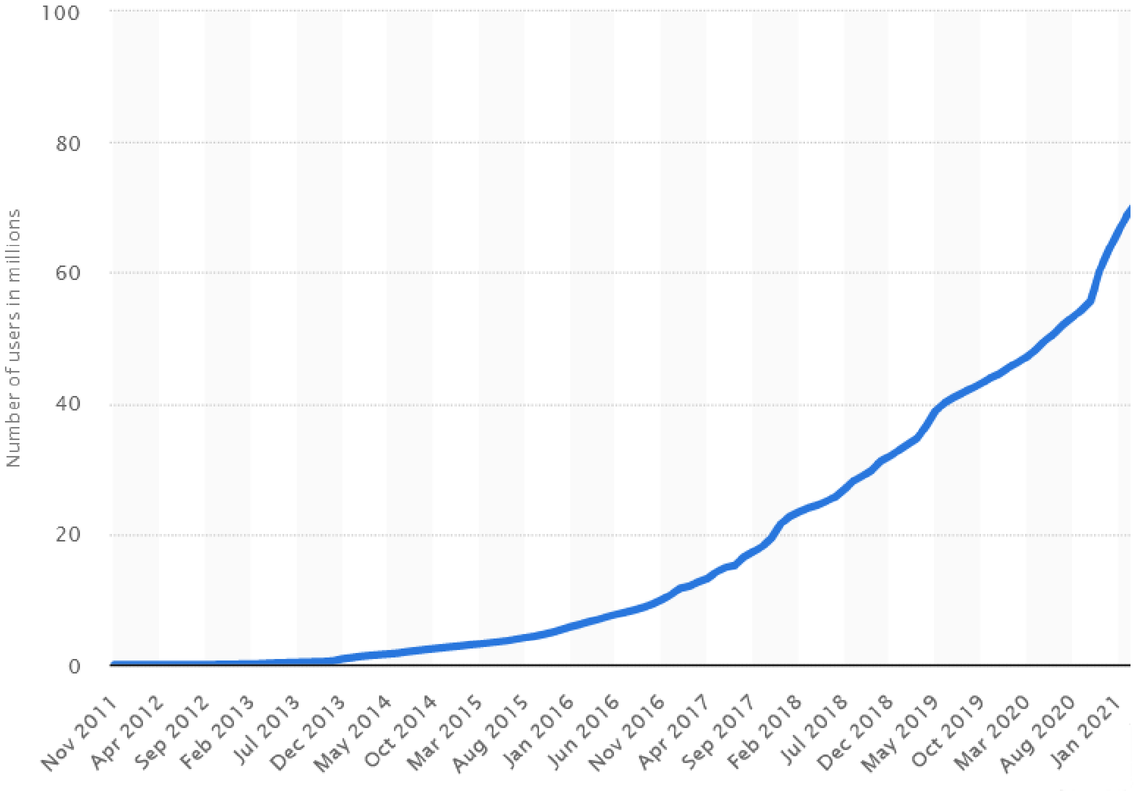


Figure 3 Linearly scaled graph of total sum of blockchain wallet users.

A third input variable that influences the blockchain implementation costs is the Firm Size (the firm refers to any echelon in the supply chain that may be considered the subject of the model). This variable is associated with internal-facing processes, the velocity at which these processes are executed, and the range of possible processes that stand to be digitized. The model assumes that increased firm size and its supply chain relationships will result in an increased complexity of the application necessary to satisfy that firm's desired degree of supply chain digitization. The established correlation between costs of blockchain implementation and the size of the firm is supported by Perboli *et al.* (2018). Thus, the degree of supply chain digitization, the firm size, and the supply chain network size are all correlated with the complexity associated with developing and implementing the appropriate blockchain-based supply chain management system. Naturally, this development and implementation complexity are positively contributing to the costs necessary to implement this system as will be highlighted by the model's analysis. Furthermore, the linear inputs for Firm Size and SCNS (1, 2, or 3) are representative of power-law distribution that firms follow (Ge *et al.* 2020; Bryan *et al.* 2020), each input representing an order of magnitude difference between the other possible inputs. These discrete values are used in the interest of capturing the relative differences between small, medium, and large sizes. While we lack quantitative data to ascribe specific firm sizes to certain revenue amounts, the formulation of the quantitative relationships presupposes that, if a firm with annual revenue of $100,000 has a size of 1, a firm with a size of 2 would have revenue between $1 to 10 million. These power-law relationships DoSCD shares with firm and network size are captured in the cost side equations.

Essentially, these three inputs are selected for the reason that they are the primary consideration in understanding possible network effects. With more constituents in the supply chain network, there will be more participants interacting in the network. By sharing and connecting through a common platform, the network may gain value through the members' capacity to facilitate automated process execution between a larger number of parties. This level of inter-firm connectedness is enabled by the blockchain features of security, transparency, trustfulness, information visibility, process integrity, and durability described in literature review. By better understanding these network effects on both the cost and benefit side and understanding how the technological value propositions of blockchain contribute towards financial benefit, we can gain actionable insight into a theory of how blockchain will mature in supply chain contexts. We elaborate on the nature of these network effects below.

The primary input variable, Degree of Supply Chain Digitization reflects the scope and number of processes that stand to be digitized on the Blockchain. These processes stand to be designed so that they are connected, compatible, or modular thus potentially yielding *application effects*. Accordingly, increases in the input value of DoSCD represent large increases in the functions enabled by the system. The conversion of the system's application effects into actual monetary benefit is dependent upon the variety and frequency of the processes execution as well as the cost efficiency and effectiveness of the new automated process. The variety and frequency of execution is associated with both firm size as well as the degree of digitization that the system enables. Meanwhile the cost efficiency is more closely tied to the *application effects* that arise from interconnected process in the system.

Based upon a synthesis of empirical studies on network effects in software markets, Kemper (2009) concludes that software incompatability is a leading consideration in corporate decision making and thus highlight the importance of network effects that may arise from software compatibility. Specifically, Enterprise Resource Planning (ERP) and Electronic Data Interchange (EDI) platforms are identified by Kemper as markets where network effects 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.

In a separate but relevant line of research Xu et. al (2016) highlight the importance of understanding Blockchain as a software connector. They highlight that Blockchain fulfills the software connector services of communication, coordination, and facilitation. In addition, they describe trade-offs between blockchain as a software connector and existing legacy software connectors. Xu et. al's (2016) analysis compares centralized software connectors to blockchain based ones. It reiterates many of the benefits and challenges facing blockchain technology that were mentioned in the above literature review. These areas of comparison include cost reduction, data and contract management, privacy, scalability, performance, incentives, and re-intermediation. In this context, Xu et. al's framing of blockchain technology as a software connector further supports the underlying potential for *application effects*, power-law behavior, and theoretical capacity to facilitate network effects. In the context of Kemper's (2010) analysis of network effects in software markets, it stands that this software connecting capacity may yield yet another echelon of possible application network effects – namely network effects arising from the number of interconnected business departments with their respective software systems. This may align with the fourth, transformational, level of supply chain digitization.

To summarize these network effects as they pertain to the DoSCD input, the first 'single use' tier of DoSCD does not reflect any *application effects*. At this level only *direct horizontal network effects* arise from system utilization. This system utilization is associated with Firm Size and Supply Chain Network Size- it impacts the cost/benefit structure at every level of DoSCD. The second 'localization' tier of DoSCD reflects *application network effects* that begin to emerge as the scope of automated processes increases. The *horizontal effects* of system utilization compound upon these *application effects.* The third 'substitution' tier reflects an increase in *application network effects* from additional scope of automated processes and from the possibility that multiple compatible processes may begin to generate another echelon of network effects associated with either inter or intra-firm software compatibility. The fourth ‘transformational’ tier of DoSCD would reflect the maturation of these multiple tiers of network effects. In terms of the cost side impact of DoSCD, Ohgeneovo (2014) details the relationship between software complexity, development costs, and maintenance costs. In line with the complexity necessary to ensure network effects and process compatibility, DoSCD proliferates into the cost side of the model as well as the benefit side.

The nature of the value of the DoSCD suggested in this research is shown in equation 1. The values for each digitization level is will follow a linear range (1, 2, 3, or 4) to represent the tiers of digitization described by Iansiti and Lakhani (2017). These tiers are a proxy for capturing the range and nature of the processes that will be digitized on the blockchain as the exact network effects associated with each progressive tier are indeterminate. These values were selected for sake of simplicity to demonstrate the effect of this variable on the cost/benefit dynamics. The specific value of this variable will depend on the type of supply chain, the nature of process digitization, and is suggested for further research.

$$DoSCD(x) = Range(1,4) \qquad (1)$$

3.2 Blockchain Implementation Cost Elements

Within this framework of the three inputs, we add four other categories to encompass the costs incurred by the firm during the implementation process: *staffing* and training costs, *system migration* costs to overhaul pre-existing systems, and *shared costs* between the firm and its supply chain network (Perbioli *et al.* 2018). The logic behind selecting these four implementation cost categories is that blockchain is considered a type of information technology that requires alteration or replacement of legacy systems (Swan 2015; Mougayar 2016). Furthermore, shared costs may be thought of as the joint analysis and collaboration that is required to establish the system to be implemented.

It is expected that the firm size has a direct positive correlation with all cost variables while supply chain network size only acts upon the shared costs. These shared costs are inherent to the collaboration in developing and establishing a supply chain management system. In parallel, the degree of supply chain digitization is the basis for these costs and underlies the effects produced by both the firm and network size.

It is also important to note here that the model differentiates two different types of implementation costs through two different modeled system dynamics stocks: *ongoing costs* as well as the initial *implementation costs* level. Staffing costs, system migration costs, and shared costs are all relevant in determining initial implementation costs. Conversely, only staffing/training and maintenance expenses are considered ongoing costs. To contextualize these staffing and IT infrastructure expenses, firm size and degree of supply chain digitization are incorporated in the ongoing cost rate. The ongoing costs synthesize as a *maintenance expense* total. The ongoing costs variable captures the essence of all the expenditures a firm must make to successfully maintain a blockchain in a supply chain system. Case studies support the correlation between ongoing costs and the size and scope of the system infrastructure (Perbioli *et al.* 2018).

3.3 Blockchain Implementation Cost Elements Structure Relationships

Based on the previously explained three input variables with the four implementation cost categories and the two general types of blockchain implementations costs, various relationships were developed to capture how these inputs affect the costs associated with blockchain implementation in supply chain networks. In this section, we present these suggested structured relationships.

The relationship between staffing cost and DoSCD and firm size is captured in equation (2). *Staffing* in this model represents the human capital necessary to implement and maintain blockchain within the supply chain management system. The constant, *capacity level,* is raised to the power of Firm Size summed with DoSCD. This represents the relationships between system complexity and the staffing/training necessary to implement that system. That is, a higher degree of digitization necessitates more highly qualified developers and additional time or employees. Firm size compounds upon this complexity and reflects the power law distribution of the inputs. The purpose of the constant *capacity level* is to establish an administrative and operational basis upon which Firm Size and DoSCD act. This constant also inflates the basis for technical capacities needed for hiring and training

$$Staffing = CapacityLevel \,\hat{}\, (Firm\,Size + Degree\ of\ Supply\ Chain\ Digitization) \qquad (2)$$

Similar to staffing, *System Migration* in equation (3) is a function of DoSCD that sets the basis for the range of processes or systems that must be migrated. Raising DoSCD to the power of firm size reflects the compounding effect of the size or number of legacy systems to be replaced and the respective complexity associated with implementing new systems across an organization. That is, DoSCD is the basis for system migration costs and Firm Size reflects the magnitude of the effort required for the migration. The exponential inflation of Firm Size reflects the above-mentioned exponential difference between an input of 1, 2, or 3 for that variable. The exponential inflation of DoSCD reflects the complexity and difficulty of this migration that is associated with how embedded legacy systems are in the firm structure. Ge *et al.* (2020) support that Firm Size is associated with the age of the firm. It follows that the degree to which legacy systems are embedded in the firm are associated with firm size and firm age. These relationships are shown in equation (3).

$$System\ Migration = (Degree\ of\ Supply\ Chain\ Digitization) \,\hat{}\, (Firm\ Size) \qquad (3)$$

Shared Costs in equation (4) reflects the portion of development or collaborative costs the firm can expect to assume. The equation has two parts: the first reflects the overall scope of the project costs, as determined by the Supply Chain

Network Size raised to the power of DoSCD. SCNS is the basis for this exponential relationship, compared to DoSCD being the basis in equation (3), because we consider *shared-costs* to be more closely associated with the inter-organizational complexities and negotiations that are necessary to develop the blockchain system. DoSCD has an exponential effect on these costs given the network effect of increased system functionalities that give rise to exponential complexity and costs. In the second part of the equation we show that the ratio between the Firm Size and Supply Chain Network Size will determine the distribution of the above-mentioned development and collaborative costs. The exact cost distribution and quantitative nature of this relationship is an area for future research. Equation (4) reflects this relationship.

$$Shared\ Costs\ =\ ((Supply\ Chain\ Network\ Size)\ \hat{}\ (Degree\ of\ Supply\ Chain\ Digitization))\ *\ (Firm\ Size\ /\ Supply\ Chain\ Network\ Size) \qquad (4)$$

Total initial *Implementation Costs* are merely the sum of the previous three captured cost elements as shown in equation (5).

$$Blockchain\ Implementation\ Costs\ =\ Shared\ Costs\ +\ Staffing\ +\ System\ Migration\ Costs$$
(5)

The *Ongoing Costs* to maintain the blockchain based supply chain system is captured using equation (6). DoSCD is amplified (using a second-degree modeling) to reflect the number of processes that must be digitized and then published on the chain, each incurring some cost for computational effort that grows in accordance with the complexity of the process. This is combined with staffing costs to reflect the two main ongoing expenditure areas. The costs associated with these areas are largely influenced by the firm size which represents the frequency of process execution and staff that the system requires. This effect is balanced by a Ramp function that represents the trend for technology to advance, saturate and eventually decrease associated expenditures.

$$Ongoing\ Costs\ =\ (Degree\ of\ Supply\ Chain\ Digitization\ \hat{}\ 2\ +\ Staffing)\ *\ (Firm\ Size\ -\ RAMP(0.02, 0, 100))(6)$$

Maintenance Expenses are represented as a stock that is directly related to the ongoing costs as shown in equation (7).

$$Maintenance\ Expenses\ =\ Ongoing\ Costs \qquad (7)$$

Costs Outflow synthesizes initial implementation costs and ongoing costs as they relate to the overall net effect: shown in equation (8). Initial implementation costs are inflated to capture indirect administrative, executive, or operational costs that may be associated with the described cost areas. A pulse function is used to capture how these costs affect the overall costs only during the initial onset of implementation. During subsequent periods, only maintenance expenses are relevant cost outflows.

$$Costs\ Outflow(t)\ =\ (Blockchain\ System\ Implementation\ Costs\ \hat{}\ Implementation\ Inflator\ *\ PULSE(0, 1))\ +\ Maintenance\ Expenses \qquad (8)$$

3.4 Blockchain Implementation Benefits Elements

The potential benefits of implementing a blockchain in supply chains are classified into two types in this model. One type reflects internal benefits within the supply chain-measured in the 'Integration' variable - while the second reflects the external related benefits through what we called the 'Customer Willingness to Buy' variable. To capture these benefits, the model attempts to quantify the positive contributions or capacities that result from the degree of supply chain digitization as well as the sizes of both the firms and the network.

In overview, the inputs; DoSCD, firm size, and network size impact the benefits to be gained from implementation. These benefits are mediated by the variables *trust, collaboration, smart contracts, supply chain information and visibility,* and *increase in customer willingness to buy.* Respectively, these represent the level of *trust* existing between supply chain constituents, the level of *collaboration* between constituents in creating and implementing the blockchain solution, the *smart contracts* (automated processes or actively mediated processes) that result from collaborative processes, the *supply chain information and visibility* that is enabled through smart contracts, and the *increase in customer willingness to buy* that results from increased supply chain visibility and information. These benefits are synthesized into *savings* that impact the overarching *net effect.*

The capacities that are most directly tied to DoSCD variable include a higher level of collaboration between the network constituents, the increased utilization of smart contracts as active mediators that automate processes, and utilization of smart contracts as choreography monitors that enable increased information sharing. Essentially, these variables represent the blockchain system that is developed. The blockchain system, depending on utilization and network dynamics, yields benefits for firms implementing it.

The degree of supply chain digitization positively influences the level of collaboration across the supply chain since increased digitization necessitates additional collaboration in both planning and execution. Research supports that the joint planning and decision making inherent to realizing some degree of supply chain digitization yields increased partnership and collaboration effectiveness (Johnston 2004). It is important to note that the improved collaboration, system complexity, and the smart contract or information sharing outcomes are all impacted in this model by the DoSCD and the trust level amongst the supply chain members.

In the context of blockchain implementation, an important outcome of collaboration among supply chain echelons is the positive effect on both smart contract effectiveness, and the supply chain information sharing. The effect of this transparency carries back over to the level of trust between the entities resulting in a positive feedback loop based on the positive reinforcement that the trust has on collaboration level. Existing research clearly indicates the benefit of collaboration and information sharing in supply chain especially in terms of improved trust as well as the positive reinforcement trust has over the collaboration level (Almeida *et al.* 2014). Ko (2018) states that these effects also arise from blockchain technology because of this its ability to enable transparency, thus allowing firms to reduce verification and surveillance costs. Catalini and Gans, (2016) mention that implementing blockchain technology can structure confident relationships with their counterparts, thereby reducing costs associated with low-trust relationships. Omar *et al.* (2021) show that smart contracts can be used to cost-effectively automate procurement contracts with supply chain partners. These findings synthesize into a positive feedback loop where trust is generated through the collaborative development process. The collaborative process yields insight to the trustful nature of the blockchain system in development; and, because blockchains provision trust through information visibility and guaranteed execution, collaborating parties can work together more effectively to bring those features to fruition. This part of the model reflects the impact of the inputs on the nature of the blockchain system being developed.

The above variables are unified into the Integration variable that flows into the ‘Savings’ stock in the model. This integration variable is also adjusted by the supply chain network size and firm size to reflect the actual utilization of the blockchain system developed. Supply chain network size and firm size are reintroduced at this level to capture system level network effects that are not present in the above-mentioned development feedback loop. Furthermore, to be more reflective of the practical nature of supply chain improvement benefits, the effects that the system has on the saving stock will be balanced by the incorporation of a time-dependent deflationary variable. This variable represents the industry relative standard that reflects the saturation of supply chain technology efficiencies over time.

The other type of benefits captured in this model that feeds into the savings stock is related to the anticipated improved customer willingness to buy. This is due to the enhanced visibility and traceability based on successful supply chain information sharing mentioned earlier. Multiple researchers state that product visibility and traceability increase customer’s trust in product characteristics (Tian 2016) and, subsequently, their willingness to purchase the product (Ward 2017).

3.5 Blockchain Implementation Benefits Elements Structure Relationships

The *Collaboration* variable’s relationship with the Supply Chain Network Size (SCNS) and ‘Trust’ variable is shown in equation (9). Trust and SCNS are simply added together to reflect the effectiveness or level of collaboration. This collaboration variable sets the stage for the blockchain system to be developed. That is, depending on the desired DoSCD, the network size and trust between constituents will determine the nature of the smart contracts, the depth of process automation and the quality/quantity of information availability. Research supports the importance of this network collaboration in blockchain adoption. In their research, Kouhizadeh, *et al.* (2021) conclude that a leading barrier to blockchain adoption is this lack of trusted network constituents willing to implement new joint systems.

$$Collaboration = (Trust + Supply\ Chain\ Network\ Size) \quad (9)$$

Smart Contracts in equation (10) represent the active mediators that are realized through collaboration. The nature of these mediators is that they can interact with each other and execute tasks in a programmable fashion. As such, a higher DoSCD yields additional mediators that exhibit application network effects through their capacity to inter-operate with each other. Collaboration and DoSCD are added together to reflect the system of smart contracts that is developed. More specifically, with Collaboration representing the Supply Chain Network Size and the Trust between those entities, Collaboration level is an initial condition for the range of possible processes that may be digitized with a sufficiently high digitization level. To capture the multi-faceted application network effects associated with a higher DoSCD, the sum is inflated exponentially by DoSCD reflecting the above-mentioned order of magnitude difference between these levels. The application network effects of the smart contracts are represented through a quadratic function as shown below in equation (10). Essentially, raising the sum of collaboration and DoSCD to the power of DoSCD reflects the logarithmic gain of function represented by changes in the digitization level and how collaboration levels are an important factor in smart contract outcomes.

$$Smart\ Contracts = (Collaboration + DoSCD)\ \hat{}\ DoSCD \quad (10)$$

Supply Chain Information and Visibility in equation (11) is a variable that represents the quantity and quality of information made available through the smart contract system. Accordingly, it is a primary consequence of collaboration and the DoSCD. Smart contract functionalities record and store information as they monitor the information system processes. The effects of collaboration on supply chain information are introduced at two levels in equation (11) – indirectly through smart contract functionality captured in equation (10) but also through the additional collaboration necessary to ensure those smart contracts produce, record, and distribute desired supply chain information.

$$Supply\ Chain\ Information\ and\ Visibility = Smart\ Contracts + Collaboration \quad (11)$$

The information recorded through the smart contract system has the potential to yield an increase in customer willingness to buy. *Increase in Customer Willingness* (12) to Buy captures the amount of information made available to the customer as shown in equation (11) and (12). Only a fraction of information that is captured through the system will be available to customers so the total Supply Chain Information impacting the customer is deflated significantly through a logarithmic function. There are many extenuating factors regarding quantitative estimation of the information to be made available and its impact on customer purchasing habits. Accordingly, we recommend industry-specific studies into the estimation of traceability and verification on customer purchasing habits. In short, this variable reflects the value perceived by the customer due to improved traceability and visibility of the supply chain and the firm's ability to capitalize on that willingness.

$$Increase\ in\ Customer\ Willingness\ to\ Buy\ = log2(Supply\ Chain\ Information) \quad (12)$$

The beneficial impact of *Trust* is modeled using equation (13). Research supports the correlation between trust, collaboration, and information (Alameida *et al.* 2014). The dynamic effect of the information is deflated through a logarithmic relationship to reflect inherent limitations of such effect on trust and maintain stability of the positive feedback loop.

$$Trust = log2(Supply\ Chain\ Information\ and\ Visibility) \quad (13)$$

The flow of Integration rate into Savings stock is the crux of the benefits to be gained through implementation of a blockchain-based supply chain management system. The variable represents the developed blockchain system and its functionality with the financial benefits gained through its utilization. These benefits in this model are generated by the smart contracts, the information sharing, and their compounded effect that results from the size of the supply chain network and the firms' sizes in the supply chain. More smart contracts lead to more features and automation, more supply chain constituents mean more inter-organizational processes are improved, and a larger firm size means these improved intra-organizational and inter-organizational processes are utilized more frequently.

The Integration equation is intended to model the utilization of the system that was developed. That is, variables like SCNS, Trust, and DoSCD impact the programmatic functions of the blockchain system that is developed while Network Size and Firm Size refocus how that system is utilized in a given context. We explore these relationships in more detail given their importance to the overall model behavior.

Equation (14) distinguishes between the value associated with smart contracts active mediation function and that of the supply chain information and visibility (SCIV). First, to model the value associated with Smart Contract active mediation, it captures the horizontal network effects of Smart Contracts that are generated by increases in Firm Size. That is, Smart Contracts are raised to the power of Firm Size. Supply Chain Network Size is not incorporated in this part of the equation as its associated impact on Smart Contract functionality is accounted for in the Collaboration (9) and Smart Contract (10) equations. While SCNS may be associated with more savings through automation of external-facing processes, Firm Size is expected to be the leading factor in modeling smart contract system utilization.

Second, to model the value associated with Supply Chain Information and Visibility we reintroduce Supply Chain Network Size as an important factor. It is worth noting again that SCNS is included in our understanding of collaboration (9) which carries over to smart contract development (10) and SCIV (11). In those equations, SCNS reflects the nature of the system being developed: the internal and external processes that are being automated as well as the amount of information generated in SCIV by the Smart Contract system. In the context of this Integration equation (14) SCNS acts on SCIV to reflect the additional value of information visibility in a large network as opposed to information visibility within a single large firm or a small network. To model this relationship, Supply Chain Network Size is raised to the power of two to reflect the exponential difference between firm sizes at each level. That is multiplied by SCIV to capture the value of instant, automated, and reliable information flow throughout the network.

Finally, these two portions of the equation are both inflated by a Firm Size multiplier for two effects. On the active mediator side of Smart Contracts – the exponential difference between each Firm Size input level is captured. On the SCIV side, the multiplication of Firm Size reflects the possible scope, relevance, and frequency of information aggregation as well as the general horizontal application effects that result in additional information and visibility. These interactions are shown in equation (14).

$$Integration = ((Smart\ Contracts\ ^\wedge\ Firm\ Size) + (Supply\ Chain\ Information\ and\ Visibility\ * (Supply\ Chain\ Network\ Size\ ^\wedge\ 2)) * Firm\ Size \quad (14)$$

Savings stock modeled in equation (15) combines savings as defined in the increase in customer willingness to buy and benefits captured in the Integration variable above.

$$Savings = (Integration + Increase\ in\ Customer\ Willingness\ to\ Buy) \quad (15)$$

An 'Industry Standard Deflator' variable is introduced in equation (17). This deflator reflects the natural rate of technological development and saturation in the firm's industry. As time goes on, other firms will implement their own updated systems and, as they do so, the relative savings from supply chain digitization slowly decrease. This deflation dynamic is modeled in (16) using a Ramp function with time step γ. The value of γ depends on a given supply chain industry's rate of technological change and saturation.

$$Industry\ Standard\ Deflator = RAMP(\gamma, 0, 100) \quad (16)$$

Savings inflow in equation (17) represents the flow of benefits into the overall net effect of supply chain digitization. It captures the benefits gained by implementing a blockchain system while being regulated by the specific industry standard deflator to capture the savings dynamics over time as firms successfully implement blockchain-based solutions within their supply chains.

$$Savings\ Inflow(t) = Savings/ Industry\ Standard\ Deflator \quad (17)$$

The overall value generated from implementing blockchain technology in supply chain is captured in this model in terms of 'Net Effect', which is the difference between savings inflow and cost outflow over time. This dynamic relationship is shown in equation (18).

$$Net\ Effect(t) = Savings\ Inflow(t) - Cost\ Outflow(t) \quad (18)$$

4. INVESTIGATING BLOCKCHAIN IMPLEMENTATION COST/BENEFIT DYNAMICS

The analysis in this paper will focus on the overall 'Net Effect' or the value of blockchain implementation in supply chain as the major performance index that will capture the cost/benefit dynamics. It is important to remember that the net effect is calculated as the difference between the overall cost and the overall benefits or savings with monetary units using dollars as highlighted in equation (1). The presented numerical simulation analysis is intended to explore the impact of the three main input parameters on the Net Effect, namely firm size, network size and degree of supply chain digitization. Through analysis of theoretical outcomes with the context of various input scenarios, we hope to identify main considerations for real-world blockchain system development and implementation in Supply Chains. Each figure below shows multiple comparable scenarios represented by different lines. The scenarios shown in each figure were selected based upon comparative outputs to ensure easy visual assessment of the relationships between different outputs. Each figure seeks to represent a spectrum of scenarios from a similar DoSCD. The legend for each figure shows three numerical values that each represents the respective inputs for DoSCD, Firm Size, and Network size in that order. The values of these parameters will be assumed to vary between three levels (low, medium and high) following a simple linear function (1, 2, and 3 respectively) for simplicity. These levels reflect various supply chain environments or scenarios that are candidates for blockchain implementation. This will serve to establish a framework for understanding how a firm's circumstances may affect blockchain implementation outcomes. The analysis and findings below reflect the theoretical impact of blockchain implementation in supply chain. This is due to the theoretical nature of these qualitative relationships and the extrapolation of quantitative relationships based upon findings from cited literature. The selected values for the constant functions in the conducted simulations are shown in Table 1.

Table 1 Input values selected for the numerical simulation

Variable	Value	Description	Justification/Rationale
DoSCD(x)	1–4	Reflects the level of digitization	Adopted from digital transformation maturity models (e.g., Venkatraman, 1994; Deloitte's Digital Maturity Model). These levels are commonly used to describe increasing complexity and impact of IT systems.
Firm Size	1–3	Based on company scale	Simplified categorization based on OECD/SME frameworks, distinguishing SMEs from large firms; also used in empirical studies of tech adoption.
Supply Chain Network Size	1–3	Network extent	Mirrors common tiers in supply chain research (e.g., small: <10 partners, medium: 10–50, large: >50); based on the expected range of blockchain-enabled visibility.
Industry Standard Deflator (γ)	RAMP(0.005, 0,100)	Models tech benefit decay	Selected small γ value reflects conservative decay assumption of benefit over time, as blockchain adoption reaches maturity; sensitivity-tested.
α	0.01	Info gain saturation	Calibrated based on prior diffusion literature (e.g., Rogers' diffusion of innovations), simulating gradually diminishing marginal gains.
β	0.002	Trust loop limitation	Ensures bounded positive feedback to avoid unrealistic exponential behavior; based on model stability tests.
Capacity level	2	Hiring level	Reflects moderate hiring required for blockchain integration; assumed for typical mid-scale implementation (can be changed in sensitivity analysis).
Implementation Inflator	3	Initial cost multiplier	Reflects 2–3x cost spike due to legal, compliance, and training expenses reported in case studies (e.g., IBM Food Trust, Maersk).

4.1 Impact of Firm Size on Blockchain Implementation Value Dynamics at the First DoSCD Level

Results shown in Figure 4 capture the positive effect of firm size on the Net Effect at a first degree of supply chain digitization on increasing the BC implementation value. Figure 4 also shows the comparable output resulting from a DoSCD of 2 with small firm size and small network size. As mentioned earlier, the first degree of supply chain digitization pertains only to 'single-use' or highly specific processes within an organization. Also mentioned above, the legend for each line below represents the respective inputs for DoSCD, Firm Size, and Network size in that order. For example, [1,2,3] represents DoSCD = 1, Firm Size = 2, and SCNS = 3. With that groundwork laid, the most notable from the figure below is the nearly identical output resulting from scenarios [1,2,1] and [2,1,1]. At low digitization levels, DoSCD and firm size are expected to have similar impacts on cost/benefit analysis. That is to say, comparatively, the gain of function yielded by a DoSCD of 2 is similar to the increase in utilization when firm size increases. When considering firm size as an indicator for process execution frequency and variety, these results show that an increase in process utilization may yield similar results as increases in the digitization level, other variables held constant.

We maintain that the change in Firm Size represents an exponential difference between the firm's size in each scenario. This means the costs and benefits are of greater relative significance in scenario [2,1,1] than in [1,2,1]. The relative significance of costs and benefits are an important consideration in the context of firm size. Initial costs of $5000 will be less significant for a medium firm than a small firm. This relative significance of costs also serves as an indicator of risk associated with implementation. Another consideration across all scenarios is the tapering of benefits as time goes on. This behavior is modeled intentionally to represent the loss of relative advantage that happens as time progresses and as the industry standard catches up to new innovative technologies.

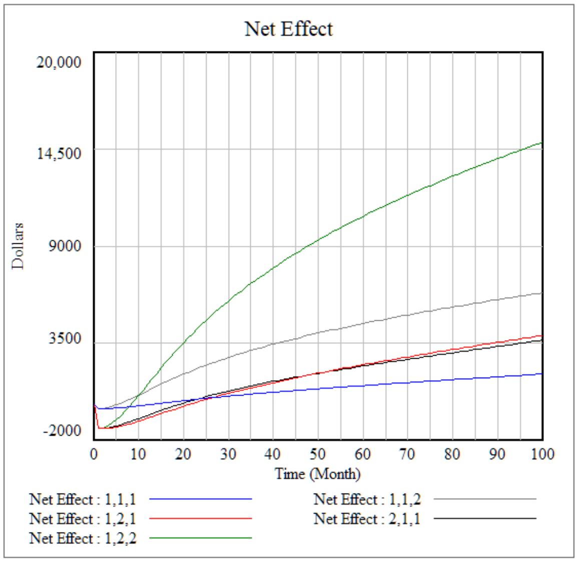


Figure 4 Cost/benefit dynamics at 1st DoSCD and similar scenario outcomes

More broadly, results suggest that additional benefit of blockchain implementation is realized from the increased process scale that accompanies increased firm size and network size. The firm size in this context reflects the level of internal processes of a specific organization that blockchain solutions will help integrate and improve. The network size, SCNS, represents the quantity and frequency of external facing, often more costly, processes existing in a supply chain network. We can see from scenarios [1,2,1], [1,2,2] and [2,1,1] that both Firm Size and DoSCD are associated with similar, higher, initial costs than scenarios where firm size is small and DoSCD = 1. Of these, scenario [1,2,2] stands out as with the largest positive net impact. This benefit would arise from a medium firm in a medium sized network that is able to leverage a simple system for streamlining a process common to its network constituents. Similarly, scenario [1,1,2] yields significant benefit from a similar system where one of the participants in that network is relatively smaller. As a smaller firm in that network, the firm is expected to assume fewer of the development and implementation costs while accumulating similar or increased benefit through the supply chain network efficiencies gained. For the firm size of 1, this scenario represents the highest relative yield compared to scenario [1,2,2] where the firm is an order of magnitude larger but still yielding similar benefit. This is an important theoretical finding that implies significant value stands to be created for supply chain constituents participating in a larger network of blockchain implementation. This dynamic, small firms having relatively low costs when participating in a larger network, was found to persist across all scenarios explored.

4.2 Exploring Blockchain Implementation Value Dynamics at the Second DoSCD Level

Different scenarios are explored when the supply chain is at the second level of supply chain digitization. This level represents a blockchain application designed to replace and integrate some localized process within a larger scheme. At time of writing, this scenario is typically a private blockchain within a large network for multiple supply chain echelons upstream and downstream. Figure 5 below shows the wide range of possible results at DoSCD = 2 depending on firm or network size.

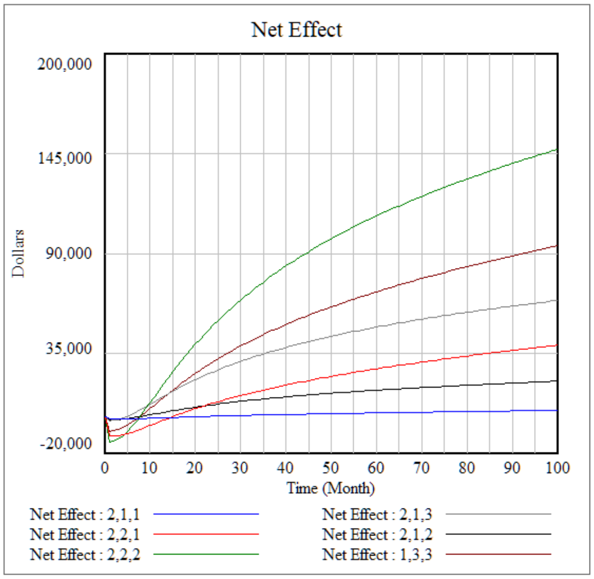


Figure 5 Cost/benefit dynamics at 2nd DoSCD and similar scenario outcomes

Another important relationship arises in the Figure 5 comparison: [2,2,2] has a larger net benefit than [1,3,3]. Literature supports that the possible network effects in [1,3,3] may be limited by DoSCD = 1. Meanwhile the increase in net benefit in [2,2,2] shows the application network effects described in the literature review and equation analysis. In other words, there is a limitation to the benefits to be gained from frequency of process execution within the firm and its network. In a medium or larger firm/network, there are additional opportunities to enable process interoperability. This automated process interoperability can be captured at the second level of digitization whereas the first level of digitization is limited to single-use cases. These results correspond with Philipp's (2019) results that indicate the potential of blockchain applications in multinational and multi-mode supply chains. Looking at these same scenarios, we can see that additional costs result from higher DoSCD while firm size and network size have a smaller impact. This additional cost of DoSCD may be associated with migration from legacy systems – increases in DoSCD represent additional functions being migrated to the new system, as well as more labor and more experienced labor to implement and maintain.

In the [2,2,2] scenario, we can also see that the firm whose size is comparable to its overall network size will assume additional costs in the implementation. If we consider scenario [2,2,1] in this context we see that, despite the firm being relatively large in its network, it does not assume as many costs or benefits as [2,2,2]. This may stand for a variety of reasons. First, there may be additional functionality or collaborative costs to participating in a larger network of constituents. Second, in a larger network of constituents it is reasonable to expect additional inter-organizational functionality in the system being implemented. This additional functionality comes at additional cost in terms of development and implementation. These costs may not be as large in a network where the power dynamic is shifted in favor of the larger firm. That is, a larger firm in a smaller network may have the authority to more easily demand compliance with their developed system. Power dynamics and decision making in inter-firm information system implementation is an opportunity for further research.

With regard to scenarios [2,1,2] and [2,1,3] we see very large relative benefits for a small firm. The exact nature of these benefits is an area for further investigation, analysis, and validation. Despite limited research in this regard, we posit that the inclusion of a small firm within a large network that is utilizing blockchain based solutions may yield accelerated growth and demand for the small firm. This accelerated growth and demand may be supplemented by the efficiencies and competitive advantage gained by the network as a whole through system implementation.

Figure 6 explores scenarios across a variety of digitization levels but with comparable cost/benefit curves. Some scenarios are also included above in Figures 4 and 5 but are revisited for additional context.

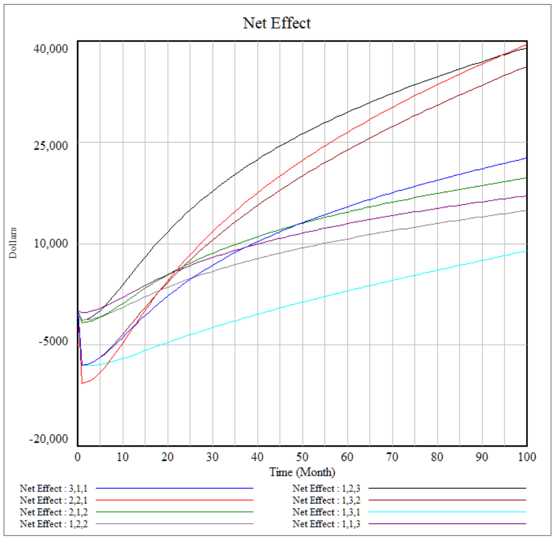


Figure 6 Comparative analysis of similar scenario outcomes across multiple input dimensions with focus on lower DoSCD paired with higher Firm and Network Sizes.

Scenarios [2,1,2], [1,2,3] and [1,1,3] hold to the above-mentioned relationship between a firm and a network that is relatively larger. In these three scenarios, the costs and associated risks are lower compared to scenarios of similar benefit. Another important consideration in scenarios like these is the power dynamic in influencing the decision making behind the implementation of a blockchain based system. It is worth noting again the lack of research in cost and power dynamics in inter-firm information system implementation. This is to be expected as current legacy information systems normally do not have significant inter-firm functionality and thus do not necessitate significant inter-firm decision-making processes.

Scenarios [2,2,1], [1,2,3], and [1,3,2] are the three highest yielding scenarios in Figure 6 they exhibit cost benefit patterns like scenarios [1,2,1] and [2,1,1] where changes in Firm Size are comparable to changes in DoSCD. These all reinforce the notion that at low DoSCD levels, increases in firm size yield similar benefit as increases in DoSCD. Of these scenarios, and in the context of their respective firm sizes, scenario [1,2,3] has the lowest costs and earliest break-even point. In other words, its large network is taking on some of the costs and the medium firm in question has relatively low risk. We discussed how this relationship stems from the similarity between the gain of function associated with DoSCD and the increase in utilization that is associated with larger firm size or network size. An important nuance arises from the similarity between [3,1,1] and [2,1,2] - this increase in SCNS is similar to an increase in DoSCD. In [3,1,1] the small firm and small network may not be able to maximize network effects that a DoSCD = 3 system would be capable of. Conversely, even with DoSCD = 2, a larger network (SCNS = 2) would allow for better capitalization of the interfirm process improvements that smart contracts enable and utilize the higher SCIV that follows.

4.3 Exploring Blockchain Implementation Value Dynamics at the Third DoSCD Level

The third level of DoSCD considered in the analysis is when the level of digitization and substitution systems are high in coordination needs because they involve broader and increasingly public use cases. The processes that the supply chain echelons hope to replace in this level may be full-blown and deeply embedded within their organizations and institutions from upstream to downstream. At this level of digitization there is opportunity for both horizontal network effects and application network effects to manifest. As discussed in Figure 6 results, these network effects are dependent upon the firm's circumstances in terms of their size and their network size as these two variables represent the variety and scope of possible processes for automation. Figure 7 shows a range of possible outcomes at higher digitization levels in larger firms and networks, Figure 8 shows the impact of firm size and network size specifically at the third digitization level, and Figure 9 shows the output for a scenario with DoSCD = 3, Firm Size = 3, and SCNS = 3. Finally, we include Figure 10 to show a hypothetical fourth level of digitization and discuss these results in the context of the research describing the attributes of the various digitization levels.

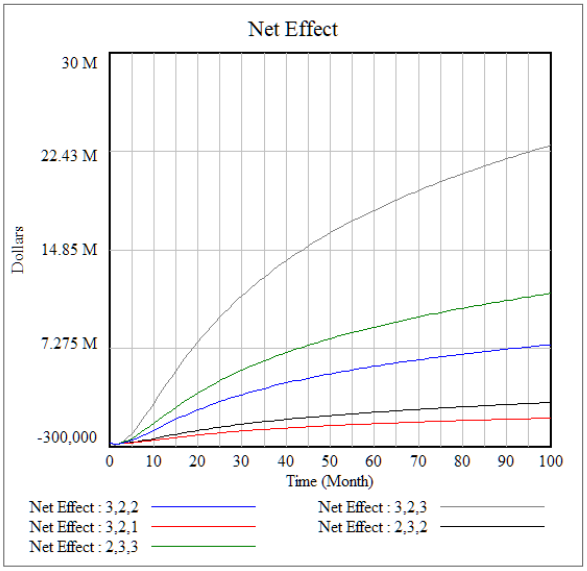


Figure 7 Cost/benefit dynamics at 3rd DoSCD and similar scenario outcomes

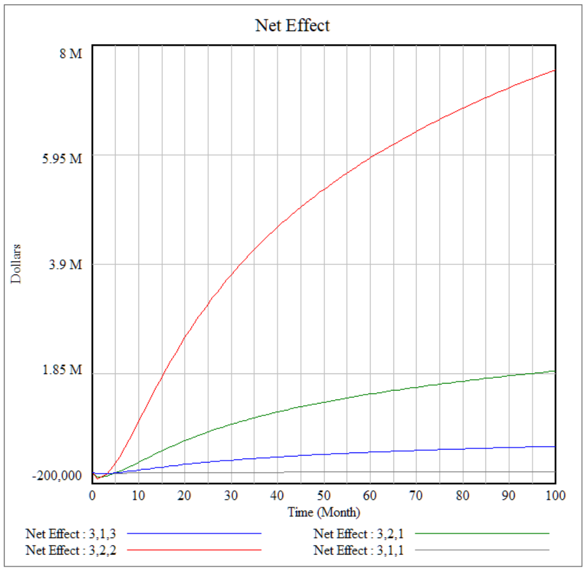
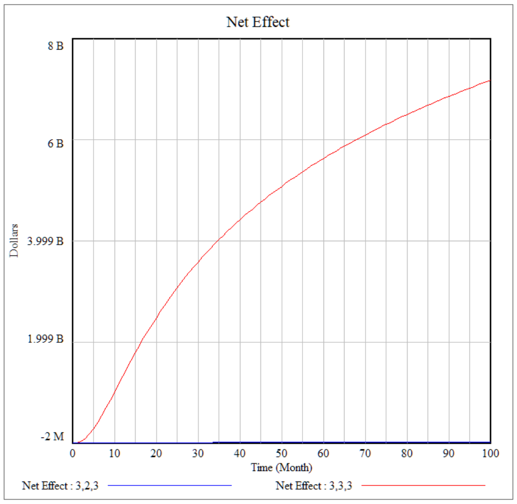


Figure 8 The impact of network size on net effect of cost/benefit dynamics at 3rd DoSCD for large firm size

At these higher digitization levels in larger firms and networks, application and horizontal network effects are expected to manifest. Scenario [3,2,1] reflects limited benefit resulting from a lack of scope associated with a small supply chain network. The high degree of digitization is not as useful in this context yet is still expensive in both initial and ongoing costs. Scenario [2,3,2] has a larger net impact but smaller relative benefit for the large firm size. Its more horizontal slope, showing the rate of benefit accrual, reflects the larger firm's assumption of its network's costs. The upper echelon of application effects that happen at higher DoSCD and SCNS levels are not as impactful in this scenario. Scenarios [3,2,2] and [3,2,3] shows a very large benefit relative to the firm size. With these high profit outcomes that are modeled, it is again important to note that the substitution, or third, level of digitization is contingent upon the technological development and ongoing maturation of blockchain technology and solutions. This research again seeks to explore the qualitative relationships established in literature and model how those fundamental features of blockchain technology stand to impact or be integrated into supply chain contexts. Similarly, the benefits projected in these scenarios must be considered relative to firm size.

Figure 8 above explores the impact of network and firm size on the Net Effect of cost/benefit dynamics at this third DoSCD level. These scenario outcomes primarily reinforce the large impact associated with differences in utilization levels and network effects that manifest in larger networks. We see again that a small or medium firm in a larger network that implements a high digitization level blockchain system stands to profit significantly. Reasons for this would be the significant competitive advantage gained through network-wide process automation, inter and intra-firm process streamlining, integrated network software systems, and high information visibility despite the challenges of information flows in large networks.

We see again that a small or medium firm in a larger network that implements a high digitization level blockchain system stands to profit significantly. Reasons for this would be the significant competitive advantage gained through network-wide process automation, inter and intra-firm process streamlining, integrated network software systems, and high information visibility despite the challenges of information flows in large networks. At this higher level of digitization, especially in larger firms and supply chains, the systems being implemented are likely to be increasingly modular and public. Accordingly, the benefits to be gained are not likely to be unique to any single blockchain based system, rather the benefits will be attained through utilizing a suite of interoperable blockchain based applications. We explore this trend in more detail below.



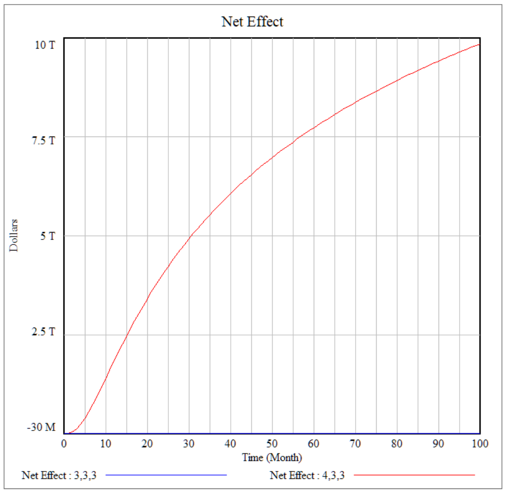


Figure 9 and 10: The impact of Network Size on Net Effect of cost/benefit dynamics at 3rd and 4th DoSCD for large firm and network sizes

Scenarios depicted in Figures 9 and 10 are contingent upon the full maturity of blockchain technology and the interoperability of many blockchain based systems that congeal into one larger, *transformational*, ecosystem. In the context of the research describing these levels of digitization, it would be inaccurate to consider the net-effect of these outcomes as unique to the firm implementing the system. As digitization levels increase, blockchain systems trend towards being increasingly public and modular as these two attributes are closely associated with the promises of upper echelons of network effects – namely blockchain as a software connector. As Kemper (2009) and Westarp (2003) specify, there is a need for integrated and standardized EDI and ERP systems. The above scenarios reflect a level of digitization and network participation that closely aligns with the idea of blockchain-based EDI and ERP systems. Specifically, at the fourth transformational level of digitization, these standardized and modular EDI/ERP systems stand to possibly interface with other business departments and processes. In line with the increasingly public nature of these systems, the multi-billion and multi-trillion dollar outcomes in scenarios [3,3,3] and [4,3,3] can be better understood as an overall economic impact amongst supply chain networks participating in those transformational systems. It is unclear what costs will be assumed prior to the pre-supposed maturation of blockchain technology but firms can expect for the technology to develop independently of their private investment.

While the results in Figures 7–10 show financial impacts in the millions, billions, and trillions, these values are not intended to represent the financial effect on a *single firm* but rather the cumulative economic benefits across entire supply chain networks over time, especially under high-digitization and large-network scenarios (e.g., [4,3,3]). The simulation assumes an interconnected supply chain ecosystem where blockchain integration leads to compound savings, reduced friction, and increased customer demand at scale. Such impacts are amplified due to:

- Network effects (as more firms join, savings grow non-linearly),
- Integration-level compounding (trust, visibility, and automation feedback loops),
- Assumption of widespread adoption in scenarios with high digitization.

Additionally, these scenarios illustrate *upper-bound outcomes* under optimistic but structurally plausible conditions. They serve more as boundary projections to understand the theoretical potential rather than predictions of guaranteed outcomes. Real-world outcomes would depend on adoption pace, governance, regulation, and interoperability challenges, which are outside the model's scope. This research is primarily focused with understanding the underlying factors in understanding the large promise of blockchain systems in supply chain and providing a framework for understanding the main considerations for implementing and developing these systems.

5. SUMMARY AND INSIGHTS

In this paper, a system dynamic model was developed to explore the cost dynamics associated with blockchain implementation in supply chain. The model is based on the analysis of a variety of supply chain, system dynamics, and blockchain research literature that describe a variety of inter-related phenomena regarding blockchain implementation among supply chain echelons. The model synthesized the relationships between these phenomena into an organized framework for understanding some aspects of the cost/benefit dynamics for blockchain implementation. Quantitative results from this model correlate with many of the qualitative relationships established in research.

Due to the early stage of the quantitative research in the field of blockchain implementation in supply chains, it is important to acknowledge the limitation that the reported quantitative results are, to a degree, arbitrary as they result from the model's translation of available qualitative phenomena into mathematical representations of those phenomena. Further empirical validation of the model and some of its parameters are the natural extension of this research work. Within this limitation and given the selected model settings, the analysis lead to some useful managerial and practical insights for supply chain mangers when it comes to deciding on whether to implement blockchain technology and to what extent. The questions we sought to answer are:

1. What are the attributes of blockchain technology that stand to impact business processes?
2. How do those attributes relate to the larger question of theoretical cost-benefit expectations for a given firm?
3. What are the main considerations in understanding whether a firm or supply chain stands to profit from blockchain adoption and what features are most important for maximizing profit?

These insights are summarized as follows:

- The two most fundamental aspects of blockchain based systems in supply chain are (1) process automation through smart contracts (active mediators) and (2) the information visibility that arises from those automated processes.

- Value arises from the features of active mediation and information visibility. This value is amplified by both horizontal network effects and application network effects enabled by these smart contract functions, the processes they automate, and the services they interconnect. These inter-departmental or inter-organizational efficiencies are possible through the secure and transparent platforms blockchain systems provision.
- Blockchain systems are capable of enabling new echelons of network effects when utilized as a software-connecting technology. Blockchain application design in interest of accessing these upper echelons of benefits is crucial for accessing this value. Modularity and platform architecture are key features in this regard.
- Theoretical costs and benefits are closely associate with digitization levels, firm size, and the supply chain network size. There is interplay between these factors but generally, small firms in small networks benefit from lower digitization levels and larger networks with high digitization stand to theoretically generate the most value for all firms in the network.
- When a small or medium firm participates in a relatively larger network that adopts a blockchain system, the model predicts especially large profit relative to the size of the firm. Literature supports that this results from the increase in network effects in combination with the decrease in associated risks and costs that result from network cooperation.
- Similarly, results and literature support the role of firm size in realizing the value of blockchain cost benefits. It was shown that medium and large firms managed to capitalize on the network effect arising from blockchain implementation more than smaller firms do.
- In addition, results validate that small to medium firms, especially those in smaller networks, face significantly more risk in blockchain adoption than larger firms and firms in a larger network. These risks are reflected by the proportion of initial costs to the size of the firm.
- Small or medium firms and networks, with their lower level of process scope and frequency, inherently limit the possible benefits offered by higher digitization levels. This results from limitations in the network effects that arise from interconnected processes, software, and participants that are possible at high degrees of digitization.
- With the highest available digitization infrastructure involving public and private use cases, blockchain solutions show the full potential to replace deeply embedded processes in supply chains to create high value. However, results suggested that such value is faster and bigger in larger networks involving medium and larger firms. This is due to compounding network effects arising from the blockchain capability to improve supply chain process integration and visibility leading to better information sharing and trust and while meeting expectations of system security and resilience.
- Small and medium firms at high digitization levels exhibit the best cost performance when they participate in a larger network. After considering the risks and benefits relative to their firm size, these scenarios reflect the most desirable outcome of almost all scenarios.

In summary, the analysis indicates that, at comparable blockchain implementation investment, there is additional benefit to be gained for supply chain through increased digitization. The proposed model establishes a framework for understanding network effects and how they stand to drive blockchain adoption. Essentially, direct financial benefits arise from automation and information visibility efficiencies gained through implementing the system. Direct benefits grow through increased system utilization and process execution frequency. Increases in firm size and network size are associated with increases system utilization and process execution. Underlying these direct benefits are two categories of network effects that increase the efficiencies that drive direct benefit. The two categories are direct horizontal network effects and application network effects. Horizontal network effects are associated with the efficiencies gained through additional interconnected network participants. Application network effects are associated with efficiencies gained through additional interconnected processes, business departments, or software systems. Application network effects reflect blockchain capabilities at higher digitization levels. The possible benefits that arise from these capabilities are sometimes limited by circumstantial variables associated with firm or network size. Similarly, these features are only significant in the context of the secure and transparent platform that blockchains stand to provide, as described in the literature review.

This paper proposed a tentative theoretical framework for understanding the main considerations in blockchain implementation in supply chain contexts that will pave the road for further research in this growing area of interest within the supply chain field. Finally, this work can help mangers and practitioners to understand the nature of blockchain implementation in supply chain from a cost dynamics perspective.

Future work will include further exploration of network effects in the context of blockchain-based systems. The positive feedback loop surrounding trust and system development and the ongoing process of creating modular and interconnected systems is another area for investigation. Furthermore, we recommend additional research as to the impact of customer role in driving blockchain implementation. For more specific and applied usage of this model for forecasting we recommend a detailed sensitivity analysis for the optimal settings of some of the selected parameters like α, β, γ, capacity level, implementation cost inflator, and industry standard deflator is required to understand the practical context of blockchain implementation decisions. The industry standard deflator is another important consideration in the context of higher digitization level systems that reflect increasingly public use cases. With more publicly available systems, the question or relative benefit compared to industry standard becomes especially important. The importance of firm size and network size in terms of both cost/benefit analysis and in terms of adoption is an area for further investigation. We encourage further research and specification of the various digitization levels and the respective blockchain functionalities they entail. Finally, and as mentioned earlier, this early analytical work needed to be complemented with field empirical studies. Most relevant in these empirical studies would be a deeper investigation into the nature of network effects in smart contract systems and the blockchain, decentralized application ecosystem.

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Ahmed Deif is a Professor of Operations and Supply Chain Management at Cal Poly with research interests in supply chain innovation & sustainability, lean and green systems, lean gamification in STEM education. He is ranked among top 2% most impactful researcher in Industrial Engineering field. He published around 100 works in books, journals, and conferences. His teaching profile includes teaching in more than 10 universities across 5 continents as an adjunct and visiting professor. With 20+ years of experience across automotive, steel, electronics, and assembly industries, he has worked in R&D and consulting roles. A certified lean and six sigma expert, he has conducted training and consulting in the USA, Canada, and Middle East, including government advisory roles in education and training.

Lorenzo Lynberg Lynberg graduated from Cal Poly San Luis Obispo's Business Administration program in 2018 with a concentration in Accounting and in 2019 with an MBA from Cal Poly as well. He has academically and personally invested in understanding blockchain technology from a multitude of perspectives: technological, sociological, political, and economically. His practical experience covers various fields including logistics, management and leadership.