Impact of Blockchain implementation on food supply chain performance

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Abstract

Blockchain has gained considerable interest in food supply chain (FSC). While literature has adequately explored the potentials of Blockchain to single process/company, there are limited studies attempting to examine the impact of Blockchain on the food supply chain network. Thus, this study attempts to model the FSC using System Dynamics (SD) approach to evaluate the impact of Blockchain on key supply chain performance metrics. SD models are built on the collected empirical data and relevant literature. The simulation results with illustrative parameters indicate that Blockchain has strong potentials to improve inventory level, lead time, service level and supply chain effectiveness.

Keywords: Blockchain implementation, food supply chain, supply chain performance.

Introduction

Agriculture and food supply chain (which is referred to as FSC in the rest of this paper) has a very important role in today's society, as it is responsible for producing and supplying food, a fundamental necessity for the human life. The FSC can generally be described as a chain of activities for moving food products from the original source to the end consumers, including stages such as producing/ acquiring raw food material, processing, supply, and distribution (Barbosa, 2021). The food chain of today is typically long and complex, with several stakeholders in the network working in the silos (Li *et al.,* 2021). Therefore, the FSC has faced numerous critical and persistent challenges over the years, such as information symmetry between parties, lack of transparency and visibility, and difficulties in monitoring safety and integrity of food throughout the supply line (Rana *et al.*, 2021; Vu *et al.*, 2021). Managing food waste and environmental impact of the FSC were among the most researched in the last 10 years, signifying another important challenge to the FSC (Barbosa, 2021).

As one mean to tackle these critical issues in managing food products, FSC has focused on developing and implementing advanced information systems and technologies (Kamble *et al.*, 2020). Among these technologies, Blockchain arises as a promising solution, addressing various issues in food supply chain management (FSCM). The technology is anticipated to improve FSC on multiple fronts, such as establishing reliable and complete food traceability process, streamline and enhance processes, and reduce environmental footprints of the FSC (Martinez *et al.*, 2019; Rana *et al.*, 2021).

As Blockchain is gaining strong momentum in the industry (Rana *et al.*, 2021), the number of studies on Blockchain adoption in the context of FSCM has also grown over the years. However, studies that holistically examine the impact of adopting Blockchain on the FSC are limited, as the current academic literature mostly studies exemplary use case of Blockchain (e.g., Martinez *et al.*, 2019; Danese *et al.*, 2021), or the events that led to the adoption of the technology (e.g., Wong *et al.*, 2020; Vu *et al.*, 2021) and lack in capturing the after-effects. Understanding the overall impact of Blockchain on supply chain performance is particularly important, as it is the next logical step to expand the understanding of Blockchain in SCM domain (Martinez *et al.*, 2019). Further, to understand how a supply chain network behaves once the technology is implemented is just as critical as how it was assimilated (Wong *et al.*, 2020).

To the best knowledge of the authors, there is lack of analytical research examining the impact of Blockchain implementation on key performance indicators in the specific context of FSC. Thus, this study aims to fulfil the gap in the current literature by answering the research question "*What is the impact of Blockchain on the performance of FSC*?". Specifically, this study proposes a holistic analytical modelling approach (SD modelling) to evaluate the effect of Blockchain on key performance indicators of the FSC: inventory level, lead time, service level, and effectiveness. These indicators are typically used to capture the performance of a supply chain under the impact of interventions such as new technological interventions (Kochan *et al.*, 2017) or supply chain disruptions (Kara *et al.*, 2020).

Due to the lack of existing approaches for capturing the changes to the operation of FSC by Blockchain, a mixed methodology approach was attempted. Insights combined from questionnaire survey and relevant literature were utilized to develop SD models for the two scenarios: a conventional FSC and a Blockchain-integrated FSC. Later, simulation results were compared to examine the changes to the four key FSC performance metrics between two scenarios, highlighting the impacts to FSC performance brought by the use of Blockchain.

Background to the research

Blockchain adoption in food supply chain

Fundamentally, Blockchain can be understood as a distributed ledger technology with the ability to store data in a highly secured manner and communicate stored data to every participant of the Blockchain network almost instantly (Kumar *et al*., 2020). The technology is able to provide such features due to a very unique mechanism: information is bundled into a block of information, then each block is validated by pertinent members in the system, before being added to the existing chain of blocks, that are tamper proof (ibid.) These special characteristics subsequently enable Blockchain to be a transformative approach to saving and sharing data with high level of security and trustworthiness (Danese *et al.*, 2021).

Since the introduction, Blockchain is mostly utilized as additional layer of data storage and data verification on top of existing operations, enabling companies to trace food products from farm to folk and to streamline processes (Vu *et al*., 2021). Thus, companies can gain more visibility of the food chain, acquire reliable information in a relatively quick fashion for better management of food quality and safety, and communicating information about products provenance to the end-consumers. The last capability cannot be underestimated in today FSCM, as consumers have become aware and vocal about the information asymmetry between them and food actors, and demand more information of food products at the point of purchase (Kendall *et al*., 2019). Furthermore, Blockchain can be used to establish a tamper-resistance track of records for companies' history of compliances to sustainable practices, sustainable developments, and human rights (Rana *et al*., 2021), thus becoming a useful tool for strengthening the sustainability of the FSC.

System thinking and system dynamics modelling

The underpinning theoretical perspective used for this study is system thinking. System thinking is "*the ability to see the world as a complex system, in which we understand that 'you cant just do one thing' and 'everything is connected to everything else'* "(Sterman, 2000, p.4). In essence, system thinking perspective advocates to holistically view the world as a complex system, where every component (which might be a complex sub-system itself) is interlinked to others and changes in certain part of the system will likely have effects on the other parts and the system as a whole. Subsequently, SD approach, based on system thinking, is a method to analyse, evaluate, and enhance the learning about the behaviour of complex systems over time (Sterman, 2000). SD approach is useful to model the relationships between critical factors, to simulate the overall interaction, and especially powerful to evaluate different policies and their impacts on the system following the simulation of the system (Kara *et al*., 2020).

SD modelling have been applied to examine the adoption of technologies. In the field of information system for example, most studies assume a variance logical structure – where relationships between constructs are one-way and time invariant, whereas SD approach offers an alternative viewpoint that takes into account the possibility of feedbacks between constructs, circular causality within a system, and changes over time (Fang *et al.*, 2018). Thus, the former is powerful to study why and how a technological innovation diffuses into a population, whereas the latter is useful to examine what factors can drive/hinder the expansion of such innovation after successful adoptions of the first few, and to paint a picture of the diffusion process over time (ibid.). SD approach also has been employed to study various phenomenon in the domain of SCM/FSCM. Kochan *et al.* (2017) used this approach to assess the effect of cloud-based information sharing in the context of hospital supply chain (HSC), simulating and comparing the results of a conventional HSC versus a cloud enabled HSC. Kara *et al.* (2020) employed this approach to model the impact of climate change risk on supply chain performance. Kazancoglu *et al.* (2020) evaluated the performance of the reverse logistics operation in the food industry with SD modelling and simulation.

Research methodology and the modelling process

In order to evaluate the impact of Blockchain adoption to the FSC, data combined from questionnaire survey and relevant literature is used to develop two SD models. The goal is to simulate and compare between the two scenarios- Conventional FSC and Blockchain-enabled FSC, and then draw conclusions about the effects of Blockchain adoption on various key performance indicators of the FSC. Vensim software is used to aid the modelling process.

Development of models

Sterman (2000) recommended to use the SD approach to focus on the issue at hand, rather than trying to replicate the exact structure of the whole system. By utilizing SD model in this manner, the modelers can direct their time and efforts into solving actual problem/ understanding interesting phenomenon, rather than simple recreation of reality in SD terminologies and notations. Adapting this perspective, a three-echelon FSC is chosen to be modelled, capturing the key movement of food products from raw material supplier to manufacturer to distributor. This choice of inclusion has been commonly employed in other SD simulation studies to represent a supply network (Kochan *et al*., 2020; Ghadge *et al*., 2021). Further, this study follows a logical approach, starting with developing a casual loop diagram (CLD) to represent the key variables and their relationships, converting them into a stock-and-flow diagram (SFD) to identify the stocks, inflows, outflows, and auxiliary variables of the system; and finally simulating the SFDs.

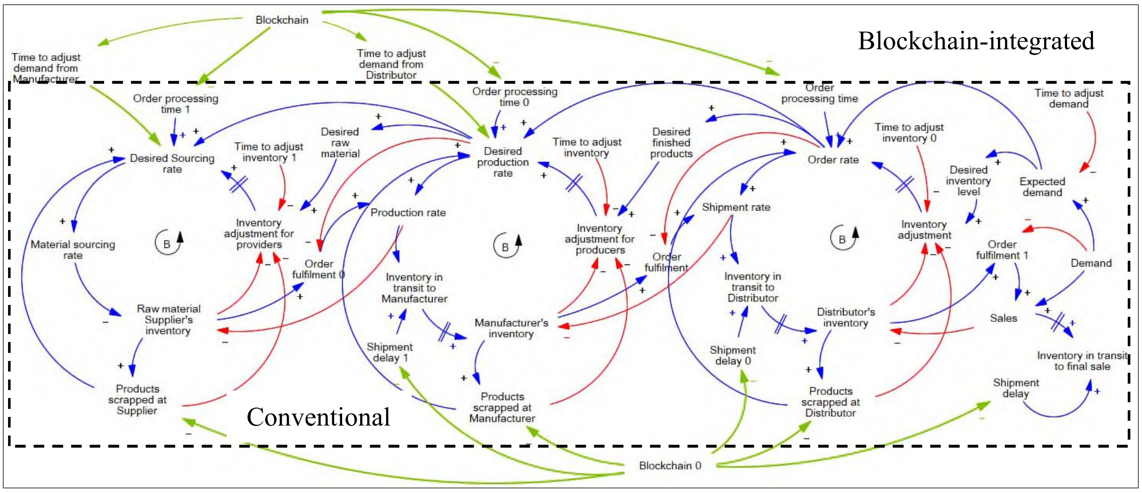


Figure 1. CLD of a conventional FSC and with the adoption of Blockchain.

Figure 1 presents the CLD for both scenario, a conventional FSC and a Blockchain-enabled FSC. Key movements of food products, from raw material stage to production stage and finally to distribution stage, are represented. Besides the movement of food products, the CLD takes into consideration inventory at each echelon, loss of products as results of discarding due to mislabeling or quality issues, and pulls for products at each echelon (demand, order, and so on). Important balancing loops in the system are denoted in Figure 1 (with letter B and counterclockwise arrow). These balancing loops implies how each entity manages their inventory to sufficiently fulfil the demand from the immediate buyer as well as to keep their stocks at a desired level. Delays features in various processes of the system (arrow line with two bars crossing), taking into account the fact that it actually takes time for products to move from one location to the others, and information to be processed.

In general, Blockchain does not alter the flow of products significantly, as it mainly serves as an additional support layer (for gathering, storing, and communicating data between food actors securely) to the existing infrastructure (Li *et al.,* 2021). Moreover, insights from a survey conducted by the authors and literature are utilized to determine the potential improvements brought by Blockchain. As part of a different project looking at the implementation of Blockchain in food industry, a survey was distributed to professionals working in food industry to gauge their perspectives regarding various aspects of Blockchain technology. Despite not being tailored specifically for this study, the survey provides useful insights to understand the potential impacts of Blockchain. Practitioners in the field with experience of Blockchain initiatives for food products, were asked to rate a number of factors related to the technology usage in food industry using a five-point Likert (1 is "Strongly disagree" and 5 is "Strongly agree"). The results shown in Figure 2 are based on 159 respondents to the survey.

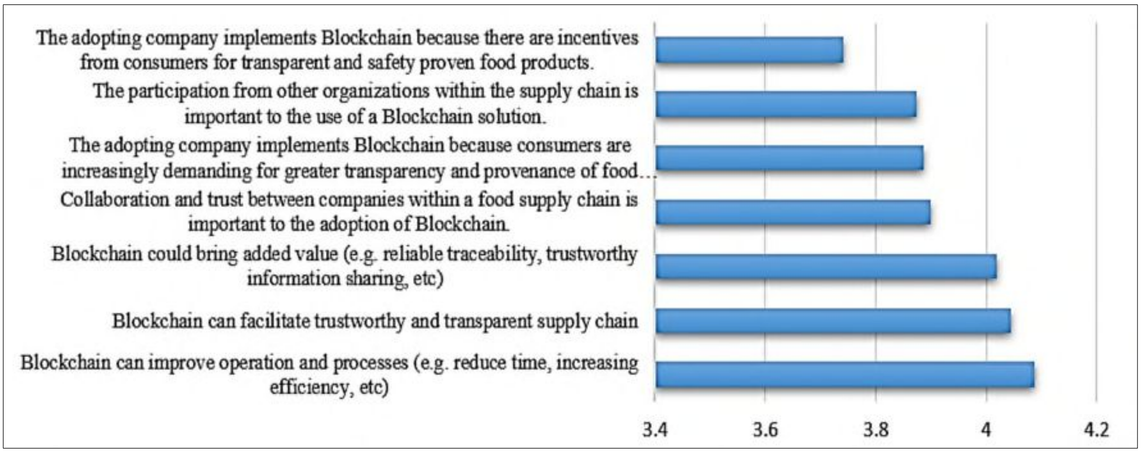


Figure 2. Some insights from practitioners regarding Blockchain.

The answers to a number of questions of the survey can be useful in grasping the potential changes brought by the use of Blockchain. Respondents highly rated the potential of Blockchain to bring improvements to the current FSC (via facilitating a more transparent supply chain, reliable traceability, and more trustworthy information sharing), and also strongly agreed (giving 4.08 points on a five-point Likert scale) that Blockchain can help to improve the speed and the efficiency of processes in FSCM. Respondents also firmly believed that the technology needs full presence and collaboration of actors in a food network for it to be successfully adopted. Furthermore, from the respondents' perspectives, there is a strong drive from consumers for safer and authentic food products, which could potentially lead to increase in demand for food products, that are verified with Blockchain technology. To gain a more holistic picture of what Blockchain could provide, extant literature is examined to aid the process of building the SD model of a Blockchain integrated FSC. Past studies also found that Blockchain could be able to speed up certain activities (i.e. quality and authenticity check upon receiving goods), facilitate quicker and more reliable information sharing, strengthen consumers' confidence in the brand, and reduce food waste by better informed inventory management (Li *et al.,* 2021; Vu *et al*., 2021). Following multiple-case study of using Blockchain for countering counterfeit wine, Danese *et al.* (2021) found that Blockchain can offer different level of assurance to consumers about the authenticity of the products, and at the very least provides strong mechanism to discourage fraudulent behaviour. Drawing from these insights, the impacts of Blockchain are captured in Figure 1 by relationship arrows linking variables "Blockchain" and "Blockchain 0" to various variables of the conventional case (such as lead time or scrap rate).

The next step is to develop stock-and-flow diagrams (SFD) from the previously defined CLD, as the basis for running simulations to evaluate the changes to the system brought by Blockchain adoption. Subsequently, two SFDs were constructed to represent the conventional scenario and the Blockchain case scenario (BC case), as shown in Figure 3 and Figure 4. The main difference brought by the use of Blockchain is now manufacturer and supplier apply a process of analyzing and smoothing the incoming order rate into their operation (represented by stock variables ED2 and ED3, and corresponding inflows of CD2 and CD3). One advantage of Blockchain for FSC performance is that it can helps actors to better match supply with demand (via real-time holistic information on supplies, demands, inventories, delays, and so on) (Li *et al.,* 2021), thus in facing demand with uncertainty, such as the hypothetical scenario used in this study's simulations, upper-stream entities of the FSC will receive the information about changes in demand down-stream sooner and have more time to formulate their approach to match the changes.

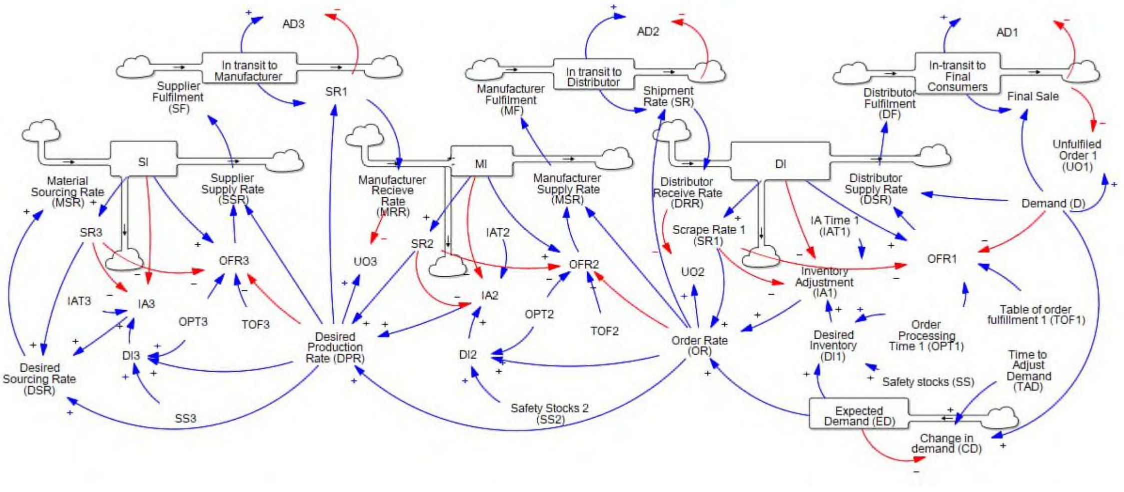


Figure 3. SFD for a conventional food supply chain.

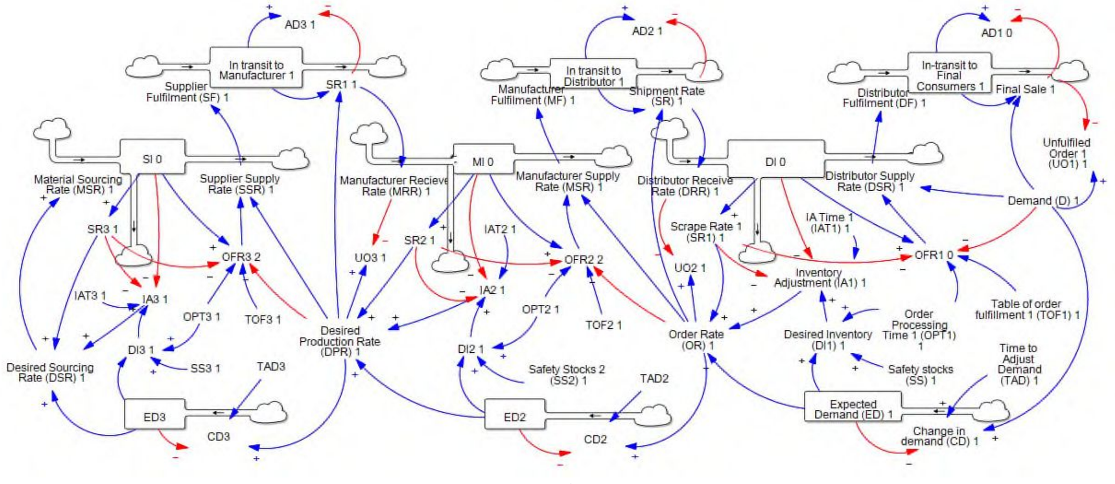


Figure 4. SFD for a BC case.

Simulation

To simulate the models and compare the two scenarios, illustrative parameters and the key inputs to the models must be initially set. Table 1 shows the parameters used for the simulation of the two scenarios. The behaviors of the FSC system were observed for a period of 500 weeks for each scenario.

Parameters/ Inputs	**Conventional model**	**BC case model**
Demand (D)	Random distribution with μ = 10,000 items and σ = 5000	
Time to adjust demand (TAD)	8 weeks	8 weeks
Safety stocks (SS) 1, 2, 3	2 weeks	2 weeks
Inventory adjustment time (IAT) 1, 2, 3	2 weeks	2 weeks
Order Processing Time (OPT) 1, 2, 3	2, 2, 8 weeks	1, 1, 7 weeks
Scrape rate 1, 2, 3	10%, 20%, 10%	7%, 14%, 7%

Table 1. Parameters for SD models.

For the simulation, it is assumed that demand is stochastically distributed (with a mean of 10000 units and standard deviation of 5000), and varies on a weekly basis. TAD reflects the time distributer takes to adjust their expected demand to meet the actual D, and is set to be 8 weeks (adapted from Sterman, 2000). SS1, 2, and 3 represents the amount of time that one entity wishes to be able to cover with their inventory level. These three parameters are set to be 2 weeks, corresponding to the Order Fulfillment Ratio (OFR) utilized in the system. Adapted from Sterman (2000) and Kochan *et al.* (2017), OFR is a non-linear function for determining the rate of supplying product from one entity to the next based on the received order and the amount of inventory available for fulfillment. For example, according to Table 2, if the ratio of the inventory to order is 1 then 85% of the order will be shipped to the customers. Thus, to maintain 100% OFR, each actor in the network needs 2 weeks of SS. To simplify the models, it is further assumed that there is no capacity constraint to any of the food supply chain echelon and shipment will assume to be one week time.

$\frac{\text{Inventory}}{\text{Order}}$	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
OFR	0.0	0.20	0.40	0.58	0.73	0.85	0.93	0.97	0.99	1.00	1.00

Table 2. Order fulfillment ratio table (Sterman, 2000).

Scrap rate in the SD models illustrates the amount of product scraped at each echelon due to quality or safety issues. The scrap rate at each echelon is inspired by a report from Food and Agriculture Organization of the United Nations (FAO) where wastage percentage was estimated to be 10% at the agricultural production of raw material, 25% at processing, and 10% at the distribution of processed food & vegetables (17% for fresh food) (Gustavsson *et al.*, 2011). We took a more conservative view about the rate and set them as 10%, 20%, and 10% for each echelon. Further, Boston Consulting Group estimated that up to 30% of the food loss during the process of storing, transporting, and manufacturing could be achieve using innovations such as Blockchain (Hegnsholt *et al.*, 2018), thus the scrap rate for the BC case is set as shown in Table 1. OPT represents the necessary time it takes for one actor to prepare and ship out received orders. For the BC case, OPT is theorized to reduce because with the help of Blockchain, actors in a food network now have access to trustworthy and timely information from their partners (Li *et* *al.,* 2021), thus any development of demand and inventory balancing activities in the future would be communicated efficiently and immediately, thus decreasing the preparation time for order fulfillment (Kochan *et al*., 2017). Moreover, OPT for manufacturer is significantly longer than the other two entities because it is assumed that OPT2 includes manufacturing lead time.

To initiate the model, all the stock variables' values at t_0 must be defined, including Expected Demand (ED), Distributor's Inventory (DI), Manufacturer's Inventory (MI), Raw material Supplier Inventory (SI), and In-transit inventory to final consumers (ITI1), Distributor (ITI2), and Manufacturer (ITI3). Given that D is randomly generated with a mean of 10,000, the following setting is used to ensure that the initial state of the model is at equilibrium with a demand of 10,000 units (thus avoiding the model to seek equilibrium while also reacting to the stochastic D and creating unnecessary noise in the results).

In-transit Inventory	**Inventory level at each echelon**	**Other**
$ITI1_{t0} = 10{,}000\ units$ $ITI2_{t0} = OR_{t0}$ $ITI3_{t0} = DPR_{t0}$	$DI_{t0} = \frac{D \times 2}{(100 - SR1)}$ $MI_{t0} = \frac{OR \times 2}{(100 - SR2)}$ $SI_{t0} = \frac{DPR \times 2}{(100 - SR3)}$	$ED_{t0} = 10{,}000\ units$

Table 3. Setup of Stock variables to initialize the models.

Analysis and discussion

To evaluate the impacts of Blockchain adoption in food supply chain, four supply chain performance metrics, namely inventory level – unfulfilled order – lead time – supply chain effectiveness, are used to compare the system behavior of the FSC in both cases.

Figure 5 reports the inventory level at each echelon after simulations, with Distributor Inventory (DI), Manufacturer Inventory (MI), and Supplier of raw material Inventory (SI). In the first scenario, it is observed that the bullwhip effect occurs in the conventional FSC. Variation in demand pattern leads to oscillation in DI, as the actor is trying to keep inventory level at a reasonable level, while still fulfilling the demand from the end consumer. Oscillation gets amplified through-out the supply line, leading to MI and SI to fluctuate at a greater rate. It is further observed that with the introduction of Blockchain, both inventory level at each echelon is reduced, and the fluctuations are much more dampened. These are the results of Blockchain providing timely and accurate information, leading to each actor in the supply chain to possess comprehensive information of the other entity's demand and inventory level, allowing for more proactive approach to meet highly fluctuated demand. MI remains relatively high comparing to the others, as the manufacturer still needs to maintain a considerable level of inventory in house to account for typically longer lead time of manufacturing.

OFR reflects the percentage of the order from one actor that can be fulfil by the direct supplier, with the maximum value of 1. Any time available inventory does not match the requirement for fully supplying an order, a lower rate of OFR is used to determine shipment rate. Thus, OFR can also indicate the service level of each echelon. Table 4 summarizes the results of OFR for both scenarios. Average service level is slightly less for Distributor in the Blockchain case, but is considerably increased for Supplier of raw material, the furthest upstream in the supply line. This could be explained as the inventory level of Distributor is reduced (almost 50%) and there is less room for buffer when demand varied too widely. However, this slight decrease in service level is acceptable since the inventory cost is greatly lowered.

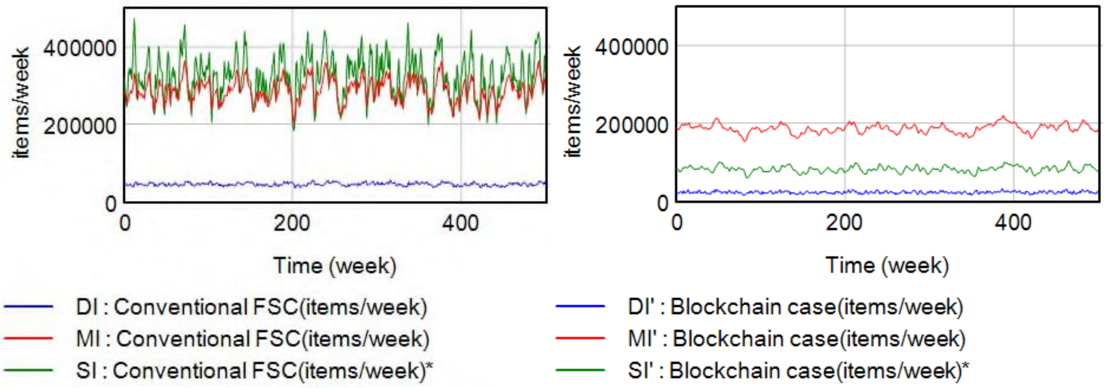


Figure 5. Inventory level.

		Min	Max	Avg	STDev			Df	t-stat.	P value
Base	OFR1	0.91	1	0.991	0.0138	**Conventional vs Blockchain***	OFR1	499	2.1	0.01
	OFR2	0.97	1	0.996	0.0042					
	OFR3	0.86	1	0.991	0.0168		OFR2	499	2.2	0.001
BC	OFR1	0.81	1	0.989	0.0239					
	OFR2	0.95	1	0.996	0.0064		OFR3	499	-4.7	0
	OFR3	0.94	1	0.996	0.0076					

**Confidence level 99%, N = 500, t-Test equal variances not assumed, $H_0 : \mu_1 = \mu_2$.*

Table 4. OFR comparision for both cases.

To assess the impact of using Blockchain on the overall lead time of the system, actual delivery delay (AD) at each echelon is examined. Majority of the variables related to the lead time of each entity are constant, such as time to adjust inventory (IAT) or order processing time (OPT). It is assumed that even if the information about immediate customers' demand and inventory is shared instantly, and reliably, using Blockchain, other factors such as machine capacity or personnel need to be adjusted in order for manufacturing time or inventory adjustment time to change. Hence, as can be seen in Table 1, IAT and OPT are constant. AD is introduced in the model to measure the change in actual delivery time (with assumption of 1 week delivery time as stated previously). Adapted from Sterman (2000), AD is the ratio of the rate of goods received by one actor in the food chain over the amounts of good in-transit from the supplier of such actor. In Figure 6, it can be seen that with better management of inventory, supplier can match the order better, resulting in less delay in delivery, and total lead time. Especially the lead time for Supplier of raw materials has seen considerable improvement.

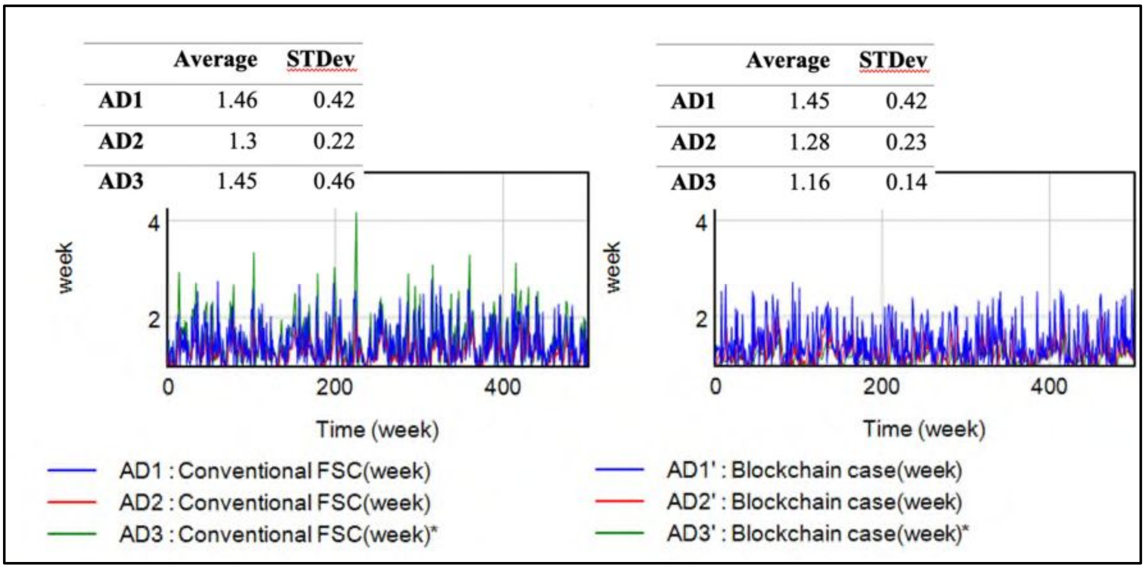
Total effectiveness of the FSC is last, but not least, metric to be evaluated in this case. Adapted from Kochan *et al.* (2017), effectiveness is calculated as:

$$SC\ Effectiveness = 100 - ((0.4*(UO1+UO2+UO3) + 0.2*((AD1-1)*100) + 0.2*((AD2-1)*100) + 0.2*((AD3-1)*100))/10)$$

With:

$$UO1 = \frac{D - Final\ Sale}{D} \times 100\ ,\ UO2 = \frac{OR - DRR}{OR} \times 100, UO3 = \frac{DPR - MRR}{DPR} \times 100$$

As indicated from the formula, the effectiveness is measured at a 100%, and will get lower value any time an event such as delay is prolonged, or an order is unfulfilled. Figure 7 depicts the SC effectiveness for both scenarios. The graphical comparison indicates that SC effectiveness has seen improvement, when the FSC fully adopted BC. Numerical results from simulation further shows effectiveness for the BC has a higher min value (94.73 vs 91.90 for the conventional case) and higher average value (98.1 vs 97.5 for the conventional case).



	Average	STDev
AD1	1.46	0.42
AD2	1.3	0.22
AD3	1.45	0.46

	Average	STDev
AD1	1.45	0.42
AD2	1.28	0.23
AD3	1.16	0.14

Figure 6. Delivery delay.

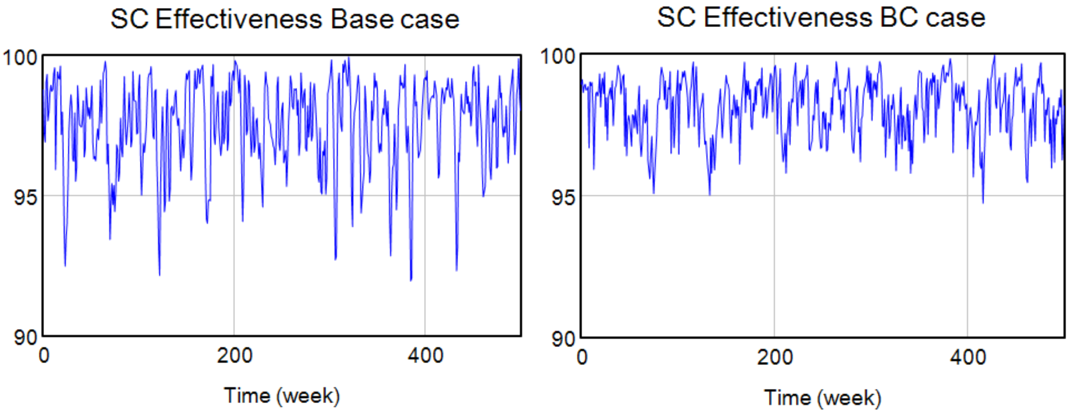


Figure 7. SC Effectiveness for both scenarios.

Conclusion

This study attempted to evaluate the impact of Blockchain adoption on FSC performance. The underpinning theoretical lenses used in this study are system thinking and system dynamics modelling, which advocate to view the phenomenon of Blockchain adoption in FSC from a holistic perspective and evaluate the affluence of the technology on the food network over a period of time. Drawing from insights of a survey regarding various aspects of Blockchain for FSCM, and relevant literature, CLD were constructed for two scenarios of a conventional FSC and a Blockchain integrated FSC. SFDs were developed based on the CLD, and simulated with inputs and parameters adapted from relevant studies and reports. The results indicated that Blockchain can potentially have positive impacts on the performance of a FSC, particularly in terms of inventory level, service level, lead time, and overall effectiveness.

Several implications for theory and practice are brought by the study. First, this study proposed a simulation model using system dynamics approach to evaluate the FSC performance. This can enrich our current understanding about the phenomenon of

Blockchain in the context of FSC, and further in a wider domain of SCM; as well as provide a useful framework for future studies to build upon and continue to expand the cumulative knowledge of the topic. For managers in the field, a number of business applications are offered from the results of the study. Blockchain can improve the visibility of inventory throughout the FSC. Blockchain further can bring improvement to the inventory holding level and other decisions related to fulfilling order of customers.

This study has few limitations. First, the key findings of this study can further be enhanced through validated empirical data. As Blockchain is still emerging phenomenon, acquiring actual data from supply networks with successful adoption of Blockchain can be a challenge. With the growth of Blockchain, future studies can potentially gain access to such data, and thus support the validation of the findings presented in this study. Moreover, as the study is set to examine a very specific context of FSC, findings are difficult to generalize.

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