



The impact of Blockchain adoption on supply chain performance: evidence from food industry

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ABSTRACT

The food supply chain (FSC) constantly needs to address persistent challenges such as information asymmetry, low transparency, food quality and authenticity, and unnecessary waste. Blockchain is perceived as a promising solution to overcome these FSC challenges. Existing literature captures a conceptual understanding of various aspects of Blockchain for FSC, such as how the technology can enhance transparency, efficiency, and food authenticity. However, a quantitative assessment of the overall impact of Blockchain adoption on the FSC operational performance is still missing. This study combines empirical and analytical approaches to investigate the evident research gap. Under the lens of systems thinking and System Dynamics (SD) modelling perspective, the study collected questionnaire and interview data to develop different FSC models for evaluating the impact of Blockchain on key operational performance metrics. The findings indicated that Blockchain positively affects inventory level and lead time in the immediate term, and cost in the long term. The results also warn that forgoing inventory buffers can come with the cost-of-service level. This study provides quantitative evidence of the positive influence of Blockchain on the FSC. This research contributes by extending the understanding of Blockchain's implications on broader supply chain performance from a systems perspective.

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1. Introduction

The food supply chain (FSC) plays an important role in producing and supplying agricultural products to sustain the world population (Barbosa 2021). Due to specific characteristics of the FSC (globalised, fragmented, and complex) and food products (perishability, seasonality, temperature sensitivity, etc.), the FSCs often face the challenges of monitoring and maintaining food quality, safety, authenticity, fragmented data, and promoting sustainability (Rana, Tricase, and De Cesare 2021; Zhao et al. 2019). These tasks can be daunting and costly. For instance, in a large food network, agricultural actors can be reluctant to share data due to the fear of not knowing who is gathering, collating, and using the data (Durrant et al. 2021). Food quality management requires a comprehensive collection of timely and reliable data, increasing the cost of producing safe and high-quality food products (Song et al. 2017). In the wake of Industry 4.0 and digitalising the supply chain, advanced technologies, such as Blockchain, offer promising means to overcome such persistent challenges in managing supply chains (Ivanov et al. 2021). Recognising the potential of the technology, FSC practitioners and researchers have extensively

explored the application of Blockchain for better food management in recent years (Antonucci et al. 2019; Li, Lee, and Gharehgozli 2023).

Under the principle of storing and sharing secured and trustworthy data (using *cryptography* and *consensus mechanism*), Blockchain improves Supply Chain Management (SCM) by enabling stakeholders to communicate critical information in a timely and reliable manner (Ghadge et al. 2023; Rao et al. 2021). In the specific setting of the FSC, Blockchain can enhance transparency and traceability at the supply chain level (Casino et al. 2021; Peng, Chen, and Wang 2023), prevent counterfeit food products and unethical practices (Saberi et al. 2019), and improve the overall food manufacturing processes with better and more reliable inter-organisational data sharing (Zhao et al. 2019). The growth of research on Blockchain in the FSC has been exceptional, with some prominent works evident in the extant literature (e.g. Antonucci et al. 2019; Casino et al. 2021; Danese, Mocellin, and Romano 2021; Li, Lee, and Gharehgozli 2023; Rana, Tricase, and De Cesare 2021; Vu, Ghadge, and Bourlakis 2023; Zhao et al. 2019) as summarised in Appendix I. These studies effectively capture the key

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aspects of the current body of knowledge regarding applying Blockchain in the FSC, identifying Blockchain applications, Blockchain-based platforms, benefits, challenges, adoption process, and potentials of the technology for sustainability development.

Nevertheless, there are areas in the literature that need further investigation. As showcased in reviewing prior works (Appendix I), the majority of them concluded Blockchain impact from the perspective of a single organisation, most often the early adopter of the technology. An extensive explanation of how Blockchain can bring changes and improvements to the operation at an FSC level is yet to be established empirically. While the extant literature emphasises the positive effects of Blockchain on the particular processes of food supply chain management (FSCM) such as food traceability and food authentication (Casino et al. 2021; Danese, Mocellin, and Romano 2021), there is still a need for robust research linking Blockchain to the wider topic of operational performance of a supply chain (Stranieri et al. 2021; Wamba, Queiroz, and Trinchera 2020). Practitioners also echo the need for such research. In a recent report about how to successfully adopt and make use of Blockchain in the industry by Capgemini, it was highlighted that ‘*Organisations need to know what success looks like. How will it be measured? What metrics will be key?*’ (Capgemini 2021, 8).

To close this evident gap, this study aims to evaluate the impact of Blockchain adoption on operational performance of FSC. Subsequently, two research objectives are defined:

- To develop models that depict the FSC system and capture the implications of Blockchain-induced changes to this system.
- To assess the impact of Blockchain adoption on key performance metrics of the FSC.

A mixed method was followed to achieve the objectives. Empirical data about FSC-level use of Blockchain was collected. Then key insights from empirical data analysis were fed into analytical models for further evaluation. This study adopts the System Thinking theory and System Dynamics (SD) approach for modelling. SD is a holistic analytical modelling and simulation approach that aims to understand complex systems (Sterman 2000). The FSC can be understood as a complex system with numerous nodes and flows (Antonucci et al. 2019). Blockchain technology is an intervention that can potentially affect the relationships and interactions in the system. The extant literature has had multiple examples of utilising SD modelling to study the impact of technological innovations on SC performance, such as RFID

(De Marco et al. 2012), cloud computing (Kochan et al. 2018), and Internet-of-Things (Qu et al. 2017). Thus, SD can be a very effective tool to investigate what impacts to FSC are brought by Blockchain and how the impacts are manifested.

This study answers the call by Li, Lee, and Gharehgozli (2023), encouraging further studies regarding Blockchain for FSC with analytical modelling and focus on the use of Blockchain from farm-to-fork. Bai and Sarkis (2022) further suggested researchers to focus on how Blockchain’s ability to support and improve operational efficiency can translate into performance results through analytical methods. The motivation for this call was that the extant literature offered a plethora of empirical and case studies, while the analytical modelling approach was seldom used to study Blockchain. Thus, the SD approach followed in this study empowers decision-making for managers by experimenting with different settings without the need to physically construct a new system (Rathore, Thakkar, and Jha 2021), predicting the effects of long-term decisions at a lower cost (Kazancoglu et al. 2021). Compared to other quantitative approaches for modelling the supply chain, SD can provide an understanding and a learning environment for managers to examine different scenarios and outcomes (Akkermans and Dellaert 2005; Sterman 2000). Thus, managers can better understand not only the change but how different components of a system interact to facilitate such change. Finally, this study also contributes to the ongoing advocacy for in-depth and specialised research on how businesses and processes in particular industries can benefit from Blockchain-enabled digital transformation (Ahmed, MacCarthy, and Treiblmaier 2022; Martinez et al. 2019; Wang, Han, and Beynon-Davies 2019), including the FSC.

In summary, the study seeks to understand the impact of Blockchain on the operational performance of the FSC using an empirical-analytical approach. Subsequently, the study makes the following contributions. First, by examining this phenomenon from an analytical perspective, it expands the current literature on Blockchain for FSC. The modelling and simulations in this study not only validate past knowledge about the benefits of Blockchain to food products (such as increased visibility, optimisation of processes, etc.) but also shed light on the mechanisms by which Blockchain can improve the performance of the FSC (e.g. distributing information instantaneously to all stakeholders, matching downstream demand to upstream supply rate, etc.). Second, this study showcases that SD modelling and Systems thinking are effective tools to comprehensively model and examine the impact of a phenomenon at a supply chain level. Third, the SD models built in this study

can be applied in specific Blockchain adoption cases to evaluate the impacts of the technology on FSC performance, which can help practitioners and policymakers make informed, robust decisions.

The rest of the paper is structured as follows: the following section provides the background to the research. Next, the methodology is discussed. The findings from the empirical data and the modelling process are presented in the subsequent section, followed by the report of the simulation results. After that, an in-depth discussion of the overall findings is provided. The final section concludes the study and highlights the contributions to theory and practice, limitations, and future research avenues.

2. Background of the research

2.1. Blockchain in the food supply chain

The modern FSC faces persistent challenges such as maintaining food quality, reducing food waste, monitoring food safety and authenticity, and lack of transparency (Danese, Mocellin, and Romano 2021; Gligor et al. 2022). These challenges stemmed from modern FSCs being typically globalised, complex, and consisting of numerous stakeholders and activities. Blockchain is a promising solution that can help the FSC to overcome these identified challenges. The core attributes of Blockchain include real-time information sharing, enhancing cyber security, and providing an immutable, unified, and trustworthy track of records (Casino et al. 2021; Li, Lee, and Gharehgozli 2023). Subsequently, Blockchain can significantly improve communication, traceability, and food quality control (Casino et al. 2021; Gligor et al. 2022).

Furthermore, as Blockchain is append-only and has embedded validation protocols (also known as consensus mechanism), existing records cannot be tampered with, and all changes to the data are recorded faithfully in the system. Thus, businesses will get further visibility up and downstream of a supply chain and are assured of the trustworthiness and auditability of the information stored on the Blockchain platform (Vu, Ghadge, and Bourlakis 2023; Zhao et al. 2019). Wu, Fan, and Cao (2023) found that, under certain conditions, adopting Blockchain in the fresh products supply chain can increase the profit of the entire network due to consumers' preferences for transparent products.

There are compelling cases of Blockchain applications in the food industry. Well-known projects such as the IBM food trust platform, Walmart's Blockchain pilot for tracking mango and pork, and Provenance's Blockchain-based solution for monitoring commercial fishing activities and catches were highlighted in the extant literature

(Cole, Stevenson, and Aitken 2019; Vu, Ghadge, and Bourlakis 2023). Many more Blockchain applications in the FSC have gone live in recent years, such as Famerconnect, OriginTrail, TE-Food, and Wholechain, alongside established projects such as the IBM Food Trust platform. Regulatory bodies are also interested in the use of Blockchain for FSC. For instance, the US Food & Drug Administration highlighted that Blockchain is a key technology for food producers and suppliers to meet the upcoming requirements of traceability set by the agency (USFDA 2021). Enhancing the traceability of food products continues to be among the most highlighted benefits of Blockchain for the FSC, illustrated by not only industry use cases but also research specialised in Blockchain solutions development, such as Caro et al. (2018), Casino et al. (2021), and Zhang et al. (2020). As FSC stakeholders are required to take accountability for the trustworthiness and correctness of information shared with Blockchain, the technology can assure the end-consumers of the provenance and certifications of food products (Danese, Mocellin, and Romano 2021).

Even though the applications of the technology can be commonly referred to under the general terminology of 'Blockchain solution', differences exist between variations. Notably, public and private Blockchain solutions are inherently distinctive regarding data accessibility and the right to record data. For the former, transactions are made available to all participants; whereas only permitted entities can record and read data in the latter (Li, Lee, and Gharehgozli 2023). There are advantages and disadvantages to each variation. For instance, a public Blockchain can be more transparent, while a private one is more flexible and adjustable for FSC stakeholders (Li, Lee, and Gharehgozli 2023). Some examples of industry solutions mentioned previously include both public (e.g. OriginTrail) and private (e.g. IBM, TE-Food) Blockchain solutions. While acknowledging the differences, the focus of this study is not on how different settings of the technology can affect the performance of an FSC. Rather, this study considers the effects of adopting a Blockchain solution on an FSC, regardless of the configurations.

2.2. Systems thinking and system dynamics

The underpinning theoretical perspective used for this study is Systems thinking. Systems thinking is *'the ability to see the world as a complex system, in which we understand that 'you can't just do one thing' and 'everything is connected to everything else'* (Sterman 2000, 4). In essence, the systems thinking perspective advocates for a holistic view of the world as a complex system, where every component (which might be a complex sub-system itself) is interlinked to others, and changes in a certain

part of the system will likely have effects on the other parts and the system as a whole (*ibid.*) Subsequently, based on systems thinking, the SD approach is a method to analyse, evaluate, and enhance the learning about the behaviour of complex systems over time (Akkermans and Dellaert 2005). It is a powerful tool for modelling the relationships between critical factors of a system and evaluating the impacts of a new policy/ intervention following the simulation of the system (Er Kara, Ghadge, and Bititci 2021; Rathore, Thakkar, and Jha 2021).

SD modelling has been applied to examine the implications of adopted technologies (De Marco et al. 2012; Fang et al. 2018). In the field of information systems, for example, most studies assume a variance logical structure – where relationships between constructs are one-way and time-invariant. In contrast, the SD approach offers an alternative viewpoint that considers the possibility of feedback between constructs, circular causality within a system, and changes over time (Fang et al. 2018). Moreover, the SD approach is widely employed to study different facets of SCM. Kochan et al. (2018) used this approach to assess the effect of cloud-based information sharing in a hospital supply chain (HSC) context, simulating and comparing the results of a conventional HSC versus a cloud-enabled HSC. Er Kara, Ghadge, and Bititci (2021) employed this approach to model the impact of climate change risk on supply chain performance. Kazancoglu et al. (2021) evaluated the performance of the reverse logistics operation in the food industry with SD modelling and simulation. Rathore, Thakkar, and Jha (2021) studied the impacts of risks in India's grain supply chain under the lens of SD modelling.

3. Research methodology

This research aims to understand how Blockchain influences processes and interactions between FSC stakeholders and then evaluate the effects of the technology on the overall performance of the FSC. Systems thinking, subsequently, is a suitable lens for examining this subject since the FSC can be viewed as a complex and dynamic system with numerous participants who constantly trade and interact with each other (Kumar and Nigmatullin 2011; Melkonyan et al. 2020). At the same time, Blockchain technology can be considered an intervention in the FSC system. The SD approach (following Systems thinking) is effective in assessing not only changes but also the causes of changes for interventions in a system for varying scenarios (Kazancoglu et al. 2021).

A challenge with modelling in this study is that, to the best knowledge of the authors, there has not been an explicit and widely agreed approach to model the blockchain-integrated supply chain system. Therefore,

this study used a mixed methods approach to achieve the research aim. Empirical data was collected to uncover the changes in business processes after the adoption of Blockchain. Later, empirical insights were combined with relevant literature to develop the SD models for two different scenarios: a conventional FSC and a Blockchain-integrated FSC. By simulating and comparing the two scenarios, this study can determine the impact of Blockchain adoption on FSC. Figure 1 presents a summary of the research methodology employed in this research. This particular approach of gathering empirical data to help develop the SD models is evident in the SCM literature (e.g. Er Kara, Ghadge, and Bititci 2021; Kumar and Nigmatullin 2011; Melkonyan et al. 2020). Empirical insights provide an effective means for determining the context (what phenomenon is under examination), understanding the key components of the models (material and information flows), and setting the boundaries of the models (process, entities, and variables inclusion/exclusion).

The study is conducted in three phases. To develop the SD simulation, empirical data was first collected through a questionnaire survey and semi-structured interviews to investigate a typical structure of the FSC and the effects of Blockchain on the processes and key aspects of operations. Details about empirical data collection are discussed further in Sections 4.1 and 4.2. Observations made from the empirical data were utilised to develop two SD models that quantify the impacts of Blockchain on the FSC. An in-depth discussion of the construction of the models is provided in Section 4.2. Finally, simulation studies were conducted, and the results were analysed and discussed in Sections 5 and 6.

A questionnaire survey was distributed to professionals working in the food industry to gauge their perspectives regarding the adoption of Blockchain and its associated aspects. The targeted respondents were primarily based in the UK and come from businesses that are either stakeholders in a food supply chain network (producer, food processor, retailer, etc.) or related to Blockchain applications for agri-food products (IT service provider, IT consultancy, etc). From 200 responses received initially, 159 responses were checked and deemed valid. SurveyMonkey and Qualtrics were used to reach out to the potential respondents in September 2021. The survey data provided useful insights to understand the potential impacts of Blockchain on the FSC.

Later, between September and November of 2022, semi-structured interviews were conducted to gather in-depth data regarding the effects of using Blockchain in the FSCs. A critical challenge of this phase is to select suitable cases according to the scope of the study. As discussed in prior sections, this study aims to examine

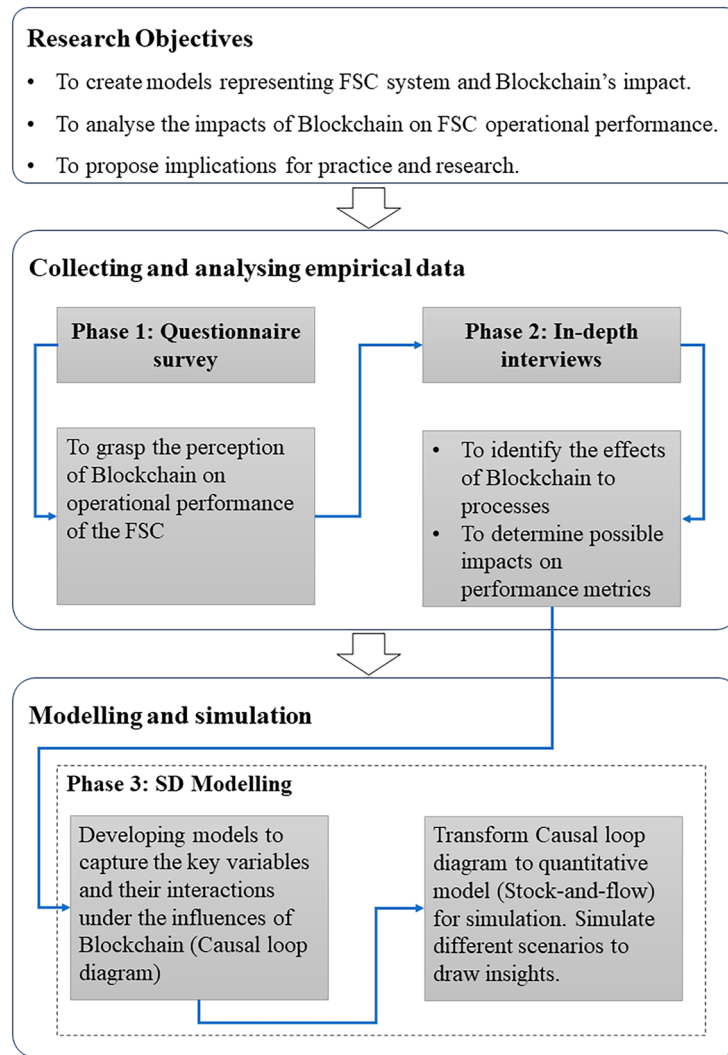


Figure 1. Research methodology.

the impact of Blockchain on a food chain network that consists of multiple firms rather than the effects of the technology experienced by a single firm. Therefore, key requirements for selecting potential candidates for the interview phase include the following: the Blockchain project must be ongoing, and the system must be adopted and used by more than one firm. Coupled with the infancy state of Blockchain implementation in the FSCs, and the lack of willingness to share information, limited data can be found on the subject. Ongoing Blockchain projects were identified to capture a holistic view of how the technology would impact the flow of products and information between stakeholders of an FSC. Invitations were sent out via emails and LinkedIn messages to several companies in the food industry. Due to limited companies adopting Blockchain in their FSCs and a lack of willingness to share information, four interviews were conducted online, each lasting approximately an hour, producing 100 pages of transcripts. The rights of data,

alongside the consent for the recording and using data, were communicated to interviewees in written form and verbally. Nvivo software was used to aid the qualitative data analysis.

Findings from the empirical data aided the SD modelling process in the next phase (which will be elaborated more in the next section). SD methodology follows a specific and logical approach to modelling. A causal loop diagram (CLD), a visual presentation of key variables and their relationships (including feedback), is constructed initially, utilising insights from the empirical data. The CLD plays an important role in determining the crucial components (entities, activities, etc.) of the FSC system, the key relationships between those components (including feedback relationships), and the changes to the system brought about by adopting Blockchain. This led to the development of the stock-and-flow diagrams (SFD) for the two scenarios (a conventional FSC and a Blockchain-integrated FSC). The SFDs include input, output, and

rates (fulfilment, consumption, etc) of the system, which are defined by mathematical equations and parameters. The SFDs are derived directly from the CLD and are further inspired by fundamental SD principles and practices introduced in Sterman (2000) and other established works of modelling the supply chains following the SD approach, such as Kochan et al. (2018), Ghadge et al. (2020), and Er Kara, Ghadge, and Bititci (2021). Finally, simulations on the SFDs were conducted to derive implications.

4. Empirical findings and the modelling process

4.1. Findings from questionnaire survey

The questionnaire survey was distributed to practitioners in the food industry. To ensure that respondents have relevant experience with Blockchain initiatives for agri-food products, a screening question was used before respondents could access the main survey. Respondents were asked to rate a number of factors related to Blockchain for FSC using a five-point Likert scale (1 is 'Strongly disagree' and 5 is 'Strongly agree'). The results shown in Figure 2 are based on 159 responses to the survey. Table 1 summarises the demographic profile of the respondents to the survey.

The respondents come from various businesses in the food industry, spreading across the value chain from raw food producers to retailers and food services. 57% of them currently assume managerial roles at their organisation, and a majority have considerable experience in the field (with 81% having more than 5 years of working in the food industry). Regarding the current stage of the Blockchain adoption projects, the majority of the companies (approximately 43%) mentioned that they are in the early phase of adopting Blockchain (researching, planning for the project, or piloting). 6% of the respondents claimed that Blockchain is used in their businesses. These developments further signal that Blockchain is progressing well in penetrating the FSC.

Insights from the survey highlighted the potential changes and perceived benefits of adopting Blockchain in FSCs (Figure 2). Respondents highly rated the potential of Blockchain to bring improvements to the current FSC through transparency, traceability, and trustworthy information sharing. They strongly agreed that Blockchain can help to improve the efficiency of processes in the FSC. Respondents also firmly believed that the technology needs significant collaboration of stakeholders in a food network for successful adoption. Furthermore, from the respondents' perspectives, consumers

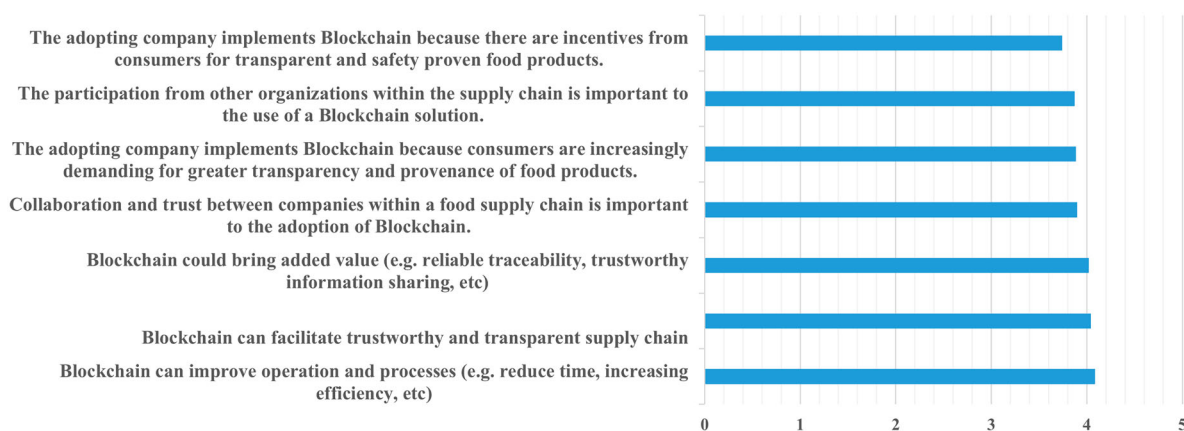


Figure 2. Response for potential benefits of Blockchain to operation.

Table 1. Overview of the respondents to the survey ($n = 159$).

	<i>n</i>	%		<i>n</i>	%
Current position			Experience		
Senior managers	36	22.6	Less than 5 years	30	18.9
Middle-level managers	56	35.2	5–10 years	57	35.8
Staffs	52	32.7	10–15 years	37	23.3
Not specified/Others	15	9.4	More than 15 years	35	22
Company main function			The current stage of Blockchain project		
Raw food producer	10	6.3	Researching	22	13.8
Food processor	28	17.6	Planning/Developing	25	15.7
Food distributor/wholesaler	35	22	Piloting	21	13.2
Food services	26	16.4	Considering a full adoption	30	18.9
Retailer	30	18.9	Starting to implement at large scale	30	18.9
Blockchain service provider	21	13.2	In use	10	6.3
Other	9	5.7	Other	21	13.2

have a recognised drive for safer and authentic food, which could lead to an increase in demand for food products verified using Blockchain technology.

Findings from the survey call for attention to an interesting aspect of Blockchain, which is the impact of the technology on the operation and processes of companies in the FSCs (highest score given). Blockchain is hypothesised to enhance, optimise, and streamline processes in the SCM, as highlighted in early works (e.g. Cole, Stevenson, and Aitken 2019; Wang, Han, and Beynon-Davies 2019); however, the literature has yet to explore this dimension extensively. Since the industry highly regarded Blockchain's ability to improve processes and performance, it provides further motivation to investigate the impacts of Blockchain on the operation of the FSCs. To bring robustness to the data collection process, in-depth interviews with managers from

Blockchain-adopted FSC companies were planned and conducted.

4.2. Findings from interviews

Three cases of Blockchain applications in the FSC were identified. The common denominators across the cases are that the Blockchain application is currently active and different stakeholders in the same FSC are participating in the platform (summarised in Table 2). When possible, the authors interviewed different members in the same supply line. This allowed to capture the effects of Blockchain at different nodes of the FSC. The semi-structured interviews focused on the changes to the operation and supply chain performance observed by the experts when their FSCs adopted Blockchain. The protocol for the interviews is presented in Appendix II. The

Table 2. Overview of the Blockchain applications and the interviewees. (P stands for Participant).

Details about participant (P) and data collection	Organization's main function	Experience	Blockchain project overview
P1 – Production manager One virtual interview, one call, and multiple rounds of exchanging emails afterwards.	Coffee processor and wholesaler	5 years	The coffee supply chain for case 1 Blockchain project consists of 4 main stakeholders: individual coffee farmers, Farmer Produce Organizations (FPOs, which represent a group of farmers, aggregate products, and deal with buyers), processors (which buy green bean coffee, roast, package and sell to buyers), and cafes and other retail outlets which distribute coffee to the end-consumers. The blockchain platform is built to track the movement of coffee from bean to cup. The platform has been successfully deployed, and the stakeholders are expanding the range of products managed with the system. The first three entities are mainly responsible for providing inputs to the Blockchain system, whereas the last one receives traceability information from the upper stream.
P2 – General manager One virtual interview.	Coffee farms co-operatives	7 years	
P3 – Team leader/ Product owner One interview and a follow-up email after to discuss more about the case.	Blockchain service provider	3 years	The juice supply chain for case 2 Blockchain project consists of 4 main stakeholders: fruit farmers, processors/producers who process raw fruit into concentrate or purée (mixed and blended fruits in liquid form with uniform), bottlers who mix and finalise the end products, and retailers. The blockchain platform is built to track juice production from sourcing fruits to the end product. The platform has been successfully piloted for a number of products and is projected to go live at the end of 2022. The first three entities are currently active with the Blockchain platform, and retailers will come on board at a later stage.
P4 – Co-founder One virtual interview, follow-up email to discuss the case, and secondary data shared with the interviewer by P4.	Blockchain service provider	10+ years	The palm oil supply chain for case 3 Blockchain project connects various stakeholders of that supply chain. In general, the supply chain can be categorised into five main stages: farmers which produce fruits, mills which process fruits into oil; other entities which refine and process the oil further, producers, which make food and beauty products using the oil, retailers, and end-consumers. The blockchain solution is developed to trace palm oil products from the source and verify their origin to make sure fruits are grown sustainably and the sourcing is ethical. The solution is successfully adopted and currently onboarding farmers, mills, and producers of palm oil. The future plan of this project is to include final users of the oil (food processing companies, beauty products producers, etc.) in the platform.

research team was aware of the limitations concerning the number of cases. To ensure the relevance and robustness of data collected from these Blockchain cases, the authors interviewed high-level managers who not only directly oversee the deployment of Blockchain in their supply chains but also have extensive experience working in the food industry. Beyond the virtual interviews, the authors maintained continuous dialogues with the interviewees (e.g. follow-up email exchanges, secondary data sharing, etc.), contributing to the data's depth and comprehensiveness.

Inductive coding was utilised to interpret the qualitative data and derive inferences. The authors carefully reviewed each transcript, assigned each datum with a code that captures the overall meaning of the datum, and later grouped related codes into an appropriate theme. Three main themes emerged from the qualitative data: the overview of the respective FSCs for each Blockchain case, the changes to process and stakeholders' interaction brought by Blockchain adoption, and the Blockchain's impacts on key performance indicators of their FSCs. Table 3 summarises the key findings from the interviews. The interviewees shared that their respective food chains are complex systems with numerous entities. Broadly, food products go through three principal states – raw materials, processed food products, and finalised food products, before reaching the end consumers. Findings from the in-depth interviews further cement the perspectives from the survey results and shed light on the impact of Blockchain adoption. The interviewees echoed the positive effects of Blockchain on the FSC.

Acting as a single and reliable source of information, Blockchain facilitates effective communication and extensive data sharing between stakeholders of the FSC. The timeliness, availability, and trustworthiness of data on the Blockchain system further help to improve certain processes such as improving food quality, communicating back orders and market-specific requirements, production planning, and inventory management. Interviewees expressed that Blockchain, as an engine for traceability, can share critical information across the stakeholders of the food value chain, which, previously, was a challenge due to siloed information systems and the lack of a safe and unified communication channel. Consistent with what the extant literature has found (Danese, Mocellin, and Romano 2021; Vu, Ghadge, and Bourlakis 2023), interviewees highlighted the improvement in the traceability process and the certification of food origin, organic status, and various compliances to safety regulations and sustainability developments, using Blockchain technology. Further, two interviewees (P1 and P2) strongly acknowledged and experienced an

improvement in their inventory level, waste reduction, shorter lead time, and higher service level, as detailed in Table 3.

Findings from the interviews helped develop the SD models in later stages in several ways. First, by understanding the entities involved in the Blockchain use case and their roles, it is possible to determine the model's focus. It is unnecessary to attempt modelling the entire FSC when the Blockchain-enabled changes to operation are most visible at certain supply chain echelons. This is indeed the case, as the three Blockchain cases considered in this study were initiated and deployed in upstream supply chains (such as farmers, processors, and food producers). This allows the modellers to set the focus of the models to where Blockchain impact would be most apparent. Second, insights from the interview help the modellers pinpoint the processes under the influence of Blockchain adoption. Findings from the empirical data extracted the effects of using Blockchain technology on supply chains. The SD models are developed to capture all such relevant processes and associated insights. For instance, when P1 and P2 described that the orders from their final customers (retailers and end consumers) can now be communicated instantly via the Blockchain platform, it can be inferred that the technology significantly transforms the communication and decision regarding procurement among the stakeholders. By reflecting on this change in process, the SD models can represent the differences brought by Blockchain and examine the behaviour of the system with simulation.

4.3. SD model development

CLD development

A broad schematic of an FSC is depicted in Figure 3. The model development in this study focuses on the three echelons of raw food providers, primary processors, and secondary processors. Sterman (2000) recommended using the SD approach to focus on the issue at hand rather than trying to replicate the exact structure of the whole system. By utilising the SD model in this manner, the modellers can direct their time and efforts to solving the actual problem/ understanding interesting phenomena rather than simply recreating reality in SD terminologies and notations. Moreover, the choice of the model's boundary considers the empirical findings. From the interview insight, upstream stakeholders adopted and used the technology. Whereas the downstream stakeholders, such as the retailers and end-consumers, are at the receiving ends of the information provided by Blockchain but are not actively interacting with the platforms. Hence, when adopting Blockchain, raw material providers and food processors experience

Table 3. Key findings from interviews.

Main themes	Insights from interviewees	Notes/ Representative quotes	Contributions to the modelling process
Understanding the FSCs in the three cases	A common problem across the FSCs is fragmented data and low transparency.	<i>A vast amount of data in the food supply chain, juice chain included, are in silos and not used or utilised in any way – P3. The supply chain we work with has never had this level of transparency before, and there are a lot of concerns regarding the deforestation issue of palm oil production. With our solution, the chain of custody is clear, we can confidently show where the palm comes from and who has it all the way through the process – P4. More details are in the next subsection – The SD modelling process.</i>	This is to set up the principal relationship in the Causal Loop Diagram (CLD).
Changes to processes and interactions between stakeholders brought by Blockchain	The flow of products and information, and the basic process of order, production, and fulfilment.		
	Enhance the fulfilment and planning processes with holistic and real-time information on stocks.	<i>Our customers inquire us about their purchases, I can immediately check the system and communicate with farmers to check the stocks, it helps us organise and plan better, even in a little more chaotic situation – P1. Farmers and FPOs understand not only where they sell to here, but where products ultimately end up, maybe Korea or Japan. That helps with planning for particular markets. – P2</i>	For the CLD: signifying the impact of adopting Blockchain on processes related to planning and fulfilment in the CLD (Order processing time, order placing to the supplier) For the Stock and Flow Diagram (SFD): predicting a decrease in the order processing time variable.
	Increase the efficiency of procuring with better communication and information availability.	<i>It helps me personally in procuring coffee; instead of calling 70 farmers a day and visiting many of them via the platform, I know when stocks are coming in and when stocks are available to pick up – P1.</i>	
	Better quality control process with reliable records of supply and production.	<i>With buyers sharing back the information with farmers on this platform, together with the farmers, we analyse to see what is lacking. It could be that they picked un-ripened coffee, which would turn into black beans – a defect. Then we work with farmers to improve their farming practices and in turn the quality of coffee – P2.</i>	
	Strengthened communication process across the supply chain.	<i>The Blockchain platform gives entities like processors of the juice a voice to speak to the end consumers in a safe and controllable environment of Blockchain – P3. The nice thing about Blockchain and the way we implemented it is that it is really easy to spot if somebody is trying to make a fraudulent update, since all the data is there, the numbers just do not add up – P4.</i>	
	Potential changes can depend on how robust the SCM processes are.	<i>For us, since there are already strong processes in place and information is required in many steps of product movement, all we do is pick up the information and add it to the Blockchain solution. Our solution does not require people to do anything differently – P4. I can see and control inventory movement in my production with real-time information. With this platform, we are looking to cut our roasted beans product cycle time by half – P1. With a total view of the inventory, we can plan transportation better and constantly move the coffee to reduce the waste of sitting inventory. With better quality control we also reduce the waste of unqualified products, with the example of the black bean earlier – P2. With the availability and reliability of data, we can organise fulfilment for buyers faster and more effectively. We have seen a huge cut down in lead time, 50–60% of what it was – P2</i>	
Impacts of Blockchain on the operation.	Inventory: <ul style="list-style-type: none"> • Real-time view of inventory. • Reduce inventory level by better grasping and monitoring stocks. • Reduce waste. 		For the SFD: predicting a reduction for the spoil rate variable.
	Lead time: improvement due to a real-time, reliable, and holistic view of the supply line, and better planning for dispatch.		For the SFD: predicting a reduction in the lead time variable.
	Service level: Improvement is due to more control of the stocks at the upper stream.	<i>When customers ask if I have something, I can see it on my system, then send a message to everyone (farmers) to get hold of the stocks because we have an offer. Thus, I can fulfill orders reliably and in a timely manner and satisfy my buyers – P1.</i>	For the SFD: predicting an increase in the service level variable.
	Cost: <ul style="list-style-type: none"> • Have to consider the cost of investment and incurring costs. • Have to consider the return on investment • The cost of Blockchain currently is not a significant part of the cost of the products 	<i>We currently charge a one-off fee of a few thousand EUR for companies to join our platform (the exact number is omitted to ensure the company's confidentiality – authors note). It is relatively small compared to the cost of production of juice – P3. Blockchain platform has an initial investment for development, followed by the monthly maintenance cost. For me, it does not increase our production cost significantly, but it is all about opportunity cost. For instance, I can choose to buy more coffee or invest in Blockchain. If I don't think Blockchain will work, I would rather have more coffee. But I do believe in this technology – P1.</i>	For the SFD: Set the cost component when calculating the cost variable.

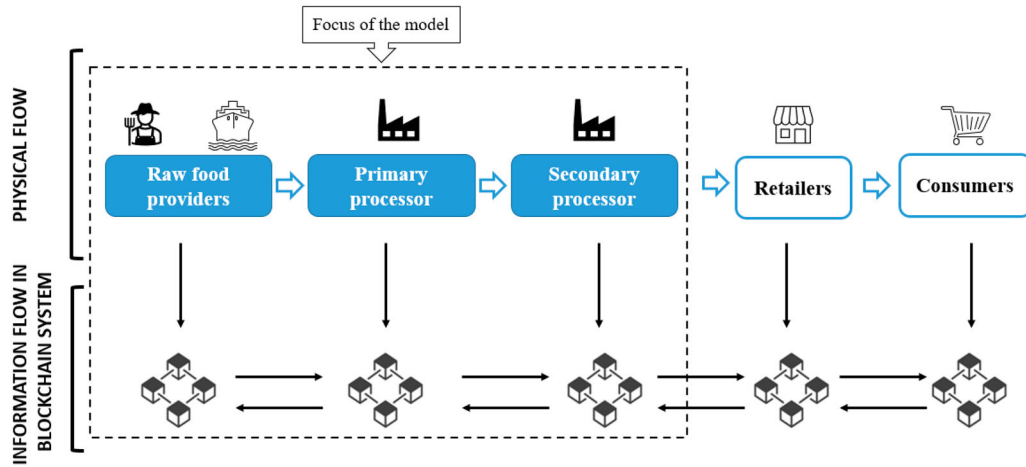


Figure 3. A simple schematic of an FSC and the focus of the model.

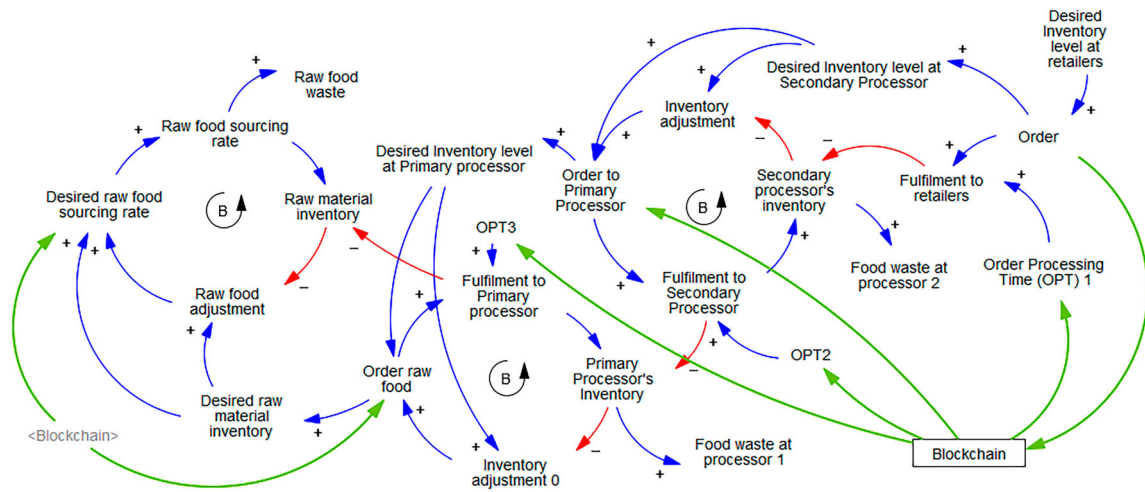


Figure 4. Causal Loop Diagram capturing the impact of Blockchain on FSC.

the most changes in their processes, interactions, and operations.

Figure 4 presents the developed CLD that describes the processes of ordering, processing, storing, and selling food products for raw food providers along with primary and secondary processors in a food network. These processes were chosen to be included in the CLD following observations made through the semi-structured interviews. The CLD conceptualises the key components of processes in the studied system and represents the relationships and feedback structures between these components. Each arrow depicts a causal link between two components. The positive or negative notation associated with one arrow indicates a positive (an increase in one element causes an increase in the related element) or negative relationship (an increase in one element causes a decrease in the related element).

The process starts with the retailers placing an order to maintain a certain inventory level to meet the demand

and achieve a defined service level. The secondary processors process and ship their finished products to the retailers. The secondary processors also want to keep a desired level of inventory, therefore they replenish by placing an order to the primary processors, after calculating the adjustments needed for their desired inventory. This typical process will be repeated for other upstream echelons. Important balancing loops in the system are denoted in Figure 4 (with letter B and counter-clockwise arrow). These balancing loops imply how each entity manages inventory to sufficiently fulfil the demand from the immediate buyer and keep the stocks at the desired level. Further, food waste can occur at each echelon, which reduces the available inventory at each SC node.

Findings from the interviews further help to assess the impact of Blockchain on these processes. For each order received, a company must spend time communicating with their supply bases, procuring the necessary

ingredients, gathering stocks or processing food to fulfil their customer's demand. Blockchain can improve this process by connecting stakeholders and providing real-time, reliable, and holistic data on a unified platform. For instance, P1 and P2 highlighted that the Blockchain platform makes them aware of available raw products from farmers (upstream FSC entities). They can source, organise, and produce in time for the cafes and other retailers (downstream FSC entities). Insights from Blockchain cases 1 and 2 further indicate that holistic and trustworthy information stored on Blockchain can inform all parties of the downstream demand and need for production at each node. This leads to better organising and planning to match production closer with demand.

SFDs development

The next step is to develop stock-and-flow diagrams (SFD) from the previously designed 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 and Blockchain case scenarios (BC cases), as shown in Figures 5 and 6. The variables' values and formulas for the base case are presented in Appendix III. The parameters and equations for the SFDs were determined based on the empirical data given by the interviewees, secondary sources (literature and industry reports), and several logical assumptions (due to the lack of available data on Blockchain impacts in the FSC and to companies unable

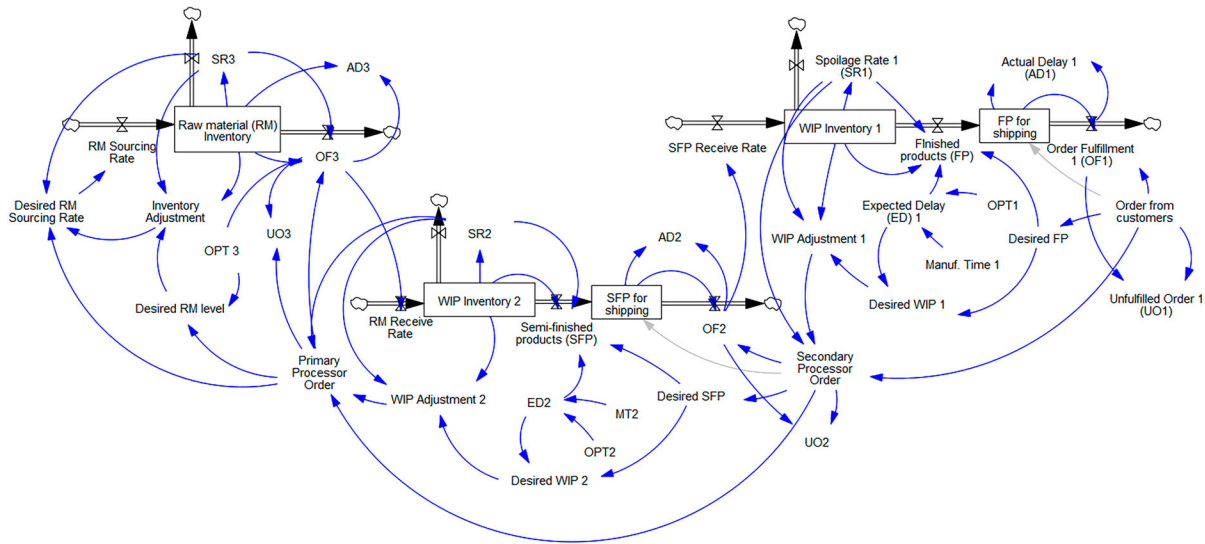


Figure 5. Stock and Flow Diagram for conventional FSC.

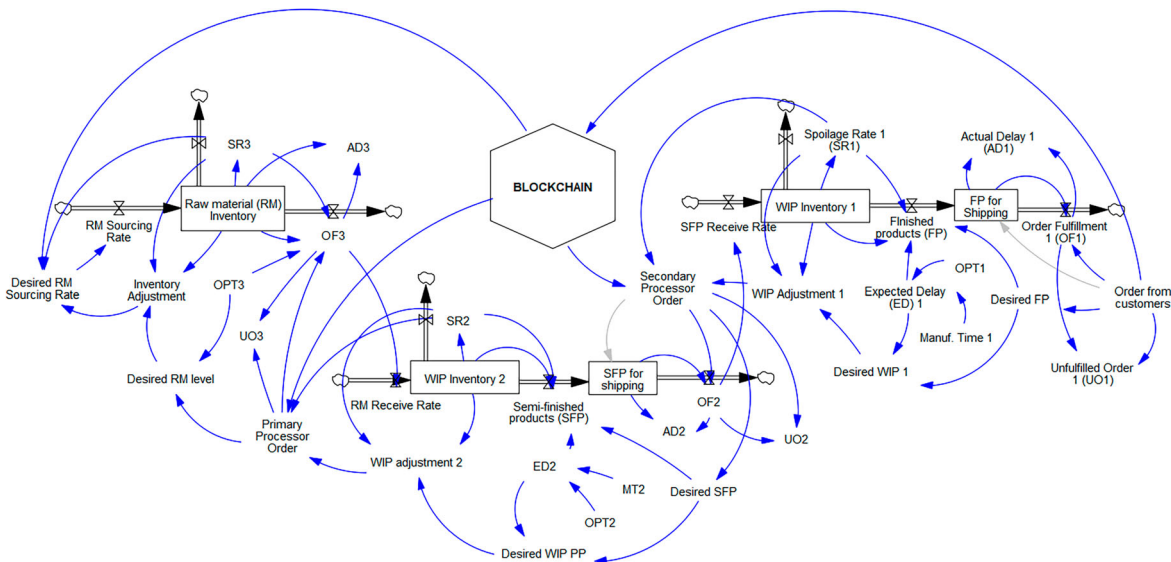


Figure 6. Stock and Flow Diagram for Blockchain-integrated FSC.

to disclose certain confidential information of their operation).

Similar to the CLD presented in the previous section, the process initiates when an *Order from customers* is logged in the system. At the secondary processor, finished products are shipped to the customers, measured by the *Order Fulfilment 1* rate, and thus, the inventory level at *Finished Products for shipping* is lowered. *Finished Products for shipping* represents the number of goods that the secondary processor has ready on hand for fulfilling customers' orders. Since the inventory level is now reduced, the manufacturing of food is now triggered to generate fresh inventory to achieve a *Desired Finished Products level*. The *Desired Work In Process 1* (WIP) is also set to determine the quantity of semi-finished products that the secondary processor needs, to meet the target production. The company also needs to take into account *Order Processing Time 1* and *Manufacturing Time 1* when planning their production, as these two factors serve as a delay to the process. The *WIP Inventory 1* needs to be adjusted accordingly to ensure the *Finished Products* rate (output rate of the production) is adequate to replenish the finished food products inventory to the desired level. The difference between the current level of *WIP Inventory 1* and the desired state (*Desired Work In Process 1*) is reflected by the *WIP Adjustment 1* variable, implying the act of monitoring and adjusting inventory for production at the secondary processor echelon. *Spoilage Rate 1* simultaneously occurs, due to the perishability and quality control of food products. In the end, the secondary processor evaluates their need and put in a *Secondary Processor Order*, which comprises the amount needed for producing and meeting the customer's order, the stock loss due to spoilage, and any adjustment to their WIP inventory.

The primary processor follows the same processes when they receive an order from the secondary processor. Subsequently, they will place an order to the raw food providers, with sufficient raw food products to cover the desired inventory and incoming orders. The last echelon, the raw food provider, does not have any processing/manufacturing capacity, as their main task is to produce or collect raw food and sell it to the primary processor. Subsequently, the following assumptions were made for modelling a conventional FSC, and subsequently the BC-integrated FSC:

- There are no backorders for food manufacturers (the primary and secondary processors). In the FSC, unavailable food products often result in lost sales due to consumers easily finding and buying substitutes, thus SD modelling works for the food system typically does not include the backorder variable (For

example see Kumar and Nigmatullin (2011) and Stave and Kopainsky (2015)).

- Orders are shipped immediately when products are available in stock.
- The production orders are assumed to be unconstrained by capacity and/or workforce. This helps to reduce the complexity of the model (Kochan et al. 2018).
- The raw material-to-semi-finished product ratio is assumed to be 1. This is not always the case for the food industry, for instance, coffee beans can retain the 1:1 ratio from raw materials to processed products but fruits typically will need a different ratio of conversion as a number of fruits are needed to make a unit of fruit concentration. The assumption is made to simplify the model and is inconsequential to the system behaviours.

In the BC case scenario, the same processes are followed at all echelons captured in the model, with two main differences. First, the information about the order from the downstream stakeholders is now recorded and shared via the Blockchain platform. Thus the primary processor and the raw food provider have better visibility of the demand and can plan their acquisition of stocks accordingly. Adjustments of inventory needed for production are still captured in the orders from one echelon to the next. Second, based on the empirical observations, the *Order Processing Time* will see improvements due to the reliable data-sharing capability of the Blockchain platform, and this change will be represented in the inputs for simulating the two scenarios in the next section.

5. SD assessment and findings

Before simulating the scenarios for comparison, sensitivity checks were performed to test the robustness of the developed SD models. Sensitivity analysis is necessary to check if the model behaves in a realistic fashion, regardless of how extreme the inputs or policies are imposed on it (Sterman 2000). Developed models showcase the ability to generate realistic behaviours of the entities of an FSC. After the robustness of the models was assessed and validated, the two SFDs for a conventional FSC and a Blockchain-integrated FSC were simulated. A condition of uncertain demand from downstream stakeholders is set for both scenarios. Key inputs and parameters for simulating the models are presented in Table 4. Findings from empirical data and secondary sources such as industry articles and reports were utilised to define some of the demonstrative values for the simulations, as explained in Table 4.

Table 4. Parameters for SD models.

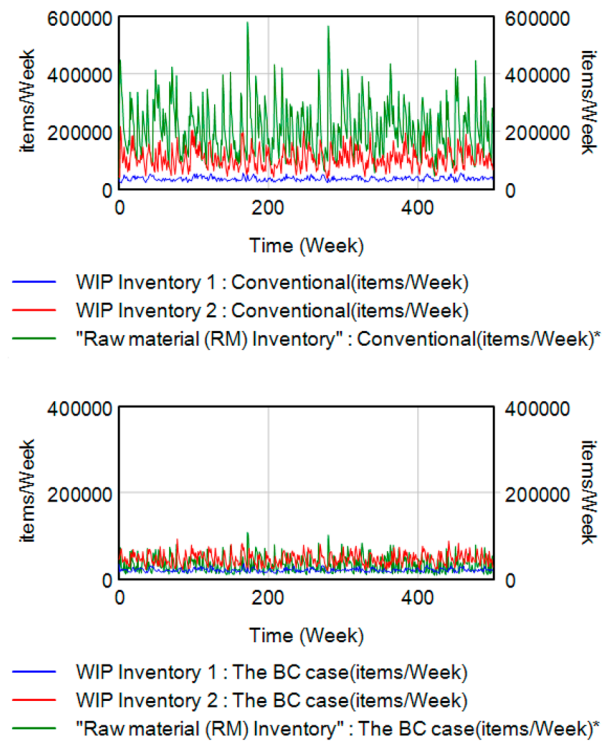
Parameters/ Inputs	Conventional	BC case	Justifications
Order from customers	Normal distribution with $\mu = 10,000$ items and $\sigma = 5000$		
Order processing time (OPT) 1, 2, 3	2 weeks	1 week	P1 and P2 reported a 50% decrease in their processing order time due to holistic information on stock availability.
Manufacturing time (MT) 1	1 week	1 week	In Blockchain case 1, the processing time for semi-finished products (dry coffee beans) is twice the time for finished products (roasted beans in packages).
MT2	2 weeks	2 weeks	FAO (2011) estimated that 9% and 25% of food are wasted as raw products at post-harvest and processed foods at manufacturers, respectively. Further, recent industry publications such as Hegnholt et al. (2018) and Birch (2022) estimated that solutions such as Blockchain can reduce food waste by 30–50%. Therefore, we made the assumptions for SR in the conventional and BC cases accordingly.
Spoilage Rate (SR) 1	10%	7%	
SR2	20%	14%	
SR3	20%	14%	

To evaluate the impacts of Blockchain adoption in the FSC, four supply chain performance metrics, namely inventory level, service level, lead time, and operation cost, are used to compare the system behaviour of the FSC in both cases. These metrics are utilised in other SD studies of the SC in the past (Er Kara, Ghadge, and Bititci 2021; Kochan et al. 2018), and further these metrics are relevant to evaluate the efficiency, flexibility, and responsiveness of an FSC (Aramyan et al. 2006).

5.1. Impact on inventory level

Figure 7 reports the inventory level at each echelon after simulations. WIP Inventory 1 refers to the inventory level at the secondary processor echelon, WIP Inventory 2 refers to the inventory level at the primary processor echelon, and Raw material Inventory refers to the inventory level at the raw food provider echelon. In the first scenario, it is observed that the bullwhip effect occurs in the conventional FSC. Variation in demand leads to oscillation in WIP Inventory 1, as the entity is trying to keep the inventory level at a reasonable level, while still fulfilling the demand from the end consumer. Oscillation gets amplified throughout the supply line, leading to WIP Inventory 2 and Raw material Inventory fluctuating at a greater rate.

It is further observed that with the introduction of Blockchain, the inventory level at each echelon is reduced, and the fluctuations are much more dampened. These are the results of the timely and accurate information provided by the Blockchain platform. When each stakeholder in the supply chain can have access to comprehensive information on the other entity's operation, they can proactively plan and organise their production and sourcing to meet the highly fluctuating demand. Instead of information sitting in a silo at each echelon, companies now are well aware of the actual demand further downstream and the changes in the preceding entity's inventory, enabling them to align their supply rate

**Figure 7.** Inventory level scenarios for Conventional and Blockchain-integrated FSC.

to the exact demand and thus maintain an optimal level of inventory.

5.2. Impact on service level

When the available inventory cannot fulfil an order, the Unfulfilled Order (UO) number increases to reflect the number of products that a company fails to supply to their customer. Since there is no backlog order for FSC, any unfulfilled order will become a missed opportunity for sale, leading to service level impact and unsatisfied customers. Kumar and Nigmatullin (2011) referred to this as a stockout situation and suggested that UO is

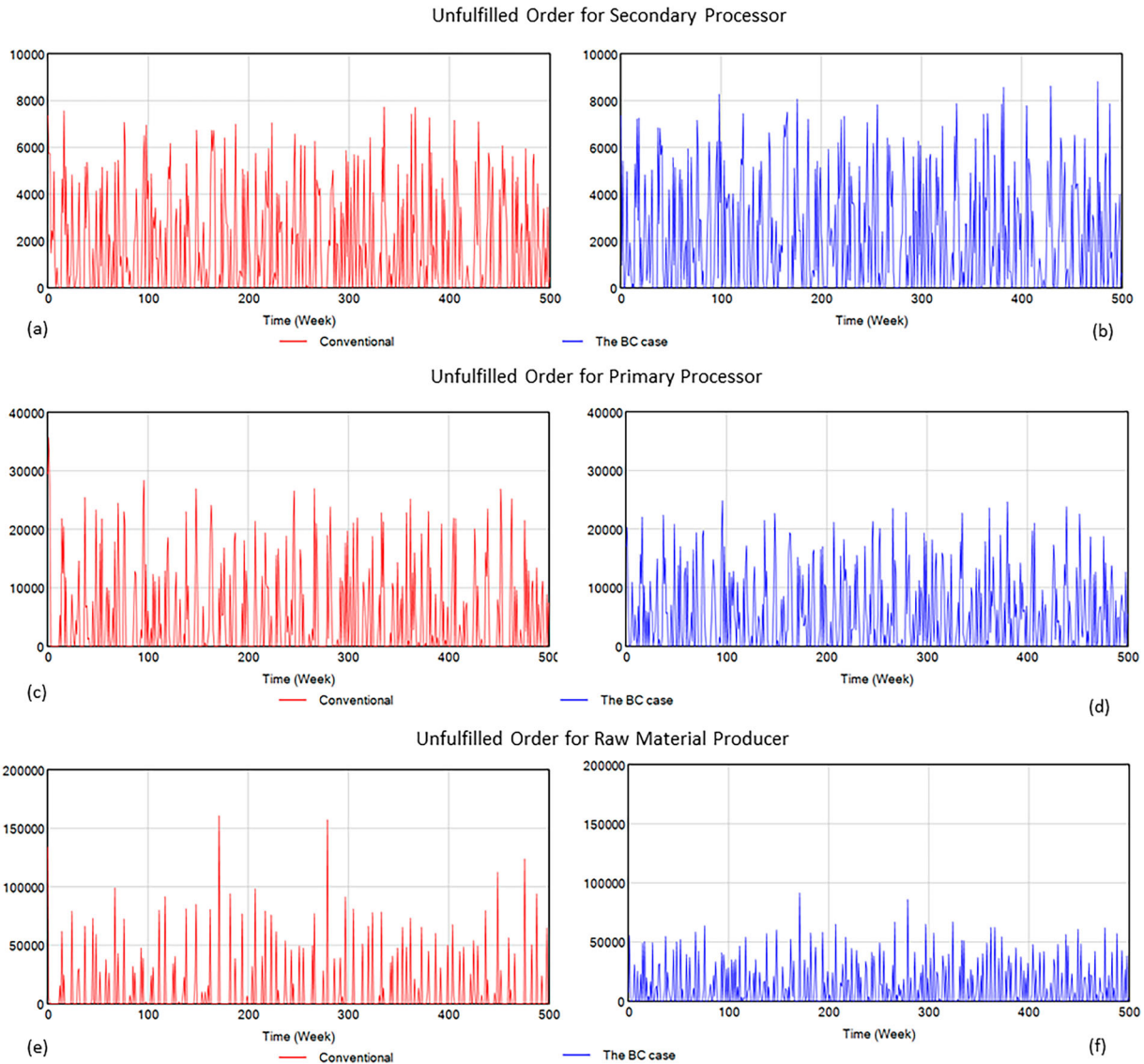


Figure 8. Cross-scenario comparison of unfulfilled orders in three echelons. (a line in one chart represents an occasion when supply doesn't meet the order. X-axis is time, y-axis is number of products).

an important metric for measuring the performance of an FSC.

Figure 8 compares the UO of each echelon across the two scenarios. It contains 6 graphs, labelled as a, b, c, d, e, and f. To make comparison of one FSC echelon across the two cases, a pair of graphs is considered (i.e. 8a vs 8b, 8c vs 8d, and 8e vs 8f). Further, descriptive statistics of the variable UO for three echelons in two cases are presented in Table 5. Two notable implications when comparing UO for the three echelons across the two cases are the size of the UO (how many products are unfulfilled) and the frequency of UO events (how often an entity failed to meet the order from its direct customer).

Regarding the number of products missing from an order, the graphs paint a relatively similar situation for the primary and the secondary processors. The difference is

more pronounced for raw food providers, as Figure 8(e) presents noticeably more high-number UOs than Figure 8(f). When analysing numerically, the average amount of unfulfilled products in 500 weeks is higher for the BC case for all three FSC echelons, while the largest missing order for the primary processor and the raw food provider happened in the conventional case (as indicated in Table 5). The secondary processor performed slightly better in the conventional case than the BC case (regarding average UO, distribution of UO value around the average, and largest UO). In contrast, noticeable improvements were made with Blockchain for the primary processor and the raw food provider (UO value fluctuates less around the mean, and largest UO value is considerably lower compared to conventional cases). A possible explanation is that when inventory is lower and fulfilment

Table 5. Descriptive statistics regarding the unfulfilled order (UO) at three different levels of the FSC across the two cases.

Unfulfilled Order		Average	STDev	Largest UO	Number of UO occurrence
Secondary Processor	Conventional	1824.3	2148.9	7731	305
	BC case	2208.7	2361.7	8826	338
Primary processor	Conventional	4895.27	7523.7	35733	226
	BC case	5534.94	6537.3	24869	311
Raw food provider	Conventional	10380.5	24988	160838	110
	BC case	11886.6	18191	91661	223

processes are synchronised better across the FSC, driven by the visibility brought by Blockchain adoption, the number of products missing in a stockout situation gets reduced.

However, when evaluating the occurrence of lost sales of the three echelons, companies perform worse in the BC case than the conventional case. As indicated in Table 5, the number of stockout events were noticeably higher for the BC case across three FSC echelons and became more pronounced for upstream entities. Figure 8(e and f) also illustrate clear difference in terms of UO frequency. The reason for this behaviour is when companies in the BC case are intensely reducing their inventory level and matching their production levels with incoming orders, the amount of buffer inventory is consequently lower than that in the conventional case. Thus, when demand variability is high, companies can have more stockout situations. It should be noted that the specific setting for the simulation (with demand varies considerably weekly and companies make adjustment after a change in demand) can contribute to the stark difference.

5.3. Impact on lead time

Lead time, the latency between the point of food products entering one echelon to the point of moving to the next echelon, is another critical indicator of an FSC performance (Aramyan et al. 2006). Under the SD perspective, lead time serves as a delay that can generate system inertia, leading to fluctuations in inventory levels (Kumar and Nigmatullin 2011).

For the SD models designed in this study, the total lead time of the system consists of the expected delay, which is controlled by the companies (such as the manufacturing time and order processing time), and the Actual

Delay (AD), which measures how quickly products (raw materials, semi-finished food products, or food products depending on the echelon) are to be moved to the next echelon. Table 6 presents the simulation results of the AD of all echelons in the two scenarios. Suppose a company has more products in its storage (indicated by the inventory for shipping stock variables in the models) than the immediate order. In that case, the products remain on hold until the next order, thus delaying other operational activities. AD is introduced in the model to measure the change in actual delivery time, which can be measured by the ratio of the rate of actual shipment to the next entity over the available read-for-shipping products (Sterman 2000).

As shown in Table 6, the average delay for all echelons in the BC case is much improved compared to the conventional case. Further, a t-test analysis was conducted to see if there is a significant difference in delay between the two scenarios. The results summarised in Table 6 indicate a significant difference in the AD3 values in both cases, with a confidence level of 99%. The differences in the AD1 and AD2 values in the two scenarios are much less pronounced, as the confidence level is 90%. Similar to the comparison of inventory levels, the raw material provider is conventionally more prone to variation in downstream demand due to inherently being the furthest away from where it is first placed. Thus, with the introduction of the Blockchain platform capturing and sharing real-time and reliable information, the raw material providers gained the most improvement in terms of inventory management. This subsequently leads to better shipment planning and significantly reduces the delay for this entity. By comparing the average and the standard deviation of the AD value for the primary and secondary processors between the two scenarios, it can be

Table 6. Actual delay in product movement.

		Avg	STDev			Df	t-stat.	P value
Conventional	AD1	1.13	0.262	Conventional vs Blockchain	AD1	1000	1.87	0.06
	AD2	2.85	21.27					
	AD3	10.9	78		AD2	1000	1.11	0.10
BC case	AD1	1.10	0.226					
	AD2	1.75	6.31		AD3	1000	2.34	0.009
	AD3	2.72	8.15					

N = 500, t-test assuming equal variances, $H_0: \mu_1 = \mu_2$.

Table 7. Inputs and parameters used in estimating operation cost for the models.

Variable	Value/Formulas	Comment
Inventory holding cost per unit	$= UnitCost \times 0.4\%$	Inventory holding cost is estimated to be 20% of the unit cost per annum, thus it is 0.4% per week, assuming there are 50 working weeks per year. The unit cost is assumed to be \$0.5 per unit. The percentage is adapted from Er Kara, Ghadge, and Bititci (2021).
Delivery cost per unit	$= Unitcost \times 0.5\%$	
Manufacturing cost per unit	$= Unitcost \times 50\%$	Explained in a prior discussion.
Blockchain development cost	\$150,000 one-time cost	
Blockchain maintenance cost	\$250 per week	
	$For\ the\ conventional\ case = Inventoryholdingcost + Deliverycost + Manufacturingcost$ $For\ the\ BC\ case$	
Cost accumulation rate	$= Inventoryholdingcost + Deliverycost + Manufacturingcost + Blockchainimplementationcost + Blockchainmaintenancecost$	

observed that improvements are also recognised in those two echelons.

5.4. Impact on operational cost

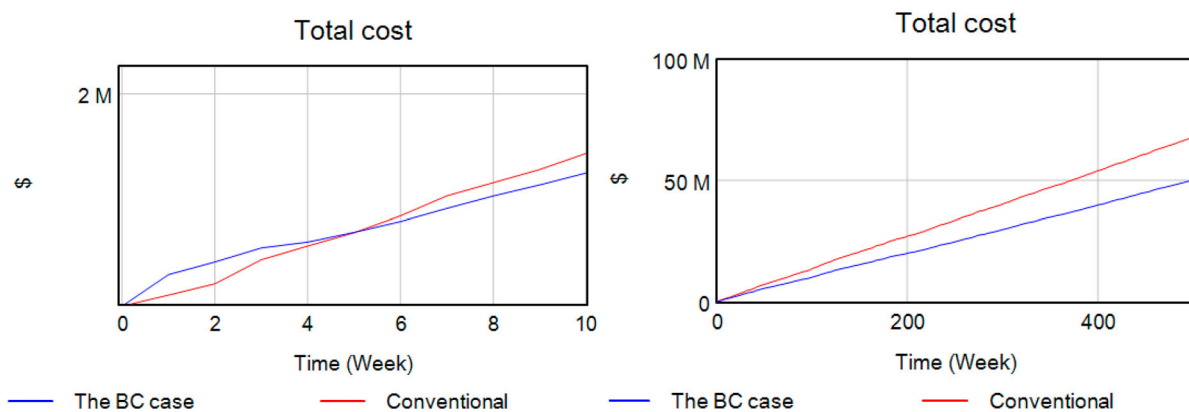
The operations cost for the two scenarios is evaluated to uncover the potential impacts of Blockchain on the cost of FSC operations. In this case, the operational cost of the FSC consists of the inventory holding cost, manufacturing cost, and delivery cost. The administrative cost is not included in the model. The detailed calculation and modelling of the operational cost are presented in Appendix IV.

The input and parameters for simulating the cost of the two scenarios are explained in Table 7. A demonstrative value of \$10 per unit is used to create the basis for comparison between the conventional and the Blockchain-integrated FSC scenario. This study primarily focussed on evaluating the behaviour of the system under the influence of Blockchain adoption, thus using a demonstrative value for the unit cost is an appropriate approach when the unit cost is expected to vary for different food products. The same approach has been utilised in other SD studies such as Er Kara, Ghadge, and Bititci (2021).

The assumptions regarding the cost of Blockchain were made based on Gopalakrishnan, Hall, and Behdad (2021) and an estimation tool for Blockchain development

price (Leewayhertz, 2022). According to these sources, integrating Blockchain into an existing platform could be broken down to a development cost from \$ 102,900 to \$161,700 in an estimated time of 30 weeks, and a maintenance cost from \$11,172 to \$12,348 per year. These figures are consistent with the insights shared by P1, as the company was quoted approximately \$100,000 for the development of the Blockchain solution and two to three hundred dollars per month for maintenance. Therefore, to illustrate a generic cost of a Blockchain platform, a development cost of \$150,000 and a recurring cost of \$250 per week (\$12,500 per 50-week year) are used in the setup.

Figure 9 summarises the results of the simulations of operational costs in both scenarios. The accumulation of costs was reported and compared in two timescales: 10 and 500 weeks. The reason is to observe the behaviour of the cost variable in the short and long term for the whole system. As seen in the 10-week graph, at the beginning, the cost of the BC case far exceeds the cost of the conventional case. This is due to the high implementation cost associated with technology. However, the difference is quickly offset due to the savings generated from lower inventory, manufacturing, and delivery costs. The total cost in the BC case starts to become lower than the conventional case, starting from week 5. Looking at the longer term (the 500-week graph in Figure 9), the

**Figure 9.** Total cost scenarios for conventional and Blockchain-integrated FSC (10 and 500 weeks).

operational costs for both scenarios continue on their trajectory. Thus, it can be seen that adopting Blockchain will increase the total operational cost at first; however, after some time, the cost savings benefits will start to offset the initial investment. Moreover, in the long term, the savings from using Blockchain to improve operations can be far more than the adoption cost.

6. Discussion

From the simulation results presented in the last section, insightful observations regarding the impact of Blockchain on the performance of the FSC were drawn by comparing the results of the two scenarios. Particularly, improvements are seen in inventory level and overall lead time. In the long run, FSCs that use Blockchain will likely save on costs. Findings regarding the service level were surprising, as it was anticipated that the service level of FSC would be greatly improved under the influence of Blockchain. As indicated by the simulation results, when matching the inventory and production level strictly with the final demand of downstream entities, there is a risk of forgoing buffer inventory. Therefore, companies might experience stockout situations often under volatile demand.

More importantly, the SD models show not only what performance metrics are influenced by the introduction of Blockchain, but also the mechanisms by which Blockchain can facilitate such change. The key ingredient for harnessing the improvements is that Blockchain can transform the data sharing between stakeholders, leading to changes in critical operations such as ordering, forecasting, fulfilment, etc. In the conventional model, demand information is typically held and processed within one entity before an order is placed with the immediate supplier in the other echelon. In the BC scenario, it can be seen that information about the downstream demand is instantly shared with all stakeholders by a unified Blockchain system. The word 'unified' implies that companies in the same FSC network use the same Blockchain solution to share and gain information. This is facilitated by two key features of Blockchain. First, data in Blockchain is distributed, thus participants can access the information almost instantly no matter where in the network it was submitted. Second, due to the immutability of data by design, companies can trust the reliability of information, and data accountability is ensured. Therefore, companies can act upon the information with a high level of confidence. Subsequently, FSC-level operations can be fine-tuned and agreed upon among firms in the same FSC to better match the demand.

Furthermore, a number of conditions must be met for the simulation results to replicate in real business cases. First, the models are set up in a way that companies would trust the information shared by Blockchain to make instantaneous changes to their operation. This can be a challenge in a long and complex FSC. While data sharing has long been an important aspect of FSC, and a plethora of solutions can be applied to enhance this process (Durrant et al. 2021), trust is not necessarily warranted by just the availability of information. Nonetheless, Blockchain possesses unique traits that can facilitate the trustworthiness of data. The decentralisation nature of Blockchain, coupled with the inherent immutability of verified data blocks, can ensure the trustfulness and accountability of information distributed by the technology.

It should be noted that Blockchain is not a perfect solution, as there is still room for errors such as wrongful data entry. However, having an auditable track of records can increase a firm's responsibility in providing information. In the case of error, transparency provided by Blockchain can help businesses quickly narrow and amend their processes (Vu, Ghadge, and Bourlakis 2023). Another critical aspect is selecting what data to share. Casino et al. (2021) highlighted that Blockchain technology, at the moment, cannot handle large amounts of data generated from SCM activities due to latency and scalability issues. The cases examined in this study provided interesting examples of what to include in the Blockchain. In case 1, as the main concerns are with the availability of raw coffee, stock information was heavily focused on by the project. In case 3, due to severe sustainability issues associated with palm oil (particularly the deforestation in planting palm trees), certifications and traceability were mainly communicated for a faster process of admitting raw products into processing facilities. Depending on the actual business cases, key information must be identified and shared by Blockchain to realise the reduction in order processing time as assumed in the SD models.

Moreover, the simulation results also advocate for close collaboration between FSC stakeholders. Interestingly, Blockchain's impacts on inventory level and lead time are more apparent upstream in the supply line. This creates an interesting situation for Blockchain adoption in the FSC, as currently, large enterprises are leading the exploration of Blockchain and typically initiate the project. As an example, blockchain case number 2 is part of the empirical data. Therefore, for possible large-scale adoption of Blockchain in the FSC, collaboration and long-term partnership remain the key, since the benefits of Blockchain to the operational aspect might not be realised immediately by the early adopters of the technology.

Finally, findings from this study validated and leveraged prior literature on the subject. Li, Lee, and Gharehgozli (2023) highlighted that the technology can enable companies in the FSC to better match demand with supply to improve operations. The simulation results agreed with this statement, as inventory management and lead time can improve when demand information is communicated throughout the network. Other benefits of Blockchain for the FSC are mentioned in the literature, such as enhancing food traceability, facilitating trust, and increasing transparency (Cole, Stevenson, and Aitken 2019; Vu, Ghadge, and Bourlakis 2023; Zhao et al. 2019). This study investigated further to explain how those benefits can improve FSC operation. Particularly, transparency and trust can translate into a better data-sharing process, leading to more efficient ordering, stocking, and fulfilling activities.

7. Contribution and future research

This study attempts to expand the current understanding of Blockchain technology in the FSC domain from practice and research by providing a unique SD perspective. Our approach provides a holistic view of the FSC network, describes how Blockchain can influence the supply chain system, and further prescribes important conditions for realising improvements. The study accomplishes three objectives: first, our in-depth discussion concerning the development of SD models (Section 4.3), alongside key parameters and formulas (Appendix III), provided specialised tools to represent the FSC system and evaluate the impacts of interventions such as Blockchain. Second, the simulation results (Section 5) indicated the evident improvement in inventory level, lead time, and operational cost for companies when adopting Blockchain. Surprisingly, service levels can be affected when inventory is matched too closely with demand, especially in volatile demand situations. Blockchain's ability to improve data sharing, trust in information, and selecting what to share among stakeholders are highlighted as critical factors to achieve improvements. Third, implications and contributions to theory, practice, and policy are drawn and presented in the following sections.

7.1. Contribution to theory

This study's contributions to the literature are three-fold. First, this study contributes to the research on Blockchain interfacing supply chains, providing in-depth insights into the behaviours and performance of a (food) system under the influence of Blockchain adoption. While the extant literature has highlighted certain benefits of

using the technology, such as establishing total transparency, enhancing traceability, and combatting food fraud (Danese, Mocellin, and Romano 2021; Gligor et al. 2022; Rana, Tricase, and De Cesare 2021), a critical aspect of adopting Blockchain to improve operational processes was not examined extensively. Our study fills that literature gap by building toward a more comprehensive understanding of Blockchain technology in an FSC setting. Second, our study provides SD models of a food system, specifying the interplays between Blockchain technology and critical SC processes such as procurement, fulfilment planning, etc. The models not only shed light on the impact of technology adoption on the operation of an FSC but also contribute by providing a holistic approach to model a supply chain system, following the systems thinking theory. Third, this study proposed systems thinking and SD modelling as an effective approach to investigate the effects of interventions on the SCM. Bai and Sarkis (2022) endorsed the use of modelling, including SD modelling approaches, in explaining and understanding the integration of Blockchain and supply chain, and this study provides another example of how SD modelling and Systems thinking can be a powerful tool to analyse and evaluate the impacts of Blockchain on performance at an FSC level.

7.2. Contribution to practice

The contributions of this study to practice are two-fold. First, managers in the field can adopt this study's approach to examine specific use cases of Blockchain in their respective FSCs. This study followed a logical process, from gathering empirical data to constructing analytical models grounded in practical insights and assessing the impacts with numerical study. Similarly, decision-makers could review their supply chain and processes to map where and how Blockchain can bring changes before evaluating different scenarios with simulations. SD models developed serve as a useful framework for managers to consider different scenarios and draw conclusions. Furthermore, this approach can be extended to investigate Blockchain and other industry 4.0 technologies interfacing supply chains.

Second, implications for business can be induced from the simulation findings. Companies in the FSC can expect improvements to their inventory management, lead time (which can lead to better shelf-life of food products), and operational costs, using Blockchain. Blockchain can transform and improve the data-sharing facet between FSC stakeholders, enabling managers to make better, timelier, and strategic decisions regarding ordering, stocking, and fulfilment. To achieve that,

it is suggested that a sufficient understanding of key Blockchain features (such as immutability, decentralisation, etc.) is required, allowing the technology to facilitate trust between companies on the information being communicated. Once again, collaboration is emphasised by this study's results to harness the benefits of Blockchain for an entire FSC network. Finally, alongside improvements, the risk of decreased service level when forgoing too much inventory is raised in this study's findings.

7.3. Contribution to policy

Moreover, this study can be useful for food regulators, especially when several regulatory bodies are looking to promote Blockchain adoption as an effective means of tracking food movements and monitoring food safety. The models and the simulation results of this study suggest that multiple echelons of the FSC need to collaborate closely to reap the most benefits from Blockchain technology. Thus, regulatory agencies can play an important role in connecting businesses and fostering consortiums for effective Blockchain adoption. Further, as the impact of Blockchain on the operation is most visible to upstream entities who are typically not technically savvy (farmers, fishermen, etc.), regulators can communicate the operational benefits of using Blockchain technology (as evidenced by the results of this study) to such entities and direct sufficient efforts to bring them to the Blockchain platform, realising improvements to the whole FSC.

7.4. Limitations and future research directions

This study has a few limitations. First, developed SD models were considered only a three-echelon FSC network (raw material provider, primary, and secondary processor), and the model designing process was strongly guided by the empirical findings from the three Blockchain use cases. Second, reasonable assumptions were made when constructing the SD models. Under different circumstances, these assumptions need to be revised and used with caution to ensure the accuracy and robustness of the models. For example, at the time of this research, the cost of a Blockchain implementation was acquired through a quote provided by a technology service provider (Leewayhertz), and we assume that a major stakeholder in the FSC would initiate a Blockchain adoption and bear the initial investment. Future studies can improve on this aspect by considering various cost structures, taking into account different business models (build in-house vs outsource vs subscription), and data

storage design (e.g. off-chain and on-chain storage). Nevertheless, the approach to calculating the operational cost in this study can be adapted to represent specific cases if inputs are available. Third, due to the lack of an established approach to model Blockchain technology in the SCM setting, we had to rely on empirical data to design our models. It is acknowledged that there are only 3 cases considered for this work due to the difficulty in determining successful large-scale adoption of Blockchain and the unwillingness to share critical operational information. Secondary data sources were utilised when there was a lack of primary data. Moreover, as the study is set to examine the specific FSC context, findings are difficult to generalise.

Two potential future research directions are recommended. First, our work can be extended to include other echelons (particularly retailers) and other important variables related to FSC performance. As mentioned above, one limitation of this study is that empirical cases ground the scope of the SD models; therefore, only three supply chain echelons are included. The inclusion of downstream FSC stakeholders, especially retailers, would be useful in expanding our work and validating our findings. The findings suggest that Blockchain can alleviate the impact of the bullwhip effect on the FSC by strengthening communication and data sharing between FSC stakeholders, which aligns with past research. For example, Dejonckheere et al. (2004) found that enriching information sharing can significantly reduce the bullwhip effect for upstream entities. The findings of this study also indicate that while Blockchain can improve the operation of an FSC, it can possibly make it more susceptible to the adverse effects of demand volatility, demonstrated through the impact on the service level. The topic of demand volatility has become especially contemporary in recent years in light of large-scale growing disruptions across the world. For instance, COVID-19 created significant challenges to the operation and resilience of supply chains through drastic changes in consumers' behaviour, logistics disruptions, and high demand volatility (Ramanathan, Aluko, and Ramanathan 2022). By extending our work with the inclusion of downstream entities, future research can explore whether better demand forecasting and management can be achieved with the inclusion of downstream FSC entities in the Blockchain solution and whether the bullwhip effect can be mitigated without compromising service level when Blockchain is integrated into the whole FSC.

Furthermore, by gaining a comprehensive view of the FSC, future studies can explore where buffer stocks can be positioned to mitigate the risk of over-streamlining the supply chain, how much stocks should be kept to

harness the benefit of Blockchain without penalty to service level, and how it affects costs of the FSC. Appendix V proposes potential ideas for future works to expand our models by including FSC resilience and sustainability variables. Finally, we suggest the complementary use of other advanced technologies from Industry 4.0 for supply chains with Blockchain, resulting in added benefits. For instance, quantum computing has the power to leverage the capability of Blockchain by potentially solving the scalability issue (Awan et al. 2022).

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that empirical data used for this study is available within the article and its supplementary materials. Models and derived data supporting the findings of this study are available from the corresponding author on reasonable request.

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Appendices

Appendix I. Summary of key Blockchain aspects in FSC and pending research questions

Study	Key insights regarding Blockchain for FSC	Pending issues to be investigated
Antonucci et al. (2019)	Blockchain applications in the domain of FSC are extensively explored by both the scientific community and practitioners. Researchers tend to focus on the designing aspects of a Blockchain system, comparing different solutions, and applying theoretical insights in building the applications. Companies often select a specific case or product to develop and pilot Blockchain solutions.	To generate a robust Blockchain solution for the FSC, issues such as ownership, maintenance duty, functional economic model for the technology, etc. must be addressed.
Zhao et al. (2019)	Blockchain applications in the FSC are perceived to bring improvements to key areas including food traceability, information security, agrifood manufacturing, and sustainable resource management in food production. Key challenges to this technology remain, such as scalability, privacy, high cost, regulation problems, and lack of skills	It is suggested that empirical research is needed to examine the real-life application of Blockchain in the FSC, how to integrate Blockchain with other advanced technologies, and how to address the identified challenges of Blockchain technology.
Li, Lee, and Gharehgozli (2023)	Prevailing Blockchain-based platforms are reviewed based on three dimensions of data accessibility, knowledge requirements, and software integration. Further, sets of benefits (improving traceability, reducing food waste, reduction of time, improving performance, and so on) and challenges (technology, cost, governance, regulation, and awareness) are identified from the literature.	Future research avenues regarding Blockchain in the FSC include incorporating Blockchain in analytical models, evaluating realised Blockchain benefits in early adopters, and exploring Blockchain-based platforms for food delivery and sharing.
Vu, Ghadge, and Bourlakis (2023)	Under the lens of Innovation Adoption theories, Blockchain implementation in the FSC can be categorised into three phases Initiation, Adoption decision, and Implementation. Relevant determinants to such a process include drivers and barriers to Blockchain adoption, application of Blockchain, and management characteristics.	There is a need for empirical work exploring the adoption and implementation of Blockchain for food products. Further, challenges such as scalability, privacy-transparency trade-off, incentivization, and regulations need to be investigated.
Rana, Tricase, and De Cesare (2021)	A number of Blockchain use cases for sustainability development in the FSC are reviewed. In essence, the Blockchain's properties of immutability and security can help provide transparency of sustainable food products, monitor ethical compliances, audit energy usage and emissions, and enable recycling and circular economy of food.	Governments and researchers have roles to play in order to facilitate successful Blockchain applications for sustainability development in the FSC.
Casino et al. (2021)	A single case study is presented, with real life use case scenario and corresponding requirements/ features for a functional Blockchain based architecture.	Based on this work, future research is recommended to explore the Blockchain design in this study in a larger setting.
Danese, Mocellin, and Romano (2021)	Multiple cases of using Blockchain for preventing counterfeit food products were investigated. Key variables (e.g. data veracity, data-entry frequency, communication channels, and accessibility) were found as important determinants of how Blockchain system can help preventing upstream and downstream risks of counterfeiting.	More efforts are needed to explore the use of Blockchain in a complex supply network.

Appendix II. The interview protocol

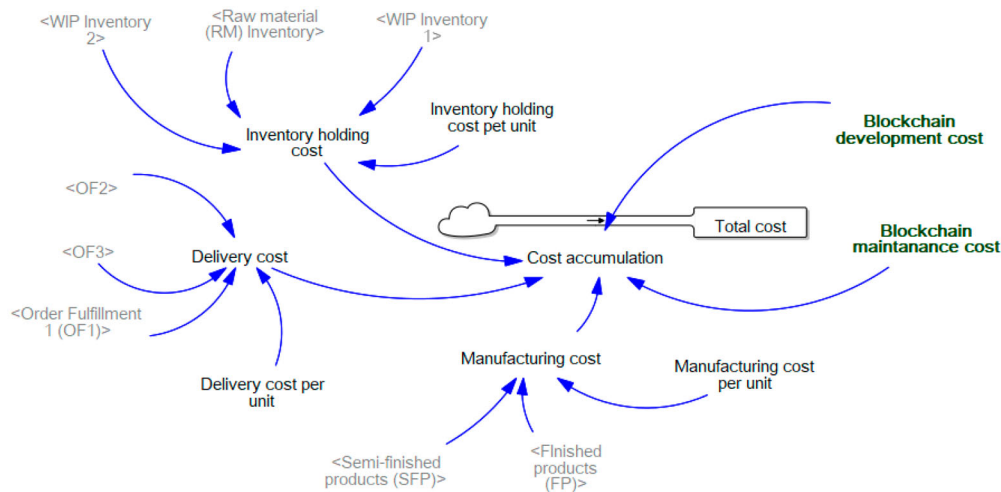
Section	Question
Introduction	
Overview	<ol style="list-style-type: none"> 1. Ask the interviewee about the Blockchain project, which is the focal point of the interview 2. Follow-up questions if not all information is uncovered with the initial introduction: <ul style="list-style-type: none"> • What is the scope of this project? • What is the main use of Blockchain in this case? • What is the current progress of the project? • What are the companies participating in this Blockchain solution at the moment? • How integrated is Blockchain into the current operation of the involved companies?
Main section	<ol style="list-style-type: none"> 3. Can you explain the roles, tasks, and contributions of each company in this Blockchain system? 4. Can you describe the structure of the food supply in this case? (ask the participant about how products and information move between each node of the supply chain to help with mapping the process and modelling the system) 5. What are the changes/improvements to the process as the result of using Blockchain? Do you anticipate any changes/improvements to any process, once Blockchain is integrated? 6. What are the impacts of Blockchain on the supply chain in this case? 7. Follow-up questions if not all information is uncovered with the initial answers: <ul style="list-style-type: none"> • About (certain aspect), how exactly does Blockchain help to improve it in this case? • For this specific case of Blockchain use, have you observed any effects of Blockchain on the inventory management and inventory level of the companies? If yes how Blockchain can make a difference here? • For this specific case of Blockchain use, have you observed any effects of Blockchain on lead time of the companies? If yes how Blockchain can make a difference here? • For this specific case of Blockchain use, have you observed any effects of Blockchain on the service level of the companies? If yes how Blockchain can make a difference here? • For this specific case of Blockchain use, have you observed any effects of Blockchain on the cost for companies? If yes how Blockchain can make a difference here?
Other	<ol style="list-style-type: none"> 8. Have you observed any other impacts to the operation from using Blockchain? 9. Can give an estimate of the cost of Blockchain in this case for the companies that are using it? Ideally like percentage estimation against product price? 10. Outside of what we have discussed so far, do you expect Blockchain to bring any other benefits? Especially to the operating performance of the companies.
Concluding the interview, and ask to be connected with others	

Appendix III. Equations and parameters

Formulas and values for variables used in simulating the SFD models of this study are presented here. Note that some are already explained in the main text and thus will not be included here.

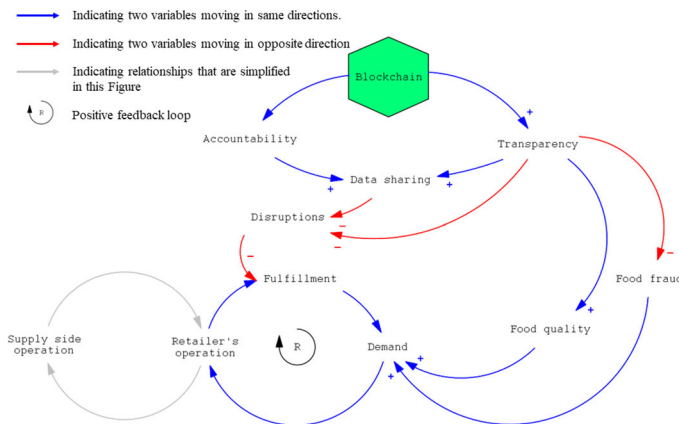
Variables	Formulas/ Values	Description
Order from customers	$= \text{RANDOMNORMAL}(5000, 15000, 10000, 5000, 1)$ Unit: product	To generate uncertain demand for the system.
Desired Finished Products (Desired FP)	$= \text{Orderfromcustomers}$	Desired number of finished products that secondary processors need to meet the order.
Order Fulfilment 1 (OF1)	$= \min(\text{FPforshipping}, \text{Orderfromcustomers})$	Rate of fulfilment from the secondary processor. When inventory ready for shipping is insufficient, even if the order is higher, the entity can only send what they have in stock. On the contrary, when there is more inventory than demand, the entity can only send what was ordered and the rest stays at the warehouse.
FP for shipping	$= \int (\text{OF1} - \text{Finishedproducts}, \text{FPforshipping}_{t0})$ $\text{FPforshipping}_{t0} = \text{Orderfromcustomers}_{t0}$	Finished products on hand and ready for shipment.
Finished products	$= \min\left(\text{DesiredFP}, \frac{(\text{WIPInventory1} - \text{SR1})}{\text{ED1}}\right)$	Rate of making finished food products.
WIP Inventory 1	$= \int (\text{SFPReceiverate} - \text{Finishedproducts} - \text{SR1}, \text{WIPInventory1}_{t0})$	Work in process inventory for manufacturing finished products. The spoilage rate takes away from the available inventory.
SFP Receive rate	$= \text{OF2}$	Expected delays that the secondary processor knows they have. This is the combination of Order Processing Time (OPT) and Manufacturing time (MT)
Expected Delay 1 (ED1)	$= \text{OPT1} + \text{MT1}$	
Desired WIP 1	$= \text{DesiredFP} \times \text{ED1}$	Desired level of WIP stocks for the secondary processor, which has to take into account the delay in processing orders and manufacturing.
WIP Adjustment 1	$= \text{DesiredWIP1} + \text{SR1} - \text{WIPInventory1}$	Adjustment to make sure the WIP inventory aligns with the desired level.
Secondary Processor Order	$= \max(0, \text{Orderfromcustomers} + \text{SR1} + \text{WIPAdjustment1})$	Order put forward by the secondary processor, which is constrained to be always positive (Sterman 2000). The order needs to be sufficient to cover the order from a customer, the difference in desired WIP inventory, and any stock lost due to spoilage.
OF2	$= \min(\text{SecondaryProcessorOrder}, \text{SFPforshipping})$	Same logic as the secondary processor
Desired Semi-finished products (SFP)	$= \text{SecondaryProcessorOrder}$	Desired number of semi-finished products that the primary processor needs.
SFP for shipping	$= \int (\text{OF1} - \text{SFP}, \text{SFPforshipping}_{t0})$ $\text{SFPforshipping}_{t0} = \text{SecondaryProcessortOrder}_{t0}$	Semi-finished products on hand and ready for shipment.
SFP	$= \min\left(\text{DesiredSFP}, \frac{(\text{WIPInventory2} - \text{SR2})}{\text{ED2}}\right)$	Fulfilment rate of the primary processor
ED2	$= \text{OPT2} + \text{MT2}$	Work in process inventory for manufacturing semi-finished products.
WIP Inventory 2	$= \int (\text{RMReceiverate} - \text{SFP} - \text{SR2}, \text{WIPInventory2}_{t0})$	
Desired WIP at Primary processor	$= \text{DesiredSFP} \times \text{ED2}$	This is a flow to the ED, which is a stock valuable. When there is a gap between the actual demand and the expected demand, this value changes to update the expectation of the seller about demand.
WIP Adjustment 2	$= \text{DesiredWIPPP} - \text{WIPInventory2} + \text{SR2}$	This adjustment is to keep the inventory level in line with the desired level.
Primary Processor Order	$= \max(0, \text{WIPAdjustment2} + \text{SecondaryProcessorOrder} + \text{SR2})$	Order put forward by primary processor.
OF3	$= \min\left(\frac{\text{Rawmaterial(RM)Inventory} - \text{SR3}}{\text{OPT3}}, \text{PrimaryProcessorOrder}\right)$	Same logic as the other two echelons.
Raw material (RM) Inventory	$= \int (\text{RMSourcingrate} - \text{OF3} - \text{SR3}, \text{WIPInventory2}_{t0})$	RM kept at the warehouse of the raw food provider
Desired RM level	$= \text{PrimaryProcessorOrder} \times \text{OPT3}$	Same logic as the other two echelons.
Desired RM Sourcing rate	$= \text{PrimaryProcessorOrder} + \text{InventoryAdjustment}$	
Inventory Adjustment	$= \text{DesiredRMlevel} - \text{RMInventory} + \text{SR3}$	The desired rate of sourcing raw food into the warehouse of the raw material provider.
RM Sourcing Rate	$= \text{DesiredRMSourcingrate}$	

Appendix IV. Calculating the cost of the operations for the two scenarios



This figure showcases the components that make up the total operations cost for a conventional FSC and a Blockchain-integrated FSC scenarios. In Vensim software, we developed the calculation of cost in a different view, using inputs directly from the main models in the form of ‘shadow variables’ (with the name of the variable inside the < > notation). This function allows modellers to continue building on different parts of the system without compromising the readability and clarity of the main models. Cost calculation for both scenarios is similar for the most part, except in the BC case the costs of Blockchain development and Blockchain maintenance are included (variables in green text).

Appendix V. A potential CLD of Blockchain impacts on other key performance metrics



Direct link	Indirect link	Anticipated impacts
Blockchain increases Transparency	<ul style="list-style-type: none"> Transparency and Accountability can improve data-sharing process. Transparency can enhance Food quality. Transparency can reduce the chance of food fraud. 	<ul style="list-style-type: none"> Under a better data-sharing environment (more transparent and reliable), disruptions to the supply chain is better prevented and reduced. A reduction in disruption would lead to increase in fulfillment success. Transparency can influence disruptions rate, as increases in transparency can reduce risk of disruptions (due to prevention). Reduced food fraud and increased food quality can stimulate demand for specific food products from end-consumers. A reinforcement feed back loop (denoted by the R symbol) exists when demand is raised (due to more trust in the products), leading to increasing supply to meet the new demand.
Blockchain increases Accountability		