Improvement of public distribution system efficiency applying blockchain technology during pandemic outbreak (COVID-19)

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Abstract

Purpose – The purpose of this paper is to analytically examine the viability of using blockchain technology (BT) in a public distribution system (PDS) supply chain to overcome issues of shrinkage, misplacement and ghost demand.

Design/methodology/approach – The authors use a standard news vendor model with two objectives, the first of which includes a reduction of the total cost of stock, while the second includes minimization of the negative impact of human suffering due to the nonavailability of subsidized food supplies to the needy people.

Findings – The authors applied the model to a real-life case to draw meaningful insights. The authors also analyzed the cost/benefit tradeoff of adopting BT in a PDS supply chain. The results show that the adoption of BT in a charitable supply chain can reduce pilferage and ghost demand significantly.

Originality/value – The paper is positioned for utilizing inventory visibility via consistent and tamper-resistant data stream flow capability of BT to enhance the overall efficiency of PDS. Notably, Indian PDS faces three major challenges in terms of its supply chain efficiency.

Keywords Blockchain technology, Newsvendor model, Public distribution system, Charitable supply chain, COVID-19

Paper type Research paper

1. Introduction

The world has been facing an unprecedented outbreak of the novel coronavirus (COVID-19). The ongoing effect of the pandemic has broken the economy for virtually all the countries. The virus has affected almost every dimension of the human ecosystem. The outbreak started around November 2019 in Wuhan, China, and within the next six months, it covered almost all the member countries of the United Nations. Both the direct and indirect costs of this pandemic are going to be very high. While the direct costs include ones that are associated with patient care and loss of human life (i.e. size of the population affected by the disease), the indirect cost is associated with loss of production during the duration of the pandemic.

Although China, South Korea and Japan seem to have better control over the outbreak of COVID-19, it is still uncontrollable in most countries. The world at large has been facing a huge challenge in controlling the pandemic. The World Health Organization (WHO) has instructed all its member countries to maintain social distancing or lockdown and isolation of the affected population. Almost all the countries are facing a variety of economic challenges that include loss of production and/or the challenge to feed the needy/daily wage workers. Importantly, the challenges of COVID-19 have been very prominent on the global supply chain, and the restoration strategies for the future are one of the main research topics under supply chain resilience (Chesbrough, 2020; Ivanov and Das, 2020; Ivanov and Dolgui, 2020). Moreover, the impact of COVID -19 on the supply chain vis a vis its managerial implications are also a novel research agenda during this pandemic (Currie *et al.*, 2020; Mogaji, 2020; Queiroz *et al.*, 2020; Remko, 2020; Sarkis *et al.*, 2020). The literature has been replete with

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innovative solutions and suggestions for dealing with the ongoing challenge. Choi (2020), for example, has proposed a "fixed-cost-subsidy" (FCS) scheme, "operations-cost-subsidy" (OCS) scheme and/or safety-technology-support (STS) scheme in order to help logistics operations within a country. Specifically, India, given its size, both in terms of geography/landmass along with its population, has been no exception in facing similar challenges. Importantly, although India does have a strong public distribution system (PDS) to feed its populous, it does face challenges in terms of its efficiency. As there seems to a considerable lack of studies that deal with food distribution challenges within a pandemic, we took up this study to explore the situation.

By and large, the food supply chain has become a persuasive issue for farmers, scientists, administrations, users and other stakeholders (Galvez *et al.*, 2018). India adopted the food security system to cater to the menace of hunger and poverty. This was conceptualized during the Second World War and has been practiced since through a PDS. Currently, India is one of the fastest-growing economies, but ironically, in reality, it is still striving to eradicate hunger and poverty among its populous. India ranks poorly (at 103) on the world hunger index, which falls under the "serious" [1] category. The Indian government has adopted various measures to tackle the situation by categorizing the level of poverty within the country and subsidizing food grains accordingly (Biswal *et al.*, 2018). Notably, poverty has been categorized into three levels: Antyodaya Anna Yojana (AAY; poorest of the poor), Below Poverty Line (BPL) and Above Poverty Line (APL).

The Indian targeted public distribution system (TPDS) is facing problems of corruption, theft, misplacement, shrinkage and leakage of food grains that are taxing in turn both the taxpayers and the governments (Overbeck, 2016). It is estimated that the "inclusivity and the possibility of leakage reduction have the potential to deliver a net gain of $1 billion in social welfare from the status quo" (Surpluses, 2015).

The total subsidy burden for the charitable supply chain of food program was INR (Indian Rupee) 1349.19bn in 2015–2016. The goal of the subsidy is to provide food items at a highly discounted price to the needy people through PDS. However, some people have been using corrupt ways to entitle himself or herself to the list. This has led to the generation of "ghost demands" in the PDS supply chain. Ghost demands refer to demands from nonexistent/nondeserving people. The existence of ghost demand indicates that food items are being diverted to the "nondeserving" and/or to the open market to be sold at a premium.

The Indian Ministry of Petroleum and Natural Gas estimated that the potential savings in liquefied petroleum gas [2] (LPG) subsidy for 2015–2016 would be INR 9,211 crores after identifying ghost demands. These (i.e ghost demands) were identified by linking the AADHAR [3], the authentic ID of Indian consumers to the LPG Supply chain [4]. AADHAR is a unique ID database that identifies the legitimate inheritor of charity and/or subsidy. Notably, AADHAR is only a database, and it cannot be used for tracking the transactions in the distribution chain. Further, there seem to be some security issues in the AADHAR system too.

Both tracking and authenticating a food supply chain to understand its attributions is critical. One has to assess, ascertain and tackle corrupt sources in the global food supply chain worldwide; and one of the feasible ways to do the same is by implementing blockchain technology (BT) to store data so that it becomes almost impossible to make any subsequent influence (Galvez *et al.*, 2018). BT is expected to remove the drawbacks of AADHAR related to security. Therefore, we propose that BT may be used in the Indian PDS to improve efficiency and thereby eliminate ghost demands. On the other hand, the humanitarian supply chain needs to be digitized and designed both for quick response and transparency. Importantly, finding an appropriate design of the humanitarian network for quick response is a major concern in the charitable supply chain.

BT has already gained popularity among the business community at large and is expected to be used by almost 65% of industries by 2020 [5]. The need for BT is also accentuated due to its capability to ensure visibility, operational improvements and secure record keeping. Most importantly, it provides good quality, consistent and tamper-resistant data records in a supply chain (Wang *et al.*, 2019). It may be used for demand and supply information visibility and could facilitate supply chain coordination and trust-building to enhance efficiency in the supply chain (Choi *et al.*, 2019). BT can form a peer to peer distributed network, where nontrusting participants could transact with each other without trusted intermediaries (Christidis and Devetsikiotis, 2016).

Governments and NGOs are increasingly facing challenges in terms of refining the efficiency and the effectiveness of their disaster relief efforts. These challenges are mainly due to a lack of trust, poor collaboration and an inability to respond to disaster-affected areas in an appropriate manner (Dubey *et al.*, 2020). Notably, both traceability and transparency are two important dimensions of BT, and the lack of trust and poor collaboration are the antecedents of the BT adoption (Clohessy *et al.*, 2020). Along with the IoT platform, it can also be used for tracking product flow within a supply chain (L'Hermitte and Nair, 2020). These barriers to the humanitarian supply chain have been potentially reduced by the adoption of BT (Ozdemir *et al.*, 2020).

Several researchers have already advocated the adoption of BT in managing a sustainable supply chain due to the above-said capabilities (Saberi *et al.*, 2018a, b). However, before using any technology, one should have a comprehensive understanding of the technology in itself to finally adopt it. Deciding on which type of BT one has to adopt is largely dependent on the type of database that's been in use, type of partnerships, access control, along the type of transaction. Prior literature has conducted the qualitative analysis for BT adoption within a supply chain (Table 1).

However, the extant literature has particularly failed to identify the value of adoption quantitatively. Our study looks to address this gap, especially, in the context of a charitable supply chain. The following flow diagram is the reason we propose to adopt BT in TPDS.

The flow diagram (Figure 1) is specifically designed for answering the question of whether adopting BT is worthy, as per the flow diagram, i.e. a hybrid blockchain seems more suitable for TPDS.

To the best of our knowledge, this is the first paper that analytically examines the viability of using BT in a charitable PDS supply chain. The proposed model is a significant modification of the published report of Biswal *et al.* (2018). Notably, the modifications in this proposed approach include issues like ghost demand rate, shrinkage and misplacement, reflecting thereby its suitability in the Indian socio-economic environment, while also considering the integration of BT with RFID. This study is positioned for utilizing the inventory visibility via consistent and tamper-resistant data stream flow capability of BT, to enhance the overall efficiency of PDS. Importantly, the Indian PDS faces three major challenges in terms of its supply chain efficiency. The first challenge includes shrinkage and misplacement of procured food grains; the second one is that of "ghost demands", while the third includes moral hazards (i.e. farmers and the stock is not able to get their intended value). The first problem may be minimized by adopting RFID technology, while the last two could be eliminated by BT adoption. We use a standard news vendor model for this purpose with two objectives; the first is to minimize the total cost of the stock, while the second is to minimize human suffering due to the hindrances in supplies of critical food grains for the poor. The total inventory cost is modeled both with and without BT. We carry out numerical analysis using real data from the Indian PDS supply chain. We justify our proposal by a cost-benefit analysis of adopting BT within a PDS. We believe that the outcome of the analysis would enable and incentivize policymakers to adopt BT within a PDS and enrich the relevant knowledge

S. No	Article	Application	Usage of blockchain technology (BT)
1	Di Francesco Maesa and Mori (2020); Azzi *et al.* (2019); Wang *et al.* (2019)	Survey on the use cases of BT	This discussed the following application scenarios: end to end verifiable electronic voting, healthcare records management, identity management systems, access control systems, decentralized notary (with a focus on intellectual property protection) and supply chain management
2	Dwivedi *et al.* (2020)	Pharmaceutical supply chain system	This paper describes how the blockchain mechanism combines with the traditional pharmaceutical supply chain system and to achieve a better SCM system, we present a blockchain-based scheme for information sharing securely in the pharmaceutical supply chain system with smart contracts and consensus mechanism
3	Feng *et al.* (2020); Behnke and Janssen (2020)	Agrifood supply chain	Application of BT to improve agri-food traceability
4		Food supply chains (FSC)	Boundary conditions were identified for the application of BT in a food supply chain
5	Bumblauskas *et al.* (2020)	Food distribution	This article explained the implementation of BT in the production and supply chain delivery system for eggs from farm to consumer
6	Casino *et al.* (2019)	FSC	This paper proposed a distributed functional model to provide decentralized and automated FSC traceability based on BT and smart contracts
7	Chang *et al.* (2019)	Supply chain process design	Proposed a blockchain-based framework along with the use of an affiliated technology, i.e. smart contracts, to derive the feasible benefits of the supply chain process design
8	Choi (2019)	Diamond supply chain	It shows a comparative analysis of BT-enabled authentication, certification and selling platform with traditional diamond supply chain operations. It also analyses the conditions under which it lowers the cost of laser marking operations and benefits the chain partners
9	Chod *et al.* (2018)	Finance supply chain	Blockchain is adopted to bring transparency into the firm's operations which leads to favorable financing terms at lower signaling costs
10	Wang *et al.* (2019)	Food, pharmaceutical and luxury-item supply chain	Blockchain is adopted to create permanent, shareable and actionable records of products' digital footprints

(*continued*)

Table 1.
Application of blockchain technology in supply chain

S. No	Article	Application	Usage of blockchain technology (BT)
11	Choi *et al.* (2019)	Air logistic global supply chain	Due to the emergence of BT, supply chains are becoming digital now. The paper highlights a promising application of blockchain technology in supply chain risk analysis
12	Ying *et al.* (2018)	E-commerce platform	The study proposes that blockchain-enabled e-commerce platform can be used by companies to secure critical data
13	Ambler (2017)	Diamond supply chain	BT is used to track and ensure diamond authenticity
14	Abeyratne *et al.* (2018)	Manufactured cardboard boxes supply chain	BT is used in the manufacturing supply chain of cardboard boxes for decentralized and transparent transactions
15	Kim and Laskowski (2018)	Food supply chain	Ontologies are used for blockchain design to determine food supply chain provenance
16	Tian (2016)	Food supply chain	Real-time traceability and safety control system is proposed by integrating blockchain with the Internet of Things
17	Ali *et al.* (2017)	Food supply chain	BT is applied for information security of the food supply chain in China

Table 1.

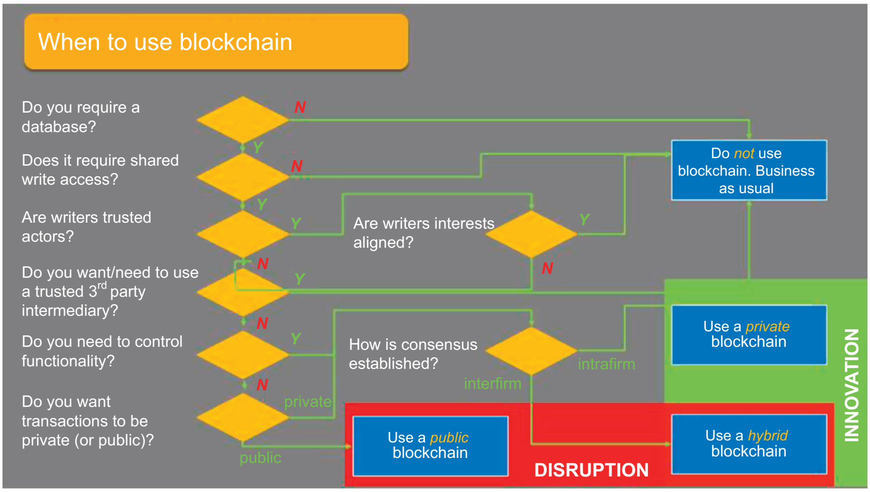

Figure 1.
Flow diagram

base to both the academia and the research community at large. The paper is focused to answer the following questions:

(1) How blockchain and RFID improve the charitable supply chain efficiency?

(2) What is the quantitative value of BT adoption within a charitable supply chain?

The rest of the paper is structured as follows; section 2 presents a review of related literature. Section 3 includes the modeling formulation, followed by its analysis in section 4. The application of the proposed model in PDS is presented in section 5. Conclusion, managerial and policy implications are provided in section 6. Finally, section 7 includes a discussion on the limitations and future research directions.

2. Review of literature

2.1 Supply chain and COVID-19

The outbreak of COVID-19 has impacted logistics activities; the governments across the world have witnessed unprecedented difficulties in matching supply and demand in a vast network of PDS because of the implementation of lockdown (Singh *et al.*, 2020). An intertwined supply network (ISN) for a supply chain was proposed to handle the disruptions during COVID-19 and to enhance the resilience of the supply chain (Ivanov, 2020; Ivanov and Das, 2020; Ivanov and Dolgui, 2020). The important controllers for de-risking the supply chain include the need to balance global sourcing with nearshore and local sourcing, the adoption of multiple sources and greater utilization of information technology to drive more complete and immediate information availability. Most importantly, supply chain management needs to promote a focus not just on costs but also on resilience as well as on learning from current events to improve decision-making (Béné, 2020; Remko, 2020).

The food supply chain has been widely affected due to COVID-19 (Singh *et al.*, 2020). Actions adopted to mitigate risk from the COVID-19 have had severe impacts on food systems, food security and livelihoods (Farrell *et al.*, 2020). The vulnerability of the food supply chain has impacted millions of people across the world. Gradually, scholars of food security, food systems and poverty have come to realize that the hunger and malnutrition associated with COVID-19 may kill or debilitate more people than the disease itself, especially in regions of the world with weaker social safety nets (Garnett *et al.*, 2020). Therefore, it is imperative to adopt technologies that increase the resiliency of the food supply chain (Béné, 2020; Farrell *et al.*, 2020; Kumar *et al.*, 2020; Mussell *et al.*, 2020; Singh *et al.*, 2020).

2.2 Charitable supply chain

Supply chain management deals with the management of material, money and information flow from production to consumption. A charitable supply chain is a little different from a commercial supply chain in terms of its objective and sustainability. The objective of a commercial supply chain is to maximize overall supply chain surplus, whereas the goal of a charitable supply chain is to meet the needs of the people, especially those who are both socially and financially deprived, either due to natural disasters, exigencies and/or unemployment (i.e. disaster relief, humanitarian work) (Carland *et al.*, 2018). The Indian PDS deals with the distribution of food grains from production to the people who are below the poverty line (as defined by the Indian Government); thus, it may be considered a classic case of charitable supply chain management. Both the efficiency and effectiveness of a charitable supply chain are highly affected by an asymmetry in information flow, stock inaccuracy, leakage, ghost demands and moral hazards. The Indian PDS has been facing problems similar to charitable supply chains for a long time (Ahluwalia, 1993). An efficient and effective public distribution system is a major concern, especially in countries like India, where the populous is as large (Chakraborty and Sarmah, 2019). Leakage within the PDS system has multiple dimensions (i.e. misplacement, ghost demands and shrinkage) (Bhattacharya *et al.*, 2017; Kozicka *et al.*, 2016; Nagavarapu and Sekhri, 2016).

Technological advancements may lead to several landmark solutions for eradicating leakages in the PDS system. Some of the major interventions in this context include: 1. use of RFID in warehouses (Biswal *et al.*, 2019) and 2. direct cash transfer using AADHAR ID (Bhattacharya *et al.*, 2017; Kozicka *et al.*, 2016; Nagavarapu and Sekhri, 2016). Although these major technological interventions could reduce shrinkages significantly, they are not able to eliminate ghost demands; neither are they effective enough in enhancing the quality of food delivery. BT may help in overcoming these shortcomings and could considerably improve the performance of the supply chain. Below we review the related literature on the application of BT in the supply chain.

Notably, to cater to the various needs and provide differential services to these categories, the PDS has been changed to TPDS. Figure 2 depicts the existing structure of the TPDS.

2.3 Blockchain technology in supply chain

The power of BT to enhance visibility and transparency was advocated by (Azzi *et al.*, 2019). Blockchain-based logistics monitoring system (BLMS), a reference implementation was programmed and tested based on Ethereum. The purpose of BLMS is to provide a solution for parcel tracking within a supply chain to support an open and immutable history record for each transaction (Helo and Hao, 2019). An IoT-based BT was also proposed to enhance the traceability and transparency of the supply chain at large (Feng *et al.*, 2020; Moin *et al.*, 2019).

However recently, various research reports have emerged with the applications of BT in supply chain management. They revealed the conditions under which, this authentication process effectively reduces the cost, which in turn benefits all the partners in a value chain. In another application, Choi *et al.* (2019) proposed that BT could help in the execution of mean-variance risk analysis associated with air logistics operations of a global supply chain. Kshetri (2018) analyzed 11 cases (supply chain applications) and showed that the integration of BT with IoT can indeed make a positive contribution in achieving the supply chain goals of minimizing cost, accelerating the speed of delivery, sustainability and flexibility. Recently, the Hainan Airlines (HNA) group, successfully implemented a blockchain-enabled e-commerce platform to offer its employees flexible benefits (Ying *et al.*, 2018). Queiroz and Wamba (2019) found a distinct blockchain adoption behavior in the logistics and supply chain field, both in India and the US. Wang *et al.* (2019) presented a systematic and comprehensive overview of BT-enabled smart contracts. Wang *et al.* (2019) proposed a novel

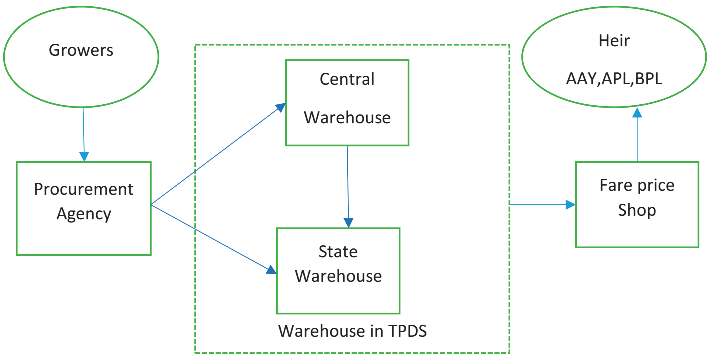

Figure 2.
TPDS charitable supply chain

concept of BT-based anonymous reporting and rewarding scheme. Table 1 exhibits the contribution of published articles related to the application of BT in various supply chains.

The adoption of BT in the supply chain does have the capability of minimizing the lack of traceability and accounting, and in the process, benefitting the stockholders (Aste *et al.*, 2017). However, BT adoption outside the function of finance is still at its nascent stage; industries are now exploring its applicability in other functions as well. Most of the published research reports support the fact that BT adoption would certainly help in achieving the larger supply chain objectives, like minimizing cost, while enhancing flexibility, agility, trust, transparency and coordination (Kshetri, 2018). Herein, it may be noted that product traceability, for instance, is an important aspect of stock and logistics management, especially within a charitable supply chain. Traceability in the system helps in identifying the origin and location of the product both during manufacturing and distribution. Origin chain (an Irish company) implemented a BT-based product traceability system to gain the trust of its consumers (Aste *et al.*, 2017). By and large, BT would be able to help a supply chain become more sustainable by leveraging upon information symmetry (Abeyratne *et al.*, 2018; Saberi *et al.*, 2018a, b).

Recently, BT has also emerged as a disruptive innovation with applications for non-for-profit organizations, politics, governance and society at large. BT is now being considered as a new form of government infrastructure. Recently, more than 30 countries around the world have adopted about 100 BT-based interventions to improve the efficiency and effectiveness of their governance systems (Jun, 2018).

Although blockchain has been termed as a future generation technology, it has its own set of challenges in terms of its applicability and complexity (Prybila *et al.*, 2017; Risius and Spohrer, 2017). Moreover, the exact benefit of BT is still unknown or possibly it has not been explored yet. Through this study, we look to explore the quantifiable benefit from BT adoption in combination with RFID for a charitable supply chain. RFID is a sensor-based tracking technology that is widely used in the commercial supply chain; in recent times, it has been gaining importance in the charitable supply chain too (Biswal *et al.*, 2018). RFID along with BT could be integrated, in order to take advantage of the online tracking capability of RFID with the distributed ledger-tracking capability of BT with trust and security. An integrated framework of BT, RFID along with IoT has been developed for the agro-food supply chain, which provides traceability, transparency and audibility of the system (Thomason *et al.*, 2018; Tian, 2016, 2017). BT can serve as an immutable ledger, which enables transactions in a decentralized manner; this helps in e-governance and social record keeping. In addition, this integrated framework promotes transparency, by allowing a consensus-based transaction (Batubara *et al.*, 2018; Pilkington *et al.*, 2017; Sullivan and Burger, 2017).

2.3.1 Smart contract in blockchain. A smart contract is a program that enforces the terms of an agreement between entities, without the need for a trusted third party inside the blockchain framework. The contracts execute automatically on the Ethereum blockchain network. Peer-to-peer contracts are executed and enforced by the software. The smart contract is invoked when a transaction calls it (through function calls). As it executes, its balance and variable values can change. Anyone can call the contract; thus, it needs to be monitored. For example, a smart contract-based solution was proposed to utilize its features in Ethereum blockchain to govern and manage interactions between a sender and a receiver (Hasan *et al.*, 2019).

The adoption of BT has been increasing across several industries owing to low cost and fast learning curve (Davidson *et al.*, 2016). Thus, the integration of BT and RFID could offer a low-cost technology solution for the Indian PDS system. The government of India has been using the AADHAR card as an identity of its residents; it could be integrated with BT and RFID to deliver food grains to the real recipients through a corruption-free PDS system. In the next section, we present the modeling framework of the paper.

3. Modeling framework

This study looks to explore the quantitative benefits of BT adoption in a charitable supply chain. Further, the study looks at identifying the expected gains vis a vis the cost involved while adopting BT in an uncertain demand situation. The news vendor model (NM) is a mathematical model that specifically deals with the same; thus, this model would certainly be an appropriate tool for quantifying BT's adoption benefits. NM was successfully given optimal results for logistics optimization when suppliers are not reliable (Dada *et al.*, 2007; Xanthopoulos *et al.*, 2012). It is also widely used in the literature, and usually based upon the assumption of risk neutrality, the model equally fit for loss-averse manager's decision-making behavior (Qin *et al.*, 2011; Wang and Webster, 2009). NM has rich applicability in handling logistics in the charitable supply chain (Chen *et al.*, 2017, 2018; Gonçalves and Castañeda, 2013; Heaslip, 2018; Ortuño *et al.*, 2013; Overstreet *et al.*, 2011; Scott and Rutner, 2019).

This model deals with situations where neither supplier is reliable nor distribution channel. Therefore, to handle the situation where the parties in the distribution channel are not reliable BT enabled NM is suitable. We considered TPDS as a charitable supply chain with stock keeping units (SKUs) owned by the Food Corporation of India (FCI). The SKUs get supplies of seasonal food grains from upstream farmers at a fixed minimum support price "p". The SKU manager is supposed to maintain the intended quantity stock in the TPDS. Issues like shrinkage, misplacement and ghost demands in the Indian PDS system is defined as follows:

3.1 Shrinkage and misplacement

Shrinkage is defined as stock inaccuracy due to asymmetric information and poor technology for stock management. This can be mitigated by using technologies like RFID (Biswal *et al.*, 2018; Fan *et al.*, 2015). Misplacement, on the other hand, is primarily the theft of food grains and/or an error in record keeping of the stock item I; it may be defined for a particular period of 't' as (Overbeck, 2016)**:**

$$\text{Misplacement}_{it} = 1 - \frac{\text{Total Consumption}_{it}}{\text{off take}_{it}}$$

where offtake refers to the official total offtake of food grains. Notably, this information may be obtained from the official monthly food grain bulletin of the Indian government, whereby "misplacement" shows the quantity of food grains that has not reached the intended inheritors.

3.2 Ghost demand rate

The current PDS system distributes the food grains to the intended beneficiaries through various state governments. The ghost demand is essentially generated due to a wrong entry in the system and/or error in recording the data that leads to the generation of ghost cards and shadow ownership (illegal migrants). In 2012, about 16.7% of ghost cards/fake ration cards were noted (Sivadasan, 2012). Ration Card is an official document issued by various state governments in India to households that are eligible to purchase subsidized food grains from the PDS.

According to 2011 census data, shrinkage, misplacement and ghost demands in PDS were estimated to be about 46.7% [6].

3.3 The news vendor model

We model the total inventory cost with and without BT. We use a standard news vendor model with two objectives: 1. reduction in the total cost of the stock and 2. minimize the negative impacts that lead to human suffering due to the hindrances in supplies of critical food grains for the poor people (Itani, 2014). Suffering costs are economic values of human suffering and are defined as the function of suffering time and socio-economic characteristics of the recipients of the supplies. Following Holguín-Veras *et al.* (2012, 2013, 2016), the human suffering cost is modeled as a function of suffering time, which is directly proportional to the backlogged quantity. Two types of BT have been used for various use cases, including cryptocurrencies (Bitcoins) and hyper ledgers (namely public and private). In the public blockchain ledger storage, transaction validation, access management and functionality are public and visible to all peers in the network, while in a private blockchain the network ledger storage and transaction validation are public and visible to peers, but access management and functionality are controlled by a central consortium. We thereby propose a mix structure of blockchain, called enterprise blockchain (or hybrid blockchain) for TPDS. The proposed structure of the TPDS supply chain with BT and RFID is shown in Figure 3.

The shrinkage and misplacement costs are represented by variables α and β, respectively. They reflect the effect of shrinkage and misplacement on the actual quantity available for TPDS. Here,

$$\alpha = \frac{\text{Actual available quantity}}{\text{Initial procured quantity}} \text{ (due to shrinkage) and}$$

$$\beta = \frac{\text{Actual available quantity}}{\text{Initial procured quantity}} \text{ (due to mispalcement)}$$

The ghost demand (i.e. ghost stock using ghost TPDS cards) is expressed as a fraction of the total demand, which in turn is represented as "ρ". Let us consider two scenarios; in the first, the SKU manager acknowledges a ghost demand and leakage due to shrinkage and misplacement. She/he takes stock decisions with prior estimations of ghost demand and leakage. In the second scenario, the SKU manager decides to invest in BT and RFID to reduce leakage and ghost demand and takes the stock decision accordingly. Post modeling, we can gauge the benefits of the adoption of an integrated framework of BT with RFID. The following are some other assumptions in our modeling:

(1) Extra demand (more than what is available) from the stock is backlogged and fulfilled with emergency procurement at an additional cost.

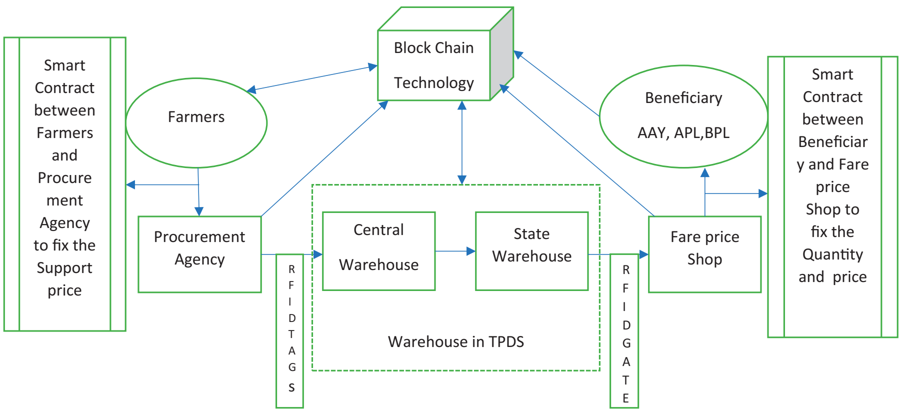

Figure 3.
Blockchain technology and RFID in a TPDS supply chain

(2) The human suffering time is directly proportional to the backlogged quantity, as the total time required for processing the backlogged demand reflects human suffering. The suffering cost, in turn, is a linear function of suffering time.

(3) Stock shrinkage and misplacements are independent of each other, and inventory error occurs the moment an order is placed.

(4) After the implementation of BT and RFID, ghost demands and misplacements are eliminated, but shrinkage is still not reduced completely. However, the smaller shrinkage cost could be merged with inventory holding cost, while estimating the per unit inventory holding cost.

(5) The minimum support price is independent of the demand and decided by the government for the farmers' benefit.

Table 2 includes the notations used in the proposed model.

Table 3 displays the loss due to stock inaccuracy under two scenarios, namely with or without the intervention of the integrated technology. In the first case (i.e. without BT and

Symbols	Definitions
Π	Ordered items without the adoption of BT (decision Variable)
Π^*	The optimal ordered items without the adoption of BT
Q_{BT}	The ordering items with the adoption of BT (decision Variable)
Q_{BT}^*	The optimal ordering items with the adoption of BT
$C(\pi)$	The total stock cost without BT
$C(Q_{BT})$	The total stock cost with BT
p	The purchasing cost per unit Item
h	The holding cost per extra unit during the assessment period
u	The per-unit emergency procurement cost for the sudden demand
d	The human suffering cost factor
t	The time required to replenish one backlogged item
T	The marginal cost of adoption of the BT
X	The random demand
$f(x)$	The probability density function of the demand function
$f(x)$	The cumulative distribution function (CDF) of the demand function
μ	Mean of the demand
ρ	The ghost demand rate (The fraction of the demand function that is generated due to inactive consumers, illegal consumers and unauthorized consumers)
α	The rate of available quantity due to shrinkage
β	The rate of available quantity due to misplacement
t_1	The available rate of order quantity without BT
t_2	The available rate of order quantity with BT
Γ	The upper limit of uniformly distributed demand
I	The fixed cost of BT adoption

Table 2. Symbols used in the model

	Case without BT	Case with BT
Loss due to shrinkage	$\pi\ \alpha$	0
Loss due to misplacements	$\pi\ \beta$	0
Loss due to ghost demand	$\pi\rho$	0
Total loss	$\pi(\rho+\alpha+\beta)$	0
Remaining stock	$\pi-\pi(\rho+\alpha+\beta)=\pi(1-(\alpha+\beta+\rho))$	π
Available rate	$t_1=[1-(\alpha+\beta+\rho)]$	$t_2=1$

Table 3. Comparison of loss in stock keeping units (SKUs) with and without BT

RFID) out of the ordered quantity of π, (1-α) is lost in shrinkage and (1-β) in misplacement with $\rho\pi$ being the total ghost demand.

3.3.1 Stock ordering policy without BT. Figure 4 shows the flow diagram of the value of quantification for adopting an integrated framework of BT and RFID.

The total expected cost without BT can be given as:

$$C(\pi) = (1+\rho)h\int_0^{t_1\pi}(t_1\pi - x)f(x)dx + u(1+\rho)\int_{t_1\pi}^{\infty}(x - t_1\pi)f(x)dx + h(1-\beta)\pi + p(1-\alpha)\pi + (1+\rho)\int_{t_1\pi}^{\infty}dt(x - t_1\pi)f(x)dx \tag{1}$$

The right side of equation (1) has five parts. Part 1 represents the expected holding cost for leftover stocks and ghost demands. When demand (e.g. ghost demand) is more than the stock available, additional supplies need to be procured with additional costs. Part 2 represents this additional cost function. The third part represents the holding cost due to misplaced quantity. The cost of lost stock due to shrinkage is represented by part 4. The fifth part presents the human suffering cost (deprivation), which was calculated using the method provided by Holguín-Veras *et al.* (2012) with a few rearrangements; we thereby get the expected cost, $C(\pi)$ as:

$$C(\pi) = (1+\rho)h\int_0^{t_{1\pi}}(t_1\pi - x)f(x)dx + (1+\rho)(u+dt)\int_{t_{1\pi}}^{\infty}(x - t_1\pi)f(x)dx + h(1-\beta)\pi + p(1-\alpha)\pi \tag{2}$$

This looks similar to the well-known news vendor model. Notably, as the model function is convex, we can obtain a minimum value of this function for a particular optimal order quantity π^* by differentiating $C(\pi)$ with respect to π using Leibniz rule and solving for the first-order condition:

$$\frac{\partial C(\pi)}{\partial \pi} = 0$$

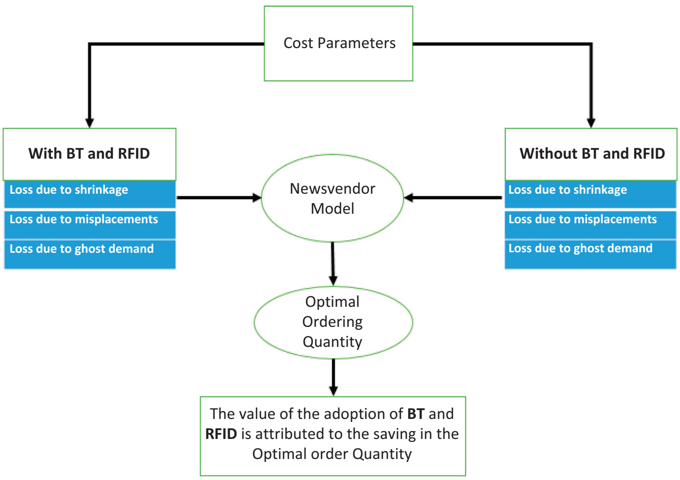

Figure 4.
Flow diagram of the quantification

$$\pi^* = \frac{1}{t_1} F^{-1}\left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right] \tag{3}$$

Since $\pi^* > 0$ hence from equation2, $t_1 > \frac{[h(1-\beta)+p(1-\alpha)]}{[(u+dt)(1+\rho)]}$. If we assume that the stock is accurate, then suffering cost, $d = 0$ and t_1, α, β *are all unity*. Therefore, the optimal quantity becomes $\pi_c^* = F^{-1}(\frac{u}{h+u})$. This result is similar to that of the standard news vendor problem.

The optimal cost function without BT can be calculated from equation (2) as:

$$C(\pi) = (1+\rho)h\int_0^{t_1\pi}(t_1\pi - x)f(x)dx + (1+\rho)(u+dt)\int_{t_1\pi}^{\infty}(x - t_1\pi)f(x)dx + h(1-\beta)\pi + p(1-\alpha)\pi$$

After deriving the cost function as the optimal quantity π^* the cost function becomes:

$$C(\pi^*) = (1+\rho)\left[\mu(u+dt) - (h+u+dt)\int_0^{t_1\pi^*} xf(x)dx\right] \tag{4}$$

If the ghost demand is zero, i.e. $\rho = 0$, then

$$C(\pi^*) = \mu(u+dt) - (h+u+dt)\int_0^{t_1\pi^*} xf(x)dx \tag{5}$$

3.3.2 Stock ordering policy after the adoption of BT. In this case, we consider BT eliminating the ghost demands, i.e. $\rho = 0$. Moreover, the SKUs improve stock accuracy by adopting the integrated framework of RFID with BT. Then, the improved stock available would be $t_2 = 1$. The marginal deployment cost of the technology is given by T toward implementing RFID and BT with a fixed cost of an investment equal to I.

$$\mathrm{C}\ (Q_{BT}) = h\int_0^{t_2Q}(t_2Q - x)f(x)dx + u\int_{t_2Q}^{\infty}(x - t_2Q)f(x)dx + QT + I + \int_{t_2Q}^{\infty} dt(x - t_2Q)f(x)dx \tag{6}$$

The first term on the right side of the above equation (6) represents the holding cost of the leftover quantity. The second term represents the emergency procurement cost due to extra demand, while the third term represents the variable cost of adopting BT and RFID. Notably, the fourth and fifth terms represent the fixed cost of implementation of BT and RFID infrastructure and the human suffering cost, respectively. As mentioned earlier, ghost demand and misplacement costs are eliminated by adopting the integrated framework, while shrinkage cost becomes negligible, and thereby may be factored in the inventory holding cost (h). For calculating the optimum ordering quantity Q_{BT}^* in the presence of BT and RFID, let us differentiate equation (6) using the Leibniz rule:

$$\frac{\partial C\ (Q_{BT})}{\partial Q} = 0$$

$$Q_{BT}^* = \frac{1}{t_2}F^{-1}\left[\frac{u+dt}{(h+u+dt)} - \frac{T}{t_2(h+u+dt)}\right] \tag{7}$$

As $Q_{BT}^* > 0$, $\left[\frac{u+dt}{(h+u+dt)} - \frac{T}{t_2(h+u+dt)}\right] > 0$, then $T < (u+dt)t_2$, Moreover, as $t_2 = 1$, it may be concluded that $T < (u + dt)$.

Putting the value of the optimum quantity in equation (6) and solving for the optimal total cost at the Q^*_{BT} we get the following equation

$$C\left(Q^*_{BT}\right) = I + (u + dt)\mu - (u + dt + h)\int_0^{t_2 Q^*_{BT}} xf(x)dx \tag{8}$$

4. Analysis of the model

The optimal order quantities with and without BT may be compared using equations (3) and (7). Here, we assume for an expositional purpose that the demand follows a uniform distribution with an upper bound that equals to γ and lower bound equals to 0, that is, with the range of $[0, \gamma]$. By assuming a uniform distribution of demand, we could thereby extract some meaningful managerial implication on the total cost expected both with and without BT, along with a marginal adoption cost of BT with RFID.

With the above uniform distribution, the following solution may be derived:

$$\pi^* = \frac{\gamma}{t_1}\left[\frac{u + dt}{(h + u + dt)} - \frac{h(1-\beta) + p(1-\alpha)}{(1+\rho)t_1(h + u + dt)}\right] \tag{9}$$

$$Q^*_{BT} = \frac{\gamma}{t_2}\left[\frac{u + dt}{(h + u + dt)} - \frac{T}{t_2(h + u + dt)}\right] \tag{10}$$

$$C(\pi^*) = \frac{(1+\rho)\gamma}{2}\left[(u + dt) - (h + u + dt)\left[\frac{u + dt}{(h + u + dt)} - \frac{h(1-\beta) + p(1-\alpha)}{(1+\rho)t_1(h + u + dt)}\right]^2\right] \tag{11}$$

$$C\left(Q^*_{BT}\right) = I + \frac{(u + dt)\gamma}{2} - \frac{(h + u + dt)\gamma}{2}\left[\frac{u + dt}{(h + u + dt)} - \frac{T}{t_2(h + u + dt)}\right]^2 \tag{12}$$

Similarly, the cost of suffering (deprivation cost) can be calculated for the two cases with and without BT (Holguín-Veras *et al.*, 2012) using the fifth term of the objective function for the two scenarios (See equation (1) and (6)).

$$\text{Human Suffering cost (without BT)} = \frac{dt}{2\gamma}(\gamma - t_1\pi^*)^2 \tag{13}$$

$$\text{Human suffering cost (with BT)} = \frac{dt}{2\gamma}\left(\gamma - t_2\ Q^*_{BT}\right)^2 \tag{14}$$

Based on these results, we propose the following theorems:

Theorem 1. When demand is uniformly distributed and for a given value of π^* and $Q^*_{BT} > 0$ there exists a threshold value of the marginal cost (T_c) for the adoption of BT and RFID such that $Q^*_{BT} \geq \pi^*$ if and only if $T \leq T_c$ and T_c may be computed as

$$T_c = (u + dt)t_2 - \frac{t_2^2}{t_1^2}[(u + dt)t_1 - h(1-\beta) - p(1-\alpha)]$$

We can prove it by equating equation (9) and (10) and obtaining the value of T as T_c.

Theorem 1 indicates that when the marginal cost of adoption of BT and RFID (T) goes below a critical value (T_c), it is worthwhile to order more quantity under BT and RFID. This may reduce human suffering costs. Therefore, it is advisable to keep the marginal cost of adoption of $BT \leq T_c$.

Theorem 2. At any given value of T there exists a limiting value of BT fixed cost I_c, so that, $I < Ic \;\; C(Q^*_{BT}) < C(\pi^*)$. I_c maybe computed as

$$I_c = \frac{(u+dt+h)\gamma}{2}\left\{\left[\frac{u+dt}{(h+u+dt)} - \frac{T}{t_2(h+u+dt)}\right]^2 - \left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right]^2\right\}$$

Theorem 2 indicates that investment in BT for PDS is viable when the fixed cost of adoption of BT and RFID I is less than or equal to Ic, i.e. $I \leq I_C$.

Theorem 3. At any given value of I there exists a limiting value of marginal BT adoption cost T_c so that if $T < T_{c1}$, then $C(Q^*_{BT}) < C(\pi^*)$.

$$T_{c1} = (u+dt)t_2 - t_2(h+u+dt)\sqrt{\frac{2I}{(u+dt+h)\gamma} - \left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right]^2}$$

Theorem 3 indicates that for a given value of I, the investment for the adoption of BT and RFID is viable when, $T \leq T_{c1}$.

5. Illustrative example and sensitivity analysis

Now, let's try and validate the proposed approach along with the theorems through an illustrative case example. The data for this analysis are collected from various secondary sources available in government websites and sourced from reports of various government agencies and research papers (see Table 4 for data).

It could also be noted here that

$t_1 = [1-(\alpha+\beta+\rho)]$ and $t_1 > 0$, as $(\alpha+\beta+\rho) < 1$

In order to check the robustness of the results with respect to change in various model parameters, we have attempted to compute total costs for various values of $\alpha, \beta,$ and ρ. The range of parameters considered for this sensitivity analysis (using R code, Appendix 3) are ρ [0.15–0.16],

α [0.03–0.06] and β [0.03–0.05]. For the sake of illustration, we have taken the human suffering cost (d) = 1000. These ranges do reflect the real changes in these parameters. Table 5 presents the total costs of satisfying the demand without BT and RFID and also shows its sensitivity to the change of parameter values within the ranges defined. Further, the result shows that a small change in shrinkage, misplacement and ghost demand imposes huge costs on the government. The reason for the same is high loss due to operational hazards, coupled with negative effects due to the existence of ghost demands.

Table 6 presents the total cost of satisfying the demand with both BT and RFID. We considered various values of I and T to check the robustness of total cost, along with the resultant benefits of adopting BT and RFID. The range of possible fluctuation of the fixed cost associated with BT Implementation (I) is considered to be INR [1400000–2000000] and that of the marginal cost of implementation of the BT (T) is taken to be INR [50–150] here. We

Table 4.
Input parameters of the illustrative example [7], [8]

Model parameters	Value
The weight of a food grain bag (Wheat, Rice, Sugar), we considered a rice bag for the analysis	50 Kg
Ghost Demand (ρ)	15–16 %*
MSP per bag(p)	INR1200
Holding cost per bag (h)	INR 500
Emergency procurement cost per bag (u)	INR 250
Human suffering factor (d)	20–20000
Replenishment time for unit backlogged demand (t)	1 day
Stock keeping units (SKUs) capacity (γ)	5000–50000 Metric Tone
The marginal cost of adopting BT and RFID (T)	INR [50–150]
Shrinkage Rate (α)	3–6 %*
Misplacement Rate (β)	3–5%*
Fixed cost to adopt BT and RFID (I)	INR [1,400,000–2,000,000] [9], [10]

Note(s): *In the government reports, ghost demand, misplacement and shrinkage are known as leakage. The total leakage varies between 10% to more than 50% [11]. We have taken the range for leakage as 10%–25%, which may be considered as moderate leakage rate

Table 5.
Sensitivity analysis of the cost function without BT and RFID

ρ	α	β	Total cost in INR 1000bn (without BT)
0.150	0.030	0.030	91.803
0.151	0.033	0.032	94.516
0.152	0.037	0.034	97.322
0.153	0.040	0.037	100.225
0.154	0.043	0.039	103.228
0.156	0.047	0.041	106.336
0.157	0.050	0.043	109.553
0.158	0.053	0.046	112.883
0.159	0.057	0.048	116.332
0.160	0.060	0.050	119.904

Table 6.
Sensitivity analysis of the cost function with BT and RFID

d (INR)	I (INR)	T (INR)	Total cost after the adoption of BT and RFID in INR 1000 million
1000	1400000	50	0.01067997
1000	1466667	61.1111	0.01105923
1000	1533333	72.2222	0.01143495
1000	1600000	83.3333	0.01180716
1000	1666667	94.4444	0.01217583
1000	1733333	105.556	0.01254097
1000	1800000	116.667	0.01290259
1000	1866667	127.778	0.01326069
1000	1933333	138.889	0.01361525
1000	2000000	150	0.01396629

obtained these values from the quoted amount by major BT solution providers in India having conducted similar projects.

It is very interesting to observe from Tables 5 and 6 that the total cost after the adoption of BT is very less compared to the case without BT and RFID.

Figure 5 suggests that the decision-maker may be willing to pay for the marginal cost of adoption of BT (i.e. INR 2570) with 1-day replenishment time if he/she wants to make human suffering cost (*d*) equals to zero. This cost is sufficiently higher than the quoted marginal cost of BT implementation. The willingness to pay for the marginal cost of adoption of BT decreases with an increase in tolerance to human suffering cost (*d*). Figure 5 also shows that when the tolerance replacement time increases to ($t = 7$) along with the human suffering cost ($d = 1200$), the willingness to pay for the marginal cost of adoption of BT becomes zero.

6. Conclusions, managerial and policy implications

The disruptions in the supply chain may be seen in various situations like natural disasters, man-made disasters and during an outbreak of a pandemic, the outbreak of infectious disease, COVID-19 has brought a global tragedy not only for human lives, but also economical activities like manufacturing operations, supply chain and logistics, and several other sectors a simulation model of the PDS network is developed with two different scenarios to demonstrate the benefits of BT adoption in the PDS; the simulations reveal that there is a need to adopt an agile technology to support the transparency and resiliency of PDS.

Policymakers during COVID-19 work on unfamiliar ground and must make tough decisions. Information Technology and operations research models play a vital role in supporting this decision-making process (Nikolopoulos *et al.*, 2020). Therefore, it is imperative to adopt a robust and transparent IT technology to support the agility of the supply chain. The outcome of this research supports the policymakers to decide to adopt BT enabled PDS system.

Research on quantifying the adoption value within a charitable supply chain has given a new dimension to BT adoption especially in PDS at large. This study has identified some of the challenges in the Indian TPDS system using secondary data sources and has looked to quantify losses due to shrinkage, misplacements, and ghost demands. We modeled a warehouse's optimal ordering quantity using the Newsvendor model, post which, the ordering cost was attributed under two scenarios (i.e. with BT and RFID, and without BT and RFID) for calculating the actual value of adoption of BT integrated with RFID.

Management of a public distribution supply chain is a complex task for any government or organization. It requires efficient utilization of logistics and subsidized resources to benefit the

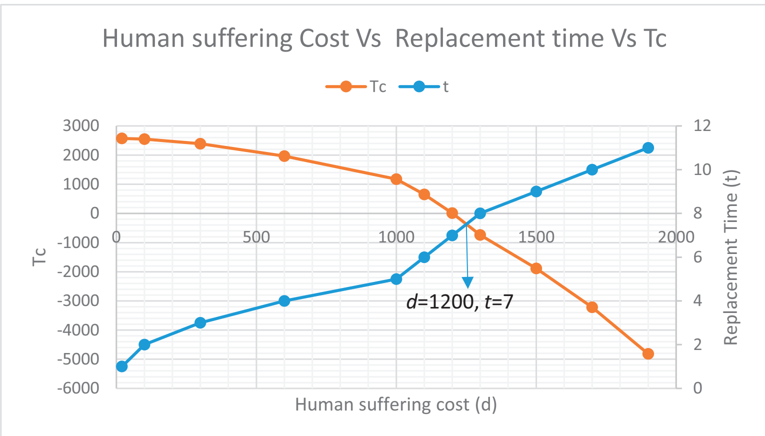

Figure 5.
Analysis of marginal adoption cost of BT

intended recipients. The Indian public distribution supply chain has been encountering several issues that demanded serious attention for its performance improvement. In this study, we proposed a BT- based solution to handle these challenges. BT is already being used in the financial sector to avoid manual transaction and recordkeeping mechanism by replacing the old centralized ledger with a newly decentralized one. This decentralization of ledger is expected to bring about transparency in the system and reduce moral hazards like corruption. Our results show that the adoption of BT in a public distribution supply chain not only addresses the issues of leakage and moral hazards but also reduces the total cost significantly.

Further, we addressed three crucial challenges of TPDS. The first includes shrinkage and misplacement of procured food grains; the second is the issue of ghost demands, while the third includes moral hazards (i.e. farmers and stocks are not able to get their intended value). The first problem may be minimized by adopting RFID technology, while the last two could be eliminated by adopting BT.

Based on our analysis, we propose that the Government of India may consider a BT-based intervention and implementation in the procurement, storage, and distribution stages of its PDS supply chain. Importantly, we found that BT can play an important role in overcoming the issues of shrinkage, misplacement, and ghost demands. Furthermore, BT-based intervention may also reduce auditing requirements in TPDS. Our study provides an important policy implication regarding the implementation of BT in the Indian public distribution supply chain. Our cost-benefit analysis shows that the implementation of BT not only reduces the problem of shrinkage, misplacement, and ghost demands but also decreases the total cost substantially.

7. Limitations and future research directions

The proposed model has been developed for charitable supply chain management where food is to be distributed to the needy people. It may also be extended with suitable modification for its application in the commercial supply chain, which also suffers from challenges of transparency and corruption. Moreover, in the proposed model, we assumed that the minimum support price is independent of the demand and decided by the government for the benefit of the farmers. In the case of commercial supply chains, a demand curve (which establishes a price-demand relationship) needs to be estimated. The goals of the study may also be modified for profit maximization and satisfaction of customer demands, which in fact, is a complex function comprising various factors. Notably, this study also does not include any discussion on smart contracts in PDS. As a future extension, it is proposed to explore the use of smart contracts for the benefit of the potential food grain suppliers (farmers), which is a major political issue in India.

Notes

1. https://www.globalhungerindex.org/results/.
2. “LPG is used as fuel for cooking purpose in India. More than 200 million households use this clean fuel, which is subsidized by the government”.
3. “Aadhaar is a 12-digit unique identity number that can be obtained by residents of India, based on their biometric and demographic data”.
4. “https://cag.gov.in/sites/default/files/audit_report_files/Union_Commercial_Compliance_Report_25_2016_Chapter-9.pdf”, Downloaded on 17/11/2018.
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6. “http://www.prsindia.org/uploads/media/DFG2017-18/DFG-FoodandPublicDistribution.pdf, /Downloaded on 19/11/2018”.

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Appendix 1

A.1. Derivations of Eq. (A3)

$$C(\pi) = (1+\rho)h\int_0^{t_1\pi}(t_1\pi - x)f(x)dx + (1+\rho)(u+dt)\int_{t_1\pi}^{\infty}(x - t_1\pi)f(x)dx + h(1-\beta)\pi + p(1-\alpha)\pi \tag{A2}$$

$$\frac{\partial C(\pi)}{\partial \pi} = 0$$

$$\Rightarrow (1+\rho)h\int_0^{t_1\pi}\frac{\partial}{\partial\pi}(t_1\pi - x)f(x)dx + (1+\rho)(u+dt)\int_{t_1\pi}^{\infty}\frac{\partial}{\partial\pi}(x - t_1\pi)f(x)dx + \frac{\partial}{\partial\pi}h(1-\beta)\pi + \frac{\partial}{\partial\pi}p(1-\alpha)\pi = 0$$

$$\Rightarrow (1+\rho)ht_1\int_0^{t_1\pi}f(x)dx - (1+\rho)(u+dt)t_1\int_{t_1\pi}^{\infty}f(x)dx + h(1-\beta) + p(1-\alpha) = 0 \Rightarrow$$

$$\Rightarrow (1+\rho)ht_1\int_0^{t_1\pi}f(x)dx - (1+\rho)(u+dt)t_1\left[\int_0^{\infty}f(x)dx - \int_0^{t_1\pi}f(x)dx\right] + h(1-\beta) + p(1-\alpha) = 0 \text{ as } \int_0^{\infty}f(x)dx = 1 \text{ and } \int_0^{\infty}xf(x)dx = \mu$$

$$\Rightarrow (1+\rho)ht_1\int_0^{t_1\pi}f(x)dx - (1+\rho)(u+dt)t_1\left[1 - \int_0^{t_1\pi}f(x)dx\right] + h(1-\beta) + p(1-\alpha) = 0$$

$$\Rightarrow [(1+\rho)ht_1 + (1+\rho)(u+dt)t_1]\int_0^{t_1\pi}f(x)dx - (1+\rho)(u+dt)t_1 + +h(1-\beta) + p(1-\alpha) = 0$$

$$\Rightarrow (1+\rho)t_1(h+u+dt)\int_0^{t_1\pi}f(x)dx = (1+\rho)(u+dt)t_1 - h(1-\beta) - p(1-\alpha)$$

$$\Rightarrow \int_0^{t_1\pi}f(x)dx = \frac{(1+\rho)(u+dt)t_1 - h(1-\beta) - p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}$$

$$\Rightarrow \int_0^{t_1\pi}f(x)dx = F(t_1\pi^*) = \frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}$$

$$\Rightarrow t_1\pi^* = F^{-1}\left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right]$$

$$\pi^* = \frac{1}{t_1}F^{-1}\left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right] \tag{A3}$$

A.2. Derivations of Eq. (A4)

$$C(\pi^*) = (1+\rho)h\int_0^{t_{1\pi^*}}(t_1\pi^*-x)f(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}(x-t_1\pi^*)f(x)dx + h(1-\beta)\pi^* + p(1-\alpha)\pi^*$$

$$= (1+\rho)ht_1\pi^*\int_0^{t_{1\pi^*}}f(x)dx - (1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}xf(x)dx - (1+\rho)(u+dt)t_1\pi^*\left[1-\int_0^{t_{1\pi}}f(x)dx\right] + h(1-\beta)\pi^* + p(1-\alpha)\pi^*$$

$$= (1+\rho)t_1\pi^*(h+u+dt)\int_0^{t_{1\pi^*}}f(x)dx - (1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}xf(x)dx - (1+\rho)(u+dt)t_1\pi^* + h(1-\beta)\pi^* + p(1-\alpha)\pi^*$$

$$= (1+\rho)t_1\pi^*(h+u+dt)\left[\frac{u+dt}{(h+u+dt)} - \frac{h(1-\beta)+p(1-\alpha)}{(1+\rho)t_1(h+u+dt)}\right] - (1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}xf(x)dx - (1+\rho)(u+dt)t_1\pi^* + h(1-\beta)\pi^* + p(1-\alpha)\pi^*$$

$$= (1+\rho)(u+dt)t_1\pi^* - h(1-\beta)\pi^* - p(1-\alpha)\pi^* - (1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}xf(x)dx - (1+\rho)(u+dt)t_1\pi^* + h(1-\beta)\pi^* + p(1-\alpha)\pi^*$$

$$C(\pi^*) = -(1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\int_{t_1\pi^*}^{\infty}xf(x)dx$$

$$= -(1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\left[\int_0^{\infty}xf(x)dx - \int_0^{t_1\pi^*}xf(x)dx\right]$$

$$= -(1+\rho)h\int_0^{t_1\pi^*}xf(x)dx + (1+\rho)(u+dt)\left[\mu - \int_0^{t_1\pi^*}xf(x)dx\right]$$

$$C(\pi^*) = (1+\rho)\left[\mu(u+dt) - (h+u+dt)\int_0^{t_1\pi^*}xf(x)dx\right] \tag{A4}$$

A.3. Derivations of Eq. (A7)

$$\frac{\partial C\ (Q_{BT})}{\partial Q} = \frac{\delta}{\delta Q}\left[h\int_0^{t_2Q}(t_2Q-x)f(x)dx + u\int_{t_2Q}^{\infty}(x-t_2Q)f(x)dx + QT + I + \int_{t_{2Q}}^{\infty}dt(x-t_2Q)f(x)d = 0\right]$$

$$\Rightarrow ht_2\int_0^{t_2Q}f(x)dx - ut_2\int_{t_2Q}^{\infty}f(x)dx - dtt_2\int_{t_{2Q}}^{\infty}f(x)dx \quad + T \ = 0$$

$$\Rightarrow\ ht_2\int_0^{t_2Q}f(x)dx - t_2(u+dt)\int_{t_2Q}^{\infty}f(x)dx + T = 0$$

$$\Rightarrow\ ht_2\int_0^{t_2Q}f(x)dx - t_2(u+dt)\left[1-\int_0^{t_2Q}f(x)dx\right] + T = 0$$

$$\Rightarrow t_2(h+u+dt)\int_0^{t_2Q}f(x)dx - t_2(u+dt) + T = 0$$

$$\Rightarrow t_2(h+u+dt)\int_0^{t_2Q}f(x)dx \ = t_2(u+dt) - T$$

$$\Rightarrow\int_0^{t_2Q}f(x)dx \ = \frac{t_2(u+dt)}{t_2(h+u+dt)} = \frac{t_2(u+dt)}{t_2(h+u+dt)} - \frac{T}{t_2(h+u+dt)}$$

$$\Rightarrow t_2\ Q^{*}_{BT} = F^{-1}\left[\frac{(u+dt)}{(h+u+dt)} - \frac{T}{t_2(h+u+dt)}\right]$$

$$Q^{*}_{BT} = \frac{1}{t_2}F^{-1}\left[\frac{u+dt}{(h+u+dt)} - \frac{T}{t_2(h+u+dt)}\right] \tag{A7}$$

Appendix 2

Leakages in PDS: leakage is a broad term that includes misplacement, shrinkage, and inclusion errors. Inclusion errors are known as “Ghost Demands”. Therefore,

$$\text{Leakage} = \text{Misplacement} + \text{Shrinkage} + \text{Inclusion\ \ error\ (Ghost\ \ Demand)}$$

Misplacement: It is the theft of food grains or errors in record keeping.

Shrinkage: Shrinkage is due to poor quality procurement of food grains or due to environmental conditions of storage, pilferage, and/or damage during transportation of food grains.

Inclusion errors (Ghost Demand): Is the list of beneficiaries who are not entitled to PDS, benefit from the same as they’ve been mistakenly/maliciously included in the list. Due to this, the ineligible people get undue benefits. Inclusion errors in the Indian PDS system have increased [12] from 29% in 2004–05 to 37% in 2011–12. Despite a decline in the poverty rate, the non-poor are still identified as poor by the government, due to poor visibility and verifiability of data. Thus, they continue to use the subsidy benefit of PDS.

Appendix 3

(R-code)

```
# simulation of TPDS system With and Without Block Chain
    p <- 1200
    h <- 500
    u <- 250
    #d <- seq(1000, 20000,length.out = 10)
    d <- 1000
    t <- 1
    T <- seq(50,150,length.out = 10)
    sr <- seq(0.03,0.06,length.out = 10)
    gd <- seq(0.15,0.16,length.out = 10)
    mc <- seq(0.03,0.05,length.out = 10)
    I <- seq(1400000, 2000000,length.out = 10)
    cap <- 50000
    t1 <- 1-(sr+gd+mc)
    t <- 1
    a <- 1200*(1-sr)
    b <- 500*(1-mc)
    c <- 1+gd
    f <- 1/(h+u+d*t)
    dt <- d*t
    n <- c(u+dt,u+dt,u+dt,u+dt,u+dt,u+dt,u+dt,u+dt,u+dt,u+dt)
    l <- (b+a)/(c*t1)
    j <- (n-l)^2
    g <- c*cap/2
    tcn <- g*j
    pi <- (cap/t1*f)
    pi2 <- n-(l/t1)
    pi_star <- pi*pi2
    pidata <- data.frame(gd,mc,pi_star)
    pidata <- as.matrix(pidata)
    library(plotly)
    plot_ly(z = ~pidata,type = "surface")
    #tcn <- tcn/100000000000
    resul <- data.frame(gd,sr,mc,tcn)
    results <- as.matrix(resul)
    library(plotly)
    plot_ly(z = ~resuls,type = "surface")
    op <- par(mfrow = c(2, 2),pty = "s")
    plot(sr,tcn)
    plot(gd,tcn)
    plot(mc,tcn)
    ne <- u+d*k
    ge <- cap/2
    TCN <- I+ne*ge-ge*f*(ne-T)^2
    TCN <- data.frame(d,I,T,TCN)
    TCN <-TCN/1000000000000
    write.csv(TCN,"E:/Blockchain s jhaker/economics letter/TCN.csv")
    write.csv(resul,"E:/Blockchain s jhaker/economics letter/tcn.csv")
    library(plotly)
    data <- data.frame(tcn,TCN,gd)
    BTValue <- as.matrix(data)
    plot_ly(z = ~BTValue,type = "surface")
    d <- c(20,100,300,600,1000,1100,1200,1300,1500,1700,1900)
    t_f <- c(1,2,3,4,5,6,7,8,9,10,11)
```

```
pi_star <- c(-126999.8193,-91940.38343, −26679.477, 16682.69167, 38639.69767, 44768.65518,
49311.10628, 52829.55486, 56281.54485,58805.07492, 60922.49367)
datan <- data.frame(t_f,d,pi_star)
Pi_Star <- as.matrix(datan)
plot_ly(z = ~datan,type = “surface”)
```

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