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From Physical Food Security to Digital Food Security. Delivering value through blockchain

Anup Kumar
Institute of Management Technology, Nagpur, anunewin@gmail.com

Manas Paul
Institute of Management Technology, Ghaziabad, mpauleco@gmail.com

Parijat Upadhyay
Indian Institute of Management, Shillong, parijat.upadhyay@gmail.com

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Delivering value through blockchain

Anup Kumar
Institute of Management Technology, Nagpur
anunewin@gmail.com

Manas Paul
Institute of Management Technology, Ghaziabad
mpauleco@gmail.com

Parijat Upadhyay
Indian Institute of Management, Shillong
parijat.upadhyay@gmail.com

Abstract. The objective of this study is to present a technology-enabled public distribution system (PDS) for a developing economy that faces significant leakages and misplacements. It is in this respect that we explore the quantitative benefits of the integration of Radio Frequency Identification (RFID) with Blockchain Technology (BT) in the Indian Targeted Public Distribution System (TPDS). A mathematical formulation has been proposed to identify the potential benefits of adopting such technologies to minimise the social costs of both human suffering (deprivation cost) and the economic costs associated with it. Secondary data pertaining to the PDS has been analysed to gain insights into the extent of leakages of food grains from the system and the probable benefits of using these technologies in addressing them. The findings of the study reveal that the adoption of the Blockchain-based framework can significantly reduce the overall leakages and eliminate ghost demand from the system. Also, the study recommends the usage of Blockchain technology for information sharing in a secure, scalable, traceable, and transparent environment to address the institutional independence and accountability over the entire TPDS process.

Key words: Food security, blockchain technology, and public distribution system.

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1 Introduction

Eradicating poverty and hunger by 2030 is one of the most prominent Sustainable Development Goals (SDGs) set by the United Nations. A robust digital food security program in developing countries such as India can contribute to that in a significant way. At this backdrop, it also becomes pertinent to highlight the notion of amalgamation of social needs and technical affordances (Kampf 2019; Rossi et al. 2019; Mattke et al. 2019). Therefore, the value for and need to adopt a new technology including Blockchain needs to be analytically tested. The impact of Information Technology (IT) adoption into various social welfare schemes has been widely studied for its agility and practicality (Aanestad 2016), and the results show that it has a significant effect on the economics of social welfare and the overall development (Liu and Whinston 2019; Prüfer 2018; Rahman and Mamun 2017). India has been one of the fastest-growing countries in recent times, with notable achievements in areas including IT and satellite technology. However, even then, it continues to face a contradictory rise in the hunger index. Despite being the fifth largest economy in the world, India ranks 103 on the global hunger index, which is considered to be in the serious[1] category. Over the years, various governments have adopted different measures to address this issue. The public distribution system (PDS) could be the oldest measure that has been in vogue in the country in different forms, besides the more recent additions such as the midday meals and Mahatma Gandhi National Rural Employment Guarantee Act.

Governments across the globe have been aggressively exploring new technologies for streamlining the transformation of smart services to achieve strategic objectives such as citizen well-being and happiness, service efficiency, and cost optimisation (Alketbi et al. 2018). The PDS, in its current format in India, is differentiated by the beneficiary status namely, those falling under the Antyodaya Anna Yojana (poorest of the poor), below poverty line (BPL), and above poverty line and implemented via a Targeted Public Distribution System (TPDS). The entitlements under the TPDS vary with the poverty status, with maximum entitlements for the poorest and minimum entitlements for the rest. The TPDS has gained increased importance in recent times due to its direct role in addressing food security, especially under the National Food Security Act (NFSA) 2013[2].

The PDS in different forms over time has undoubtedly yielded some benefits, but there remain several areas of concern as well. Such concerns require immediate attention, especially given its increased role under the NFSA 2013. Food and Agriculture Organization has highlighted the importance of PDS in achieving a higher level of household food security and eliminating the threat of famine from the country[3]. At the same time, there are concerns about the PDS facing the common problems of corruption, theft, misplacement[4], shrinkage, and leakage of the food grains, which tax the taxpayers as well as the government (Overbeck 2016). It is estimated that "inclusivity and the possibility of leakage reduction, thereof, has the potential to contribute to a net gain of $1 billion in social welfare from the status quo" (Surpluses 2015).

The whole issue about the proficiency or otherwise of PDS/TPDS has often been related to the literature on the efficacy of public spending. However, concerns about the efficiency of public spending, in general, and PDS, in particular, are not specific to India alone but apply to other developing countries as well. This is more germane to countries with weak institutions, which leads to a lack of transparency in the government process and accountability (Campos and Pradhan 1996; Filmer et al. 2000; Reinikka and Svensson 2004; Olken 2005). In their study on India, Khera (2011) points to the existence of a PDS underutilisation puzzle[5] in the state of Rajasthan. The study pointed to instances of people not utilising the full entitlements under the programme despite being desperate to have PDS access. Also, many of those same households covered under the PDS programme were purchasing the same items from the market at higher prices. This was attributed to a variety of reasons, such as households lacking financial means to buy food grains when they are available in the shops, unsuitable food grains supplied through PDS, transaction costs incurred due to inappropriate functioning of the ration shops or fair price shops (FPS)[6], and fraudulent diversion of PDS food grains into the open market amplified by low profitability of FPS[7]. However, Jha et al. (2013), in their study, support the welfare aspects of TPDS in the Indian states of Rajasthan, Andhra Pradesh, and Maharashtra, pointing to the price subsidy of the programme resulting in larger real income transfers. The study also discusses the aspects of rampant corruption in Food Corporation of India (FCI)[8] in terms of the actual amount supplied is frequently lower than than the recorded and issues of commission paid to officials for expediting supplies. There is also the mention of the organisation's "abysmal inefficiency in procuring, storing, and distributing food", and about 10% of all grains under this programme are spoiled during storage and transportation. The Comptroller and Auditor General (CAG)[9] of India has pulled up the FCI for several issues, such as procurement undershooting allocation, buffer norm lacking in specificity, and storage gaps along with the inadequacy of internal audit and physical verification. The CAG audit pointed out that internal audit and physical verification arrangements followed by the FCI lacked the requisite independence and effective follow-up processes. Such concerns pointed to the need for increased automation amid minimal human intervention in the process to enhance efficiency—right from procurement, storage, transportation, to the targeted delivery of food grains under TPDS.

Such concerns and criticisms led to focused redressal measures by the government. One of the major steps was "End-to-End Computerisation of the TPDS" under XIIth Five Year Plan 2012-2017[10], which is at either a fairly advanced state or a completed state across Indian states.

The formal evaluation studies of Indian PDS/TPDS post the end-to-end computerisation are few and far between. However, some of the extant studies[11] continue to cite instances of leakages in the form of food grain diversion because of systemic weakness, inappropriate identification of BPL families, cost of misidentifications, and inefficiency in the supply chain despite some improvements in these processes.

Moreover, the overall emphasis on end-to-end computerisation appears to be focused on procurement and delivery (identification of beneficiaries, online allocation of food grains, and automation of FSPs) rather than on the movement and distribution mechanism within TPDS. This gets reflected in the report of the High-Level Committee on Reorienting the Role and Restructuring of Food Corporation of India (January 2015). The report, while recognising the notable job on computerising the procurement operations, acknowledged "it is dovetailing with movement and distribution in TPDS has been a weak link where much of the diversions take place".

It is in this perspective that this article attempts to quantify the benefits of integrating radio frequency identification (RFID) with blockchain technology (BT) from procurement to delivery in the Indian TPDS process. The study focuses on answering the following questions.

1. How will Blockchain Technology (BT) improve the efficiency of PDS?
2. How to eliminate ghost demand from the PDS system and quantify the adoption benefits of BT in PDS?

At the back of the suggested integration of RFID and BT, our analysis points to the potential for substantial gains in the form of a significant reduction in human suffering as well as the expected cost of process inventory. It highlights the need for exploring policy options that facilitate the adoption of advanced technology in addressing social needs and enhancing social welfare. Perhaps this could be the first academic attempt to quantify the benefits of BT along with RFID in a humanitarian not-for-profit supply chain considering ghost demand. The technology enabled food supply chain in the government sector in several emerging economies like India is still at conceptual and design phase and so availability of reliable data to test the implication of the suggested model is a challenge. Nevertheless, the merit of this study lies in contemplating the usage of a superior technology, when technology adoption per se even without Blockchain and/

or RFID have been useful in reducing wastage and ghost demand in the TPDS system. In terms of policy implication, it may nudge the government to validate the outcome proposals through some prototypical implementation before adopting it on a larger scale. Besides, the paper also bring to force the aspect of applying traditional economic models to the novel phenomenon like blockchain technology to derive better theoretical knowledge.

The rest of the paper is structured as follows. Section 2 provides a review of the literature. Section 3 describes the Indian TPDS process and introduces the concepts of deprivation, leakage, shrinkage and ghost demand as building blocks for the theoretical model developed in the paper. Section 4 describes the relevance of BT and RFID within Indian TPDS to address issues of leakage, shrinkage and ghost demand while section 5 covers the modeling formulation. Section 6 focuses on the analysis of results applying the estimated parameters in the literature on Indian PDS to the model. Section 7 discusses aspects of model validation while section 8 discusses the managerial and economic implications. Section 9 concludes the paper by pointing out its limitations and proposing directions for future research.

2 Review of literature

From a more technical standpoint, the entire discussion in the paper can also be viewed from the perspective of technology adoption in supply chain management literature. This literature deals with the management of material flow, money flow, and information flow from sourcing and production to consumption. A humanitarian supply chain differs from a commercial supply chain in terms of objective and sustainability. In the commercial supply chain, the objective is to maximise overall supply chain surplus, while in the humanitarian supply chain the objective is to meet the needs of the people following natural disasters or complex emergencies (i.e., disaster relief, humanitarian work) (Carland et al. 2018). The PDS in India deals with the entire process from collection to the distribution of food grains to people who are BPL, as defined by the government of India. This constitutes a perfect case of the humanitarian supply chain to meet the needs of people as against maximising supply chain surplus.

RFID is a sensor-based tracking technology that is widely used across the commercial supply chain, mainly for tracking and locating purposes. The use of RFID gained importance in the humanitarian supply chain as well. A hybrid[12] framework using RFID for a disaster logistics management system can be developed to track and avoid the misplacement of relief materials as well as people in the occurrence of any disaster (Castaño and Rodriguez-Moreno 2010; Yang et asl. 2011). RFID applications in emergencies can be useful to provide real-time tracking of inventory when the relief team faces stochastic demand (Ozguven and Ozbay 2013; 2015). RFID is also useful in tracking and locating the movement of people in a localised building, in a hospital, at a social gathering, or at a public place to deal with any emergencies that may arise (Baldini et al. 2012; Ganz et al. 2015).

If RFID tags are effective for tracking inventory items in a finite and localised condition, BT may be applicable for tracking people and transactions over a large population base. BT is supposedly very useful in governance as well due to its capability of both tracking and recording business operations. It may be helpful for government transactions: tracking and tracing[13] of records as well as people transactions, in addition to tracking, tracing, and recording the distribution of subsidised services for social benefits (Bäckman 2018; Rajan 2018; Zwitter and Herman 2018).

RFID and BT can be integrated to take advantage of the online tracking of RFID and record-keeping and distributed ledger tracking capability of BT, ensuring that the entire process remains secure with adequate safety checks. The integrated framework of BT and RFID, along with the Internet of Things (IoT), has already been developed for the agro-food supply chain, which provides traceability, transparency, and auditability of the system (Thomason et al. 2018; Tian 2016; 2017). The characteristic of BT to serve as an immutable ledger that allows transactions to take place in a decentralised manner to aid e-governance and social record-keeping can be used to eliminate poverty and corruption, to an extent. It can also promote transparency through consensus-based transactions (Batubara et al. 2018; Pilkington et al. 2017; Sullivan and Burger 2017).

The adoption of BT in industries and across business functions is on the rise due to its economics of low cost and fast learning curve (Davidson et al. 2016). The integration of BT and RFID has the potential of becoming a low-cost but efficient technology for the TPDS in India. The government of India uses the AADHAAR card as an identity card for its residents for various government policies. The AADHAAR card may be integrated with BT and RFID for efficient delivery of food grains to the beneficiaries under TPDS, without the inefficiencies and hence the costs of corruption, leakages, shrinkages, and ghost demands.

Blockchain technology is an example of an evolving technology that has appeal for government attention. Many government bodies across developed and developing countries such as Singapore, Denmark, the United Kingdom, Honduras, Estonia, Australia, and others have taken steps to explore the benefits of Blockchain technology. The government of Dubai aims to become paperless by adopting the Blockchain technology for all transactions by 2021 (Alketbi et al. 2018).

A taxonomy of the applications of BT in the supply chain is listed in Table 1.

Article	*Application*	*Utility of blockchain technology*
DiFrancescoMaesa (2020)	Survey on the use cases of BT	This paper discussed the following application scenarios: end-to-end verifiable electronic voting, healthcare records management, identity management systems, access control systems, decentralised notary (with a focus on intellectual property protection), and supply chain management (SCM).
Dwivedi (2020)	The pharmaceutical supply chain system	This paper describes the role of the Blockchain mechanism within the traditional pharmaceutical supply chain system to make it better as well as present a Blockchain-based ecosystem for sharing information securely along with the pharmaceutical supply chain system with smart contracts and consensus mechanism.
Feng (2020)	Agri-food supply chain	This paper discusses the application of blockchain technology to improve agro-food traceability.
Behnke (2020)	Food supply chains	This paper identified the boundary conditions were for the application of BT in a food supply chain.
Bumblauskas (2020)	Food distribution	This article explained the implementation of blockchain technology in the production and supply chain delivery system for eggs from farms to consumers.
Casino (2019)		This paper proposed a distributed functional model to provide decentralised and automated FSC traceability based on Blockchain technology and smart contracts.

Article	*Application*	*Utility of blockchain technology*
Chang (2019)	Supply chain process design	This paper proposes 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
Choi (2019)	Diamond supply chain	This article provides a comparative analysis of Blockchain technology-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.
Chod et al. (2018)	Finance supply chain	Blockchain is adopted to bring transparency into the firm's operations, which leads to favourable financing terms at lower signalling costs.
Wang et al. (2019a)	Food, pharmaceutical, and luxury-item supply chain	Blockchain is adopted to create permanent, shareable, and actionable records of the digital footprints of products.
Choi et al. (2019); Alketbi et al. 2018; Behnke and Janssen (2020); Bumblauskas et al. (2020); Garrard and Fielke (2020); Helo and Shamsuzzoha (2020); Kamble, Gunasekaran, and Sharma (2020); Köhler and Pizzol (2020); Mirabelli and Solina (2020); Sund et al. (2020); Yadav, Singh, Raut, and Govindarajan (2020); Yong et al. (2020); Zhang et al. (2020)	Air logistic global supply chain, distribution, agro-food supply chain	Due to the emergence of Blockchain technology, supply chains are becoming digital now. These papers highlight a promising application of Blockchain technology in supply chain risk analysis.

Article	*Application*	*Utility of blockchain technology*
Alketbi et al. (2018); Chen and Wang (2020); Di Vaio and Varriale (2020); Dwivedi et al. (2020); Feng et al. (2020); Fosso Wamba, Queiroz, and Trinchera (2020); Köhler and Pizzol (2020); Kouhizadeh et al. (2021); Mazzei et al. (2020); Mirabelli and Solina (2020); Pal and Yasar (2020); Schinckus (2020); Tönnissen and Teuteberg (2020); Venkatesh et al. (2020); Wang et al. (2020); Wong et al. (2020); Zhang et al. (2020)	Supply chain sustainability efficiency	These studies highlight the capabilities of BT are used to enhance traceability, transaction, and security without using an intermediary to achieve sustainability and improve efficiency.

Table 1. Application of blockchain technology in supply chain

Although the extant literature describes the applications of BT to improve supply chain efficiency, it falls short of quantifying the benefits of technology adoption, while missing the cost-benefit analysis of BT applications. The study focuses on fulfilling the specified gap with the live case of Indian TPDS.

3 Description of Indian TPDS process

There are two major harvesting seasons in India: Rabi (the winter crop harvest) and Kharif (the summer crop harvest). Before the harvests of each of the Rabi and Kharif crops, the Indian government pronounces the minimum support prices (MSP) for procuring the agricultural produce. This is done on the basis of the recommendation by Commission of Agricultural Costs and Prices. The MSP amongst other factors considers the cost of various agricultural inputs and a reasonable margin for the farmers for their produce.

To facilitate the procurement of food grains, FCI and various state agencies in consultation with the state government plan to establish a large number of purchase centres at various Mandis[14] and key points. The state government decides the number of centres and their locations, taking into account various parameters, so as to optimise the

MSP operations. For instance, for wheat procurement, more than 19,000 procurement centres were operated during Rabi Market Season 2018-2019 and for rice procurement, more than 40,000 procurement centres were operated during Kharif Market Season 2017-2018.

The stocks brought by the farmers to the purchase centres those fall within the set specifications of the government of India are procured at the support price fixed by the government. However, farmers are allowed to sell their produce to other buyers, such as traders, millers, etc., if they get better prices from them. The FCI and the state government/its agencies ensure that the farmers are under no compulsion to sell their produce below the support price.

We argue that the features (traceability, tracking, secure transaction without third party, and consensus) of a Blockchain-based framework integrated with RFID will be beneficial in plugging the existing leakages over the entire path of the TPDS/PDS (i.e., from procurement, to transport and storage, to its ultimate delivery to beneficiaries), which the end-to-end computerisation has not been able to address so far. Tagging of bags with RFID could provide deterrence against any type of leakage from destination to consumption as covert interventions in the new system, causing leakages would get traced easily with the help of the capabilities of BT.

3.1 Storage

After procurement, the stock will be stored in various government warehouses. The Blockchain entries will be updated with the storage locations and the qualitative attributes of the food grains, which will then be broadcast to others to ensure transparency. As the stock will have an attached digital signature, we can easily identify the stock and transactions in the Blockchain ledger.

3.2 Movement and flow of food grains along the chain

Blockchain protocol allows efficient tracking. The movement of the food grain bags from storage warehouses to the TPDS can be tracked, whereby any alteration during transportation will be visible as the data can be traced in Blockchain entries and cannot be modified. The movement is part of the network because the food grains need to be monitored when they are relocated from one location to another to keep track of their quality and quantity.

The usage of BT integrated with RFID would be effective in addressing any leakage, shrinkage, misplacement, and ghost demand over the entire TPDS process, resulting in considerable savings that help minimise human suffering and deprivation.

The building blocks of the concepts used in the model are explained herewith.

3.3 Deprivation cost

The notion of deprivation cost used here is borrowed from the literature of post-disaster humanitarian logistics, where the deprivation function is a function of time (Holguín-Veras et al. 2013), developed on the tenets of welfare economics, the deprivation cost refers to the sum of economic value of suffering of people over the period of deprivation and the cost of providing the welfare measures to end the suffering. This format of deprivation cost allows us to capture the social cost of the response effort to deal with deprivation. From the perspective of our discussion on Indian TPDS with BT and RFID, such a construct in the model allows the minimisation of social costs including both the deprivation cost of public suffering and the cost of response efforts through technology to address that.

Deprivation costs, however, vary with individuals, indicating the need for a unique deprivation cost function based on age, gender, physical condition, and other such factors. However, that becomes mathematically prohibitive to deal with and requires considerable knowledge of population demographics. At the backdrop of such technicalities, the deprivation cost in this article is assumed to be homogenous for all individuals at any point.

The deprivation cost function is perceived to be monotonic, non-linear, and convex with respect to deprivation time. Since it is difficult to model non-linearity and generalised convexity for expositional purposes, in this article we have assumed a linear deprivation cost function that is proportional to deprivation time. This indicates that deprivation cost increases at a constant rate with time, which limits this function to capture the logic that the longer the period a person is in deprivation, the greater the suffering he or she faces. However, any form of deprivation function that enables an increasing rate of deprivation over time would only strengthen the results of this study. The non-additive nature of the deprivation function indicates that demand over the entire period of deprivation will differ from the demand at delivery. For example, if a person requires 500 g of grains for his or her daily consumption, at the end of the 10th day, he or she would not be in a position to consume 5 kg of wheat. The non-additive nature leads to the next modelling challenge in terms of the economic phenomenon called hysteresis. This means if the value of deprivation exceeds a certain threshold level for individuals, it might lead to a situation where the individual might not fully recover the shock even upon receipt of the goods in question. Deprivation costs can, thus, be characterised as a hysteresis value having attributes and characteristics that are difficult to build into mathematical formulations. However, our exposition is limited to the issue of deprivation alone without rendering it to the elements of hysteresis.

3.4 Shrinkage and leakage

Blockchain protocol In this paper, the concepts of shrinkage and leakage have been used as two different phenomena. Shrinkage is defined as inventory inaccuracy due to asymmetric information and inferior technology for inventory management. It can be mitigated by adopting RFID techniques (Biswal et al. 2018; Fan et al. 2015). Leakage is defined as an outcome of theft and/or misplacement of the inventory item, which for a particular period, *t* be defined, following Overbeck (2016), as:

$$\text{Leakage}_{it} = 1 - \frac{Total\ Consumption_{it}}{offtake_{it}}$$

Where offtake refers to the official total offtake of food grains obtained from the official monthly government food grain bulletin. Leakages refer to food grains failing to reach the intended beneficiaries. As per 2011 data, leakages in PDS were estimated to be at 46.7%. These leakages are mainly of three types: (i) pilferage or damage during transportation of food grains, (ii) diversion to non-beneficiaries at FPS through the issue of ghost cards, and (iii) exclusion of eligible people from the beneficiary list[15].

3.5 Ghost demand

The current PDS takes the help of various state governments to identify and distribute food grains to the needy. At times, artificial demands are generated due to inclusion error by the government, leading to the generation of ghost cards (estimates of ghost cards stand at 16.7%) (Sivadasan 2012) and shadow ownership (illegal migrants). End-to-end computerisation with AADHAAR (a unique identification number) seeding can help control it; however, at this point, there is limited literature available regarding the efficacy of its application. This paper explores the effectiveness of solutions to eliminate shrinkage, leakage, corruption, and ghost demand from the PDS by integrating RFID and BT.

4 Blockchain technology

Blockchain technology (BT) can create a peer-to-peer distributed network, where non-trusting participants can transact with each other without trusted intermediaries (Christidis and Devetsikiotis 2016). Traceability and transparency are two important dimensions of a PDS. BT with an IoT platform can be used for tracking the product flow in a supply chain. Blockchain and Smart Contracts can maintain a formal registry of products and track their ownership through different points in a supply chain. These applications can also enable automated financial settlements on delivery confirmations (Bahga and Madisetti 2016; Huh et al. 2017). A BT platform can be used for developing applications for farmers, distributors[16], and identifying beneficiary and reputation management that can track various performance parameters (such as delivery times, customer reviews, and FPS ratings). The government of India has resorted to change PDS to TPDS to measure and control the outcomes of PDS. Figure 1 depicts the existing structure of TPDS. The TPDS is a food security supply chain, that is subsidised by the government of India. In this supply chain the food grains are procured from the farmers using a unit of 50 kilogram in standard size bags. After procurement the bags are transported (in bulk) to the government managed warehouses where it is stored and subsequently distributed to the needy through fair price shops. Government appoints agents to run the fair price shops for disbursal of the food grains.

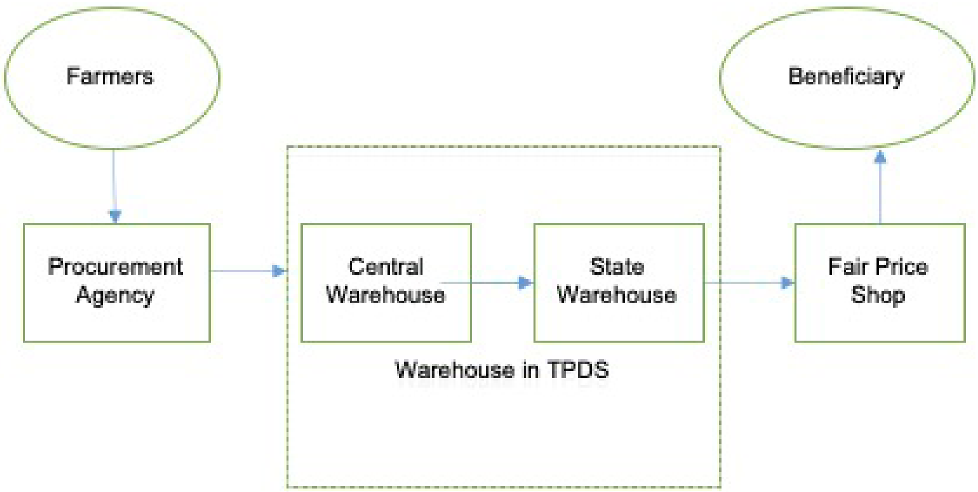

Figure 1. TPDS charitable supply chain

BT along with smart contract applications can keep a record of the transactions of food grains through the supply chain, replacing the need for manual records and human interventions that have the risk of compromising institutional independence and accountability. Many researchers have advocated for adopting BT in the humanitarian supply chain as well (Bäckman 2018; Zwitter and Herman 2018; Rajan 2018).

In this paper, we extend the work of Biswal et al. (2018), with significant modifications to the model-first, by including the ghost demand factor; second, by incorporating technological integration between RFID and BT; and third, by introducing the difference between shrinkage and leakage and including both these features in the model. To our knowledge, this is the first academic paper that attempts to quantify the benefits of BT along with RFID in a humanitarian not-for-profit supply chain considering ghost demand.

5 Research methodology and modelling framework

In this study, secondary data is used to highlight the types of leakage and its impact on the efficiency of TPDS. Further, similar (BT) use cases are analysed to identify the attributes of BT that could help reduce the leakage post its adoption. The mathematical Newsvendor model was used to quantify the adoption benefits and to optimise the ordering quantity of the food grains in two scenarios (with and without BT), and the savings on the quantity demanded are attributed to the value of BT adoption in TPDS. To validate the model, simulation was used to demonstrate the quantified benefit using secondary data.

We have considered TPDS as a non-profit humanitarian supply chain consisting of its own warehouses provided by the FCI. The warehouse gets supplies of seasonal food grains from upstream farmers at a fixed MSP, p. The warehouse is expected to maintain the inventory for the intended beneficiaries under TPDS. We model the total expected cost[17] with and without the usage of integrated BT and RFID. We have used the standard Newsvendor model, with a primary objective of optimising the total cost of inventory and a secondary objective of minimising human suffering due to a deficiency in the supplies of critical food grains. Deprivation costs are economic values of human suffering and are defined as the function of deprivation time and socioeconomic characteristics of the beneficiaries (Holguin-Veras et al. 2012; 2013; 2016). We incorporate deprivation cost in the model as a function of deprivation time that is directly proportional to the backlogged quantity. We assume that the beneficiaries incur a deprivation cost, d, per unit waiting time.

We have incorporated shrinkage and leakage costs using variables A and B, respectively. These reflect the effect of shrinkage and leakage on the actual quantity available for TPDS. Therefore,

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

and

$$B = \frac{Actual\ available\ quantity}{Initial\ procured\ quantity}\ (\ due\ to\ leakage)$$

Shrinkage in PDS is non-controllable while leakage can be controllable. We have also incorporated ghost demands (ghost beneficiaries using ghost TPDS cards) as a fraction of the total demand, which is represented as ρ. We model two scenarios from the perspective of a warehouse manager. First, when he or she acknowledges the ghost demand and leakage due to shrinkage and misplacement and takes an inventory decision with prior estimations of ghost demand and leakage. Second, when he or she invests in BT and RFID and takes an inventory decision under reduced leakage and ghost demand. Post-modelling, we are able to gauge the benefits of the adoption of BT along with RFID. In our mathematical formulation, we make the following assumptions:

1. The excess demand from the beneficiaries is backlogged and fulfilled by emergency procurement at extra cost.

2. Deprivation time is directly proportional to backlogged quantity. Deprivation cost is a linear function of deprivation time.

3. Inventory shrinkage and leakage are independent.

4. Post-BT leakage and misplacements are reduced completely.

5. MSP is independent of the demand.

Table 3 compares inventory inaccuracy in two cases. The first case is without BT and RFID, in which out of (1+G)Ω ordered quantity, (1-A) goes in shrinkage, (1-B) goes in misplacement, and GΩ is the total ghost demand.

Notation	*Description*
Ω	The procured quantity without the adoption of BT (decision variable)
Ω*	The optimal procured quantity without the adoption of BT
Q	The procured quantity with the adoption of BT (decision variable)
Q *	The optimal procured quantity with the adoption of BT
C(Ω)	The total expected cost without BT
C (QBT)	The total expected cost with BT
P	The purchase 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 deprivation cost factor (the intensity of deprivation over time and quantity)
T	The time required to replenish one backlogged item
M	The marginal cost for the implementation of BT
X	The random demand
f(x)	The probability density function of the demand function
F(x)	Commutative Distribution Function of the demand function
μ	Mean of the demand
G	The ghost demand (the fraction of the demand function that is generated due to inactive consumers, illegal consumers, and unauthorised consumers)
A	The rate of available quantity due to shrinkage
B	The rate of available quantity due to leakage
t1	The available rate of order quantity without BT
t2	The available rate of order quantity with BT
r	The upper bound of uniformly distributed demand
K	The fixed cost of BT implementation

Table 2. List of notations used in the model

	Case without BT	*Case with BT*
Loss due to shrinkage	Ω (1-A)	0
Loss due to leakage	Ω (1-B)	0
Loss due to ghost demand	Ω G	0
Total loss	Ω (2+G-A-B)	0
Remaining inventory	$\Omega\ (G + A + B - 1)$	Ω
Available rate	$t_1 = (G + A + B - 1)$	$t_2 = 1$

Table 3. Comparison of inventory inaccuracies

5.1 Ordering policy without BT and RFID

$$C(\Omega) = (1+G)H\int_0^{t_1\Omega}(t_1\Omega - x)f(x)dx + U(1+G)\int_{t_1\Omega}^{\infty}(x - t_1\Omega)f(x)dx + H(1-B)\Omega + P(1-A)\Omega + (1+G)\int_{t_1\Omega}^{\infty}Dt(x - t_1\Omega)f(x)dx \qquad (1)$$

The first term in Equation 1 represents the holding cost for ghost demand; the second term represents the emergency procurement cost for excess demand; and the third, fourth, and fifth terms represent misplacement and deprivation cost of human suffering, respectively (Hill 2011; Pertiwi et al. n.d..; Yan and Tian 2011).

By a few arrangements, we get the expected cost C(Ω) as:

$$C(\Omega) = (1+G)H\int_0^{t_1\Omega}(t_1\Omega - x)f(x)dx + (1+G)(U + Dt)\int_{t_1\Omega}^{\infty}(x - t_1\Omega)f(x)dx + H(1-B)\Omega + P(1-A)\Omega \quad (2)$$

The expected cost takes the shape of a well-known newsvendor model (Hill 2011). As the newsvendor model function is a convex function, we can have a minimum value of this function for a particular optimal order quantity Ω* by differentiating C(Ω), applying Leibniz rule with respect to Ω, and equating it to zero (see Appendix A).
Since,

$$\Omega^* = \frac{1}{t_1} F^{-1}\left[\frac{U+Dt}{(H+U+Dt)} - \frac{H(1-B)+P(1-A)}{(1+G)t_1(H+U+Dt)}\right] \qquad (3)$$

If we assume that the inventory is accurate, hence deprivation cost d = 0 and t_1, *A, B are* $\Omega^* > 0$ *hence from equation 2*, $t_1 > \frac{[H(1-B)+p(1-A)](H+U+Dt)}{[(U+Dt)(H+U+Dt)(1+G)]}$

all unity , hence the optimal quantity.
This result is similar to the standard Newsvendor problem (Hill 2011; Parsons 2004).

$$\Omega^*_c = F^{-1}\left(\frac{U}{H+U}\right)$$

The optimal cost function without BT can be calculated from Equation 2:

$$C(\Omega) = (1+G)H\int_0^{t_1\Omega}(t_1\Omega - x)f(x)dx + (1+G)(U+Dt)\int_{t_1\Omega}^{\infty}(x-t_1\Omega)f(x)dx + H(1-B)\Omega + P(1-A)\Omega$$

Cost function at the optimal quantity Ω^* has been derived as follows (see Appendix B).
The cost function will be:

$$C(\Omega^*) = (1+G)\left[\mu(U+Dt) - (H+U+Dt)\int_0^{t_1\Omega^*} xf(x)dx\right] \qquad (4)$$

If the ghost demand is zero, that is, G = 0, then:

$$C(\Omega^*) = \mu(U + Dt) - (H + U + Dt)\int_0^{t_1\Omega^*} xf(x)dx \quad (5)$$

5.2 Inventory policy after the adoption of BT

In this case, we consider that there is no ghost demand $G = 0$ and the warehouse improves the inventory by adopting RFID integrated with BT. The improved available inventory will be $t_2 = 1$. The marginal deployment cost of the technology is given by M towards implementing RFID and BT with a fixed cost investment equal to K.

$$C\,(Q_{BT}) = h\int_0^{t_2Q} (t_2Q - x)f(x)dx + u\int_{t_2Q}^{\infty} (x - t_2Q)f(x)dx + QM + K + \int_{t_2Q}^{\infty} dt(x - t_2Q)f(x)dx \quad (6)$$

For calculating the optimum ordering quantity Q^*_{BT} in the presence of BT and RFID, we have to differentiate Equation 6 using Leibniz rule (see Appendix C). After applying the Leibniz rule:

$$Q^*_{BT} = \frac{1}{t_2}F^{-1}\left[\frac{U + Dt}{(H + U + Dt)} - \frac{M}{t_2(H + U + Dt)}\right] \quad (7)$$

As, $Q^*_{BT} > 0$, $\left[\frac{U+Dt}{(H+U+Dt)} - \frac{T}{t_2(H+U+Dt)}\right] > 0$, hence $M < (U + D2)t2$.

After inserting the value of the optimum quantity in Equation 6 and calculating the optimal total cost for Q^*_{BT}, we get the following equation:

$$C(Q^*_{BT}) = K + (U + Dt)\mu - (H + U + Dt)\int_0^{t_2 Q^*_{BT}} xf(x)dx \qquad (8)$$

6 Cost-benefit analysis for adopting BT and RFID in TPDS

A recent estimate of leakage—including misplacement, shrinkage, and ghost demand—in TPDS is 40-50%, out of which 15-20% is ghost demand and the rest are misplacement and shrinkage (Masiero and Das 2019). For the expositional purpose, we have given an illustrative example below to understand the cost-benefit analysis for the adoption of BT and RFID in TPDS. We have collected the secondary (Table 4) data from various government reports for the purpose of illustration (Biswal et al. 2018; Biswal et al. 2019). The analysis is done using the optimal inventory ordering policy in two scenarios presented in the model in Section 3.

The sensitivity analysis of ghost demand and misplacement using equations 5 and 8 show that the total cost of inventory is significantly less after the adoption of BT and RFID (Tables 5 and 6). The Simulation of Model (Using R software) using Real data of Table 2 is shown in Tables 3 and 4.

For the expositional purpose, it has been assumed that the demand follows a uniform distribution, with the upper bond equal to γ and the lower bond equal to 0, that is, with the range of [0, γ]. By assuming a uniform distribution of demand, we were able to extract some relevant managerial implication on the total expected cost with and without BT and the marginal adoption cost of BT with RFID.

Model parameters	*Value*
Weight of a food grain bag (wheat, rice, and sugar); we have considered a rice bag for the analysis.	50 kg
Ghost demand (G)	15-20%
MSP per bag (P)	₹1,200
Holding cost per bag (H)	₹500
Emergency procurement cost per bag (U)	₹250
Human suffering factor (D)	₹100-20,000
Replenishment time for unit backlogged demand	1 day
Stock-keeping units capacity (γ)	5,000-50,000 metric tonne
The marginal cost for adopting BT and RFID	₹50-150
Shrinkage rate (A)	3-6%*
Misplacement rate (B)	3-5%*
Fixed cost for adopting BT and RFID	₹1,500,000-2,500,000

*In the government reports, ghost demand, misplacement, and shrinkage are known as leakage. The total leakage varies from 10% to more than 50%[18]. We have taken the range for leakage to be 10-25%, which is known as moderate leakage.

Table 4. Input parameters of the illustrative example[19]

G	*A*	*B*	*Total cost in INR 1,000 million (without BT)*
0.15	0.03	0.03	1,217.672
0.1556	0.0333	0.0322	1,688.131
0.1611	0.0367	0.0344	2,262.040
0.1667	0.0400	0.0367	2,951.646
0.1722	0.0433	0.0389	3,770.427
0.1778	0.0467	0.0411	4,733.223
0.1833	0.0500	0.0433	5,856.381
0.1889	0.0533	0.0456	7,157.923
0.1944	0.0567	0.0478	8,657.723
0.2	0.06	0.05	10,377.722
0.15	0.03	0.03	1,217.672
0.1556	0.0333	0.0322	1,688.131
0.1611	0.0367	0.0344	2,262.040
0.1667	0.0400	0.0367	2,951.646
0.1722	0.0433	0.0389	3,770.427
0.1778	0.0467	0.0411	4,733.223
0.1833	0.0500	0.0433	5,856.381
0.1889	0.0533	0.0456	7,157.923
0.1944	0.0567	0.0478	8,657.723
0.2	0.06	0.05	10,377.722

Table 5. Sensitivity analysis of model parameters without BT and RFID

D	*K*	*M*	*Total cost after the adoption of BT and RFID in INR 1,000 million*
1500	1500000	50	11.640
1500	1611111	61.11111	12.059
1500	1722222	72.22222	12.475
1500	1833333	83.33333	12.888
1500	1944444	94.44444	13.298
1500	2055556	105.5556	13.705
1500	2166667	116.6667	14.110
1500	2277778	127.7778	14.512
1500	2388889	138.8889	14.912
1500	2500000	150	15.308
1500	1500000	50	11.640
1500	1611111	61.11111	12.059
1500	1722222	72.22222	12.475
1500	1833333	83.33333	12.888
1500	1944444	94.44444	13.298
1500	2055556	105.5556	13.705
1500	2166667	116.6667	14.110
1500	2277778	127.7778	14.512
1500	2388889	138.8889	14.912
1500	2500000	150	15.308

Table 6. Sensitivity analysis of model parameters with BT and RFID

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

$$\pi^* = \frac{\gamma}{t_1}\left[\frac{U + Dt}{(H + U + Dt)} - \frac{H(1 - B) + P(1 - A)}{(1 + G)t_1(H + U + Dt)}\right] \qquad (9)$$

$$Q_{BT}^{*} = \frac{\gamma}{t_2}\left[\frac{U+Dt}{(H+U+Dt)} - \frac{T}{t_2(H+U+Dt)}\right] \quad (10)$$

$$C(\Omega^{*}) = \frac{(1+G)\gamma}{2}\left[(U+Dt) - (H+U+Dt)\left[\frac{U+Dt}{(H+U+Dt)} - \frac{H(1-B)+P(1-A)}{(1+G)t_1(H+U+Dt)}\right]^2\right] \quad (11)$$

$$C(Q_{BT}^{*}) = I + \frac{(U+Dt)\gamma}{2} - \frac{(H+U+Dt)\gamma}{2}\left[\frac{U+Dt}{(H+U+Dt)} - \frac{T}{t_2(H+U+Dt)}\right]^2 \quad (12)$$

Similarly, the cost of suffering (deprivation cost) can be calculated for the two cases with and without BT (Holguín-Veras et al. 2012).

Human suffering cost (without BT)

$$= \frac{dt}{2\gamma}(\gamma - t_1\Omega^{*})^{2} \quad (13)$$

Human suffering cost (with BT)

$$= \frac{dt}{2\gamma}(\gamma - t_2\, Q_{BT}^{*})^{2} \quad (14)$$

As Ω^{*} is > Q_{BT}^{*} and $t_1 > t_2$, Human suffering cost (with BT) < Human suffering cost (without BT).

7 Model validation and discussion

Similarly, The TPDS system in India has undergone significant changes in terms of automation and the usage of information and communication technology (ICT). It has led to improvements and benefits, but there are still gaps that need to be addressed.

At the back of the changes in the TPDS process already undertaken, this paper points to the benefits of adopting further technological and ICT advancements of Blockchain and RFID to plug some of the gaps that still exist and enhance the efficiency of the process. Given that the RFID and/or Blockchain is a suggestion of the paper, it may nudge the government to validate the outcome proposals through some prototypical implementation. Such prototypical implementation has not been attempted yet. Till that happens, there will be no data available to validate this process.

At the back of the problem of exact data availability highlighted above, we try to validate our claims with our model of the next best option available (secondary data Table 5 and 6). Viewing the paper from the perspective of technology adoption, we are left with the only alternative of sharing the actual evidence on how technology adoption per se even without Blockchain and/or RFID has been effective in reducing wastage and ghost demand in the TPDS system. Our presumption would then be that the added level of technological sophistication would only further this benefit.

Technology adoption in the TPDS can be considered as a prominent theme post the adoption of NFSA of 2013. However, many states in India had initiated the reforms at individual levels even before that. Chhattisgarh is one of the Indian states to do so along with some other states, though the pace of reforms was not coordinated across them. This point is highlighted here as results of reforms and ICT adoption in the early adopter states would provide useful evidence of the benefits of technology adoption in India. So are the benefits accruing to later adopter states like Bihar, which only bolsters such presumption? As has been stated in the paper, the major points of leakage in the TPDS are procurement, storage, and transportation. Until recent times, such processes were performed manually. Although computerisation as a policy existed earlier, it did to either disparate state initiatives or pilot projects[20]. However, it became a drive post-2012 at the back of a central scheme whereby central and state governments shared costs for (a) automating FPS-level data and transactions, warehouse and storage information, data on the transport of grain, and data on beneficiary transactions and (b) creating ICT-based methods for redressing grievances, such as websites and toll-free numbers.

At the back of these efforts, technology adoption in Indian TPDS yielded two most important benefits related to our study: reduction of leakages and ghost ration cards thereby contributing to the efficiency of the process.

State/UT	*Digiti-zation of Ration Cards*	*Aadhaar Seeding in Ration Cards*	*Online Allocation of Food grains*	*Comput-er-ization of supply Chain*	*Online Grievance Redressal*
Andhra Pradesh	100%	100%	Implemented	Implemented	yes
Arunachal Pradesh	100%	45%	-	-	-
Assam	100%	0%	Implemented	-	yes
Bihar	100%	69%	Implemented	Implemented	yes
Chandigarh	100%	100%	NA	Implemented	yes
Chhattisgarh	100%	100%	Implemented	Implemented	yes
Goa	100%	91%	Implemented	Implemented	yes
Gujarat	100%	95%	Implemented	Implemented	yes
Haryana	100%	86%	Implemented	Implemented	yes
Himachal Pradesh	100%	91%	Implemented	Implemented	yes
Jammu And Kashmir	100%	100%	UP to TSOs	-	-
Jharkhand	100%	97%	Implemented	Implemented	yes
Karnataka	100%	100%	Implemented	Implemented	yes
Kerala	100%	98%	Implemented	-	yes
Madhya Pradesh	100%	91%	Implemented	Implemented	yes
Maharashtra	100%	87%	Implemented	Implemented	yes
Manipur	100%	22%	Partial	-	yes
Meghalaya	100%	0%	-	-	yes
Mizoram	100%	45%	Implemented	-	yes
Nagaland	100%	7%	-	-	yes
Odisha	100%	88%	Implemented	Implemented	yes
Punjab	100%	97%	Implemented	-	yes
Rajasthan	100%	95%	Implemented	-	yes
Sikkim	100%	82%	Implemented	-	yes

State/UT	*Digiti-zation of Ration Cards*	*Aadhaar Seeding in Ration Cards*	*Online Allocation of Food grains*	*Comput-er-ization of supply Chain*	*Online Grievance Redressal*
Tamil Nadu	100%	100%	Implemented	Implemented	yes
Telangana	100%	100%	Implemented	Implemented	yes
Tripura	100%	98%	Implemented	Implemented	yes
Uttarakhand	100%	90%	Implemented	-	yes
Uttar Pradesh	100%	77%	Implemented	-	yes
West Bengal	100%	62%	Implemented	Implemented	yes
Andaman And Nicobar Islands	100%	100%	Implemented	Implemented	yes
Dadra And Nagar Haveli	100%	96%	Implemented	Implemented	yes
Daman And Diu	100%	100%	Implemented	Implemented	yes
Delhi	100%	100%	Implemented	Implemented	yes
Lakshadweep	100%	98%	-	NA	yes
Puducherry	100%	100%	NA	NA	yes
Total	**100%**	**79%**	**30***	**20**	**34**

The shaded portion in the table refers to union territories.

Table 7. Status of end-to-end computerisation of TPDS scheme (Unstarred Question No. 1464, Lok Sabha (Indian Parliament), by Ministry of Consumer Affairs, Food and Public Distribution, answered on 24 July 2017)

State	*World Bank*		*Gulati and Saini*		*Himanshu and Sen*		*DRÉZE AND KHERA*	
	2004-2005	2011-2012A	2004-2005	2011-2012A	2004-2005	2011-2012A	2004-2005	2011-2012A
Andhra Pradesh	31.1	16.6	13.2	11.1	25.4	7.8	23.2	22
Assam	89.4	51.8	88.7	60.9	88.1	45.2	88.7	50.7
Bihar	92.9	29.1	91	68.7	91.2	12.2	91	24.4
Chhattisgarh	51.8	16.9	51.8	NA	49.5	0.3	51.7	9.3
Jharkhand	86.8	51.5	85.2	74.9	84.2	34.5	85.2	44.4
Haryana	84.2	52.9	82.7	70.3	83.5	51.1	82.7	49
Madhya Pradesh	50.3	50.6	50.1	49.3	46.4	42.1	50.1	51.5
Maharashtra	52.8	47	49.3	54.9	47.7	41.3	49.3	48.2
Odisha	75.8	30.7	76.3	36.8	74.8	15.5	76.3	25
Punjab	94.8	60.3	93.2	60.7	94.2	56.5	93.2	58.8
Rajasthan	59.3	62.2	93.9	66.3	55.3	55.6	93.9	60.9
Uttar Pradesh	84.9	60.4	58	47.9	83.7	54.3	58	57.6
West Bengal	85.9	61.7	80.6	69.4	85	56.8	80.6	65.3
All India	**58.6**	**43.1**	**54**	**46.7**	**54**	**34.6**	**54**	**41.7**

Table 8. Different estimates of the reduction in leakages from household TPDS offtake as a percentage of official offtake in India for select states during 2004-2005 and 2011-2012 (Elderman et al. 2017, chapter 2, Annex table 2A.7; Drèze and Khera 2011; 2015; Himanshu 2015).

Given these experiences, in the absence of data to validate the claims of the paper, the merit of the arguments made lies in contemplating the benefits accruing from the usage of superior technology when technology adoption per se even without Blockchain and/or RFID has yielded meaningful reduction in wastage and ghost demand in the Indian TPDS system.

8 Managerial and economic implications and future direction

Technology has played an important role in human development. With the emergence of BT, the governance and delivery of public goods can become a transparent and relatively more moral hazard-free mechanism. BT has the potential to eradicate leakages from the distribution process, which is a major concern in TPDS. The cost-benefit analysis of the adoption of BT and RFID shows that technology adoption has the potential to save millions of taxpayers' money and enhance social welfare. In as much as BT and RFID are beneficial for TPDS, there are challenges as well mostly related to operationalising and adopting the technology. The government has tried to implement a Unique Identification Number (UIN) programme to eliminate ghost demand through the Unique Identification Authority of India, but the major challenges were legal (personal data utilisation in public services) and the apprehension of the public about digitisation. BT has an advantage over UIN in terms of security and transparency.

The mathematical modelling presented in the paper incorporates the aspect of the three points in the said supply chain where maximum leakges are attributed (Figure 1): (1) When grains are procured (quality) by the procurement agency (2) when the bags of the grains are stored in the warehouse (3) when the bags are distributed using faire price shop to the needy. All these intractions could be eliminated with the introduction of blockchain.

Nonetheless, the feasibility of integrating RFID with BT in TPDS at a scale that results in significant benefits depends on a number of other important factors including, but not limited to: (i) level of technology as the current immaturity of BT (given it is still evolving) can lead to increased switching costs (Shin 2016) at this stage; (ii) presence of established and acceptable procedure to prevent tampering of devices used in technologies such as the Internet of Things (IoT) and biometrics for connecting and securing physical goods in blockchain process; and (iii) an ecosystem of the governance structure for managing the system, data, and investment. Furthermore, the current insufficient technological understanding can limit our ability to handle legislative risks (Walch 2017), which can significantly affect the adoption of BT (Abramova and Böhme 2016).

9 Conclusion, limitations, and future research

In this paper, we have highlighted the importance of the integration of RFID and BT, focusing on the scope for potential gains post its adoption and implementation in the Indian TPDS. The study quantified the benefits of adopting BT along with RFID, with simulations revealing a significant reduction in ghost demand as well as savings in inventory cost for the system.

At a more basic level, research needs to focus on the behavioural issue of how users perceive and interact with different blockchain characteristics. It is limited not only to why people use the technology but also to what features enhance or constrain its dissemination in society. Besides, research also needs to effectively weigh in the resultant trade-offs. In blockchain applications, gaining transparency could lead to a trade-off of reduced anonymity due to higher identifiability through transaction pattern recognition or user meta-information. While this can be seen as a strength regarding the suitability, it can also be viewed critically from the privacy perspective (De Fillipi 2016). Future research has the scope to incorporate such considerations into the analysis to come to more robust conclusions as well as to validate the benefits of such a socio-technical system through prototypical implementation. Hence, while the current study looks more at economic returns, investigations into the importance and impacts of other ascertainable metrics, such as ease of use, trustworthiness, and so on, would be the prospects for future research. Moreover, incorporating the nuances of practical implementation issues and considerate empirical investigations would be necessary to substantiate the conceptualisation of potential benefits of integrating RFID with BT technology in the Indian TPDS context. In particular, extensive empirical studies would be desirable to move the discussion of the value of BT in TPDS to firmer grounds. However, given the literature is new and emerging, empirical studies will take time to emerge and may provide a fertile ground for future research.

Notes

1. https://www.globalhungerindex.org/results/.
2. The act provides coverage for up to 75% of the rural population and up to 50% of the urban population for receiving subsidised food grains under TPDS, covering about two-thirds of the population. The eligible persons identified by the states/union territories are

entitled to receive 5 kg of food grain per person per month at subsidised prices of INR 3/2/1 per kg for rice/wheat/nutri-grains (coarse grain).

3. http://www.fao.org/3/x0172e/x0172e06.htm.
4. There are concerns about the PDS facing a ghost demand, similar to that in LPG or cooking gas. Subsequent to the highly subsidised domestic LPG pricing well below the market price, there have been concerns that supplies are getting diverted for commercial use, unnecessarily adding to the subsidy burden. (http://petroleum.nic.in/dbt/DBTL_Handbook.pdf, downloaded on 17/11/2018) Besides, "MoPNG estimated (February 2016) that the potential savings in LPG subsidy for 2015-2016 would be INR 9,211 crores. This has been worked out after considering that 4.53 crore domestic LPG consumers would not avail of subsidised cylinders during 2015-2016 (including 1.42 crore domestic consumers who had not joined the scheme and hence not eligible to receive a subsidy and 3.11 crore blocked/inactive consumers)." (https://cag.gov.in/sites/default/files/audit_report_files/Union_Commercial_Compliance_Report_25_2016_Chapter-9.pdf, downloaded on 17/11/2018)
5. Khera (2011) *"Among those who have access to the TPDS, one-third of the sample households do not utilise their quota at all and another half do not utilise their quota fully. Further, many of these households purchase the same items from the market at higher prices."*
6. People in far-flung hamlets are not sure whether the shop would be open, or even if it is open, whether the commodity would be supplied, in addition to concerns of being cheated by ration shop (FPS) owners, leading to several trips and the resultant loss of income before they can actually purchase the commodity.
7. With the shift to TPDS and extremely low margins on sales to BPL households, the FPS has a weak incentive to maintain adequate stocks. When the stocks are adequate, large supplies are diverted to the open market at much higher margins.
8. As a part of the TPDS process, food grains are purchased by the central government through the FCI at predetermined MSP. The government also determines a uniform central issue price at which food grains are sold by the FCI to state governments for distribution through the PDS. FCI as an organisation is crucially involved in procurement, storage, and transportation. This is further explained in the text hereafter.
9. CAG Audit Report (no. 12 of 2012-13) on Performance of Storage Management and Movement of Food Grains in FCI. CAG of India has the constitutional responsibility to safeguard the interest of public exchequer through different audits.
10. https://dfpd.gov.in/End-to-end-TPDS_C.htm accessed on 08-05-2019.
11. NCAER (September 2015) *Evaluation study of targeted public distribution system in selected states*.
12. Hybrid of BT and IOT with RFID.
13. Like registry office record-tracking.
14. Large market places/purchase centres.
15. http://www.prsindia.org/uploads/media/DFG%202017-18/DFG-%20Food%20and%20Public%20Distribution.pdf, downloaded on Sept 12, 2020.
16. Distributors mainly include the FCI and FPS.
17. Cost of inventory holding and human suffering.
18. https://www.prsindia.org/administrator/uploads/general/1388728622~~TPDS%20The-

matic%20Note.pdf, downloaded on June 9, 2019.
19. https://dfpd.gov.in/EBook/examples/pdf/AnnualReport.html?PTH=/1sGbO2W68mUlunCgKmpnLF5WHm/pdf/fdhindi17-18-min.pdf#book/.
20. https://nofimaas.sharepoint.com/sites/public/Cristin/Rapport%2004-2019.pdf?cid=8bcf8ad8-ab23-4f27-b968-9d51ef1ede67.

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Appendix A

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

$$\Rightarrow (1+G)H\int_0^{t_1\Omega} \frac{\partial}{\partial \Omega}(t_1\Omega - x)f(x)dx + (1+G)(U + Dt)\int_{t_1\Omega}^{\infty} \frac{\partial}{\partial \Omega}(x - t_1\Omega)f(x)dx + \frac{\partial}{\partial \Omega}H(1-B)\Omega + \frac{\partial}{\partial \Omega}P(1-A)\Omega = 0$$

$$\Rightarrow (1+G)Ht_1\int_0^{t_1\Omega} f(x)dx - (1+G)(U + Dt)t_1\int_{t_1\Omega}^{\infty} f(x)dx + H(1-B) + P(1-A) = 0$$

$$\Rightarrow (1+G)Ht_1\int_0^{t_1\Omega} f(x)dx - (1+G)(U+Dt)t_1\left[\int_0^{\infty} f(x)dx - \int_0^{t_1\pi} f(x)dx\right] + H(1-B) + P(1-A) = 0$$

as $\int_0^{\infty} f(x)dx = 1 \ and \ \int_0^{\infty} xf(x)dx = \mu$

$$\Rightarrow (1+G)Ht_1\int_0^{t_1\Omega} f(x)dx - (1+G)(U+Dt)t_1\left[1 - \int_0^{t_1\Omega} f(x)dx\right] + H(1-B) + P(1-A) = 0$$

$$\Rightarrow [(1+G)Ht_1 + (1+G)(U+Dt)t_1]\int_0^{t_1\Omega} f(x)dx - (1+G)(U + Dt)t_1 + +H(1-B) + P(1-A) = 0$$

$$\Rightarrow (1+G)t_1(H+U+Dt)\int_0^{t_1\Omega} f(x)dx = (1+G)(U+Dt)t_1 - H(1-B) - P(1-A)$$

$$\Rightarrow \int_0^{t_1\Omega} f(x)dx = \frac{(1+G)(U+Dt)t_1 - H(1-B) - P(1-A)}{(1+G)t_1(H+U+Dt)}$$

$$\Rightarrow \int_0^{t_1\Omega} f(x)dx = F(t_1\Omega^*) = \frac{U + Dt}{(H + U + Dt)}$$
$$- \frac{h(1 - B) + p(1 - A)}{(1 + G)t_1(H + U + Dt)}$$
$$\Rightarrow t_1\Omega^* = F^{-1}\left[\frac{u + dt}{(h + u + dt)} - \frac{h(1 - B) + p(1 - A)}{(1 + G)t_1(h + u + dt)}\right]$$
$$\Omega^*$$
$$= \frac{1}{t_1} F^{-1}\left[\frac{U + Dt}{(H + U + Dt)}\right.$$
$$\left.- \frac{H(1 - B) + P(1 - A)}{(1 + G)t_1(H + U + Dt)}\right] \quad (3)$$

Appendix B

$$C(\Omega^*) = (1+G)H\int_0^{t_1\Omega^*}(t_1\Omega^* - x)f(x)dx + (1+G)(U + Dt)\int_{t_1\Omega^*}^{\infty}(x - t_1\Omega^*)f(x)dx + H(1-B)\Omega^* + p(1-A)\Omega^*$$

$$= (1+G)Ht_1\Omega^*\int_0^{t_1\Omega^*} f(x)dx - (1+G)H\int_0^{t_1\Omega^*} xf(x)dx + (1+G)(U+Dt)\int_{t_1\Omega^*}^{\infty} xf(x)dx - (1+G)(U+Dt)t_1\Omega^*\left[1 - \int_0^{t_1\Omega^*} f(x)dx\right] + H(1-B)\Omega^* + P(1-A)\Omega^*$$

$$= (1+G)t_1\Omega^*(H+U+Dt)\left[\frac{U+Dt}{(H+U+Dt)} - \frac{H(1-B)+P(1-A)}{(1+G)t_1(H+U+Dt)}\right] - (1+G)h\int_0^{t_1\Omega^*} xf(x)dx + (1+G)(U+Dt)\int_{t_1\Omega^*}^{\infty} xf(x)dx - (1+G)(U+Dt)t_1\Omega^* + H(1-B)\Omega^* + P(1-A)\Omega^*$$

$$= (1+G)(U+Dt)t_1\Omega^* - H(1-B)\Omega^* - P(1-A)\Omega^* - (1+G)H\int_0^{t_1\Omega^*} xf(x)dx + (1+G)(U+Dt)\int_{t_1\Omega^*}^{\infty} xf(x)dx - (1+G)(U+Dt)t_1\Omega^* + H(1-B)\Omega^* + P(1-A)\Omega^*$$

$$C(\Omega^*) = -(1+G)H\int_0^{t_1\Omega^*} xf(x)dx + (1+G)(U+Dt)\int_{t_1\Omega^*}^{\infty} xf(x)dx$$

$$= -(1+G)H\int_0^{t_1\Omega^*} xf(x)dx$$
$$+ (1+G)(U+Dt)\left[\int_0^{\infty} xf(x)dx - \int_0^{t_1\Omega^*} xf(x)dx\right]$$
$$= -(1+G)H\int_0^{t_1\Omega^*} xf(x)dx$$
$$+ (1+G)(U+Dt)\left[\mu - \int_0^{t_1\Omega^*} xf(x)dx\right]$$
$$C(\Omega^*)$$
$$= (1+G)\left[\mu(U+Dt) - (H+U\right.$$
$$\left. + Dt)\int_0^{t_1\Omega^*} xf(x)dx\right] \qquad (4)$$

Appendix C

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

$$\Rightarrow Ht_2\int_0^{t_2Q} f(x)dx - Ut_2\int_{t_2Q}^{\infty} f(x)dx - Dtt_2\int_{t_2Q}^{\infty} f(x)dx \;+T \quad = 0$$

$$\Rightarrow\; Ht_2\int_0^{t_2Q} f(x)dx - t_2(U+Dt)\int_{t_2Q}^{\infty} f(x)dx + M = 0$$

$$\Rightarrow\; Ht_2\int_0^{t_2Q} f(x)dx - t_2(U+Dt)\left[1-\int_0^{t_2Q} f(x)dx\right] + M = 0$$

$$\Rightarrow t_2(H+U+Dt)\int_0^{t_2Q} f(x)dx - t_2(U+Dt) + M = 0$$

$$\Rightarrow t_2(H+U+Dt)\int_0^{t_2Q} f(x)dx \;= t_2(U+Dt) \text{ - M}$$

$$\Rightarrow \int_0^{t_2Q} f(x)dx \;= \frac{t_2(U+Dt) \qquad M}{t_2(H+U+Dt)t_2(H+U+Dt)}$$

$$t_2\; Q_{BT}^{*} \;= F^{-1}\left[\frac{(U+Dt)}{(H+U+Dt)} - \frac{M}{t_2(H+U+Dt)}\right]$$

$$Q_{BT}^{*} = \frac{1}{t_2}F^{-1}\left[\frac{U+Dt}{(H+U+Dt)} - \frac{M}{t_2(H+U+Dt)}\right] \qquad (7)$$