Agri-food supply chain under labor constraints and blockchain technology

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Abstract. This paper examines the complexities of the agri-food supply chain (AFSC) and the potential benefits of integrating blockchain technology. The AFSC includes various activities from farming to consumer delivery, and recent developments have increased its logistical complexity and labor challenge. Focusing on the social aspect of supply chain sustainability, this paper proposes a mathematical model that integrates blockchain as a decentralized and adequate system to mitigate bad labor recruitment practices. By utilizing blockchain technology, stakeholders can validate and approve transactions, thereby ensuring fair labor practices and ethical operations throughout the supply chain. This paper sets the stage for a comprehensive study that integrates theoretical concepts with practical solutions to address pressing issues in the agri-food supply chain. The aim of the proposed approach is to maximize overall profit, minimize costs while having a good transparency on harmful labor practices.

Keywords: Forced labor · Agri-food· Supply chain · Small farmer · Blockchain technology

1 Introduction

An agri-food supply chain is made up of a series of activities in a "farm-to-fork" sequence, including farming, processing/production, testing, packaging, storage, transport, distribution and marketing [7]. Over the last ten years, the food chain has undergone major upheavals and its logistics organization has become increasingly complex [16]. Research into supply chain management and logistics has a long history, with numerous topics having been extensively studied, including transport, storage, and production challenges. However, contemporary logistics is influenced by several new factors that have significantly altered the landscape. Globalization and outsourcing have expanded the geographical reach and complexity of supply chains. In fact the term "supply chain" has gained widespread recognition mainly due to the globalization of manufacturing that began in the mid-1990s, especially with the expansion of manufacturing in China [18]. In the domain of agri-food supply chain (AFSCs), globalization combined with rapid demographic change and evolving regulatory and legislative interventions are driving growing demand for high-quality, value-added and customized agri-food products [16]. This context of globalization makes the supply chain an extended system that requires the synchronization of stakeholders, unlike the old models that focused on isolated actors [1]. Collectively, these factors have made today's supply chains highly interdependent and more complex with many actors and processes. In addition, changing consumer lifestyles, a liberal market economy and strict food safety regulations have introduced new requirements and higher quality standards [16, 5, 9]. Climate change presents further challenges, necessitating more resilient and adaptable supply chain strategies. Among third world countries, those in Africa are particularly threatened by the predicted effects of climate change because of their economic dependence on climate for agriculture according to [13]. Beyond these factors, modern slavery and forced labor have infiltrated the agri-food supply chain, as highlighted by researchers such as [17, 10, 2, 12, 6]. These studies reveal the disturbing prevalence of exploitative labor practices within the agriculture and its supply chain, underscoring the need for urgent and comprehensive measures to address these human rights violations. At the same time, non-governmental organizations such as [8] and [4] are sounding the alarm about the state of workers in Africa, with 3.8 million people living in such conditions. The continent remains the most vulnerable in terms of forced labor, with a 64% risk of forced labor [4]. The recruitment issue invites researchers and companies to look at the social side of corporations, as well as the conditions under which farm workers are recruited. All these factors together lead to the introduction of the concept of resilience and sustainability in the agricultural chain. Sustainability has three dimensions: economic, environmental and social. However, the social component received very little attention,

unlike the other two [19]. Economic sustainability focuses on maintaining profitable operations and efficient resource use, ensuring long-term financial viability. Environmental sustainability emphasizes minimizing ecological impacts, promoting practices that conserve natural resources, and reducing emissions and waste. The social dimension, which has been somewhat neglected, involves ensuring fair labor practices, safeguarding workers' rights, and enhancing the well-being of communities involved in the supply chain. Labour problems persist throughout the agri-food supply chain, with activities dominated by manual labour such as planting, harvesting, packaging, livestock management, etc. However optimisation of the logistics chain focuses typically on production, transport, etc., without explicitly taking into account the impact of labor, as [11] points out. To address these issues comprehensively, it is essential to integrate social sustainability into supply chain management practices. This includes enforcing labor standards, preventing exploitation, and promoting ethical sourcing. By leveraging technologies such as Blockchain for transparency and accountability, stakeholders can better monitor and enforce compliance with social and environmental standards. This holistic approach to sustainability not only improves the resilience of the supply chain but also ensures that it contributes positively to the broader goals of social justice.
The advent of new technologies has revolutionized logistics operations, offering innovative solutions but also adding layers of complexity. Blockchain technology, a distributed digital ledger system that ensures transparency, traceability, and security, shows promise for alleviating some global supply chain management issues [14]. Studies on the involvement of blockchain technology in agriculture have shown great interest in this field, particularly in terms of building trust between stakeholders and product traceability (see [3]), reducing transaction costs, facilitating decision-making increasing transparency (see [14]), and so on.
The work is organised as follows: in section 2, we develop the problem description and the mathematical model. In section 3 we propose small numerical example and analyse the result obtained from the model. Section 4 is reserved for managerial insights and the paper ends with conclusion in section 5, which includes prospects for extending the work.

2 Problem description and the mathematical model

We consider a network consisting of a set F representing the farmers, a set R for recruiters and set B for product buyers. We assume to study the supply chain of a single product between farmers and buyers and the flow of recruitment between recruiters and farmers. Farmers cultivate abundant crops and meticulously oversee their growth, ensuring quality and monitoring progress. Subsequently, they supply these crops downstream. To meet his production at a period, each farmer has to recruit enough workers from recruiters.
Let's consider the tables Tab. 1 and Tab. 2 that contain the sets, the data and decision variables of the model:

Table 1: Sets used by the model.

Sets	**Index**	**Description**
$R = \{1, 2, \cdots, r\}$	l	Set of recruiters
$F = \{1, 2, \cdots, n\}$	i	Set of farmers
$B = \{1, 2, \cdots, m\}$	j	Set of buyers
$T = \{1, 2, \cdots, d\}$	t	Set of periods

Table 2: Data summary in AFCS using blockchain technology.

Variable	**Description**
$Y_{i,t}$	Goods production of farmer i during period t
$I_{i,t}$	Inventory of stock for farmer i at the end of period t
$\alpha_{i,t}$	Level of good practice of recruitment by farmer i at period t
$\Delta_{i,t}$	Amount of money that the farmer i invests in blockchain at period t
$L_{i,l,t}$	1 if farmer i can do external recruitment from recruiter l at period t, 0 else
$\Gamma_{i,l,t}$	External number of employees provided by recruiter l for farmer i at period t
$X_{i,j,t}$	Quantity of goods farmer i delivered to buyers j at period t
Data	**Description**
ρ	Sensitivity of buyers and recruiters to the traceability of the workers
$\delta_{j,t}$	Quantity of goods demand for buyers j at period t

$p_{j,t}$	Price proposed by buyer j for the targeted product at period t
$\gamma_{i,l,t}$	Operational salary of labor payed by farmer i from recruiter l
$\psi_{l,t}$	Available number of employees in farming tasks with the recruiter l at period t
$\sigma_{i,t}$	Number of workers required by farmer i to produce a unit of product at period t
Q_i	Capacity of production for farmer i
$\lambda_{i,t}$	unit cost of inventory management for farmer i at period t
$c_{i,j,t}$	Operational unit cost of transportation between i to intermediary j at period t
U	Amount of money that must pay a farmer every period for the social audit

We first describe a mathematical formulation for the problem of agri-food supply chain without blockchain as followed:

$$\left.\begin{aligned} \text{Max } Z \ &= \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\sum_{j=1}^{m}(p_{j,t}-c_{i,j,t})X_{i,j,t}) \\ &- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\sum_{l=1}^{r}\gamma_{i,l,t}\mathit{\Gamma}_{i,l,t} \\ &- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\lambda_{i,t}(Y_{i,t}+I_{i,t-1}) \\ &- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}U\cdot Y_{i,t} \end{aligned}\right\} \tag{1}$$

Subject to :

$$\sum_{i=1}^{n} X_{i,j,t} = \delta_{j,t} \quad \forall j \in C, \quad \forall t \in T \tag{2}$$

$$Y_{i,t} \leq Q_i - I_{i,t-1} \quad \forall i \in F, \quad \forall t \in T \tag{3}$$

$$\sum_{j=1}^{m} X_{i,j,t} \leq I_{i,t-1} + Y_{i,t} \quad \forall i \in F, \quad \forall t \in T \tag{4}$$

$$I_{i,t} = I_{i,t-1} + Y_{i,t} - \sum_{j=1}^{m} X_{i,j,t} \quad \forall i \in F, \quad \forall t \in T \tag{5}$$

$$\sum_{l=1}^{r} \mathit{\Gamma}_{i,l,t} \geq \sigma_{i,t} Y_{i,t} \quad \forall i \in F, \quad \forall t \in T \tag{6}$$

$$\sum_{i=1}^{n} \mathit{\Gamma}_{i,l,t} \leq \psi_{l,t} \quad \forall l \in R, \quad \forall t \in T \tag{7}$$

$$X_{i,j,t} \geq 0 \quad \forall i \in F, \quad \forall j \in C, \quad \forall t \in T \tag{8}$$

$$Y_{i,t} \geq 0 \quad \forall i \in F, \quad \forall t \in T \tag{9}$$

$$I_{i,t} \geq 0 \quad \forall i \in F, \quad \forall t \in T \tag{10}$$

$$\mathit{\Gamma}_{i,l,t} \in \mathbb{N} \quad \forall i \in F, \quad \forall l \in R, \quad \forall t \in T \tag{11}$$

The objective function (1) includes farmers income $(p_{j,t} - c_{i,j,t})X_{i,j,t}$, the total cost of labor $\sum_{l=1}^{r} \gamma_{i,l,t} \cdot \mathit{\Gamma}_{i,l,t}$, the inventory cost $\lambda_{i,t}(Y_{i,t} + I_{i,t-1})$ and the cost of social audit $U \cdot Y_{i,t}$. We'll see in the following how audit costs can be reduced as best practices and transparency associated with $\alpha_{i,t}$ increase. Constraint (2) imply that each buyer is satisfied in each period. Constraint (3) states that a farmer cannot produce more that available space in his field and constraint (4) means that a farmer cannot deliver products more than available at period t. Constraint (5) represents the update of inventory level for each farmer. Depending on the quantity of production $Y_{i,t}$, each farmer can do external recruitment as shown in constraint (6) to meet his needs. Constraints (7) represents respectively the maximum available number of workers. Constraint (8) to (11) are non-negativity constraint for decision variables.

2.1 Blockchain-based supply chain model

In blockchain-based agri-food supply chain, three additional decision variables are added into the traditional SC design problem. The first variable $L_{i,l,t} \in \{0, 1\}$ represents the decision of farmer i to recruit workers from recruiter l at period t, this means that $L_{i,l,t} = 1$ if farmer i recruit worker from l at period t and 0 else. The second decision variable is $\alpha_{i,t} \in [0, 1]$ to represent the level of good practice between farmer i and recruiter l at period t. The third variable is the investment $\mathit{\Delta}_{i,t} \geq 0$, the amount of money that farmer invest each period to keep the transparency and the level of good practice high. Consider the stochastic model below, integrating blockchain into the agricultural supply chain:

$$
\left.
\begin{aligned}
\text{Max } Z \quad =& \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\sum_{j=1}^{m}(p_{j,t}-c_{i,j,t})X_{i,j,t}) \\
&- \textstyle\sum_{t=1}^{d}\sum_{j=1}^{m}\sum_{l=1}^{r}\gamma_{i,l,t}(1+\alpha_{i,t})\mathit{\Gamma}_{i,l,t} \\
&- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\lambda_{i,t}(Y_{i,t}+I_{i,t-1}) \\
&- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}U(1-\alpha_{i,t})Y_{i,t} \\
&- \textstyle\sum_{t=1}^{d}\sum_{i=1}^{n}\mathit{\Delta}_{i,t})
\end{aligned}
\right\} \tag{12}
$$

Subject to :

(3) − (2) − (4) − (5) − (6) − (7)

$$Y_{i,t} \leq (1+\alpha_{i,t})Q_i - I_{i,t-1} \quad \forall i \in F, \quad \forall t \in T \tag{13}$$
$$\mathit{\Gamma}_{i,l,t} \leq \psi_l \cdot L_{i,l,t} \quad \forall i \in F, \quad \forall l \in R, \quad \forall t \in T \tag{14}$$
$$L_{i,l,t} \leq \frac{\alpha_{i,t}}{\pi_t} \quad \forall i \in F, \quad \forall l \in R, \quad \forall t \in T \tag{15}$$
$$\alpha_{i,t} = \rho\mathit{\Delta}_{i,t} + \alpha_{i,t-1} \quad \forall i \in F, \quad \forall t \in T \tag{16}$$
$$X_{i,j,t} \geq 0 \quad \forall i \in F, \quad \forall j \in C, \quad \forall t \in T \tag{17}$$
$$Y_{i,t} \geq 0 \quad \forall i \in F, \quad \forall t \in T \tag{18}$$
$$I_{i,t} \geq 0 \quad \forall i \in F, \quad \forall t \in T \tag{19}$$
$$\mathit{\Delta}_{i,t} \geq 0 \quad \forall i \in F, \quad \forall t \in T \tag{20}$$
$$\alpha_{i,t} \in [0,1] \quad \forall i \in F, \quad \forall t \in T \tag{21}$$
$$\mathit{\Gamma}_{i,l,t} \in \mathbb{N} \quad \forall i \in F, \quad \forall l \in R, \quad \forall t \in T \tag{22}$$
$$L_{i,l,t} \in \{0,1\} \quad \forall i \in F, \quad l \in R, \quad \forall t \in T \tag{23}$$

In the objective function (12) the expression $(1+\alpha_{i,t})$ represents the increase in traceability and the level of good practices regarding working conditions in the farmer's activities compared to traditional SC. The quantity of products $X_{i,j,t}$ sold by a farmer i to a buyer j will depend on the level of good practice $\alpha_{i,t}$. The higher the $\alpha_{i,t}$ level, the more the farmer can increase his production capacity as shown in constraint (13). However a higher level of good recruitment processes implies a higher cost in the wages of external workers and need more investment until the level comes max ($\alpha_{i,t} = 1$).

Contrary to the traditional supply chain scenario, social auditing costs will decrease when the good practice level $\alpha_{i,t}$ is getting high and we go from $U \cdot Y_{i,t}$ in traditional SC to $U(1-\alpha_{i,t})Y_{i,t}$ in blockchain-based one.

In the constraint (15) the Boolean $L_{i,l,t}$ can be 1 if and only if $\alpha_{i,t} \geq \pi_t$. In other words, for a farmer i to be able to recruit external workers, he must have a level $\alpha_{i,t}$ that reaches at least the minimum approval rate π_t. The constraint (16) represents a condition of updating the approval rate $\alpha_{i,t}$ that depends on the investment $\mathit{\Delta}_{i,t}$ and the previous rate $\alpha_{i,t-1}$.

3 Numerical example

Let's consider an agricultural chain consisting of 4 farmers, 2 buyers and 3 external recruitment sources. These groups will have to carry out their activities over 12 periods. Considering the farmers as the epicenter of this chain, they have 4 scenarios with distinct probabilities on the possibilities of orders from the buyers. We illustrate this supply chain as the Figure 1 below :

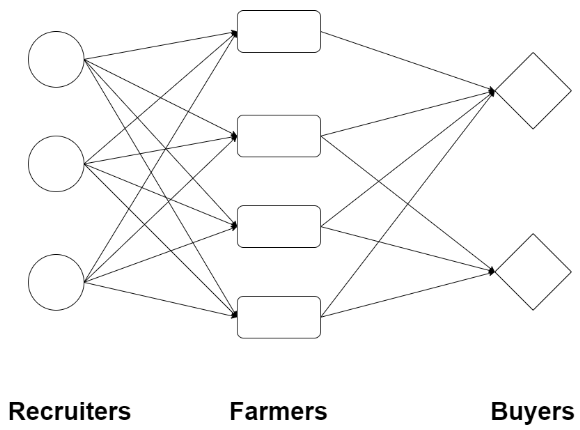

Fig. 1: Supply chain design problem

The sets are summarized in Tab. 3 below:

Table 3: Set of the Supply chain network.

Parameters	Values
Farmers	F1, F2, F3, F4
Recruiters	R1, R2, R3
buyers	B1, B2
Periods	12

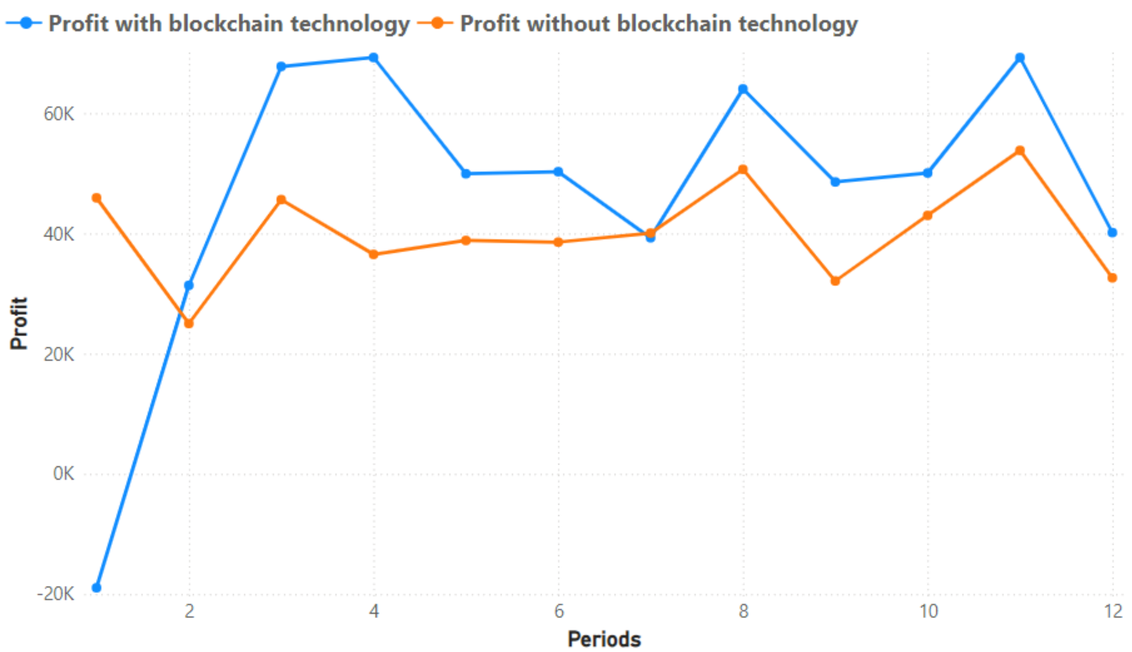

Fig. 2: Profit over periods with and without blockchain technology

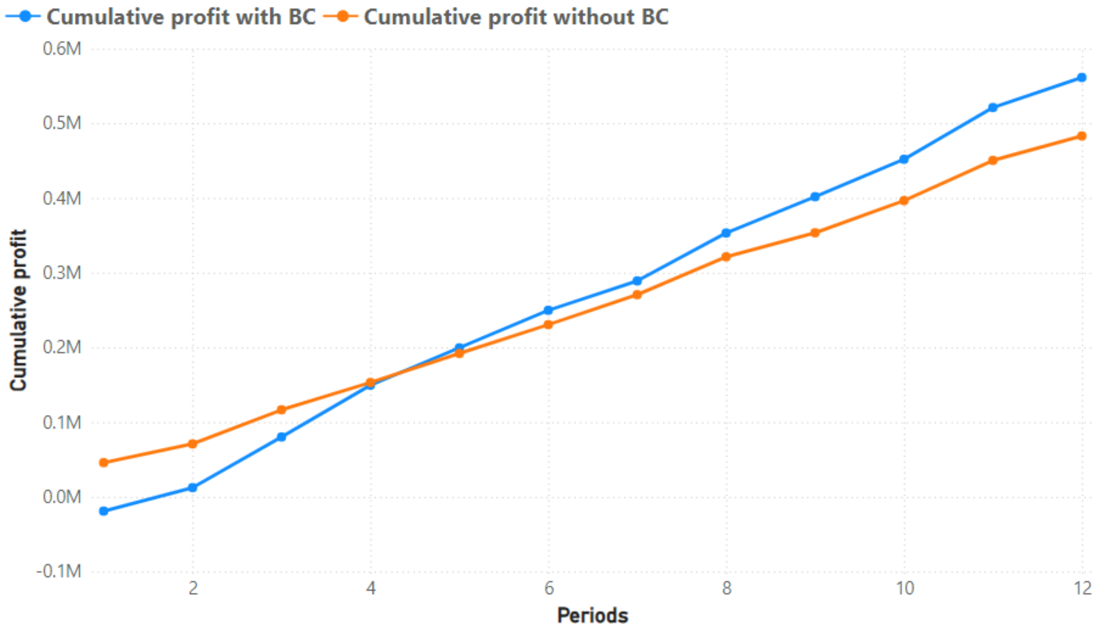

Fig. 3: Cumulative profit evolution

Figures 2 and 3 show the evolution of overall costs over the different periods. In the period $t = 0$, profit was negative due to the investment costs of the blockchain and expensive labor, as shown in figure 2. However, over time (from $t = 2$), we observe higher profits in the system using blockchain compared with the conventional chain.

Figure 3 confirms these results, with highly optimal profits over the long term and an ascending trend line. It shows the evolution of cumulative profits in the two systems, with profits in the blockchain-based system remaining low until a certain number of periods before overtaking those in the traditional system. At the same time, Figure 3 shows the crossover point between the two systems in our experiment. In other words, the number of periods that farmers would have to go through before starting to make a profit in this type of system, i.e. from the 4th period onwards.

4 Managerial insights

Based on our findings, our research offers valuable information to managers and stakeholders (farmers, recruiters, buyers...) in the agri-food supply chain, proposing concrete strategies to combat forced labour and improve supply chain sustainability.

Insight 1: Embracing technology for transparency
The adoption of Blockchain technology presents an opportunity for managers to enhance transparency and accountability throughout the supply chain. By leveraging Blockchain-enabled traceability, managers can track the movement of goods and labor inputs, thereby identifying potential areas of risk and ensuring ethical labor practices. Investing in digital infrastructure and training initiatives can facilitate the integration of Blockchain solutions into existing supply chain operations [15, 14].

Insight 2: Initial investment and long-term cost benefits
The integration of blockchain technology into the agri-food supply chain entails a substantial initial investment, particularly for ensuring compliance with ethical practices among farmers and stakeholders before transactions can occur on the blockchain. As shown in Figures 2 and 3, initial costs are elevated due to these investments. However, this expenditure should be viewed as an investment in long-term cost savings. Over time, blockchain-based systems consistently reduce overall costs, unlike traditional systems where costs remain high.

5 Conclusion

This paper underscores the increasing complexity and interdependence of modern agri-food supply chains, driven by globalization, demographic shifts, and regulatory changes. Our research highlights the critical need for integrating social sustainability into supply chain management, particularly by addressing labor exploitation and ensuring ethical practices. According to numerical experience, the initial investment remains a great challenge, but reveals that blockchain can in the long term increase farmers' profits while limiting illegal practices. Our findings suggest that while initial investments in blockchain and ethical compliance are substantial, they result in significant long-term cost savings and improved profitability. By prioritizing ethical sourcing and leveraging technological innovations, stakeholders can achieve a sustainable balance between economic viability, environmental stewardship, and social responsibility, ultimately contributing to a fairer and more efficient agri-food supply chain. The adoption of blockchain technology emerges as a pivotal solution, enhancing transparency, traceability, and accountability, thus fostering a more resilient and equitable supply chain. For future research, this problem could be expanded into a multi-objective framework to highlight the risks associated with illegal or forced labor. By employing Pareto optimum analysis, we can simulate the risk levels of these issues and compare the profits generated in the two agricultural supply chain systems.

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