Towards Blockchain-enabled Circular Closed-Loop Supply Chain and Impact of Consumers' Distrust in Price, Product Greenness Sensitivity and Carbon Tax and Subsidy

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Abstract: With the increasing emphasis on environmental sustainability, both governments and consumers are more concerned than ever about the greenness of products. In this complex landscape, Supply Chains (SCs) face challenges in building trust and avoiding greenwashing accusations. Blockchain technology offers a promising solution by ensuring transparency and circularity within SCs, particularly in identifying customers for product recycling. This study pioneers the exploration of consumers' distrust in pricing and product greenness, alongside the impact of carbon policies (taxes and subsidies) within a closed-loop supply chain (CLSC). Using classical Stackelberg game theory, we develop two models that identify equilibrium decisions for SC members, focusing on pricing, green production investment, circularity, and blockchain adoption. Additionally, we propose an evolutionary game theory model to find the optimal government policies and identify the long-term behaviour of the CLSC and government in two heterogeneous populations. Our findings reveal that if the retailer's share of blockchain costs falls below a certain threshold, blockchain adoption becomes less profitable than exclusive investment in green production. A higher (lower) subsidy rate benefits (harms) the retailer but disadvantages (benefits) the collector. Blockchain adoption is generally more profitable for manufacturers and retailers, though less so for collectors, and it also drives greater investment in green production. While subsidies encourage blockchain adoption, they are not a sustainable long-term strategy for governments. Ultimately, the evolutionarily stable strategy for SCs involves a balanced investment in both green production and blockchain or green production alone, depending on market characteristics and cost-sharing structures.

Keywords: Game theory; Blockchain technology; Circular supply chain; Evolutionary stable strategy; Data transparency technology.

1. Introduction

Organisations strive to support changes in consumer preferences and enhance consumer awareness about the durability and reparability of products encouraging consumers to make environmentally friendly choices when purchasing products (European Commission 2022b). Consumers not only value affordability but are also concerned about the environmental impact of production process. Governments, likewise, aim to measure and verify products' environmental footprint to ensure the legitimacy of sustainability claims (European Commission 2022a). In response, many companies opt for producing environmentally sustainable products. However, consumers often struggle to differentiate between green and regular products, and governments face persistent challenges related to "greenwashing" (i.e. false impressions/information given by companies rather than minimising their environmental impact). Blockchain adoption can address this problem by enhancing transparency in production process and managing inventory levels more effectively. The significance of supply chain (SC) transparency become evident in 2015 with the multi-state of Shiga toxin-producing Escherichia coli O26 infections linked to Chipotle Mexican Grill restaurants in the USA. This incident led to a substantial decrease in Chipolte's stock prices, primarily attributed by practitioners to the lack of transparency and inadequate monitoring of multiple suppliers (Cdc.gov, 2016). To mitigate the issue, solutions like the IBM Food Trust, a blockchain-based platform, emerged (IBM.com, 2020). The platform facilitated the tracking of food product movement and source identification. Similar successful blockchain adoption is seen in Walmart's food SC (Tech.walmart.com, 2021). Further, greenwashing cases, such as H&M's misleading "Conscious Collection" campaign (Guardian, 2022b), as well as false environmental claims by Coca-Cola and Unilever regarding sustainable packaging, highlight the ongoing need for transparency (Guardian, 2022a). Under these circumstances, blockchain technology emerges as a potential solution to verify the legitimacy of the sustainability clams, underlining its vital role in enhancing transparency and reliability in SCs.

In SCs, blockchain technology enables traceability of the processes, privacy, information about the sources and production processes, energy consumed, and end-of-life (EoL) of the products, and data security (Biswas *et al*., 2022; Choi, 2019; Saberi *et al*., 2019). Although, Governments must remain vigilant about the potential security and privacy risks associated with blockchain technology and work on regulations and standards to mitigate these risks, the technology's potential to combat greenwashing by offering full visibility into the manufacturing and product lifecycle is undeniable (Saberi *et al*., 2019). Blockchain can also support the circular economy (CE) process (Kouhizadeh, Zhu and Sarkis, 2020), which can be a motivation for government to support blockchain adoption by providing subsidies or tax exemptions. From the perspective of manufacturers and retailers, blockchain offers advantages beyond transparency and trust. It aids compliance with sustainability and carbon footprint reporting requirements, thereby reducing compliance risks. By automating and streamlining the tracking of carbon footprints, blockchain enhances operational efficiency and reduces costs associated with manual tracking and verification. Additionally, it enhances marketability by verifying carbon footprints, which allows companies to stand out for their sustainability effort. Finally, blockchain brings benefits such as payment facilitation, smart contracts and improved salvageability for retailers (Cao *et al*. 2025; Zhang *et al*. 2024).

For third-party collection companies, blockchain boosts both operational efficiency and compliance with environmental standards. By securely tracking product movement, blockchain can streamline EoL collection and recycling efforts, allowing collection companies to retrieve products with minimal effort. Furthermore, blockchain's transparent and verifiable records enable collectors to meet sustainability requirements more easily reducing penalties for non-compliance and enhancing their reputation. In the earlier versions of blockchain, energy consumption and environmental damage were the main issues (Biswas *et al*., 2022). However, modern blockchain technologies, like Ethereum, finalise transactions with minimum energy usage (Sedlmeir *et al*., 2020). Many SCs use blockchain, for example, the TradeLens industry platform uses blockchain technology and helps global SCs (Forbes, 2018).

Although blockchain provides many benefits to SC members and customers, its adoption involves costs that may incur losses in the short term (Kouhizadeh *et al*., 2020). The government's proactive role can incentivize SCs to adopt blockchain technology. Studies highlight tax policies to encourage SCs to invest in green production (Chen and Hu, 2018; Li, Jiao and Tang, 2019). Other studies consider government subsidies for blockchain adoption (Xu and Duan, 2022). To the best of our knowledge, no study considers these aspects together. The integration of blockchain technology into Closed-Loop Supply Chains (CLSC) represents a significant step towards enhancing transparency and sustainability. Notable examples include the partnership between IBM and Veridium Labs, where blockchain is employed to track carbon credits and facilitate carbon emission offsetting through reforestation and conservation projects. IBM's blockchain platform ensures transparency and authenticity verification of carbon credits, effectively curbing double-counting (Hankin 2018). Likewise, Provenance supports Belu Water's lifecycle tracking of plastic bottle, from production to recycling, by recording data at every stage on a blockchain ledger. The data related to production, distribution, collection and recycling of the plastic bottles is recorded on the blockchain ledger (Murray 2022). Moreover, blockchain can revolutionize partnerships, for example, between HP Inc. and Clover Imaging Group (CIG), where HP Inc. produce printers and printer cartridges as a manufacturer and CIG, as collector and remanufacturer, collect empty printer cartridges and remanufacture them for resale. However, challenges remain, including the high implementation cost, particularly for small and medium-sized enterprises, and the need for standardised platforms and collaboration among SC stakeholders. Understanding these factors can help SC managers strike a balance between consumer needs, environmental concerns, and their business objectives, while policymakers can create incentives and policies to encourage blockchain adoption in CLSCs, fostering sustainable development. Thus, in this study, we posit the following research questions in a CLSC considering consumer preferences and distrust:

(i). Does the adoption of blockchain lead to more investment in green production?
(ii). What is the best government policy to promote blockchain, e.g. tax, tax and subsidy together, or neither of them?
(iii). What are the equilibrium decisions concerning blockchain in competitive heterogeneous populations?
(iv). What is the optimal share of blockchain implementation cost for the closed-loop supply chain members?

The present study is interdisciplinary of two streams of literature, CLSC management, and blockchain/data transparency technology. We explore the strategies for motivating SCs in environmental-friendly production investment while considering the government's opinions. We present a CLSC model considering consumer preferences, distrust and CE goals. We propose a classical game theory model and obtain equilibrium prices and strategies for each CLSC participant with and without blockchain technology. We set forth an evolutionary game theory (EGT)-based model, obtain stable decisions for the SC participants and examine the long-term behaviour of SC and government in two heterogeneous populations.

We organise the paper as follows. Section 2 reviews the related literature and identifies the research gaps and key contributions. Section 3 explores two game theory models, notations, case settings and equilibrium results. In section 4, we present different numerical simulations and analyse the decisions and profit sensitivity to different parameters. We set forth a novel EGT-based model in section 5 to simulate the behaviour of government and SC in two heterogeneous populations. Sections 6 and 7 present managerial insights, conclusions and the future scope of research, respectively.

2. Literature Review

2.1. Blockchain in SC

Blockchain technology has led to a revolution in a variety of areas and industries, from electric cash systems to insurance and food (Kar and Navin, 2021). Some review articles investigated blockchain's opportunities and barriers to SCs (Queiroz et al., 2020; Zhu et al., 2022). A study on blockchain adoption in SC (Saberi et al. 2019) investigated the relationship between blockchain-led SC and sustainability. The study discussed the potential benefit of blockchain adoption and its barriers. Naoum-Sawaya et al. (2023) reported blockchain's utilisation within the drug industry to combat counterfeit products – a topic closely related to the transparency and reliability concerns in SCs. Their study underscored the critical issue of counterfeit drugs that posed risks to consumers. With the integration of blockchain technology, manufacturers now have a powerful tool to not only ensure product quality but also to prevent the distribution of deceptive counterfeit drugs, potentially reshaping the industry's approach to product differentiation. This highlights the broader impact of blockchain in enhancing consumer safety and trust across various SCs, including pharmaceuticals. Other studies compared blockchain and traditional online platforms. (De Giovanni 2020) reported that the use of blockchain diminished SC's risks and transaction costs and improved security and transparency. The article reported that the use of blockchain required coordination between all participants. Biswas et al. (2022) reported that in a global supply chain, a retailer and a manufacturer traded off between sustainability and traceability. The study proposed a single-period model assuming a monopoly market, which didn't match reality, and the study didn't consider collaboration while using blockchain. Choi (2019) studied the usage of blockchain in luxury SCs and investigated the benefits of blockchain-based platforms for diamond certification and authentication without considering the competition in the market. Liu, Tan and Zhao (2021) investigated the traceability capabilities of blockchain technology in vaccine SC and reported that blockchain improved social welfare, customer surplus and SC's whole profit. The study of Xu et al. (2023a) investigated the impact of a carbon cap-and-trade policy on a supply chain consisting of a manufacturer and an online platform. The study analysed the equilibrium production, pricing, and delivery decisions, as well as coordination between the firms under different scenarios. The results show that the cross-channel effect and blockchain technology have significant impacts on equilibrium decisions and coordination. The study reported that blockchain adoption can generate more profit for the manufacturer under certain conditions and can promote coordination between the manufacturer and the platform. Wu, Cheng, and Li (2024) examined the use of blockchain to address product sales in grey markets. They found that blockchain adoption can effectively deter grey market infiltration. This benefits high-end retailers, although it may disadvantage low-end retailers and manufacturers, depending on the associated implementation costs and penalty fees. Dong et al. (2024) extended blockchain applications by exploring its role in the commercial satellite industry, focusing on optimal launch and retail pricing strategies to improve launch success probabilities. To see whether blockchain adoption will change our understanding of SC strategies, Lu, Liao, and Chen (2024) investigated the impact of blockchain on dual channel SCs and e-tailers. Fang et al. (2024) revisited a classic question in the field of supply chain management and pricing incorporating the role of blockchain. In both wholesale and agency pricing models, the key issue is determining which supply chain member should bear the cost of blockchain adoption. Pun, Swaminathan, and Chen (2025) were among the first to explore the role of blockchain in addressing counterfeiting within secondary markets. Their study examined whether manufacturers should adopt blockchain technology to enhance transparency and disclose product attributes as a means to curb deceptive practices in second hand transactions.

Other articles discussed the factors responsible to increase the probability of successful adoption of blockchain technology in SCs (e.g. Babich and Hilary, 2019; Hastig and Sodhi, 2020). Recently, Wang *et al*. (2023) focused on the influence of blockchain adoption on SC financing strategies and reported that blockchain was positively related to trade credit management. Likewise, Wu, Wang, and He (2025) discussed blockchain's impact on smart contracts and its application in direct financing offered by e-commerce platforms, in contrast to traditional bank credit financing. Babich and Hilary (2019) identified five key strengths and five disadvantages of blockchain adoption and reported three research themes in the operation research domain that blockchain adoption could affect. The majority of the studies ignored competition between SCs, cooperation between SC members and the role of government in forming SCs strategies.

2.2. Blockchain's effect on consumers' trust and preferences

The introduction of blockchain in SC improves consumers' trust and SC transparency, which attracts new customers (Wang et al., 2024). However, storing consumers' personal information in blockchains could lead to a privacy breach (Cai, Cao, and Shang 2025; Zhang et al., 2022). Biswas et al. (2022)

reported that using blockchain in SC could lead to an increase in price and trust among consumers, but this conclusion held only when customers distrust was not high. The study considered the impact of consumers' distrust on product quality, but not on the product price. Another study by Xu and Duan (2022) considered green product-sensitive consumers and the optimal situation for blockchain, contrary to Biswas et al.'s (2022) study where they considered the influence of blockchain adoption on consumers' sensitivity to the product price. Jiang and Liu (2022) reported blockchain adoption in an SC for low-carbon sensitive consumers. However, the study didn't consider government policies for investment in green production. The considered three distribution channels (i.e. traditional retailer, direct and third-party e-tailers). In a similar study, Niu et al. (2021) proposed a model for a global SC considering blockchain for product quality, where SC participants were located in different regions with different tax policies. Choi et al. (2020b) reported customised pricing strategies of a blockchain-enabled service platform considering consumers of three types of risk attitudes. Keskin, Li, and Song (2024) examined the impact of blockchain adoption in a retailer-supplier supply chain, focusing on blockchain's capacity for freshness transparency, retailer profitability, and waste reduction. They also developed a blockchain-based smart contract that facilitated a mutually beneficial position in the supply chain. Recent studies, such as Liao et al. (2025), examine client privacy issues and incorporate the extent of blockchain technology utilization as a variable.

Dong, Jiang, and Xu (2022) investigated the ramifications of implementing traceability technology within SCs and its impact on member incentives. To comprehensively explore these effects, they devised a three-tier model encompassing multiple upstream suppliers. They found that full traceability averted uncontaminated food wastage, ensuring direct revenue benefits across the SC. However, this transparency indicated that their immediate downstream buyers could strategically cut purchase prices, leaving supply chain tiers vulnerable to such reductions. Interestingly, Iyengar *et al*. (2022) reported that blockchain adoption within SCs and related industries could yield substantial social benefits by mitigating information asymmetry and enhancing consumer welfare. However, equilibrium adoption remained elusive due to the competitive dynamics of the manufacturing sector, preventing manufacturers from capitalising on consumer gains through pricing. Despite these challenges, this study underscores the blockchain's potential to enhance societal welfare and calls for further research to devise strategies for surmounting these hurdles. In an industry-focused article, Sun, Wang, and Zhuo (2024) analysed the impact of blockchain adoption in pharmaceutical firms in a competitive market, considering pricing decisions, drug traceability and customer awareness. In a recent research, Ma *et al.* (2025) considered the impact of blockchain adoption in the food industry where there was delay in quality perception. More insights on this topic can be found in related studies by Choi *et al*. (2020b), Fan *et al*. (2022) and Liu *et al*. (2023). To the best of our knowledge, no study considered the influence of adopting blockchain on consumers' distrust of product information and its impact on price sensitivity.

2.3. Circular economy

One of the objectives of the circular economy (CE) is to minimise material waste and maximise the lifespan of products, thereby simultaneously reaching economic developments and goals (Kouhizadeh *et al*. 2020). Geissdoerfer *et al*. (2017) reported the difference between the sustainability and CE concepts and their relationship. Mishra *et al*. (2022) explored different aspects of reverse logistics and CLSC to reach CE's goals. Their study also investigated the role of industry 4.0 and CE on circular SC and its influence on efficiency and competitiveness in SCs. Huang *et al*. (2022) proposed a framework for circular SC management by analysing some factors of blockchain implementation and using an AHP-DEMATEL method. Despite recent attention to CE, studies on the linkage between blockchain technology and its abilities in CE, which is the aim of this research, are limited. Some qualitative studies on this topic (e.g. De Giovanni 2022; Kouhizadeh *et al*., 2020) explored the opportunities and advantages of blockchain adoption on CE. In a recent study Lu *et al*. (2024) examined the choice between self-implementation and third-party blockchain solutions and analyzes how this decision influences the manufacturer's investment in green production. The study comprised a manufacturer, a retailer and a third-party platform providing blockchain services. Moreover, Xu *et al*. (2025) focused on the ability of blockchain to prevent greenwashing and examined the relationship between a platform and a manufacturer and then identified conditions under which the blockchain adoption was profitable. However, no quantitative study proposes a CLSC model considering blockchain and its influence on CE (see Table 1).

2.4. Carbon Policies

To control carbon emissions, the main tool of governments is carbon pricing. In practice, carbon pricing policies are carbon tax, carbon cap-and-trade and carbon offset (Malladi and Sowlati, 2020). Quantitative research in this domain usually uses game theory to model the relationship between the government and SC decision-makers (Zhou *et al*., 2019). Some articles (e.g. Chen and Hu, 2018; Li *et al*., 2019) used evolutionary game theory to study the impact of government policies on SC decisions. Limited literature is available that addresses the combination of carbon policies and blockchain technology (e.g. Choi and Luo, 2019; Xu and Duan, 2022). Choi and Luo (2019) suggested the use of blockchain to address data quality issues in the fashion industry for sustainable SC operations. The study considered government subsidies and three different taxes that SC participants in the fashion industry should pay. The study has some limitations. First, the SC model neither defined wholesale price nor retail decisions. Secondly, the fashion industry is one of the biggest waste producers (Forbes, 2018), and a collector plays an important role in an SC to reduce waste. However, the study did not consider a collector in the SC structure.

Table 1. Comparison between the closely related studies and our article

Articles	SC structure	Blockchain technology	CLSC	Carbon Policies (tax and subsidy)	EGT	Consumer price & greenness distrust	Product greenness
Biswas *et al*. (2022)	one U, one D	●	-	-	-	●	-
Zhang *et al*. (2022)	two R	●	-	-	-	●	-
Niu *et al*. (2021)	one M, one R, one E	●	-	Tax	-	●	-

Xu and Duan (2022)	one M, one R	●	-	Subsidy	-	●	●
Choi and Luo (2019)	one M, one R	●	-	Tax & subsidy	-	-	-
Jiang and Liu (2022)	one M, one R, one E	●	-	Tax	-	-	●
Fan *et al*. (2022)	one S, one M, one R	●	-	-	-	●	-
Choi *et al*. (2020a)	two RSP	●	-	-	-	●	-
Chen and Hu (2018)	one M, G	-	-	Tax & subsidy	-	-	●
Xu *et al*. (2023b)	one M, one O, one C	●	●	-	-	-	●
Xu *et al*. (2023a)	one M, one O	●	-	-	-	-	-
Awasthy, Haldar, and Ghosh (2025)	one S, one B	●	-	-	-	●	-
Liao et al. (2025)	one M, one R	●	-	-	-	●	●
Our article	**one M, one R, one C**	●	●	**Tax & subsidy**	●	●	●

Note: RSP = Rental service platforms; G = Government; C = Third party collector, O = online platform; S = Supplier; B = Buyer.

2.5. Research gaps and contributions

The review of the extant literature reveals that the blockchain technology can revolutionise traceability in SCs across various industries. Electronics SCs are usually complex, where unethical supplier practices and information management issues persist. Blockchain offers a promising solution (Rahman and Tehranipoor 2021). Similarly, in pharmaceutical SCs, blockchain adoption can combat challenges like counterfeiting, temperature variations in shipping, and the intricacies of global supply networks (Ghadge *et al*. 2022). However, despite its numerous advantages for end-to-end SC management, especially CLSCs, research in this field remains limited. We identify the following research gaps in the extant literature and contributions to the domain:

(i) limited research is available on blockchain technology and its influence on gaining customers' trust in the product information in a CLSC;

(ii) a study examining the impact of adopting blockchain on green production investment incentives is needed in a CLSC;

(iii) no study analysed the evolution of a population in a period while members of the population are not entirely rational, which is one of the requirements. Earlier studies (e.g. Table 1) did not use EGT to model SC decisions in a population of SCs;

(iv) literature does not consider the government as a player in the EGT and explore the best strategy from the government's perspective in a CLSC; and

(v) it is crucial to elucidate the SC members' share of the cost of implementation of blockchain in the CLSC.

Our study contributes to the literature in several ways. Our study focuses on blockchain technology and circular SC. Our study is the first study that considers the impact of consumers' distrust in price and product greenness sensitivity in a CLSC. We propose an EGT model in the CE domain and examine the best strategies for a CLSC. We consider the government as a player in the EGT and then explore the best strategies from the government's perspective in a CLSC.

3. Problem Definition and Classical Game Theory Model

We model a CLSC comprising one manufacturer (M), one retailer (R) and one collector (C). A similar SC structure is available in the case of a lead-acid battery in Johari and Hosseini-Motlagh (2019), where a M sells products to a R and buys used products from a C, a R sells products to an end-user, and a C approaches consumers to collect the used batteries. Another similar network could be the smartphone SC reported by Li *et al*. (2021). In this SC, the manufacturers (e.g. Samsung) sell their phones to retailers (e.g. Amazon), and collectors (e.g. Vodafone) collect old phones from the consumers who trade in. However, the collection process of the used product is complex. Blockchain can make the process easier. An illustration of the process is the CircularTree (Supplychainmovement.com, 2021) initiative that uses blockchain to establish circular logistics networks for collecting and recycling products at the end of their life. The process tracks the return of products to recycling centres, verifies their condition, and triggers payments or incentives. Our study investigates whether the CLSC members should like to use blockchain.

We devise a manufacturer-leader Stackelberg game, where R and C are the followers. Figure 1 illustrates the sequence of decision-making in the game, where SC members must first agree on the adoption of blockchain (either Model N or Model B). After that, in the first stage, M sets transfer price, wholesale price and investment in green production, while considering Cs' and Rs' reactions. Next, R optimises the retail price based on the wholesale price and C optimises its profit function by determining the equilibrium collection investment based on M's defined transfer price. The sequence of the CLSC solution is opposite to the sequence of the game, which is quite common in the literature (e.g. Johari and Hosseini-Motlagh, 2019).

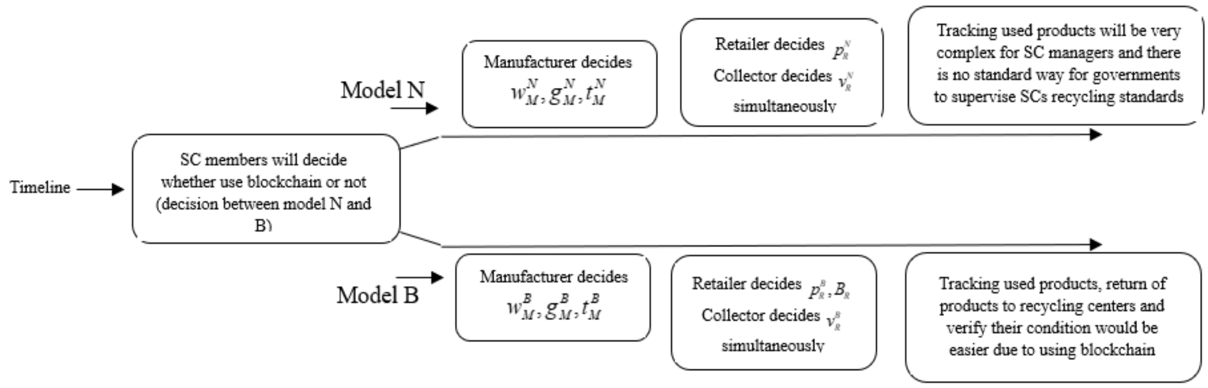

Figure 1. Sequence of decision-making

Our primary focus is to investigate the influence of blockchain technology adoption in an SC and examine whether the adoption would lead to more investment in product collection and green production. Thus, we propose two models: Model N, where blockchain is not used, and Model B, where CLSC participants adopt blockchain. Use of blockchain will guarantee the circularity of the CLSC by meticulously recording, tracking recycled materials, establishing a transparent and accountable system that guarantees their reuse in products aligned with rigorous sustainability standards and assures consumers that products marketed as recycled materials are genuine. We explore the case settings along with notations (Table 2). In section 5, we will elucidate the development of our EGT model and explore the long-term stable decisions of the SC members in response to government policies.

Table 2. Notations

Notation	Description
Indices	
$i \in \{N, B\}$	Index for SC model without blockchain and with blockchain
$j \in \{M, R, C\}$	Index for Manufacturer, retailer, and Collector
Model Parameters	
α	The market base of the product
β	Price sensitivity of product's demand
γ	Greenness sensitivity of product's demand
λ	Customers distrust to the greenness of products
c_0	Manufacturing cost of one unit product
Δ	The amount of saving by re-manufacturing one unit product instead of manufacturing
c_g	The cost coefficient of green production
c_v	The effect of blockchain adoption on the exchanging coefficient between the collection effort and the investment
k	Exchanging the coefficient between the collection effort and the amount of investment
τ	The tax rate for unit wholesale price
s	Subsidy rate for green production cost
ξ_j	Share of j in the amount of investment in blockchain technology, $\sum_j \xi_j = 1$
H_1, H_2	Environmental value gained by government when the SC members invest on green production (H_1) or on both green production and blockchain adoption (H_2)
I_C^i	Collector's investment in collection programs in model i, where $i \in \{N, B\}$
Decision variables	
p_R^i	Retail price of a unit product in the model i, where $i \in \{N, B\}$
B_R	The amount of investment on blockchain technology
g_M^i	The amount of investment in green production in the model i, where $i \in \{N, B\}$
w_M^i	The wholesale price of a unit product in the model i, where $i \in \{N, B\}$
t_M^i	The re-manufacturer's payment (transfer price) to collector for the used product in the model i, where $i \in \{N, B\}$
v_C^i	The collection rate of used products in the model i, where $i \in \{N, B\}$
Results	
D^i	Demand function in model i, where $i \in \{N, B\}$,
Π_j^i	Profit function of j in model i, where $i \in \{N, B\}$
$\Delta\Pi_j$	The profit of j in model B mines its profit in model N ($\Delta\Pi_j = \Delta\Pi_j^B - \Delta\Pi_j^N$), where $j \in \{M, R, C\}$
Π_j^{i*}	The equilibrium profit of j in model i, according to equilibrium decision variables, where $j \in \{M, R, C\}$ and $i \in \{N, B\}$

Assumption 1. We assume that consumers are sensitive to the environmental sustainability of products, which is influenced by the level of investment in green production. Consequently, we model the demand functions as linear functions that decrease with the selling price and increase with the investment in green production. This assumption is common in the literature (e.g. Huang and Swaminathan, 2009; Yue and Liu, 2006), which depends on the product's retail price (p_R^i) and its greenness (g_M^i). In model N, product information affects some consumers' trust ($\lambda \in [0,1)$) in the greenness of the products (which affects consumers' willingness to pay). In model B, due to the adoption of blockchain, consumers completely trust available information (which means $\lambda = 0$), and the amount of investment on green production and blockchain increases demand. The demand function model N and model B are as follows, respectively (computations are provided in Appendix A):

$$D^N = \alpha - \frac{\beta}{1-\lambda} p_R^N + \gamma g_M^N (1 - \lambda) \quad (1)$$

$$D^B = \alpha - \beta p_R^B + \gamma(g_M^N + B_R) \tag{2}$$

Assumption 2. As a standard assumption in the literature (e.g. Johari and Hosseini-Motlagh, 2019), we assume that the collection rate depends on C's investment in collection programs, i.e. $v_C^i = \sqrt{\frac{I_C^i}{k}}$. Without losing generality, we assume that collection costs and blockchain adoption fixed costs are zero to reduce the functions' complexity.

To comprehensively examine the influence of blockchain technology on consumers' perceptions of products and compare the profit functions and decision-making processes of the SC members, we devise a model without blockchain and a model with blockchain. In the following sub-sections, we discuss the proposed models.

3.1. Model without blockchain (Model N)

In model N, the SC participants decide to work like a traditional SC, and they do not use blockchain technology. We consider government tax and subsidy policies in the model. The Government (G) takes τ per cent of M's revenue as a carbon emission tax. M, as a leader, decides on the wholesale price (w_M^i), the amount of investment in green production (g_M^i), and the transfer price (t_M^i), which is the amount of money that M pays to C for each collected product. Then R determines the retail price (p_R^i), and C determines the collection rate (v_C^i) of the products that the consumers use. The objective functions of M, R and C in this model are as follows:

$$\Pi_M^N(w_M^N, g_M^N, t_M^N | D^N) = (w_M^N(1-\tau) - c_0 + (\Delta - t_M^N)v_C^N)D^N - \frac{1}{2}c_g(g_M^N)^2 \tag{3}$$

$$\Pi_R^N(p_R^N | D^N, w_M^N, g_M^N, t_M^N) = (p_R^N - w_M^N)D^N \tag{4}$$

$$\Pi_C^N(v_C^N | D^N, w_M^N, g_M^N, t_M^N) = t_M^N D^N v_C^N - I_C^N = t_M^N D^N v_C^N - k(v_C^N)^2 \tag{5}$$

In the above functions c_0, Δ, k and c_g are a new product's production cost, the amount of cost saving due to re-manufacturing, investment and collection effort exchange coefficient, and the greenness cost coefficient, respectively. The model is subjected to the following situations: $0 \le v_C^N \le 1, g_M^N \ge 0, p_R^N > w_M^N > 0, w_M^N(1-\tau) > c_0 > 0, \Delta > t_M^N > 0, 0 < s < 1, 0 < \tau < 1$.

Lemma 1. The equilibrium decisions and profits without blockchain adoption are as follows:

$$w_M^{N*} = -\frac{4\left(\left(A_3 + 3\left(c_0\gamma^2 - \frac{2c_g\alpha}{3}\right)(\tau-1)\lambda - c_0\gamma^2(\tau-1) + 2c_g(\alpha\tau - \beta c_0 - \alpha)\right)k + \frac{\Delta^2\alpha\beta c_g}{4}\right)(\lambda-1)}{4A_1 + \Delta^2\beta^2 c_g}$$

$$g_M^{N*} = \frac{4k(\tau-1)(\lambda-1)^2 A_2\gamma}{4A_1 + \Delta^2\beta^2 c_g}, \quad v_C^{N*} = -\frac{c_g\beta\Delta A_2}{4A_1 + \Delta^2\beta^2 c_g}, \quad p_R^{N*} = -\frac{4\left(\left(A_3 + 3\left(c_0\gamma^2 - c_g\alpha\right)(\tau-1)\lambda - c_0\gamma^2(\tau-1) + 3c_g\left(\alpha\tau - \frac{1}{3}\beta c_0 - \alpha\right)\right)k + \frac{\Delta^2\alpha\beta c_g}{4}\right)(\lambda-1)}{4A_1 + \Delta^2\beta^2 c_g}$$

$$\Pi_M^{N*} = -\frac{2kc_g{A_2}^2}{4A_1 + \Delta^2\beta^2 c_g}, \quad \Pi_R^{N*} = -\frac{(-1+\lambda)\beta k^2{c_g}^2{A_2}^2}{\left(A_1 + \frac{\Delta^2\beta^2 c_g}{4}\right)^2}, \quad \Pi_C^{N*} = \frac{\beta^2 k{c_g}^2{A_2}^2\Delta^2}{16\left(A_1 + \frac{\Delta^2\beta^2 c_g}{4}\right)^2}$$

where A_1, A_2, A_3 are defined in Appendix B and the proof of this proposition is given in Appendix B.

Proposition 1. Without blockchain adoption, the equilibrium for wholesale price, retail price, investment in green production, and used-product collection rate all increase with higher manufacturing cost. Conversely, these variables decrease with an expanding market base. Moreover, transfer price only increases with saving by re-manufacturing.

Insights from Lemma 1 and Proposition 1 reveal several key relationships. The transfer price is unique among decision variables for M in that it is increasing with cost saving by re-manufacturing. This highlights the value of focusing on improved re-manufacturing processes to drive cost savings thereby supporting circular economy goals. The relationship between green production investment, manufacturing costs and market share introduces a trade-off. While investing in green production can enhance a firm's environmental sustainability, it may also increase manufacturing costs, influencing market competitiveness. This calls for strategic decision-making that balances sustainability goals while maintaining market competitiveness as exemplified by companies like Siemens Gamesa, whose investments in green production for wind turbines involve higher manufacturing costs but appeal to environmentally conscious consumers.

The positive association between the re-manufacturer's payment (t_M^N) and the savings from re-manufacturing (Δ) emphasises the economic viability of re-manufacturing processes. As the savings increase, so does the re-manufacturer's willingness to compensate collectors for used products. This encourages a circular economy, where products are recycled and re-manufactured, contributing to sustainability goals. As an example, Apple, through its re-manufacturing programme, engages in the extraction of valuable components, including screens, processors, and batteries, from used iPhones. The continual advancements in re-manufacturing processes, characterised by technological innovation, result in augmented cost savings. Consequently, companies like apple should demonstrate an increasing willingness to remunerate collectors for the return of used devices. Moreover, the findings of this proposition underscore the importance of government intervention in preventing market dominance by major corporations. Excessive control by large companies can reduce investments in eco-friendly production and drive up product prices, underscoring the need for strategic regulations that support both sustainability and market balance.

Proposition 2. Without blockchain adoption, there exists a threshold on market base (α_0), above which the order of equilibrium profits among SC members changes. This threshold increases with sensitivity to price, manufacturing cost, tax rate and customers' distrust.

$$\begin{cases} \Pi_R^{N*} \geq \Pi_M^{N*} \geq \Pi_C^{N*} & if \quad \alpha \geq \alpha_0 \\ \Pi_R^{N*} < \Pi_M^{N*} < \Pi_C^{N*} & if \quad \alpha < \alpha_0 \end{cases}, \text{ where } \alpha_0 = \frac{\beta c_0}{\lambda(\tau-1)-\tau+1}.$$

The proof of the proposition is given in Appendix C.

Proposition 2 highlights that comparing the profits of the SC members, in a larger market, R will gain the highest profit while C will gain the lowest profit, and vice versa in a smaller market. An increase in the parameters mentioned in Proposition 2 reduces the likelihood that R will maintain the highest profit in the SC. Realistic parameter values (which are mentioned in section 4) indicate that α_0 is a very low threshold for α, meaning that only when the market base is below a certain minimum C achieves the highest profit, which is uncommon.

3.2. Model with blockchain (Model B)

This model considers the same SC with blockchain adoption, aiming to satisfy the consumers and gain their complete trust. So, in this model, the demand function follows equation (2), as customers are sure that the greenness information is 100% accurate (Niu *et al*., 2021; Xu and Duan, 2022). Moreover, by using blockchain, G can easily monitor the carbon footprint of M's production (Kouhizadeh *et al*., 2020) and offer subsidy (S) based on M's greenness contribution. In addition, blockchain technology reduces collection program costs, by providing direct access to ownership information, making it easier to retrieve used products.

Assumption 3. We assume that R determines the amount of investment on the blockchain (B), which is common in the literature (Biswas *et al*., 2022) and its cost can potentially split between the SC members as M and C also benefit from blockchain implementation. A more significant investment (B) indicates R's preference for a more extensive blockchain that enables better SC tracking from the point of origin of the goods to the end user. We do not consider any additional operational cost for using blockchain or its environmental damage since, according to Sedlmeir *et al*. (2020), modern blockchain technology's energy consumption costs are reduced.

Assumption 4. In the literature (Fan *et al*. 2022; Zhong *et al*. 2023), usually costs are considered as two types, viz. linear and nonlinear. Generally, in some cases, it may be logical to assume a linear cost function for blockchain adoption, where the cost increases proportionally with the level of adoption. This could be applicable if the cost of adopting blockchain technology is directly related to the number of transactions or data points processed (like Biswas *et al*., 2022). On the other hand, if there are fixed costs associated with adopting blockchain technology (such as implementation and training costs) or if there are economies of scale involved (where the cost per unit decreases as the level of adoption increases), then it may be more appropriate to model the adoption cost as nonlinear (like Fan *et al*., 2022). In this model, R incurs nonlinear blockchain adoption costs, which reflects potential fixed costs such as software licensing fees or customization expenses as well as economies of scale impact. In contrast, M and C face linear costs, where expenses increase proportionally with the level of block chain adoption. By considering the above assumptions, we devise the following objective functions for the SC participants in model B:

$$\Pi_M^B(w_M^B, g_M^B, t_M^B|D^B) = (w_M^B(1-\tau) - c_0 + (\Delta - t_M^B)v_C^B)D^B - \frac{1}{2}c_g(g_M^B)^2(1-s) - \xi_M B_R \quad (6)$$

$$\Pi_R^B(p_R^B, B_R|D^B, w_M^B, g_M^B, t_M^B) = (p_R^B - w_M^B)D^B - \frac{\xi_R(B_R)^2}{2} \quad (7)$$

$$\Pi_C^B(v_C^B|D^B, w_M^B, g_M^B, t_M^B) = t_M^B D^B v_C^B - \frac{k}{c_v}(v_C^N)^2 - \xi_C B_R \quad (8)$$

In the above functions ξ_R, ξ_M, and ξ_C are respectively R's, M's and C's share of the cost of using blockchain technology, where $\xi_R + \xi_M + \xi_C = 1$, and c_v represents the effect of blockchain adoption on the reciprocal relationship between investment and collection effort. Model B is subjected to $0 \le v_C^B \le 1, g_M^B \ge 0, g_M^B, B_R > 0, p_R^B > w_M^B > 0, w_M^B(1-\tau) > c_0 > 0, \Delta > t_M^B > 0, c_v \ge 1, 0 < s < 1, 0 < \tau < 1$.

Lemma 2. The equilibrium decisions and profits with blockchain are as follows:

$$w_M^{B*} = \frac{\left(\begin{pmatrix} -4\beta\left(2(-\beta c_0 + \alpha(-1+\tau))(-1+s)c_g + \gamma^2 c_0(-1+\tau)\right){\xi_R}^2 \\ -4\left(-\left((-\beta c_0 + \alpha(-1+\tau))\gamma + 2\beta\xi_M\right)(-1+s)c_g + \gamma^2\xi_M(-1+\tau)\right)\gamma\xi_R \\ -4\gamma^3\xi_M c_g(-1+s) \end{pmatrix} k - {\xi_R}^2\beta^2 c_g c_v \Delta^2\alpha(-1+s)\right)}{\left(4\left(A_4 - \frac{\xi_R\beta^2 c_g c_v \Delta^2(-1+s)}{4}\right)\beta\xi_R\right)}$$

$$g_M^{B*} = \frac{4k\big((\alpha\tau + \beta c_0 - \alpha)\xi_R + \gamma\xi_M\big)(-1+\tau)\gamma}{\left(4\left(-4\beta(-1+s)c_g + \gamma^2(-1+\tau)\right)(-1+\tau)k - \beta^2 c_g c_v \Delta^2(-1+s)\xi_R + 8k\gamma^2 c_g(-1+\tau)(-1+s)\right)}$$

$$p_R^{B*} = \frac{\left(\begin{pmatrix} -4\left(3(s-1)\left(-\frac{\beta c_0}{3} + \alpha(\tau-1)\right)c_g + \gamma^2 c_0(\tau-1)\right)\beta{\xi_R}^2 \\ -4\gamma\left(-\left((-\beta c_0 + \alpha(\tau-1))\gamma + \xi_M\beta\right)(s-1)c_g + \gamma^2\xi_M(\tau-1)\right)\xi_R - 4\gamma^3\xi_M c_g(s-1) \end{pmatrix} k - {\xi_R}^2\beta^2 c_g c_v \Delta^2\alpha(s-1)\right)}{\left(4\left(A_4 - \frac{\xi_R\beta^2 c_g c_v \Delta(s-1)}{4}\right)\right)}$$

$$t_M^{B*} = \frac{\Delta}{2}$$

$$B_R^* = -\frac{(s-1)\gamma k c_g A_6}{\left(\left(\left(-4\beta(s-1)c_g + \gamma^2(\tau-1)\right)(\tau-1)k - \frac{\beta^2 c_g c_v \Delta^2(s-1)}{4}\right)\xi_R + 2k\gamma^2 c_g(\tau-1)(s-1)\right)\xi_R}$$

$$v_C^{B*} = -\frac{(s-1)\Delta c_g\beta A_6 c_v}{\left(-16\beta(s-1)\left((\tau-1)k + \frac{\beta c_v\Delta^2}{16}\right)c_g + 4k\gamma^2(\tau-1)^2\right)\xi_R + 8k\gamma^2 c_g(\tau-1)(s-1)}$$

$$\Pi_M^{B*} = \frac{{A_6}^2 k c_g(s-1)}{2A_5\xi_R}, \qquad \Pi_R^{B*} = -\frac{{A_6}^2 k^2 {c_g}^2(s-1)^2(-2\beta\xi_R + \gamma^2)}{2A_5}, \qquad \Pi_C^{B*} = \frac{(A_8 + A_7)A_6 k c_g(s-1)}{{A_5}^2\xi_R}$$

where A_4, A_5, A_6, A_7, A_8 are defined in Appendix D and the proof of this proposition is available in Appendix D.

Proposition 3. With blockchain adoption, the equilibrium wholesale price (w_M^B), retail price (p_R^B), used-product collection rate (v_C^B) increase with manufacturing cost, market size, and investment in blockchain. On the other hand, investment in green production (g_M^B) increases with manufacturing cost and market size, while it decreases with investment in blockchain. Transfer price (t_M^B) only increases with saving by re-manufacturing.

Some insights from Lemma 2 and Proposition 3 are as follows. The implementation of blockchain technology does not alter the relationship between transfer price and market share. Furthermore, the customer trust gained through blockchain can offset any negative impact of price increases on market share. In addition, the green production investment (g_M^B) increases with investment in blockchain technology (ξ_M) meaning that as M invests more in blockchain, it seeks higher profits to justify the investment. Furthermore, as markets grow, the proclivity for investments in green production tends to diminish, often due to cost concerns or the need to meet rising demand. This aligns with the notion that, in rapidly expanding markets, immediate economic considerations might overshadow long-term sustainability efforts. To gain a comprehensive understanding, it is essential to undertake a thorough cost-benefit analysis of green production investments. It is acknowledged that in high-growth scenarios, the perceived costs associated with sustainability initiatives may be particularly conspicuous (Svenfelt *et al*., 2019). Yet, long-term advantages, such as enhanced brand reputation, regulatory compliance, and customer loyalty, should also be considered. Contrary to the previous model, it is challenging to rank profits definitively. Moreover, the transfer price for the used product is independent of blockchain adoption and only depends on Δ in both models.

Proposition 4. With blockchain adoption, the SC members' profits can be ranked as follows:

$$\begin{cases} \Pi_R^{B^*} \geq \Pi_M^{B^*} \geq \Pi_C^{B^*} \quad if \quad s \geq Max\{s_0, s_1, s_2\} \\ \Pi_R^{B^*} < \Pi_M^{B^*} < \Pi_C^{B^*} \quad if \quad s \geq Max\{s_0, s_1, s_2\} \\ specifically, \\ scenario\ (a): \Pi_R^{B^*} \geq \Pi_M^{B^*} \quad if \quad s \geq s_0 \quad ; and \quad \Pi_R^{B^*} < \Pi_M^{B^*} \quad if \quad s < s_0 \\ scenario\ (b): \Pi_R^{B^*} \geq \Pi_C^{B^*} \quad if \quad s \geq s_1 \quad ; and \quad \Pi_R^{B^*} < \Pi_C^{B^*} \quad if \quad s < s_1 \\ scenario\ (c): \Pi_M^{B^*} \geq \Pi_C^{B^*} \quad if \quad s \geq s_2 \quad ; and \quad \Pi_M^{B^*} < \Pi_C^{B^*} \quad if \quad s < s_2 \end{cases}$$

where $s_i, i \in \{1,2,3\}$ are defined in Appendix E.

The proof of this proposition is available in Appendix E.

Proposition 4 indicates that with a high subsidy rate for green production (s) (i.e. when subsidy rate exceeds a certain threshold), R achieves the highest profit, while C experiences the lowest profit among SC members. Conversely, a low subsidy rate reverses this ranking, placing C at the top and R at the bottom. Incontrast to model N the order of profit for the SC members in model B is not straightforward and it varies based of subsidy rate. We can say that a higher subsidy rate favours R with the highest profit while placing C at the lowest end of the profit spectrum; conversely, a lower subsidy rate reverses this scenario. However, in this model, various permutations of the three SC members' profits can occur. Scenario (a) shows that R benefits more from higher subsidy rate than M potentially due to increased operational efficiency or reduced costs of M. This cost saving then will pass on to R leading to higher profit margins for R, since R will have a bigger market without sharing the green production cost. This is in accordance with the data in Table J2 in Appendix J, which shows that R's profit rises at an accelerated rate with higher subsidies. According to scenario (b), as R is closer to consumers, with higher subsidy R benefits more from green production-sensitive customer demand than C. In scenario (c), the emphasis shifts to how the subsidy affects production costs, which does not impact C directly since C is not involved in production.

Proposition 5. M's profit increases with the cost savings from re-manufacturing (Δ) in both models, and greater cost savings enhance the profitability of blockchain adoption ($\frac{\partial(\Pi_M^B - \Pi_M^N)}{\partial\Delta} > 0$).

Appendix F provides the proof of this proposition.

While we cannot analytically prove the same for other SC members due to the complexity of the models, Figure J1 (in Appendix J) shows that the same holds true for R and C too. As the cost savings derived from re-manufacturing processes become more substantial, the economic advantage of implementing blockchain technology intensifies. Managers should regularly assess and optimize re-manufacturing cost savings, as increased savings shift blockchain adoption from a technological upgrade to a strategic financial choice. In industries such as pharmaceuticals, where recycling packaging and components is crucial, blockchain can verify the integrity of recycled materials and ensure compliance with environmental standards, making adoption financially beneficial as savings grow.

Proposition 6. Cost saving from re-manufacturing significantly influence investment decisions and market outcomes. Specifically, (a) investment in blockchain increases with re-manufacturing saving. (b) When manufacture's share of blockchain investment exceeds those of retailer ($\xi_M >> \xi_R$), investment in green production decreases with re-manufacturing saving, otherwise, it increases, in both blockchain and non-blockchain models. (c) With blockchain adoption (without blockchain), retail price, wholesale price, and used-product collection rate increase with re-manufacturing if $B_1, B_3 > 0$ ($B_2, B_4 > 0$) respectively; otherwise, they decrease.

Where B_1, B_2, B_3 and B_4 are defined in Appendix G, and the proof of Proposition 6 is given in Appendix G. Proposition 6 delineates critical thresholds in the dynamics between cost savings from re-manufacturing (Δ), prices, and the used product's collection rate (v_C^i). Increased cost savings by re-manufacturing may not always benefit customers; the outcome varies based on specific conditions, potentially leading to price fluctuations and influencing green production investment. The relationship between the amount of investment in green production and blockchain technology remains constant with remanufacturing savings. In both models, green production investment responds similarly to re-manufacturing savings, depending on the distribution of blockchain costs between M and R. If M covers a larger share of the blockchain costs, green investment decreases with re-manufacturing savings. Conversely, if R bears a greater share of the blockchain costs, green investment increases with re-manufacturing savings.

Proposition 7. With blockchain adoption, if $\xi_M >> \xi_R$ ($\xi_M << \xi_R$) blockchain investment and collection rate decrease (increase) with subsidy.

The proof of proposition 7 is provided in Appendix H.

Proposition 7 highlights that the relationship between blockchain technology and collection rates, which is not fixed, and it varies depending on the subsidy rate. This outcome aligns with the result of numerical simulations shown in Table J2, where $\xi_R = 0.7$. So blockchain adoption increases collection rate. While a subsidy threshold may be justified, the increasing trend of governments offering greater subsidies for green investments could potentially lead to reduced investments by SCs in blockchain technology due to higher share of M in blockchain adoption costs.

In the context of our study, equilibrium blockchain adoption refers to the point at which all SC participants have no incentive to deviate from their blockchain investment strategy, given the strategies of other participants. This equilibrium is influenced by various factors, including transfer price, market share, and green production investment. However, the primary determinants are the overall profitability of the supply chain, which is significantly affected by cost savings from re-manufacturing, and which enhance the financial appeal of blockchain.

4. Numerical simulations and Analysis of the Results

In this section, we build on previous studies (e.g. Biswas *et al*., 2022; Wei, Lu and Zhao, 2020) and use simulation methods to obtain appropriate numerical examples. Numerical simulations allow us to compare profit functions, decision variables and their sensitivity to different parameters in both models, offering a clear perspective on adoption of blockchain technology in a CLSC and its impact on each SC member.

4.1. Strategy analysis

In this sub-section, we use the numerical simulation presented in Example #1 (Appendix J) to bridge the analysis between models N and B. Our goal is to summarize the optimal blockchain adoption strategies for each supply chain member under various consumer and cost-sharing conditions.

Figures (2a–2c) illustrate the impact of the collector's cost-sharing role on the strategic dynamics of blockchain adoption within the supply chain. As the collector begins to contribute a small share to the cost of blockchain implementation, the profitability region for manufacturers and retailers expands. However, this pattern is not linear. When the collector's share reaches 40% (Figure 2c), we observe a contraction in the adoption region across all members. In contrast, when the collector contributes nothing (Figure 2a), effectively free riding, its own adoption region expands significantly. This configuration also maximizes the overlap where all members benefit from adoption. The results highlight a non-linear relationship where small increases in the collector's cost share minimal impact on coordination. However, beyond a certain threshold, coordination among SC members begins to deteriorate significantly, leading to reduce profitability for other members. Notably, this suggests that the viability of blockchain adoption is heavily influenced by how the costs are distributed among members.

From Figures (2a–2c) it becomes evident that blockchain adoption is more beneficial for manufacturers and retailer when customers exhibit a high degree of distrust. However, the collector's response to increasing distrust is non-monotonic, unlike manufactuer and retailer, its incentive to adopt blockchain is influenced more by its share of implementation costs, which shifts its profitable adoption region. Overall, blockchain adoption becomes viable when the incremental profits for the manufacturer and retailer—relative to the no-blockchain scenario—are sufficient to absorb the total cost, even without imposing financial pressure on the collector.

This insight is further validated by the simulation results presented in Figures 3a–3b. These figures explore how blockchain profitability responds to variations in customer price sensitivity and distrust. The manufacturer's adoption region is concentrated in areas with higher distrust and lower price sensitivity. This suggests that the manufacturer's benefit is strongly tied to resolving trust issues but is limited when customers are overly price sensitive. The retailer, by contrast, enjoys a broader profitable region, even when customers are moderately price sensitive. This supports the observation that blockchain delivers more direct demand-side benefits to downstream firms due to their proximity to end customers.

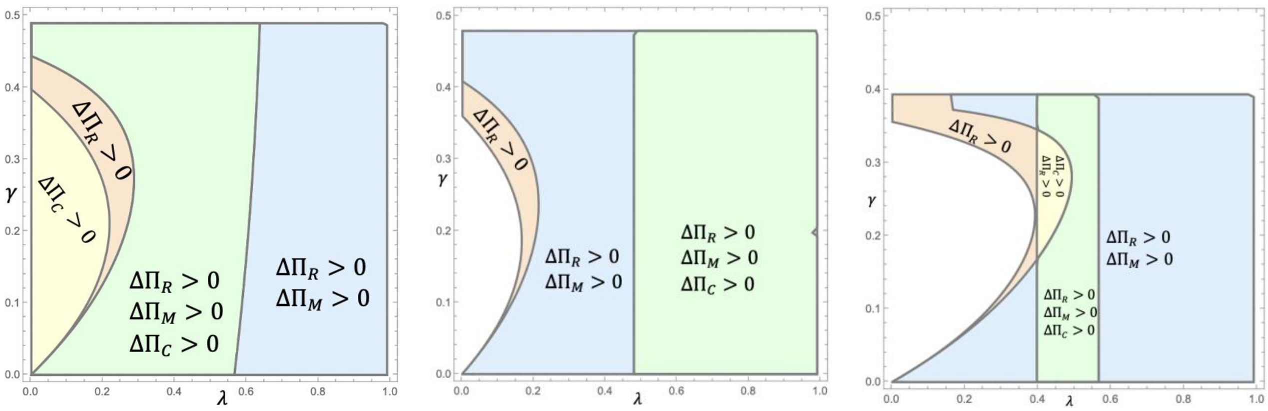

Figure 2a. where $\xi_B = 0.55; \xi_M = 0.45; \xi_C = 0$ **Figure 2b**. where $\xi_B = 0.5; \xi_M = 0.35; \xi_C = 0.15$ **Figure 2c.** where $\xi_B = 0.25; \xi_M = 0.35; \xi_C = 0.4$

Figure 2. Strategy regions for blockchain adoption under varying levels of customer distrust and greenness sensitivity

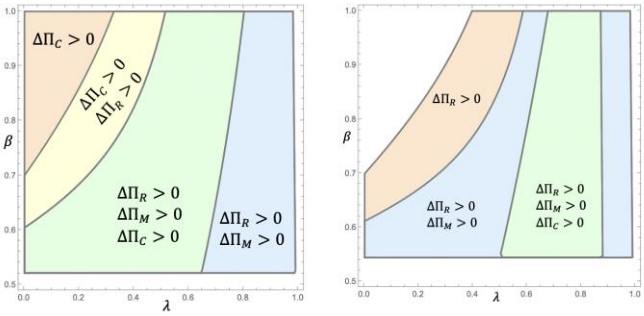

Figure 3a. where $\gamma = 0.5; \xi_B = 0.55; \xi_M = 0.45; \xi_C = 0$

Figure 3b. where $\gamma = 0.5, \xi_B = 0.5; \xi_M = 0.45; \xi_C = 0.05$

Figure 3. Strategy regions for blockchain adoption with respect to customer price sensitivity and distrust

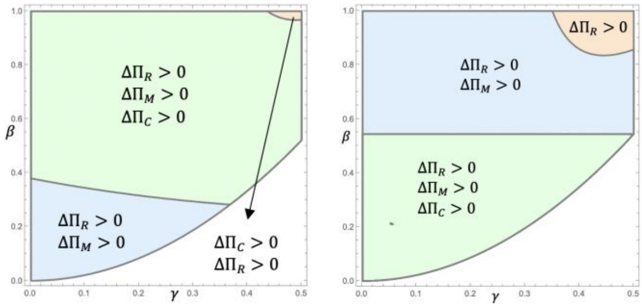

Figure 4a. where $\xi_B = 0.55; \xi_M = 0.45; \xi_C = 0$

Figure 4b. where $\lambda = 0.5, \xi_B = 0.5; \xi_M = 0.45; \xi_C = 0.05$

Figure 4. Strategy regions for blockchain adoption with respect to customer price and greenness sensitivity

Figures (4a–4b) highlight how customer's price and greenness sensitivitie interact with the cost-sharing structure. In Figure 4b, where the collector pays a portion of blockchain cost, the adoption region shrinks to scenarios with low price sensitivity and low green sensitivity. This indicates a constrained equilibrium due to the collector's financial burden. Conversely, in Figure 4a, when the collector free-rides, the adoption region expands into moderate and even high price sensitivity zones. Green sensitivity plays a less central role, showing that under free-riding, price sensitivity becomes the dominant driver of adoption profitability for collector and concequently for whole SC. To enhance visualization, we have delineated the distinct regions for each member in Appendix J.

4.2. Production sensitivity, consumer distrust, subsidy and cost saving

To assess how consumer preferences and cost-sharing arrangements affect blockchain adoption decisions across the supply chain, we conduct a series of simulations based on the benchmark parameters outlined in Appendix J. The results indicate that the collector's incentive to adopt blockchain remains weak, even when its cost burden is relatively low. While increased consumer sensitivity to environmental attributes and product trustworthiness tends to widen the profitability gap between the blockchain and non-blockchain models, this effect is mostly captured by both the manufacturer and the retailer. The collector's profit remains largely unaffected by shifts in consumer distrust but is negatively influenced when green sensitivity becomes more prominent, making blockchain adoption less attractive for this tier.

Further analysis explores the role of re-manufacturing cost savings and green production subsidies. We find that higher cost savings from re-manufacturing lead to substantial profit gains across both blockchain and non-blockchain scenarios. However, the relative benefit of blockchain adoption for the collector remains limited unless the savings become exceptionally large. Similarly, while subsidies can enhance profitability under blockchain, their marginal impact is modest within typical re-manufacturing cost ranges (detailed simulation outcomes supporting these insights are provided in Appendix J). These observations reinforce the previous subsection simulation-based findings and illustrate how supply chain members respond differently to customer behaviour and cost-sharing structures. A summary of these effects on blockchain adoption incentives across the three key players is provided in Table 3 below.

Table 3. Summary of blockchain adoption drivers for supply chain members

Parameter	Manufacturer (M)	Retailer (R)	Collector (C)
Customer distrust (λ) ↑	Profit ↑ under blockchian	Profit ↑ under blockchian	Minimal impact
Green sensitivity (γ) ↑	↑ incentive to adopt	↑ incentive to adopt	↓ incentives (unless sign $\xi_C = 0$, means increase)
Cost share (ξ_j) ↑	Adoption depends on profit	Adoption depends on profit	Adoption quickly collapses with higher ξ_C

Note: signs ↑ and ↓ stand for increase and decrease, respectively.

4.3. Sustainable practices: Implications to circular closed-loop supply chain

We have examined consumer distrust related to product greenness and quality dimension. This dimension is reflected in our demand function, where consumer distrust influences price sensitivity and the level of investment in green production. Based on our findings, we support the theory that blockchain adoption instils complete confidence in customers regarding the accuracy of information. This increased trust results in reduced price sensitivity among consumers, allowing SCs to offset some of the costs associated with blockchain adoption by adjusting their prices. Furthermore, blockchain facilitates government oversight of SCs' circular practices and recycling process. It serves as a barrier against greenwashing while fostering trust among the SC partners and consumers through enhanced transparency of materials, products and information within a CLSC.

Our work underscores the importance of companies integrating technology adoption into their broader financial strategies. Blockchain, in this context, transforms into a financial lever that achieves maximum effectiveness when synchronised with optimised re-manufacturing and CLSC processes. Additionally, we've explored the impact of blockchain on green production. As previously mentioned, we've identified that investments in green production increase with blockchain technology. This relationship signifies a strategic alignment. Manufacturers, as they invest more in blockchain, are driven by a shared goal to maximise profits through efficiency improvements, transparency assurance and potential product differentiation in a competitive market. This perspective emphasises that blockchain adoption aligns with the principles of circularity as well.

5. Evolutionary Game Theory Model

This section introduces a novel model using Evolutionary Game Theory (EGT) to study the long-term behaviour of entire SCs, including government (G), in two diverse populations. Prior research does not explore EGT's application in analysing blockchain adoption in SCs. Unlike classical game theory, EGT accounts for the limited rationality of decision-makers, a characteristic more reflective of real-world scenarios. EGT examines how players, over time, discover pure strategies through repeated interactions. In Section 3, we employ the classical game theory approach to model the decisions of the SC members within a single time period. In this section, we use EGT where SC members face the choice between three strategies, namely Model N, Model B and the traditional way (i.e. neither invest in green production nor in blockchain). This nuanced approach allows us to gain insights into the long-term behaviour of SCs as they navigate the strategic landscape and grapple with the enduring choice between these two models. The option for SC members to continue in the traditional way and G to choose between three strategies and the combination of these decisions makes our models more closely aligned with reality. This feature sets this model apart from models N and B. The consideration of bounded rationality introduces a realistic dimension, acknowledging the limitations of perfect information and rational decision-making in complex and dynamic environments. This approach facilitates the study of competition between SCs and the determination of what's best for the entire SC. Additionally, it allows the active involvement of the government (G) as a player in the game and the exploration of a stable strategy for G.

We assume that each SC member determines its decisions on its own (not centralised), but the outcome would be three strategies in total, namely, (i) traditional, i.e. M decides not to invest in product greenness, (ii) greenness investment, i.e. M invests in product greenness, but SC's participants cannot reach an agreement on investing in blockchain technology, and (iii) greenness and blockchain investment, i.e. SC's member invest in both products' greenness and blockchain technology.

To investigate G's behaviour, we assume that if the SC members invest in the product's greenness, G will gain environmental value (H_1). G will gain environmental value (H_2) if the SC participants invest in both product's greenness and blockchain technology where $H_2 > H_1$. Additionally, G has three strategies, namely, (a) encouraging green production by not taxing M, (b) taxing M, and (c) taxing while subsidizing green production to incentivize blockchain adoption.

In the first strategy of the SC, the profit function of the SC is equal to the sum of profit functions in model N with $g^N = 0$, meaning no green production or blockchain investment $\Pi_{SC}^1 = \Pi_M^N(\mathrm{w}_M^N, \mathrm{t}_M^N | D^N, \mathrm{g}_M^N = 0) + \Pi_R^N(\mathrm{p}_R^N | D^N, \mathrm{w}_M^N, \mathrm{g}_M^N = 0, \mathrm{t}_M^N) + \Pi_C^N(\mathrm{v}_C^N | D^N, \mathrm{w}_M^N, \mathrm{g}_M^N = 0, \mathrm{t}_M^N)$. In the second strategy, the SC profit function is $\Pi_{SC}^2 = \Pi_M^N(\mathrm{w}_M^N, \mathrm{g}_M^N, \mathrm{t}_M^N | D^N) + \Pi_R^N(\mathrm{p}_R^N | D^N, \mathrm{w}_M^N, \mathrm{g}_M^N, \mathrm{t}_M^N) + \Pi_C^N(\mathrm{v}_C^N | D^N, \mathrm{w}_M^N, \mathrm{g}_M^N, \mathrm{t}_M^N)$, which is exactly equal to the sum of SC members' profit functions in model N. In the third strategy, the SC's profit function is $\Pi_{SC}^3 = \Pi_M^B(\mathrm{w}_M^B, \mathrm{g}_M^B, \mathrm{t}_M^B | D^B) + \Pi_R^B(\mathrm{p}_R^B, B_R | D^B, \mathrm{w}_M^B, \mathrm{g}_M^B, \mathrm{t}_M^B) + \Pi_C^B(\mathrm{v}_C^B | D^B, \mathrm{w}_M^B, \mathrm{g}_M^B, \mathrm{t}_M^B)$, which is equal to the sum of the SC members' profit functions in model B. Considering the strategies we define the pay-off matrix in Table 4.

Table 4. Pay-off matrix

			SC		
			y_1 1) Traditional	y_2 2) Greenness investment	$y_3 = 1 - y_1 - y_2$ 3) Greenness and blockchain investment
G	x_1	1) Nether Tax nor Subsidy	$0, \Pi_{SC}^1 + w_M^N D^N \tau$	$H_1, \Pi_{SC}^2 + w_M^N D^N \tau$	$H_2, \Pi_{SC}^3 + w_M^B D^B \tau - s\left(\frac{c_g}{2}(g_M^B)^2\right)$
	x_2	2) Tax	$w_M^N D^N \tau, \Pi_{SC}^1$	$H_1 + w_M^N D^N \tau, \Pi_{SC}^2$	$H_2 + w_M^B D^B \tau, \Pi_{SC}^3 - s\left(\frac{c_g}{2}(g_M^B)^2\right)$

$x_3 = 1 - x_1 - x_2$	3) Tax & subsidy	$w_M^N D^N \tau, \Pi_{SC}^1$	$H_1 + w_M^N D^N \tau, \Pi_{SC}^2$	$H_2 + w_M^B D^B \tau - s\left(\frac{c_g}{2}(g_M^B)^2\right), \Pi_{SC}^3$

5.1. Analysis EGT Model

Let us consider Eg_1, Eg_2 and Eg_3 what G earns by choosing the first, second and third strategy, respectively. According to Table 4, G's pay-offs by considering three strategies are as follows:

$$Eg_1 = y_1(0) + y_2(H_1) + (1 - y_1 - y_2)(H_2) \tag{9}$$

$$Eg_2 = y_1(w_M^N D^N \tau) + y_2(H_1 + w_M^N D^N \tau) + (1 - y_1 - y_2)(H_2 + w_M^B D^B \tau) \tag{10}$$

$$Eg_3 = y_1(w_M^N D^N \tau) + y_2(H_1 + w_M^N D^N \tau) + (1 - y_1 - y_2)\left(H_2 + w_M^B D^B \tau - s\left(\frac{c_g}{2}(g_M^B)^2\right)\right) \tag{11}$$

Consequently, G's average earning is as follows:

$$\overline{Eg} = x_1 Eg_1 + x_2 Eg_2 + (1 - x_1 - x_2) Eg_3 \tag{12}$$

We demonstrate the SC's expected earnings in its first (Esc_1), second (Esc_2) and third (Esc_3) strategies, respectively. According to Table 4, the SC's pay-offs by considering three strategies are as follows:

$$Esc_1 = x_1(\Pi_{SC}^1 + w_M^N D^N \tau) + x_2(\Pi_{SC}^1) + (1 - x_1 - x_2)(\Pi_{SC}^1) \tag{13}$$

$$Esc_2 = x_1(\Pi_{SC}^1 + w_M^N D^N \tau) + x_2(\Pi_{SC}^2) + (1 - x_1 - x_2)(\Pi_{SC}^2) \tag{14}$$

$$Esc_3 = x_1\left(\Pi_{SC}^3 + w_M^B D^B \tau - s\left(\frac{c_g}{2}\left(g_M^B\right)^2\right)\right) + x_2\left(\Pi_{SC}^3 - s\left(\frac{c_g}{2}\left(g_M^B\right)^2\right)\right) + (1 - x_1 - x_2)(\Pi_{SC}^3) \tag{15}$$

Consequently, the SC's average earning is as follows:

$$\overline{Esc} = y_1 Esc_1 + y_2 Esc_2 + (1 - y_1 - y_2) Esc_3 \tag{16}$$

In EGT, the change in players' strategies in a population is commonly considered to be based on the replicator dynamics (Taylor and Jonker, 1978):

$$x_i{}' = x_i\left[f(x_i) - \sum_{i=1}^{n} x_i f(x_i)\right]$$

where x_i and $f(x_i)$ are the frequency and the expected payoff (fitness) of strategy i, respectively. In the above function, the change rate $\frac{x_i{}'}{x_i}$ is equivalent to the difference between the expected profit of player i and the average of the population. In other words, each time that game repeats, the player changes its chosen strategy according to the population's average fitness. We can write the above function in a more convenient matrix as follows:

$$x_i{}' = x_i[(Ax)_i - x^T A x]$$

where matrix A is a payoff matrix that contains the fitness of each strategy concerning other strategies in population.

By setting equations (9), (10) and (11) in equation (12), and having $x_1 + x_2 + x_3 = 1$, the replicator dynamics equation of G becomes:

$$F(x_1) = \frac{dx_1}{dt} = x_1(Eg_1 - \overline{Eg}) = \frac{\left(-2(x_1-1)\left((w_M^B D^B - w_M^N D^N)y_1 + (w_M^B D^B - w_M^N D^N)y_2 - w_M^B D^B\right)\tau + s(g_M^B)^2 c_g (x_1+x_2-1)(y_1+y_2-1)\right)}{2} x_1 \quad (17)$$

$$F(x_2) = \frac{dx_2}{dt} = x_2(Eg_2 - \overline{Eg}) = \frac{\left(-2x_1\left((w_M^B D^B - w_M^N D^N)y_1 + (w_M^B D^B - w_M^N D^N)y_2 - w_M^B D^B\right)\tau + s(g_M^B)^2 c_g (x_1+x_2-1)(y_1+y_2-1)\right)}{2} x_2 \quad (18)$$

Similarly, we perform the same operation for the SC by setting equations (13), (14) and (15) in equation (16) and considering $y_1 + y_2 + y_3 = 1$, and the replicator dynamics equation of the SC is as follows:

$$G(y_1) = \frac{dy_1}{dt} = y_1(Esc_1 - \overline{Esc}) = -\frac{y_1\begin{pmatrix}(y_1+y_2-1)\left(sc_g(g_M^B)^2 - 2\tau(w_M^B D^B - w_M^N D^N)\right)x_1 + \left(x_2 sc_g(g_M^B)^2 + 2\Pi_{SC}^1 - 2\Pi_{SC}^3\right)y_1 \\ + s x_2 sc_g(g_M^B)^2(y_2-1) + \left(2\Pi_{SC}^2 - 2\Pi_{SC}^3\right)y_2 - 2\Pi_{SC}^1 + 2\Pi_{SC}^3\end{pmatrix}}{2} \quad (19)$$

$$G(y_2) = \frac{dy_2}{dt} = y_2(Esc_2 - \overline{Esc}) = -\frac{y_2\begin{pmatrix}(y_1+y_2-1)\left(sc_g(g_M^B)^2 - 2\tau(w_M^B D^B - w_M^N D^N)\right)x_1 + \left(x_2 sc_g(g_M^B)^2 + 2\Pi_{SC}^2 - 2\Pi_{SC}^3\right)y_2 \\ + s x_2 sc_g(g_M^B)^2(y_1-1) + \left(2\Pi_{SC}^1 - 2\Pi_{SC}^3\right)y_1 - 2\Pi_{SC}^2 + 2\Pi_{SC}^3\end{pmatrix}}{2} \quad (20)$$

Considering equations (17 to 20), the solutions to the four equations and four unknowns by setting $\frac{dx_1}{dt} = 0, \frac{dx_2}{dt} = 0, \frac{dy_1}{dt} = 0, \frac{dy_2}{dt} = 0$, will be equilibrium points of the replicator dynamics, which are $(x_1, x_2, x_3, y_1, y_2, y_3) = \{0,0,1,0,0,1\}, \{0,1,0,0,0,1\}, \{0, x_2, 1-x_2, 0,1,0\}, \{0, x_2, 1-x_2, 1,0,0\}, \{1,0,0,0,0,1\}, \{1,0,0,0,1,0\}, \{1,0,0,1,0,0\}, \left\{x_1 = \frac{2(\Pi_{SC}^2 - \Pi_{SC}^3)}{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B - 2D^N\tau w_M^N}, 0, 1-x_1, 0, y_2 = \frac{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B}{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B - 2D^N\tau w_M^N}, 1-y_2\right\}, \left\{x_1 = \frac{sc_g(g_M^B)^2 + 2(\Pi_{SC}^2 - \Pi_{SC}^3)}{2\tau(D^B w_M^B - D^N w_M^N)}, x_2 = \frac{-sc_g(g_M^B)^2 + 2\tau(D^B w_M^B - D^N w_M^N) + 2(-\Pi_{SC}^2 + \Pi_{SC}^3)}{2\tau(D^B w_M^B - D^N w_M^N)}, 1-x_1-x_2, 0, y_2 = \frac{D^B w_M^B}{D^B w_M^B - D^N w_M^N}, 1-y_2\right\}, \left\{x_1 = \frac{2(\Pi_{SC}^1 - \Pi_{SC}^3)}{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B - 2D^N\tau w_M^N}, 0, 1-x_1, y_1 = \frac{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B}{-sc_g(g_M^B)^2 + 2D^B\tau w_M^B - 2D^N\tau w_M^N}, 0, 1-y_1\right\}, \left\{x_1 = \frac{-sc_g(g_M^B)^2 + 2(\Pi_{SC}^1 - \Pi_{SC}^3)}{2\tau(D^B w_M^B - D^N w_M^N)}, x_2 = \frac{-sc_g(g_M^B)^2 + 2\tau(D^B w_M^B - D^N w_M^N) + 2(-\Pi_{SC}^1 + \Pi_{SC}^3)}{2\tau(D^B w_M^B - D^N w_M^N)}, 1-x_1-x_2, y_1 = \frac{D^B w_M^B}{D^B w_M^B - D^N w_M^N}, 0, 1-y_1\right\}$, where $0 \le x_i, y_i \le 1, i \in \{1,2,3\}$.

Evolutionary stable strategy (ESS) is a strategy that does not change over time. Using the Jacobian matrix, if conditions $\det J = \begin{vmatrix} \frac{\partial F(x_1)}{\partial x_1} & \frac{\partial F(x_1)}{\partial x_2} & \frac{\partial F(x_1)}{\partial y_1} & \frac{\partial F(x_1)}{\partial y_2} \\ \frac{\partial F(x_2)}{\partial x_1} & \frac{\partial F(x_2)}{\partial x_2} & \frac{\partial F(x_2)}{\partial y_1} & \frac{\partial F(x_2)}{\partial y_2} \\ \frac{\partial F(y_1)}{\partial x_1} & \frac{\partial F(y_1)}{\partial x_2} & \frac{\partial F(y_1)}{\partial y_1} & \frac{\partial F(y_1)}{\partial y_2} \\ \frac{\partial F(y_2)}{\partial x_1} & \frac{\partial F(y_2)}{\partial x_2} & \frac{\partial F(y_2)}{\partial y_1} & \frac{\partial F(y_2)}{\partial y_2} \end{vmatrix} > 0$ and $\mathrm{tr} J = \frac{\partial F(x_1)}{\partial x_1} + \frac{\partial F(x_2)}{\partial x_2} + \frac{\partial F(y_1)}{\partial y_1} + \frac{\partial F(y_2)}{\partial y_2} < 0$ hold, the equilibrium point is an ESS.

Lemma 3. Considering the Jacobian matrix above, the ESS of the presented game for x and y is as shown in Table K1 of Appendix K.

Proposition 8. SC's evolutionary strategy is strongly influenced by the Government (G) intervention policies. In the absence of government intervention (x_1), the SC's evolutionary strategy can be one of the three possibilities, namely, y_1, y_2 and y_3. However, when G opts for interventions such as imposing taxes (x_2) or providing subsidies alongside taxes (x_3), the SC's sole ESS becomes the simultaneous adoption of both green production and blockchain technology (y_3).

The proof of this proposition is given in Appendix I.

Proposition 8 highlights the impact of government policies, such as taxation and subsidies, on SC's long-term strategies. When G offers subsidy to encourage blockchain adoption, the SC is most likely to adopt green production and blockchain jointly. Non-pure strategies reveal probabilities for the SC to alternate between green-only and blockchain investments alongside green investment (y_3 and y_2), or between traditional and green and blockchain investments (y_1 and y_3). This emphasises the importance of flexibility in SC management and government policymaking, with both parties needing to adjust strategies in response to changing factors.

5.2. Numerical experimentation

To solve the replicator dynamics presented above, we employ numerical simulation, as presented in Table K2 (Appendix K), based on previous research (Biswas *et al*., 2022; Chen and Hu, 2018). However, before exploring these numerical results, it's essential to outline the strategies for each participant in the game. Within the SC, the first strategy, termed 'Traditional', signifies that SC members refrain from investing in either blockchain technology or green production. The second strategy, 'Greenness investment', denotes that the SC will exclusively invest in green production. The third strategy, 'Greenness and blockchain investment', indicates that the SC chooses to invest in both green production and the adoption of blockchain technology. On the G's side, the first strategy, 'Neither Tax nor Subsidy', implies that G refrains from imposing taxes or offering subsidies. The second strategy, 'Tax', indicates that G will solely impose taxes. The third strategy, 'Tax & Subsidy', conveys that the government intends to levy taxes while simultaneously providing subsidies.

Figures (5a-5g) depict the evolutionary strategy of the G across examples 1 to 7 in Table K2 (Appendix K). In each figure, the first strategy is an unstable one. G's long-term strategy oscillates between solely imposing taxes and offering subsidies, contingent on the initial conditions. Examples 5 and 6 reveal that G's preference for tax imposition is influenced by the subsidy amount and market base size. In essence, while subsidies can incentivise SCs to invest in blockchain, there exists a subsidy threshold beyond which it becomes unprofitable for G. This threshold increases in larger markets, where higher SC sales generate more tax revenue, allowing G to provide greater subsidies. "The fixed-point ρ^* is attractive if there exists an open neighbourhood U of ρ^* such that all trajectory initially in U converges to ρ^*" (Szabó and Fáth 2007). While in example 5, the third strategy (i.e. tax and subsidy) is an attractive strategy, in example 6, with a decrease in cost coefficient of green production (c_g) and the exchanging coefficient between the collection effort and investment (c_v), the third strategy is an unstable point (Figure 5(f)).

Figures 5a-5c, and 5g demonstrate that ESS remains unchanged despite variations in parameters like H_1, H_2, τ and λ. This underscores that G's decision is considerably more sensitive to saving by re-manufacturing (Δ), greenness sensitivity (γ) and subsidy (s).

Regarding SC behaviour, Figures 6a, 6c, 6d and 6e indicate that the second (green production only) and third strategies (green production and blockchain investment) exert pure dominance over the traditional strategy (no investment). This dominance is driven by consumers sensitivity to green production and their mistrust towards SC. However, all three strategies could be attractive strategies. In the context of circular SC and CLSC principles, we observe the variation in investment strategies in Figures 6a and 6b. As the tax rate (τ) and customers' distrust of greenness (λ) decrease, there is a significant decline in the incentives for investment in both green production and blockchain. This leads to a shift in investments towards neither or solely in green production.

Comparing Figures 6d-6e and 6a-6c, we see that with the increase in customer sensitivity to green production, the trajectory and convergence rate toward ESS change, though the long-term strategy remains a combination of taxes and subsidies. Figure 6g highlights the role of cost allocation for blockchain adoption. If R's share of blockchain costs falls below a threshold, making other SC members bear the difference, blockchain adoption becomes less attractive compared to solely investing in green production. Finally, we infer from Figure 6f that the third strategy (tax and subsidy) becomes unstable when the cost coefficient of green production (c_g) and the effect of blockchain adoption on the exchanging coefficient between the collection effort and the investment (c_v) decrease. In this scenario, green production investment becomes ESS, making it the traditional (i.e. the SC's first strategy) attractive strategy. This shift reflects the inherent resistance to change often observed in established systems during the transition to blockchain-based systems.

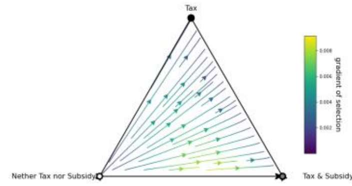

Figure 5a. Numerical example#1 of Table K2

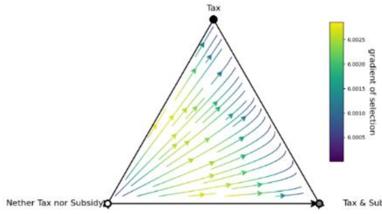

Figure 5b. Numerical example#2 of Table K2

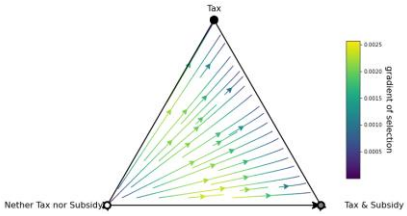

Figure 5c. Numerical example#3 of Table K2

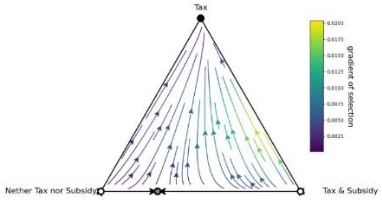

Figure 5d. Numerical example#4 of Table K2

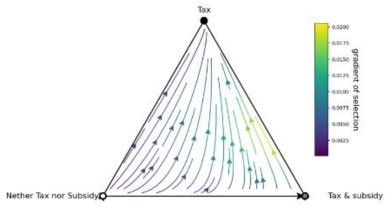

Figure 5e. Numerical example#5 of Table K2

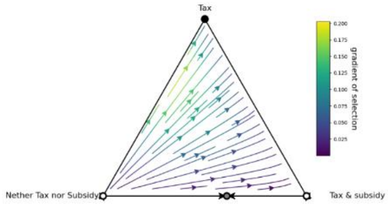

Figure 5f. Numerical example#6 of Table K2

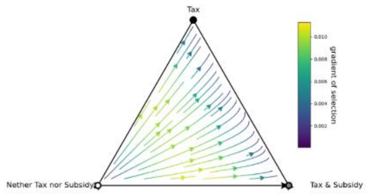

Figure 5g. Numerical example#7 of Table K2

Figure 5. The behavioural strategy of the G's evolutionary course in the replicator dynamics

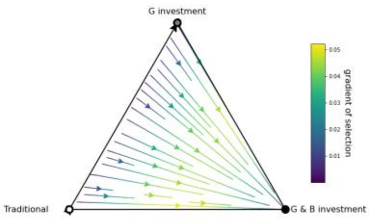

Figure 6a. Numerical example#1 of Table *K2*

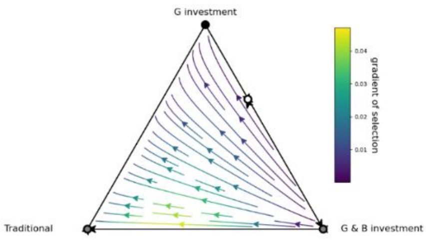

Figure 6b. Numerical example#2 of Table K2

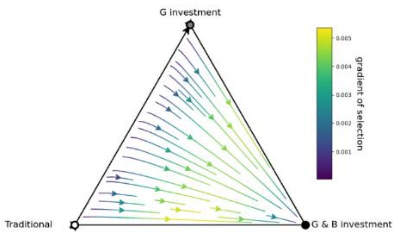

Figure 6c. Numerical example#3 of Table K2

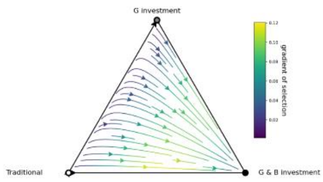

Figure 6d. Numerical example#4 of Table *K2*

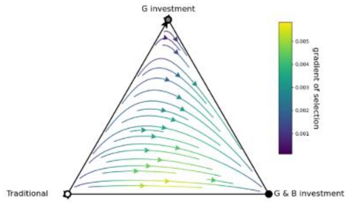

Figure 6e. Numerical example#5 of Table K2

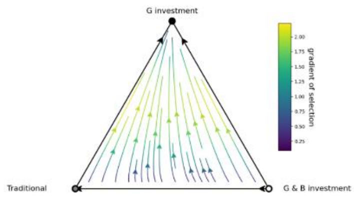

Figure 6f. Numerical example#6 of Table K2

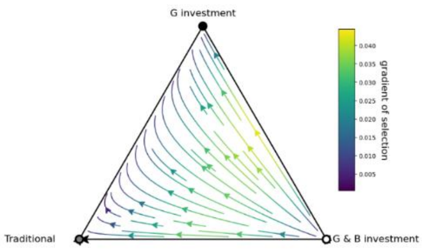

Figure 6g. Numerical example#7 of Table K2

Figure 6. The behavioural strategy of the SC's evolutionary course in the replicator dynamics

6. Discussion

6.1. Managerial implications

We identify some key implications for the managers. Although blockchain adoption could significantly increase M's and R's profits, for C it could lead to a significant loss, even if C does not participate in blockchain implement costs. Consequently, if the SC managers want to make sure that C cooperates in using blockchain technology, they have to use cooperation contracts to make it profitable for C too.

The decision to adopt blockchain technology is influenced by both consumer demand for green products and their distrust—though the effect of distrust is non-linear. Moderate distrust supports adoption, but extremely high distrust may reduce R's incentive to participate. Managers should recognize that investing solely in blockchain to enhance consumer trust, while neglecting green production (or vice versa), may not be an optimal strategy.

Long-term decisions regarding blockchain technology adoption hinge on balancing consumer price sensitivity, preferences for green production, and blockchain implementation costs distribution among the SC members. If price sensitivity dominates, the ESS strategy favours investing solely in green production. Conversely, if green production is prioritized, dual investment in both green production and blockchain is favoured. However, a critical turning point arises when the R's portion of blockchain implementation costs falls below a specific threshold with the remaining cost covered by other SC members, shifting ESS toward sole investment in green production. Therefore, a judicious consideration of the cost-sharing arrangement among SC members proves pivotal for blockchain technology adoption.

Increased savings from re-manufacturing encourage compensating collectors, promoting a circular economy. Managers should focus on improving re-manufacturing processes to boost savings and incentivize product returns (please refer to Proposition 1).

The collection rate of used products, which is essential for maintaining a circular economy, decreases (increases) with subsidies when manufacturer (retailer) bears a significant proportion of blockchain adoption costs. Consequently, higher subsidies for green production might reduce investments in collection programmes. Managers must carefully balance these investments to sustain high collection rates while benefiting from green subsidies (please refer to Proposition 7).

Larger markets can handle higher subsidy thresholds, as increased SC sales generate more tax revenue. Managers should recognize that government subsidies are not limitless and may decrease if the market base or cost savings from green investments decline (please refer to Proposition 8).

Established SCs may exhibit resistance to transitioning from traditional strategies to blockchain-based systems, especially when the cost coefficients for green production or blockchain adoption decrease. Managers should address this resistance by emphasizing the long-term advantages of sustainable investments and the risks of sticking to outdated practices (please refer to Proposition 8).

6.2. Implications for policymakers

Our study underscores the positive impact of blockchain adoption on green production investment within SCs. Policymakers and governments should consider promoting blockchain adoption as part of their strategy to incentivise SCs towards greener products. Specifically, given consumer sensitivity to green production SCs adopting blockchain technology align with an appropriate policy. However, the effectiveness of blockchain promotion may vary based on consumer behaviour. Excessive distrust can counteract the expected benefits for downstream SC members, highlighting the importance of tailored policy strategies.

In a broader context, the long-term ESS for governments (G) is influenced by multiple variables, including tax rates, subsidy rates, M's green production investment, and M's revenue aligning closely with the characteristics of H_1 and H_2.

Moreover, the adoption of blockchain technology yields a higher collection rate but, an increased subsidy amount can potentially diminish investment in collection programmes. Importantly, there exists a critical subsidy threshold, exceeding, which can render it unprofitable for governments in the long term. This threshold varies with the market base, allowing larger markets to support higher subsidy allocations due to increased tax revenue. Hence, governments must stride carefully in balancing subsidy amount and collection rate trade-off. A mere increase in subsidy may not guarantee a greener SC. However, finding the optimal subsidy level can ensure widespread blockchain technology adoption.

Raising awareness among SCs about the importance of greener practices can increase investments in blockchain. Governments can leverage this strategy to promote blockchain usage, as the study shows that green production and blockchain investments often rise together.

7. Conclusions

With a continuous increase in the consumers' sensitivity to purchasing green products, their distrust of information shared by companies, and governments' concerns about the product's environmental footprint, greenwashing and reaching CE goals, blockchain technology has attracted attention to both industry and academia (De Giovanni, 2020; Kouhizadeh *et al*., 2020; Zhu *et al*., 2022). Our study demonstrates that blockchain has the ability to monitor the manufacturing process and provide transparent information to the SC members, customers and governments. Our study identifies the equilibrium strategies of CLSC as a whole, CLSC participants individually, and the government in a complex environment with consumers. We propose two models based on classical Stackelberg game theory to analytically examine the equilibrium prices, the equilibrium collection rate for recycling, investment in green production, and investment in blockchain implementation in a CLSC. We investigate the impact of blockchain implementation in presence of a C in the CLSC. We propose an EGT model to simulate the long-term behaviour of the government and CLSCs under a similar environment.

We aim to answer four key questions. In the first research question, if the CLSC adopts blockchain, green production would become more profitable, meaning that blockchain adoption naturally supports increased investment in green initiatives. Looking at the second research question, we observe, while subsidies encourage blockchain adoption in the short term, our analysis suggests that, in the long run, taxation alone is the government's best strategy, aligning with ESS principles regardless of green production's environmental benefits. To answer the third research question, we conclude that under government intervention through taxes or subsidies, the ESS of the SC may support solely on green production or, incorporate both green production and blockchain investment. Without intervention, the CLSC's equilibrium strategy can vary, including no investment, green production only, or both green production and blockchain investment.

Our study answers the fourth research question. Since the most significant profit gained from blockchain adoption goes to R and then M, and the change in C's profit is not significant, it is beneficial for C to avoid taking part in blockchain's implementation cost. Depending on the situation, coordinated contracts may be necessary to incentivize C's participation in adopting blockchain.

This study promotes the development of blockchain-enabled CLSCs by demonstrating how blockchain technology can stimulate greater investment in green production and increase the collection rate of used products, thereby enhancing overall profitability and ensuring compliance with environmental regulations. Our findings reveal that, for all CLSC members, to fully engage in blockchain adoption, a revenue-sharing contract with the collector is necessary. By examining the long-term strategic interactions between the CLSC members and the government, we provide insights into how blockchain adoption can be optimized to create a more sustainable and efficient CLSC, particularly in response to varying levels of consumer distrust and sensitivity to green production. Additionally, our analysis highlights that simply increasing subsidies may not guarantee a greener CLSC, emphasizing the need for governments to consider other equilibrium strategies to effectively drive sustainability.

We consider that manufacturers pay tax, but retailers and collectors usually pay tax too. Future studies should consider these taxes, and it would make the model more realistic. In addition, researchers can consider blockchain adoption's role in different behaviours like collusion and Bertrand competition among the SC members. Future studies may include different coordination contracts that the M and R together can offer the C. Moreover, despite recent advancements in the blockchain adoption literature, the potential impact of collusion among supply chain members under blockchain implementation remains unexplored, which will be an extension of a recent study by Sarabi, Taleizadeh, and Jolai (2024). Finally, developing an EGT model for all CLSC participants and investigating each participant's strategy individually would be insightful.

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