How to empower commercial satellite supply chain: Insurance, government subsidy or blockchain adoption?

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Abstract

The commercial satellite industry is booming with possible launch failures, which can cause enormous loss for both vehicle manufacturer and satellite operator. To hedge such risks and reduce potential costs, they often buy launch insurance from financial companies, and/or seek possible subsidy from government-backed schemes. Recently, the innovative blockchain technology has been adopted by satellite launch supply chains to enhance data sharing, improve workflow efficiency, and thus reduce launch risks. However, very little research has been done on how these players interact, make decisions, and how the satellite supply chain (SSC) can be empowered by insurance, government subsidy or blockchain adoption. In this paper, we propose several Stackelberg games to examine the SSC cases with launch insurance (Model I), with insurance & government subsidies (Model IG), with blockchain-embedded insurance (Model B), and with blockchain-embedded insurance & government subsidies (Model BG). We investigate the optimal launch price, retail price, and the effort (for improving launch success probability) expressions by deriving models. Furthermore, we explore the conditions for optimal allocation of government subsidies and the cost thresholds for adopting blockchain technology by analyzing the equilibrium outcomes. We find that if the government wants to form a virtuous circle and optimize the allocation of funds, it should subsidize satellite operators that use cost-effective vehicles for launch activities rather than providing unconditional subsidies. In addition, we also find that the subsidy does not benefit consumers, but blockchain can. Once the blockchain technology is adopted, contract prices go up, the vehicle manufacturer exerts more effort, and the premium rate always is lower as the launch missions become more efficient and believable. Besides, the adoption of blockchain technology can also improve the benefits from government subsidies. Moreover, when the satellite operator chooses an inexpensive launch vehicle, the cost-advantage blockchain-embedded platform benefits all participants. Finally, coupling these findings, we further discuss the managerial implications for the commercial space launch market.

Keywords: Satellite launch, insurance, government subsidy, blockchain, commercial launch supply chain

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1. Introduction

1.1. Background

Man-made satellites can collect extensive and valuable data which can be used in archaeology, cartography, environmental monitoring, meteorology, and reconnaissance applications. Space is no longer confined to government and military agencies like NASA, but open to private companies since 1980s, thanks to the changes of space laws and regulatory regime (OECD, 2014). On Dec.3th 2013, the SES-8 satellite was successfully delivered by a Falcon 9 launch vehicle made by SpaceX, a private company founded in 2002 offering lower cost launches than their competitors (Tariq, 2013). This successful launch significantly promotes the global satellite industry, the total revenue of which reaches \$386 billion by 2021 (Association, 2022). The commercial satellite industry put a record 1,713 commercial satellites into orbit for the fourth consecutive year, an increase of more than 40% compared to 2020.

Behind such vigorous development, the launch failure risk can not ignored by the companies in satellite launch supply chain (SSC). Once the launch fails, the loss for both vehicle manufacturer and satellite operator is enormous. To hedge this risk, there are three solutions in practice.

First, space insurance emerged. Insurance companies like *Global Aerospace* have been providing different space insurance services, which can be roughly divided into four types according to satellite project phases: pre-launch insurance[1], launch insurance[2], in-orbit insurance[3], and launch plus life insurance[4]. Among them, the launch insurance is most popular because the launch phase is the riskiest activity and the damage is often catastrophic (Suchodolski, 2018; Gould & Linden, 2000; Kunstadter, 2020). With more and more satellite operators realizing the importance of launch insurance, nearly half of satellite launches are insured (Hussain & Cohn, 2021).

[1]Pre-launch insurance covers damage to a satellite or launch vehicle during the construction, transportation, and processing phases prior to launch.

[2]Launch insurance covers losses of a satellite occurring during the launch phase of a project. It insures against complete launch failures as well as the failure of a launch vehicle to place a satellite in the proper orbit.

[3]In-orbit policies insure satellites for in-orbit technical problems and damages once a satellite has been placed by a launch vehicle in its proper orbit.

[4]Third-party liability and government property insurances protect launch service providers and their customers in the event of public injury or government property damage, respectively, caused by launch or mission failure.

Second, the government subsidized. Since the commercial industry promotes the development of high technologies, some governments have introduced policies to subsidize the SSC. For example, the *Beijing Bureau of Economy and Information Technology* subsidized commercial space enterprises that engage in the production and manufacture of vehicles and satellites, and encouraged them to establish headquarters, sales and operation in Beijing. In addition, the Unites States not only provided subsidy for launch liability insurance but also awarded the commercial companies directly.

Third, new technology helped. Blockchain, a disruptive technology that facilitates data sharing and trust building, has been adopted by the SSC companies, such as *SpaceChain*, *IBM* and *Cloud Constellation Corporation*. It is used to share the critical data (e.g., contracts, test results) among trusted parties to make the workflow (e.g., approvals, auditing) more efficient and visible, so that the launch failure risk can be reduced as much as possible (Zheng et al., 2021).

Each solution above introduces new entity (insurance company, government, and blockchain service provider) with different interest into the SSC. Hence, both the private companies and government are keen to understand the impacts of different solutions on SSC performance.

1.2. Research questions and key findings

This paper aims to study the following research questions (RQ):

RQ1. How to analytically model the interactions among key entities in SSC, namely vehicle manufacturer (VM), satellite operator (SO) and insurance company (IC)? What is the optimal decision for each entity?

RQ2. How to analyze the impact of government subsidy on the optimal decisions in SSC?

RQ3. Is blockchain worth adopting to the SSC? How to understand its impacts on the optimal decisions?

To investigate RQ1, we propose a benchmark model with three entities, called Model I. This model is extended as Model IG to study RQ2 by considering government subsidy. Next, the blockchain technology is introduced into both models as Model B and BG. Comparing the optimal decisions in these four models, we obtain the following results:

(1) Government subsidies can be used to incentivize SO to pay higher launch prices, so that the

VM have the motivation to increase the probability of successful launches, and the overall social welfare (total profit of all players) also increases.

(2) The impacts caused by blockchain technology and government subsidy are similar; the difference is threefold: for SO, blockchain adoption (if the cost is low) increases its data retail price and profit; for VM, its profit depends on the cost of blockchain adoption and vehicle manufacturing; for satellite data customer, its surplus increases.

1.3. Contributions

Th contributions of this paper are summarized as follows: (1) Inspired by the study on satellite industry operation management by Wooten & Tang (2018), we investigate SSC in a manner of game theory to study how financial factors, government support and technology advance affect the operations of SSC entities. (2) Different from the well-known supply chain financial models such as the one proposed by Tang et al. (2018), we also consider the role of government subsidies, as well as disruptive FinTechs such as blockchain. (3) Different from the existing blockchain-related supply chain studies, our model is one of the first attempts to investigate the SSC by combining real-world practices in satellite industry (Altaf, 2019) and recent blockchain applications (Luo & Choi, 2022). Therefore, we suggest that this paper not only complements the literature, but also provides managerial insights for practitioners in satellite industry.

The rest of this paper is organized as follows. Section 2 reviews four related research streams. Section 3 establishes the benchmark case with launch insurance (Model I), and introduces government subsidies into an extended case (Model IG). Section 4 examines the impact of blockchain adoption in the SSC under two scenarios, one with launch insurance (Model B) and one with government-subsidized launch insurance (Model GB). Section 5 relaxes some assumptions to generate new findings. Section 6 concludes this paper and suggests potential topics for future research.

2. Literature review

Our paper is closely related to four research streams: supply chain insurance, space supply chain management, blockchain, and government subsidies.

2.1. Supply chain insurance

Supply chain insurance is a sub-stream of supply chain finance which is extensively studied in today's FinTech era (Zhao & Huchzermeier, 2015; Xu et al., 2018b; Wang et al., 2021a). Among the many types of commercial insurance, the one most similar to the space launch insurance in this paper is business interruption insurance (BI insurance). In management practice, companies can utilize BI insurance to hedge against risks. However, it must be pointed out that the purchase cost of BI insurance is high, and it is at the cost of sacrificing current profits to achieve risk aversion. If no interruption occurs during the insurance period, this premium will become a sunk cost for the enterprise. At this point, facing the high cost of current payment and the small probability of large economic losses in the future, the trade-off between risks and benefits becomes an important issue to be studied and solved in theory and practice.

According to the different sources of risk, BI insurance can be divided into two categories: risk of endogenous disruption which mainly comes from within the supply chain (e.g., inventory shortages, cooperator's bankruptcy, transportation delays); and risk of exogenous disruption which Mainly from the external environment of the supply chain (e.g., Natural disaster risk, social risk and economic risk) (Sodhi et al., 2012; Heckmann et al., 2015).

(1) Hedging endogenous risks. Lin et al. (2010) compared insurance contract with revenue sharing contract according to different agents' risk aversion based on the news-vendor model. With the presence of inventory risk, Dong & Tomlin (2012) applied BI insurance to a single-period product-inventory operation management. Based on Dong & Tomlin (2012), Dong et al. (2018) considered the preparation strategy. By examining a two-stage model, the effects of inventory, preparedness, and BI insurance on the product chain are comparatively analyzed. In the after-sales service context, Qin et al. (2020) constructed a principal-agent model by combining the insurance options with after-sales service contracts to reduce operational risk (e.g., machine failure). Specifically, they consider two main forms of contracts: resource-based contract and performance-based contract. Besides, Wang et al. (2021b) also discussed which contract is better for supply chain partners between the advanced payment contract, penalty contract, and time insurance contract in the express delivery supply chain. (2) Hedging exogenous risk. Lodree Jr & Taskin (2008) designed an insurance policy framework to quantify the risks and benefits. Balcik

et al. (2019) proposed a cooperative pre-deployment strategy between countries responding to hurricane disasters. The authors determined the location and quantity of relief supplies to be stored based on a stochastic programming model and developed a dataset for the network with real-world data. Yu et al. (2021) considered the interrupt probability of the supply chain, and illustrate that business interruption insurance increases the profit of each participant. Brusset & Bertrand (2018) constructed a weather index, so that entrepreneurial risk can be transferred to other risk-takers through insurance or options contracts.

2.2. Blockchain technology in supply chain management

As a “trust ledger”, blockchain has overwhelming advantage of data storage such as openness, transparency, tampering, and traceability, which make it possible to manipulate higher quality data (Choi, 2019), improving the supply chain efficiency and so on (Chod et al., 2020). According to its characters, Queiroz et al. (2019); Wang et al. (2019); Babich & Hilary (2020a); Li et al. (2022) gave the review of this topic.

Besides, more and more scholars have begun to study the application of blockchain in the supply chain. (1) Inside the supply chain, (i) in upriver of supply chain, blockchain technology facilitates the flow of raw materials from the suppliers (Naydenova, 2017; Nash, 2016); (ii) in the midstream, it promotes the exchange of manufacture information and design smart contracts between participants in the supply chain upstream and downstream and achieve coordination eventually (Moise & Chopping, 2018; Hilary, 2022; Chod et al., 2020; Korpela et al., 2017; Wang et al., 2021c). (2) Outside the supply chain, (i) face the third party, it provides an innovative way for the capital constraint companies to finance (Choi, 2020; Choi & Ouyang, 2021); (ii) face the market, it helps products to fight counterfeits, earn trust of customers and win company reputation in the market (Pun et al., 2021; Shen et al., 2021; Fan et al., 2020).

Regarding our topic, this article mainly refers to articles on the application of blockchain in the space supply chain. Luo & Choi (2022) adopted blockchain technology to enhance systems security and examined its affection on the government’s penalty system. Adhikari & Davis (2020) gave a clearly analysis on the implementation of blockchain in the area of space cybersecurity framework against global positioning system spoofing. Clark et al. (2020) developed a secure system by leveraging the distributed ledger technology of blockchain for satellite networks. This system achieves reduced latency when transmitting data across constellations and reduces the burden in terms of quality, power and cost for all users. Zheng et al. (2021) studied a three-tier space supply chain under the decision-making problem and investigated how blockchain technology optimizes decisions based on information sharing. Moreover, Hyland-Wood et al. (2020) examined three potential blockchain properties applied in space: real-time communication during the interplanetary space operating and operations realm of the solar system. Li et al. (2021) developed a framework based on blockchain technology which consists of an application layer, a contract and consensus layer, a data layer and a network layer to management the information of rocket and satellite launch.

2.3. Government subsidies

Government interventions in supply chain management include legislation (Gouda et al., 2016; Zhang & Zhang, 2018), penalties (Xiao & Xu, 2018; Luo & Choi, 2022), subsidies (Guo et al., 2019; Xiao et al., 2020; Jung & Feng, 2020) and taxes (Xu et al., 2018a; Chen et al., 2020). The stream of research closest to our work is exploring the adoption of government subsidies to promote industry growth or to support firms through difficult times.

In order to improve the social welfare and the manufacturers' profits, different types of subsidy programs has been launched by governments, such as subsidies to consumers, manufacturers, or both Yu et al. (2018). The authors of this article reveal the influencing factors that determine the optimal structure of government subsidy programs. They find that governments can develop subsidy programs involving multiple competing manufacturers to improve consumer welfare. However, the government subsidy system is not always effective. Hsu et al. (2019) find that the quality subsidy offered to the farmers quality subsidies provided to farmers may reduce not only the quality of dairy products, but also the profitability of companies. Berenguer et al. (2017) analyze the effectiveness of subsidies on a for-profit or a not-for profit firm in inducing consumption. Their study shows that the incentive to a not-for-profit counterpart is more stronger than to a for-profit firm to encourage consumption. Besides, Bai et al. (2021) investigate the design of trade-in subsidy programs by capturing the essence of the interaction between the government, the manufacturer, and consumers. They find that compared with a fixed-amount subsidy, a shared subsidy program in which government subsidies are proportional to manufacturer rebates is more effective in stimulating consumers to trade-in.

3. The case with insurance and government subsidy

To answer the first two RQs, the Model I is first presented to describe the common practice of a SSC which uses commercial insurance to hedge launch risk. Next, the Model I is extended to the Model G by introducing government subsidy, which @@@ The optimal decisions of entities under two models are compared in this section.

3.1. Model I: SSC with insurance

Consider an engineer-to-order SSC consisting of one vehicle manufacturer (VM, he), one satellite operator (SO, she) and an insurance company (IC, it). The interactions among them are illustrated in Figure 1.

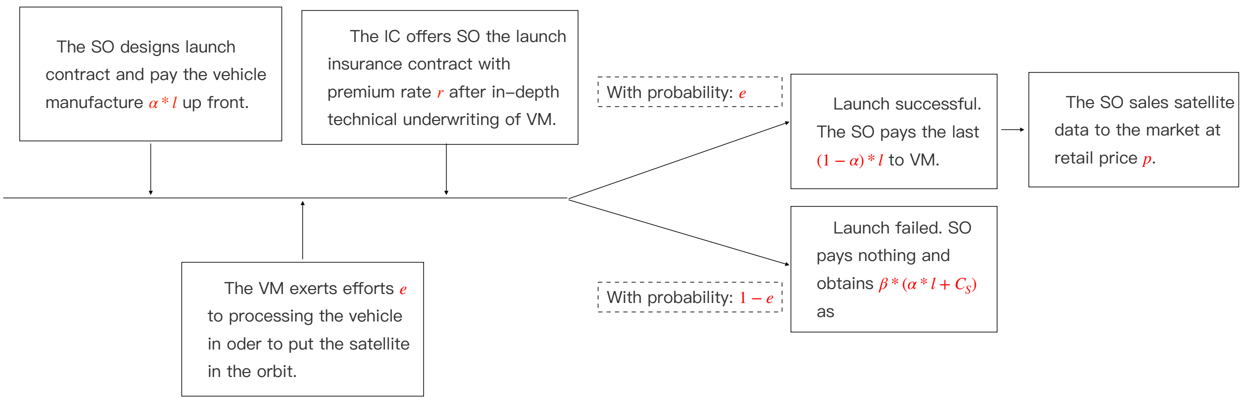


Figure 1: Sequence of events of model I. SO: satellite operator; VM: vehicle manufacture; IC: insurance company.

First, as in practice, the SO designs a launch service contract with launch price l and prepay ratio α, i.e., pay the VM αl up front (Andrews & Bonnema, 2011; Barschke, 2020). Second, as the follower, the VM decides whether to accept the contract. Following Tang et al. (2018), we scale the base launch success probability to 0. To increase the probability from 0 to e, where $e \in (0, 1)$, the VM needs to exert effort associated with a dis-utility ke^2 with $k > 0$. Third, the SO buys the launch insurance at the premium rate r to compensate the loss if the launch fails. Hence, the VM receives the remaining payment $(1-\alpha)l$, if the launch is successful; or 0, if the launch fails. Finally, once the satellite works in orbit, the SO can sell the data to the market at the retail price p. Without loss generality, data customers possess a stochastic valuation u towards the satellite data, which follows a distribution $f(u)$. Following most literature @@, we set $f(u)$ follows a uniform distribution, denoted by $U[0,1]$. To avoid facing messy mathematics, we normalize the consumer population as 1, and thus the market demand D^I is expressed as follows:

$$D^I = 1\int_p^1 f(u)\,\mathrm{d}u = 1 - p \tag{1}$$

Model I is a Stackelberg game that can be solved using backward induction. We summarize the notation used throughout the paper in Table 1.

Table 1: Notation

Variable	Remark
Model I	Satellite launch supply chain with insurance
Model IG	Satellite launch supply chain with government-subsidized insurance
Model B	Blockchain-embedded satellite launch supply chain with insurance
Model BG	Blockchain-embedded satellite launch supply chain with government-subsidized insurance
p	The satellite data retail price
l	The launching service price
α	The upfront payment ratio
e	The "rate of successful launch ", which is the same as "the level of effort the VM exerting" in this paper
k	The cost coefficient of effort
r	The premium rate
β	The claim ratio
g	The government-subsidized launch insurance premium rates
c_i	The cost of vehicle ($i=V$) or satellite ($i=S$)
θ	The penalty of a failed launch for VM
k	The effort cost factor
π_i	The profit of vehicle manufacture($i=V$) or satellite operator ($i=S$) or insurance company ($i=I$)
CS	The consumer surplus
SW	The social welfare

[a] Subscripts S, V and I denote the indices of SO, VM and IC respectively.

[b] Superscript I, IG, B and BG denote functions and decisions in model I, model IG, model B and model BG respectively.

3.1.1. *The VM's effort*

From the perspective of VM, a launch failure results in not only the current contract loss but also the damage of his reputation and future business as well as financing. To reflect the VM's additional loss, a penalty denoted by θ is adopted into his profit function π_V^I:

$$\max_e \mathbb{E}[\pi_V^I(l, p, e)] = \alpha l + (1-\alpha)el - (1-e)\theta - (ke^2 + c_V), \\ s.t.\ \pi_V^I \geq 0 \tag{2}$$

where c_V denotes the rocket cost. π_V^I can be divided into three parts: (1) the prepaid income and expected gain upon successful launch $\alpha l + (1-\alpha)el$; (2) the expected loss of failure penalty in the event of launch failure $(1-e)\theta$; and (3) the cost of effort and vehicle $ke^2 + c_V$.

The VM will reject the contract if the non-negative profit constraint is violated; otherwise, he decides the effort level e to maximize his profit π_V^I. By zeroing the first-order condition of Equation (2), the VM's best response (i.e., effort e) can be viewed as a function of launch price l:

$$e(l) = \tfrac{(1-\alpha)l+\theta}{2k}, \tag{3}$$

$$s.t.\quad 0 < e \leq 1. \tag{4}$$

By substituting Equation (3) into the VM's payoff π_V^I given in Equation (2), it can be obtained that:

$$\pi_V^I = \frac{[(1-\alpha)l+\theta]^2}{4k} + \alpha l - \theta - c_V \tag{5}$$

Hence, considering the VM's non-negative profit constraint, i.e., $\pi_V^I \geq 0$, the lowest VM's acceptance (VA) launch price can be written as:

$$l \geq l_{VA} \equiv \frac{2\omega - 2\alpha k - (1-\alpha)\theta}{(1-\alpha)^2}, \tag{6}$$

where $\omega = \sqrt{(1-\alpha)^2 k c_V + \alpha^2 k^2 - (1-\alpha)k\theta}$.

3.1.2. *The IC's premium rate*

After observing the contract price l selected by the SO, the insurance company can anticipate the VM's effort $e(l)$ as given in (3). Operating in a competitive market, the insurer sets its rate r

to its break-even point in expectation. In other words, under the rate r that it offers, the insurance company's expected payoff, $r(c_S + \alpha l)$, equals the amount of coverage, $(1-e)(c_S + \alpha l)\beta$. Thus the IC's profit function can be written as:

$$\pi_i^I = (c_S + \alpha l)r - (1-e)(c_S + \alpha l)\beta, \tag{7}$$

and its premium rate is also a function of l:

$$r(l) = \left[1 - \frac{(1-\alpha)l + \theta}{2k}\right]\beta. \tag{8}$$

3.1.3. The SO's optimal price

From the perspective of SO, her payoff π_S^I is a function of l, p, e, r to be maximized by deciding two prices: the launch price l and the data sale price p. In particular, her objective function is formulated as follows:

$$\max_{l,p} \mathbb{E}[\pi_S^I(l, p, e, r)] = epD^I - [\alpha + (1-\alpha)e]l - (c_S + \alpha l)r + (1-e)(c_S + \alpha l)\beta - c_S, \tag{9}$$

which consists of five parts: (1) the income of selling data once the satellite works in orbit epD^I; (2) the launch service price, i.e., $\alpha l + (1-\alpha)el + (1-e) \times 0 = [\alpha + (1-\alpha)e]l$; (3) the premium for the launch insurance $(c_S + \alpha l)r$; (4) the compensate she will receive from IC once the launch fails, $(1-e)(c_S + \alpha l)\beta$, where the insurance is assumed to cover β of the whole loss including the cost of satellite c_S and the prepay price αl; (5) the cost of building the satellite c_S. Without loss of generality, the data income covers its building and launch cost, i.e., the SO sets a contract only when $pD^I \geq c_S + l$.

Anticipating the VM's best response e given in (3) and the premium rate (8), the SO's payoff given in Equation (9) can be rewritten as:

$$\begin{aligned} \max_{p} \mathbb{E}[\pi_S^I(l, p)] = {} & \frac{[pD^I - (1-\alpha)l] \times [(1-\alpha)l + \theta]}{2k} - \alpha l - c_S, \\ & l \geq l_{VA}. \end{aligned} \tag{10}$$

Checking the Hessian matrix of SO's payoff, we find π_S^I is concave in l and p jointly when $0 < k < \frac{(1-\alpha)(1+4\theta)}{8\alpha}$. Hereafter, we assume that this in-equation always holds, then the optimal launch price and optimal retail price of the SO are

$$l_S = \frac{\phi - 8\theta(1-\alpha)}{8(1-\alpha)^2} \tag{11}$$

and $p^* = \frac{1}{2}$, where $\phi = (1-\alpha)(1+4\theta) - 8\alpha k$. Consider the VM's non-negative profit constraint, the SO aims to select the optimal contract price $l^* = \max(l_S, l_{VA})$ that maximizes her payoff π_S^I. The optimal contract and corresponding equilibrium outcomes are given in Lemma 3.1, in which the consumer surplus and social welfare are defined as follows:

$$
\begin{aligned}
CS^I &= 1\int_p^1 (u-p) f(u)\,\mathrm{d}u = \frac{(D^I)^2}{2}, \\
SW^I &= \pi_S^I + \pi_V^I + CS^I.
\end{aligned}
\tag{12}
$$

Lemma 3.1. *The equilibrium outcomes of Model I are shown in Table 2, in which $\phi = (1-\alpha)(1+4\theta) - 8\alpha k$ to avoid complicated writing.*

Table 2: The equilibrium outcomes in Model I.

	$c_V < H(\alpha)$ (i.e., $l_S > l_{VA}$)	$c_V \geq H(\alpha)$ (i.e., $I_{VA} \geq l_S$)
Effort of VM exerting e^*	$\frac{\phi}{16(1-\alpha)k}$	$\frac{\omega-\alpha k}{(1-\alpha)k}$
Launch price l^*	$l^* = l_S = \frac{\phi-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\omega-2\alpha k-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate r^*	$\beta(1-\frac{\phi}{16(1-\alpha)k})$	$\beta\frac{k-\omega}{(1-\alpha)k}$
SO's profit π_S^I	$\frac{\phi^2}{128(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S$	$\frac{(\omega-\alpha k)(\phi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S$
VM's profit π_V^I	$\frac{\phi^2+32\alpha k\phi}{256(1-\alpha)^2k} - \frac{\theta}{1-\alpha} - c_V$	0
Consumer surplus CS^I	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare SW^I	$\frac{3\phi^2+32\alpha k\phi}{256(1-\alpha)^2k} - \theta - c_S - c_V + \frac{1}{8}$	$\frac{(\omega-\alpha k)(\phi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S + \frac{1}{8}$

Because the launch price $l^* = \max(l_S, l_{VA})$ has two possible values, there are also two cases in our equilibrium result: $c_V < H(\alpha)$ and $c_V \geq H(\alpha)$, where $H(\alpha) = \frac{8(1-\alpha)[2\alpha k+\theta(1-\alpha)]+16\theta^2(1-\alpha)^2-192\alpha^2k^2-64\theta k(1-\alpha)(4-\alpha)}{256(1-\alpha)^2k}$. In the first case, the SO's optimal launch price l_S is higher than l_{VA}, which yields that $c_V < H(\alpha)$ by merging (6) and (11). In the second case, the SO's optimal launch price l_S is lower than l_{VA}, then the contract price l^* is l_{VA} to prevent negative profit for the VM; otherwise the VM will quit the SSC.

3.1.4. Sensitivity analysis

According to the equilibrium outcomes, we now conduct the sensitivity analyses for Model I and summarized the outcomes in Table 3.

Table 3: Sensitivity analyses for Model I and Model IG.

	Model	Situation	e^*	r^*	l^*	p^*	π_S	π_V	Consumer surplus	Social welfare
$k\uparrow$	Model I	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	–	$\downarrow (k < k_1)$ $\uparrow (k \geq k_1)$	$\downarrow$	–	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	–	$\downarrow$	–	–	$\downarrow$
	Model IG	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow (0 < g < 1)$ $- (g = 1)$	–	$\downarrow (k < k_2)$ $\uparrow (k \geq k_2)$	$\downarrow$	–	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	–				
$\theta\uparrow$	Model I	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	–	$\uparrow$	$\uparrow (\theta < \theta_{V1})$ $\downarrow (\theta \geq \theta_{V1})$	–	$\uparrow (\theta < \theta_{W1})$ $\downarrow (\theta \geq \theta_{W1})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	–	$\uparrow$	–	–	$\uparrow$
	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	–	$\uparrow$	$\uparrow (\theta < \theta_{V2})$ $\downarrow (\theta \geq \theta_{V2})$	–	$\uparrow (\theta < \theta_{W2})$ $\downarrow (\theta \geq \theta_{W2})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	–	$\uparrow$	–	–	$\uparrow$
$g\uparrow$	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	–	$\uparrow$	$\uparrow$	–	$\uparrow$
		$c_V \geq H(\alpha)$	–	–	–	–	$\uparrow$	–	–	$\uparrow$

To avoid complicated writing, we define $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$, $k_2 = \frac{(1-\alpha)\theta}{2\alpha(1-g)}$, $\theta_{V1} = \frac{8k-2\alpha k}{1-\alpha}$, $\theta_{V2} = \frac{8k-2\alpha k(1-g)}{1-\alpha}$, $\theta_{W1} = \frac{8k-6\alpha k}{3(1-\alpha)}$, $\theta_{W2} = \frac{8k-6\alpha k(1-g)}{3(1-\alpha)}$.

First, we explore how the cost coefficient of effort k affects the equilibrium outcomes mentioned above. If the cost coefficient of effort k increases:

- Independent of the manufacturing cost of the vehicle c_V, the effort exerted by the VM e and the launch price l will always decrease, the premium rate r will always increase, and the retail price p is constant;

- Depending on c_V: when $c_V < H(\alpha)$ (i.e. $l^* = l_S$), the launch price l will decrease; otherwise, it will increase. That is because the body who determines the launch price has changed. When $c_V < H(\alpha)$, it is the SO that decreases the contract price according to the decreasing effort e. But when $c_V \geq H(\alpha)$, the launch price equals the acceptance line which is determined by the VM, who will increase the contract price to compensate for the increasing effort cost.

- For the premium rate, the IC sets it according to the effort e, so it will increase with the decreasing successful launch probability.

- The VM's profit and social welfare always decrease.

- For the SO, in the situation $c_V < H(\alpha)$, her profit will increase when $k < k_1$, where $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$, otherwise π_S^I will decrease when $k \geq k_1$.

Second, we examine how penalty cost θ affects these optimal outcomes. If the failed-launch penalty θ increases:

- Independent of the manufacturing cost of the vehicle c_V, the effort exerted by the VM e and the launch price l will always increase (the VM has to exert more effort to increase the successful launch probability to avoid the expensive failed-launch penalty θ), the premium rate r will always decrease, and the retail price p is constant;

- Depending on c_V: when $c_V < H(\alpha)$ (i.e. $l^* = l_S$), the launch price l will still decrease with larger e, because the price-maker, the SO, has no motivation to increase the launch price l; in contrast, when $c_V \geq H(\alpha)$, the launch price l will increase, because the price-maker, the VM, has to increase the contract price to compensate for the increase of failed-launch penalty.

- For the premium rate, the IC sets it according to the effort e, so it will decrease with the increasing successful launch probability.

- The SO's profit always increases.

- For the VM and the society, in the situation $c_V < H(\alpha)$, their profits will increase when θ satisfies with $\theta < \theta_{V1}$ and $\theta < \theta_{W1}$, respectively, where $\theta_{V1} = \frac{8k-2\alpha k}{1-\alpha}$ and $\theta_{W1} = \frac{8k-6\alpha k}{3(1-\alpha)}$, otherwise they both will decrease; in the other situation $c_V \geq H(\alpha)$, π_S^I and SW will decreases.

3.2. Model IG: Satellite launch supply chain with government-subsidized insurance

Based on the practice of SSC and the satellite industry, we build model IG the government entity, which aims to promote the development of SSC by proposing an insurance subsidy program. The event sequence of model I is changed slightly: after the IC decides the premium rate r, the government will determine a subsidized rate g. The interactions among the SSC entities are illustrated in Figure 2, in which the only difference between model I and model IG is that the SO will obtain an insurance subsidy g.

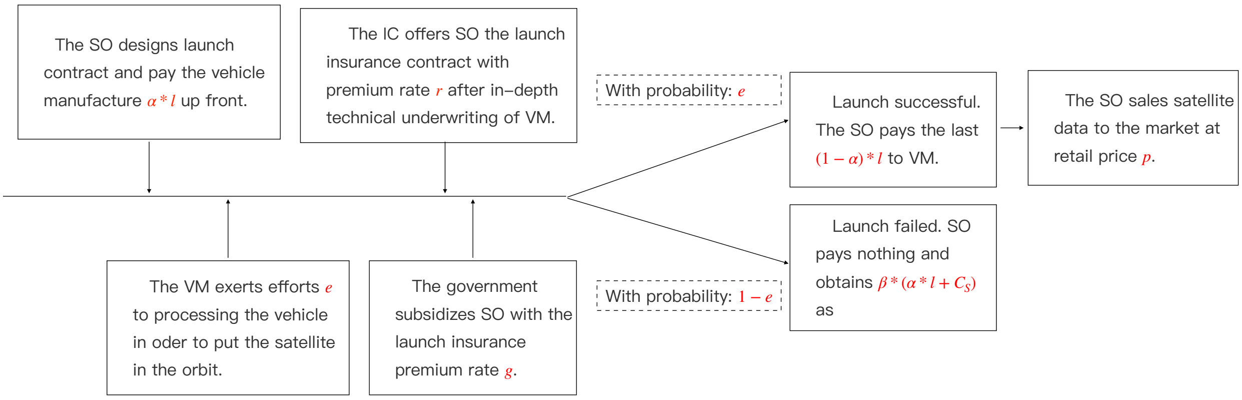


Figure 2: Sequence of events of model IG. SO: satellite operator; VM: vehicle manufacture; IC: insurance company.

The market demand is given as follows:

$$D^{IG} = 1 \int_p^1 f(u)\,\mathrm{d}u = 1 - p \tag{13}$$

Then the payoffs of all entities can be measured as follows:

$$\begin{aligned}
&\pi_S^{IG} = epD^{IG} - [\alpha + (1-\alpha)e]l - (r-g)(c_S + \alpha l) + (1-e)(c_S + \alpha l)\beta - c_S, \\
&\pi_i^{IG} = (c_S + \alpha l)r - (1-e)(c_S + \alpha l)\beta, \\
&\pi_V^{IG} = [\alpha + (1-\alpha)e]l - (1-e)\theta - (ke^2 + c_V), \\
s.t.\ &\pi_V^{IG} \geq 0
\end{aligned} \tag{14}$$

Following the similar derivation in Section 3.1, we obtain the equilibrium outcomes summarized in Lemma 3.2.

Lemma 3.2. *The equilibrium outcomes of Model IG are shown in Table 4, in which* $\psi = (1-\alpha)(1+4\theta) - 8\alpha k(1-g)$ *to avoid complicated writing.*

The optimal decisions of model IG are similar to that of model I, but there are three points worthy of notice.

- When $c_V < H(\alpha)$, both the successful launch probability e and launch price l increase as each has a positive increment, as $\psi > \phi$. The premium rate r will decrease due to government subsidy.

Table 4: The equilibrium outcomes in Model IG.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting e^*	$\frac{\psi}{16(1-\alpha)k}$	$\frac{\omega-\alpha k}{(1-\alpha)k}$
Launch price l^*	$l^* = l_S = \frac{\psi-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\omega-2\alpha k-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate r^*	$\beta(1-\frac{\psi}{16(1-\alpha)k})$	$\beta\frac{k-\omega}{(1-\alpha)k}$
SO's profit π_S^{IG}	$\frac{\psi^2}{128(1-\alpha)^2k}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S$	$\frac{(\omega-\alpha k)(\psi+8\alpha k-8\omega)}{4(1-\alpha)^2k}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S$
VM's profit π_V^{IG}	$\frac{\psi^2+32\alpha k\psi}{256(1-\alpha)^2k}-\frac{\theta}{1-\alpha}-c_V$	0
Consumer surplus CS^{IG}	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare SW^{IG}	$\frac{3\psi^2+32\alpha k\psi}{256(1-\alpha)^2k}-\frac{\theta[1-(1-g)\alpha]}{1-\alpha}-(1-g)c_S-c_V+\frac{1}{8}$	$\frac{(\omega-\alpha k)(\psi+8\alpha k-8\omega)}{4(1-\alpha)^2k}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S+\frac{1}{8}$

- When $c_V \geq H(\alpha)$, the successful launch probability, launch price, and the premium rate are independent of the government subsidy.

- The retail price remains unchanged, which means the government subsidy program doesn't affect the market retail price.

3.2.1. Sensitivity analysis

Regarding the sensitivity analysis, there are also three key findings.

First, if the cost coefficient of effort k increases, (i) when $0 < g < 1$, the launch price l will decrease in the first situation $c_V < H(\alpha)$; however, when $g = 1$ the launch price will not be affected by k; (ii) the threshold k_2 of SO's profit π_S^{IG} to change direction is higher than k_1, where $k_2 = \frac{(1-\alpha)\theta}{2\alpha(1-g)}$.

Second, if the launch-fail penalty θ increases, in the situation $c_V < H(\alpha)$, the thresholds of π_V^{IG} and SW^{IG}, θ_{V2} and θ_{W2} are both higher than these of model I, where $\theta_{V2} = \frac{8k-2\alpha k(1-g)}{1-\alpha}$ and $\theta_{W2} = \frac{8k-6\alpha k(1-g)}{3(1-\alpha)}$. That means the VM and society can bear a higher penalty when the government launch the subsidy program.

Third, if the subsidy rate g increases, (i) when $c_V < h(\alpha)$, the successful launch probability e and the launch price l will increase, the premium rate r will decrease; the SO's profit π_S^{IG}, the VM's profit π_V^{IG} and social welfare SW^{IG} will increase; (ii)when $c_V \geq H(\alpha)$, all of the optimal decisions are not affected. (iii) no matter in which situation, the consumer surplus do not change which means the government subsidy program can't benefit the customers.

3.2.2. *Values of government subsidies*

To further investigate the value of government subsidies, we define V_i^{IG} as the equilibrium changes of indicator i caused by government subsidies, where i can be the successful launch probability, the premium rate, the launch price, the retail price, SO's profit, VM's profit, customer surplus, or the social welfare:

$$V_x^{IG} = x^{IG} - x^I. \tag{15}$$

We report the results in Table 5. According to the sensitivity analysis, we obtain Proposition 3.1 and Proposition 3.2.

Table 5: Values of government subsidies.

Case	$V_{e^*}^{IG}$	$V_{r^*}^{IG}$	$V_{l^*}^{IG}$	$V_{p^*}^{IG}$	V_{SO}^{IG}	V_{VM}^{IG}	V_{CS}^{IG}	V_{SW}^{IG}
$c_V < H(\alpha)$	$\frac{8\alpha g}{16(1-\alpha)}$	$\frac{-8\beta\alpha g}{16(1-\alpha)}$	$\frac{\alpha g}{(1-\alpha)^2}$	0	$\frac{\psi^2-\phi^2}{128k(1-\alpha)^2} + \frac{g\alpha\theta}{1-\alpha} + gc_S$	$\frac{\psi^2-\phi^2+32\alpha k(\psi-\phi)}{256k(1-\alpha)^2}$	0	$\frac{3(\psi^2-\phi^2)+256\alpha kg[\alpha k+(1-\alpha)\theta]}{256k(1-\alpha)^2} + gc_S$
$c_V \geq H(\alpha)$	0	0	0	0	$g[\frac{(\omega-\alpha k)\alpha}{2(1-\alpha)^2} - \frac{\alpha\theta}{1-\alpha} + c_S]$	0	0	$g[\frac{(\omega-\alpha k)\alpha}{2(1-\alpha)^2} - \frac{\alpha\theta}{1-\alpha} + c_S]$

Proposition 3.1. *Given $\alpha,\ k,\ \theta,\ g$, then $e^{IG} > e^I$, $r^{IG} < r^I$, $l^{IG} > l^I$ if and only if $c_V < H(\alpha)$.*

Proposition 3.1 implies three findings when $c_V < H(\alpha)$. First, given k, θ, the launch insurance subsidy provided by the government can help to improve the successful launch probability e, and thus promote the development of satellite industry. Second, the subsidy also helps to decrease the launch insurance rate r. Since insurance rate is determined based on the break-even point of the IC, the larger the e, the smaller the r. Third, the launch price in model IG is also higher than that in model I, because SO is more willing to pay higher launch fees after receiving subsidies, and then the VM has the incentive to increase the probability of successful launches. However, the above findings do not hold when the SO chooses an expensive vehicle, i.e., $c_V > H(\alpha)$.

Proposition 3.2. *Given $\alpha,\ k,\ \theta,\ g$:*

(i) $\pi_S^{IG} > \pi_S^I$, $SW^{IG} > SW^I$.

(ii) $\pi_V^{IG} > \pi_V^I$ *if and only if* $c_V < H(\alpha)$

(iii) $CS^{IG} = CS^I$

Proposition 3.2 also indicates three points. First, given k, θ, and g, the profit of SO and the social welfare in Model IG are always higher than those in Model I, i.e., they always benefit from the government's insurance subsidy program. Second, the profit of VM in Model IG is higher than that in Model I if and only if $c_V < H(\alpha)$. The change of VM profit depends on the trade-off between higher effort cost and higher launch service income. However, when the cost of the vehicle is relatively high, the VM cannot benefit from the government subsidy. Third, the consumer surplus in Model IG equals that in Model I, implying that government subsidies have no impact on consumers.

To conclude, government subsidies help to improve the probability of successful launches, and to promote the formation of positive feedback in the commercial aviation industry. However, this "win-win" outcome depends on the cost of vehicle: it must be relatively inexpensive, i.e., $c_V < H(\alpha)$. Otherwise, if $c_V > H(\alpha)$, subsidies can only increase the profit of the SO, but the launch success rate can not be increased by government subsidies.

4. The case with blockchain technology

Another approach to help hedge the launch risk is adopting disruptive technologies, such as the blockchain technology (BCT). In practice, BCT affects the SSC in two ways. On the one hand, it provides a decentralized identity management with strong security features, which engenders trust among SSC members (including customers) in the quality of the information being shared (Babich & Hilary, 2020b). On the other hand, it improves the workflow efficiency of launch activities which helps to reduce the error rate, and thus increases the probability of successful launch. In a blockchain-embed launch platform proposed by IBM, as depicted in Figure 3, BCT is able to deal with order tracking, parts assembly, shipments, and other workflows for approvals, auditing, launch and control in SSC, which will help the VM save cost and increase launch success probability.

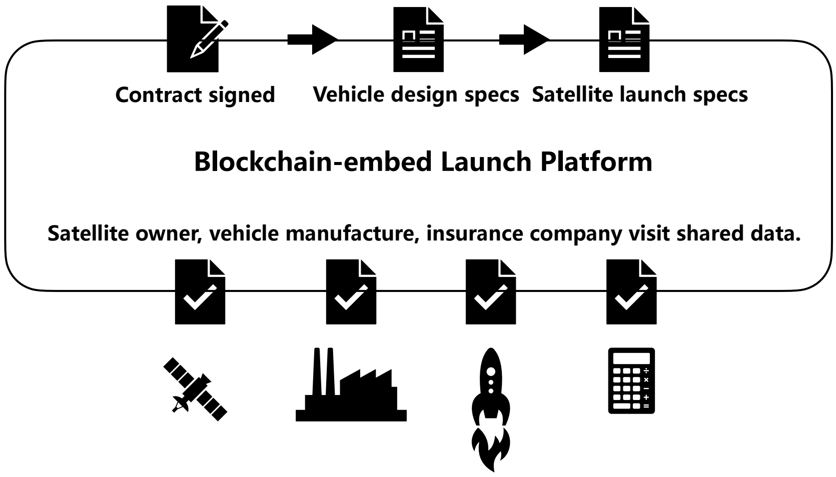


Figure 3: A blockchain-embed launch platform proposed by IBM, reproduced from source: Altaf (2019).

4.1. Model B: Blockchain-embedded SSC with insurance

Based on the above advantages of BCT, we assume that adopting BCT changes the origin model I in three ways (@@@ each add a citation):

- For customers, the benefits brought by BCT are characterized by factor b which will increase their utility. Hence the market demand can be written as follows:

$$D^B = 1 \int_{p-b}^{1} f(u)\,\mathrm{d}u = 1 - p + b \tag{16}$$

- For the VM, BCT decreases his effort cost exerting to improve the launch successfully probability from ke^2 to $k^B e^2$, where $0 < k^B < k$.

- The BCT platform, provided by a third party, charges the SO and VM for c_{SB} and c_{VB}, respectively.

Therefore, the SSC members' payoffs can be measured as follows:

$$\begin{aligned}
&\pi_S^B = epD^B - [\alpha + (1-\alpha)e]l - (c_S + \alpha l)r + (1-e)(c_S + \alpha l)\beta - c_S - c_{SB}, \\
&\pi_i^B = (c_S + \alpha l)r - (1-e)(c_S + \alpha l)\beta, \\
&\pi_V^B = [\alpha + (1-\alpha)e]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB}, \\
s.t.\ &\pi_V^B \geq 0
\end{aligned} \tag{17}$$

Using backward induction, we obtain Lemma 4.1.

Lemma 4.1. *The equilibrium outcomes of Model B are shown in Table 6, where* $\eta = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B$, $\mu = \sqrt{(1-\alpha)^2 k^B (c_V + c_{VB}) + \alpha^2 k^{B2} - (1-\alpha) k^B \theta}$.

Table 6: The equilibrium outcomes in Model B.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting e^*	$\frac{\eta}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price l^*	$l^* = l_S = \frac{\eta-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate r^*	$\beta(1-\frac{\eta}{16(1-\alpha)k^B})$	$\beta\frac{k^B-\mu}{(1-\alpha)k^B}$
SO's profit π_S^B	$\frac{\eta^2}{128(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$	$\frac{(\mu-\alpha k^B)(\eta+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$
VM's profit π_V^B	$\frac{\eta^2+32\alpha k^B\eta}{256(1-\alpha)^2k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus CS^B	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare SW^B	$\frac{3\eta^2+32\alpha k^B\eta}{256(1-\alpha)^2k^B} - \theta - c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b)^2}{8}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB} + \frac{(1+b)^2}{8}$

The equilibrium outcomes in Lemma 4.1 are similar to Lemma 3.1, but there are two notable differences. First, when $c_V < H(\alpha)$, both the successful launch probability e^* and launch price l^* are higher than those in Model I; in contrast, the premium rate r^* is lower than that in Model I. When $c_V \geq H(\alpha)$, the equilibrium outcomes of two models are compared in detail in Section 4.1.2. Second, although the retail price p^* is higher compared with Model I, the consumer surplus increases and only depends on b, no matter what the BCT cost is. In other words, adopting BCT always improves the consumer surplus.

4.1.1. Sensitivity analysis

We also obtain the sensitivity outcomes, reported in Table 3. By comparing the sensitivity analysis results of Model B and Model I, we identify three differences. First, if the effort cost coefficient increases, when $c_V < H(\alpha)$, there there exist a threshold $k_3 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8\alpha}$ so that the SO's profit decreases as k^B increases when $k^B < k_3$, otherwise π_S^{IG} decreases. Note that $k_3 > k_2$, which means BCT raises this threshold of the SO and affects her profits. Second, if the failed-launch penalty θ increases, when $c_V < H(\alpha)$, the VM's profit π_V and social welfare SW change with respect to θ_{V3} and θ_{W3} respectively, where $\theta_{V3} = \frac{32k^B-(1-\alpha)(1+b)^2-8\alpha k^B}{4(1-\alpha)}$ and $\theta_{W3} = \frac{32k^B-3(1-\alpha)(1+b)^2-24\alpha k^B}{12(1-\alpha)}$.

Table 7: Sensitivity analyses for Model I and Model B.

	Model	Situation	e^*	r^*	l^*	p^*	π_S	π_V	CS	SW
$k \uparrow$	Model I	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	–	$\downarrow (k < k_1)$	$\downarrow$	–	$\downarrow$
							$\uparrow (k \geq k_1)$			
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	–	$\downarrow$	–	–	$\downarrow$
	Model B	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	–	$\downarrow (k < k_3)$	$\downarrow$	–	$\downarrow$
							$\uparrow (k \geq k_3)$			
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	–				
$\theta \uparrow$	Model I	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	–	$\uparrow$	$\uparrow (\theta < \theta_{V1})$	–	$\uparrow (\theta < \theta_{W1})$
								$\downarrow (\theta \geq \theta_{V1})$		$\downarrow (\theta \geq \theta_{W1})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	–	$\uparrow$	–	–	$\uparrow$
	Model B	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	–	$\uparrow$	$\uparrow (\theta < \theta_{V3})$	–	$\uparrow (\theta < \theta_{W3})$
								$\downarrow (\theta \geq \theta_{V3})$		$\downarrow (\theta \geq \theta_{W3})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	–	$\uparrow$	–	–	$\uparrow$
$b \uparrow$	Model B	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	–	–	–	$\uparrow$	–	–	$\uparrow$	$\uparrow$

To avoid complicated writing, we define $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$, $k_3 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8\alpha}$, $\theta_{V1} = \frac{8k-2\alpha k}{1-\alpha}$, $\theta_{V3} = \frac{32k^B-(1-\alpha)(1+b)^2-8\alpha k^B}{4(1-\alpha)}$, $\theta_{W1} = \frac{8k-6\alpha k}{3(1-\alpha)}$, $\theta_{W3} = \frac{32k^B-3(1-\alpha)(1+b)^2-24\alpha k^B}{12(1-\alpha)}$.

It is worth noting that the implementation of blockchain technology actually reduces the threshold of punishment to change the profit trend which means that the penalty tolerated by the VM and society is reduced, that is, once $\theta > \theta_{V3}$ and $\theta > \theta_{W3}$ both profits of them will decrease. Third, if the benefits that blockchain brings to consumers b increases, all equilibrium outcomes increase when $c_V < H(\alpha)$, except the premium rate r^* that decreases. When $c_V < H(\alpha)$, both the consumer surplus and social welfare increase, even the retail price increases as well. Meanwhile, other indicators are not affected.

4.1.2. Values of adopting BCT

Similarly, we define the values of BCT by modeling V_x^B as follows:

$$V_x^B = x^B - x^I \tag{18}$$

We report the results in Table 8 and Table 9, then obtain Proposition 4.1 and Proposition 4.2, which give the condition for adopting BCT.

Proposition 4.1. *Given α, k^B, k, θ, b, then $e^B > e^I$, $r^B < r^I$, $l^B > l^I$, $p^B > p^I$.*

Table 8: Values of BCT on optimal decisions.

Situation	$V^B_{e^*}$	$V^B_{r^*}$	$V^B_{l^*}$	$V^B_{p^*}$
$c_V < H(\alpha)$	$\frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} > 0$	$-\beta\frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} < 0$	$\frac{(1-\alpha)(b^2+2b)+8\alpha(k-k^B)}{8(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$
$c_V \geq H(\alpha)$	$\frac{k\mu-k^B\omega}{kk^B(1-\alpha)} > 0$	$-\beta\frac{k\mu-k^B\omega}{kk^B(1-\alpha)} < 0$	$\frac{2(\mu-\omega)+2\alpha(k-k^B)}{(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$

Table 9: Values of BCT on members' payoffs.

Situation	V^B_{SO}	V^B_{VM}	V^B_{CS}	V^B_{SW}
$c_V < H(\alpha)$	$\frac{k\eta^2-k^B\phi^2}{128kk^B(1-\alpha)^2} - c_{SB}$	$\frac{k\eta^2-k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} - c_{VB}$	$\frac{b^2+2b}{8}$	$\frac{3k\eta^2-3k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_{SB} - c_{VB}$
$c_V \geq H(\alpha)$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} - c_{SB}$	0	$\frac{b^2+2b}{8}$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_{SB}$

Proposition 4.1 implies four points. First, the optimal effort exerted by the VM is higher after adopting BCT, which directly leads to a higher launch success probability. That also proves that BCT helps to improve work efficiency. Second, the premium rate decreases as the successful launch probability increases. Third, the launch price is higher with BCT, mainly because the probability of successful launch increases and the SO is willing to pay higher fees. Fourth, the retail price in Model B increases after adopting BCT, as the BCT utility motivates customers to pay a higher retail price.

Proposition 4.2. *Given α, k^B, k, θ, b:*

(i) *If $c_{SB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \min\{\frac{k\eta^2-k^B\phi^2}{128kk^B(1-\alpha)^2}, \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}\}$, then we have: $V^B_{SO} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$;*

(ii) *When $c_V < H(\alpha)$, if $c_{VB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{k\eta^2-k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2}$, then we have: $V^B_{VM} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$; when $c_V \geq H(\alpha)$, $V^B_{VM} \equiv 0$;*

(iii) *$V^B_{CS} > 0$;*

(iv) *When $c_V < H(\alpha)$, if $c_{SB} + c_{VB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{3k\eta^2-3k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, then we have $V^B_{SW} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$; when $c_V \geq H(\alpha)$, if $c_{SB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, then we have $V^B_{SW} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$.*

As shown above, Proposition 4.2 provides us four neat findings.

First, it computes the threshold of adopting BCT cost for the SO. When this cost is too high to be offset by extra retail revenue, launching through the BCT platform is not profitable. Actually, there are two different thresholds for the SO to decide if the BCT should be adopted in two situations. However, once BCT costs are pretty low, it is always profitable for the SO to use blockchain.

Second, it also yields the threshold and condition for the VM to adopt BCT. When $c_V < H(\alpha)$ and the cost of BCT is low, the VM is able to make a profit. When c_V is high, however, it is unprofitable for the VM to apply BCT ($V_{VM}^B \equiv 0$), as the launch price, offered by the SO, equals his acceptance level.

Third, the consumer surplus increases with the adoption of BCT, although they have to pay higher data retail prices.

Fourth, as shown in Proposition 4.2, the social welfare will be improved with the adoption of BCT, as long as the cost of using BCT is lower than a specific threshold.

To conclude, the successful launch probability is always improved by the BCT in model BG, no matter if the SO chooses a cost-effective vehicle or not. This is a significant difference compared with the impacts of government subsidies in Proposition 3.1. Besides, the BCT helps achieve an all-win situation for SSC members when the cost of BCT is relatively low. Therefore, the government may consider providing financial support for sponsoring BCT-embedded SSC to improve the successful launch rate and achieve an all-win situation.

4.2. Model BG: Blockchain-embedded SSC with government-subsidized insurance

In this section, we investigate the case when both government subsidies and BCT are applied in the SSC, which is represented by Model BG as follows:

$$\begin{aligned}
\pi_S^{BG} &= epD^{BG} - [\alpha + e(1-\alpha)]l - r(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB}, \\
\pi_S^{BG} &= (r - g)(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\
\pi_V^{BG} &= [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB}, \\
s.t.\ \pi_V^B &\geq 0
\end{aligned} \tag{19}$$

Again, we conduct backward induction and obtain Lemma 4.2.

Lemma 4.2. *The equilibrium outcomes of Model BG are shown in Table 10.*

Compared with the equilibrium outcomes in Lemma 3.2 (Model IG), the results of Model BG are different in two aspects: First, the premium rate r is lower than that in Model IG; while the

Table 10: The equilibrium outcomes in Model BG.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting e^*	$\frac{\lambda}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price l^*	$l^* = l_S = \frac{\lambda-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate r^*	$\beta(1-\frac{\lambda}{16(1-\alpha)k^B})$	$\beta\frac{k-\mu}{(1-\alpha)k^B}$
SO's profit π_S^{BG}	$\frac{\lambda^2}{128(1-\alpha)^2k^B}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S-c_{SB}$	$\frac{(\mu-\alpha k^B)(\lambda+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S-c_{SB}$
VM's profit π_V^{BG}	$\frac{\lambda^2+32\alpha k^B\lambda}{256(1-\alpha)^2k^B}-\frac{\theta}{1-\alpha}-c_V-c_{VB}$	0
Consumer surplus CS^{BG}	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare SW^{BG}	$\frac{3\lambda^2+32\alpha k^B\lambda}{256(1-\alpha)^2k^B}-\frac{\theta[1-(1-g)\alpha]}{1-\alpha}-(1-g)c_S-c_V-c_{SB}-c_{VB}+\frac{(1+b)^2}{8}$	$\frac{(\mu-\alpha k^B)(\lambda+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B}+\frac{(1-g)\alpha\theta}{1-\alpha}-(1-g)c_S-c_{SB}+\frac{(1+b)^2}{8}$

To avoid complicated writing, we define $\lambda = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B(1-g)$, $\mu = \sqrt{(1-\alpha)^2k^B(c_V+c_{VB}) + \alpha^2{k^B}^2 - (1-\alpha)k^B\theta}$.

successful launch probability e and the launch price l are higher, because k^B is less than k (smaller denominator) and $\lambda > \psi$ (larger numerator). Second, although the retail price p is higher than that in Model IG, the consumer surplus eventually increases due to a greater increase in market demand with the adoption of BCT.

4.2.1. Sensitivity analysis

The sensitivity outcomes in model BG are reported in Table 11.

Regarding the sensitivity analysis results, three differences between Model BG and Model IG are noted. First, if the effort cost coefficient increases, when $c_V < H(\alpha)$, there there exist a threshold $k_4 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8(1-g)\alpha}$ so that the SO's profit decreases as k^B increases when $k^B < k_4$, otherwise π_S^{BG} increases. Note that $k_3 > k_2$, which means BCT raises the threshold of the SO and affects her profits. Second, if the failed-launch penaltyθ increase, when $c_V < H(\alpha)$, the VM's profit π_V and social welfare SW change with respect to θ_{V4} and θ_{W4} respectively, where $\theta_{V4} = \frac{32k^B-(1-\alpha)(1+b)^2-8(1-g)\alpha k^B}{4(1-\alpha)}$ and $\theta_{W4} = \frac{32k^B-3(1-\alpha)(1+b)^2-24(1-g)\alpha k^B}{12(1-\alpha)}$. Similarly, once $\theta > \theta_{V4}$ and $\theta > \theta_{W4}$, both profits of them will decrease. @@@

In addition, compared to 3, government subsidies also play a role and have the same effect on model IG and model BG. (i) Firstly, in the case of $c_V < H(\alpha)$,when $0 < g < 1$, the launch price in both models will decrease with k. However, once $g = 1$, l will no longer vary with k. In other words, when the government subsidy covers the full insurance, the launch price is no longer affected by the cost of effort. (ii) Secondly, government subsidies have improved supply

Table 11: Sensitivity analyses for Model IG and Model BG.

	Model	Situation	e^*	r^*	l^*	p^*	π_S	π_V	CS	SW
$k\uparrow$	Model IG	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow (0 < g < 1)$ $-\ (g = 1)$	$-$	$\downarrow (k < k_2)$ $\uparrow (k \geq k_2)$	$\downarrow$	$-$	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	$-$	$\downarrow$	$-$	$-$	$\downarrow$
	Model BG	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow (0 < g < 1)$ $-\ (g = 1)$	$-$	$\downarrow (k < k_4)$ $\uparrow (k \geq k_4)$	$\downarrow$	$-$	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	$-$				
$\theta\uparrow$	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	$-$	$\uparrow$	$\uparrow (\theta < \theta_{V2})$ $\downarrow (\theta \geq \theta_{V2})$	$-$	$\uparrow (\theta < \theta_{W2})$ $\downarrow (\theta \geq \theta_{W2})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
	Model BG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	$-$	$\uparrow$	$\uparrow (\theta < \theta_{V4})$ $\downarrow (\theta \geq \theta_{V4})$	$-$	$\uparrow (\theta < \theta_{W4})$ $\downarrow (\theta \geq \theta_{W4})$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
$b\uparrow$	Model BG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	$-$	$-$	$-$	$\uparrow$	$-$	$-$	$\uparrow$	$\uparrow$
$g\uparrow$	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$	$-$	$\uparrow$
		$c_V > H(\alpha)$	$-$	$-$	$-$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
	Model BG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$	$-$	$\uparrow$
		$c_V > H(\alpha)$	$-$	$-$	$-$	$-$	$\uparrow$	$-$	$-$	$\uparrow$

To avoid complicated writing, we define $k_2 = \frac{(1-\alpha)\theta}{2(1-g)\alpha}$, $k_4 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8(1-g)\alpha}$, $\theta_{V2} = \frac{8k-2(1-g)\alpha k}{1-\alpha}$, $\theta_{V4} = \frac{32k^B-(1-\alpha)(1+b)^2-8(1-g)\alpha k^B}{4(1-\alpha)}$, $\theta_{W2} = \frac{8k-6(1-g)\alpha k}{3(1-\alpha)}$, $\theta_{W4} = \frac{32k^B-3(1-\alpha)(1+b)^2-24(1-g)\alpha k^B}{12(1-\alpha)}$.

chain performance for both model IG and BG. Specifically, when $c_V < H(\alpha)$, as government subsidies increase, the probability of a successful launch increases, premium rate decreases, launch price rises, revenues increase for both SO and VM, and social welfare increases. However, when $c_V > H(\alpha)$, government subsidies only serves to enhance the SO's profit and social welfare.

4.2.2. Values of applying both BCT and government subsidies

After deriving the equilibrium decisions in SSC under Models G and Model BG, we now explore the values of BCT with government subsidies, which is defined as follows:

$$V_x^{BG} = x^{BG} - x^{IG} \tag{20}$$

By comparing Model BG and Model IG, we report the results in Table 12 and Table 13 which leading to Proposition 4.3 and Proposition 4.4.

Proposition 4.3. *Given k^B, k, θ, g, b, then $e^{BG} > e^{IG}$, $r^{BG} < r^{IG}$, $l^{BG} > l^{IG}$, $p^{BG} > p^{IG}$.*

The above results in Proposition 4.3 are similar to those in Proposition 4.1. For given k^B, k, θ, g, and b, under the government subsidies, the BCT helps to increase the probability of successful launch e, the retail price p, and decrease the premium rate r. When the cost of vehicle is high, the effect of blockchain in increasing launch price is weakened by $\frac{\alpha g(k-k^B)}{(1-\alpha)^2}$ as shown in Table 14, compared with the case without subsidies.

Proposition 4.4. *Given k^B, k, θ, g, b:*

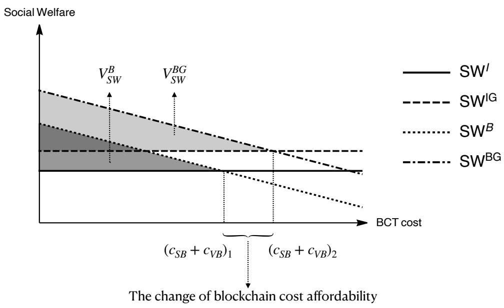
(i) *If $c_{SB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \min\{\frac{k\lambda^2 - k^B\psi^2}{128kk^B(1-\alpha)^2}, \frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}\}$, then we have: $V_{SO}^{BG} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$;*

(ii) *When $c_V < H(\alpha)$, if $c_{VB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{k\lambda^2 - k^B\psi^2 + 32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2}$, for $c_V < H(\alpha)$ then we have: $V_{VM}^{BG} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$; when $c_V \geq H(\alpha)$, $V_{VM}^{BG} \equiv 0$*

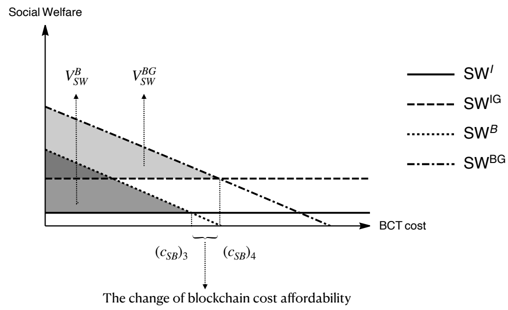
(iii) $V_{CS}^{BG} > 0$

(iv) *When $c_V < H(\alpha)$, if $c_{SB} + c_{VB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{3k\lambda^2 - 3k^B\psi^2 + 32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, then we have $V_{SW}^{BG} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$; when $c_V \geq H(\alpha)$, if $c_{SB} \begin{pmatrix} < \\ = \\ > \end{pmatrix} \frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, then we have $V_{SW}^{BG} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$.*

Compared with Model IG, the BCT in Model BG helps to increase the profit of SO and the welfare of society when the cost of BCT is not high. For the VM, when $c_V < H(\alpha)$, he will benefit from the adoption of inexpensive BCT. But he will not adopt BCT if it is too costly. For customers, the consumer surplus will be higher once the BCT is adopted.



(a) $C_V < H(\alpha)$



(b) $C_V \geq H(\alpha)$

Figure 4: The value of blockchain for social welfare with (i.e., V_{SW}^{GB}: the light grey area with the overlapping part enclosed by line SW^{IG} and line SW^{BG}) and without government subsidies (i.e., V_{SW}^{B}: the dark grey area with the overlapping part enclosed by line SW^{I} and line SW^{B}), when $k = 0.8$, $k^B = 0.6$, $c_V = 0.01$, $c_S = 0.1$, $\theta = 0.5$, $b = 0.9$, $g = 0.5$, $\alpha = 0.2$, $(c_{SB} + c_{VB})_1 = \frac{3k\eta^2 - 3k^B\phi^2 + 32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, $(c_{SB} + c_{VB})_2 = \frac{3k\lambda^2 - 3k^B\psi^2 + 32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, $(c_{SB})_3 = \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)] - k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, $(c_{SB})_4 = \frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)] - k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$.

Note that the BCT-adoption thresholds given by Proposition 4.4 are higher than those listed in Proposition 4.2. This means, government subsidies help improve the affordability of the BCT. From another point of view, BCT adoption also amplifies the efficiency of government subsidies, according to the amplifications shown in Table 15.

In conclusion, compared with the government subsidies case (Model IG), adopting BCT under government subsidies can increase the successful launch probability, and achieve an all-win situation where all SSC members benefit from low-cost BCT. Besides, compared with the value of BCT without subsidies (V_x^B), the affordability of BCT will be improved by government subsidies, and the increase in launch price will lower, which means the value of the government will be magnify as shown in Figure 4 (e.t., $(c_{SB} + c_{VB})_2 > (c_{SB} + c_{VB})_1$ and $(c_{SB})_4 > (c_{SB})_3$). It implies that government subsidies are more likely to be preferred after adopting BCT.

Table 12: Values of BCT with government subsidies on optimal decisions.

	Situation	$V_{e^*}^{BG}$	$V_{r^*}^{BG}$	$V_{l^*}^{BG}$	$V_{p^*}^{BG}$
Value	$c_V < H(\alpha)$	$\frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} > 0$	$-\beta\frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} < 0$	$\frac{(1-\alpha)(b^2+2b)+8\alpha(1-g)(k-k^B)}{8(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$
	$c_V \geq H(\alpha)$	$\frac{k\mu-k^B\omega}{kk^B(1-\alpha)} > 0$	$-\beta\frac{k\mu-k^B\omega}{kk^B(1\alpha)} < 0$	$\frac{2(\mu-\omega)+2\alpha(k-k^B)}{(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$

Table 13: Values of BCT with government subsidies on members' payoffs.

	Situation	V_{SO}^{BG}	V_{VM}^{BG}	V_{CS}^{BG}	V_{SW}^{BG}
Value	$c_V < H(\alpha)$	$\frac{k\lambda^2-k^B\psi^2}{128kk^B(1-\alpha)^2} - c_{SB}$	$\frac{k\lambda^2-k^B\psi^2+32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} - c_{VB}$	$\frac{b^2+2b}{8}$	$\frac{3k\lambda^2-3k^B\psi^2+32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_{SB} - c_{VB}$
	$c_V \geq H(\alpha)$	$\frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} - c_{SB}$	0	$\frac{b^2+2b}{8}$	$\frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_S$

Table 14: The increases in the value of BCT on optimal decisions under government subsidies.

	Situation	$\Delta V_{e^*}^{B}$	$\Delta V_{r^*}^{B}$	$\Delta V_{l^*}^{B}$	$\Delta V_{p^*}^{B}$
ΔValue	$c_V < H(\alpha)$	0	0	$\frac{-\alpha g(k-k^B)}{(1-\alpha)^2} < 0$	0
	$c_V \geq H(\alpha)$	0	0	0	0

Table 15: The increases in the value of BCT on on members' payoffs under government subsidies.

	Situation	ΔV_{SO}^{B}	ΔV_{VM}^{B}	ΔV_{CS}^{B}	ΔV_{SW}^{B}
ΔValue	$c_V < H(\alpha)$	$\frac{\alpha g[(1-\alpha)b^2+2(1-\alpha)b+4\alpha(2-g)(k-k^B)]}{8(1-\alpha)^2} > 0$	$\frac{\alpha g[(1-\alpha)b^2+2(1-\alpha)b-4\alpha(2+g)(k-k^B)]}{16(1-\alpha)^2} > 0$	0	$\frac{\alpha g[3(1-\alpha)b^2+6(1-\alpha)b+4\alpha(2-3g)(k-k^B)]}{16(1-\alpha)^2} > 0$
	$c_V \geq H(\alpha)$	$\frac{2\alpha g[\alpha(k-k^B)-\omega+\mu]}{(-1+\alpha)^2} > 0$	0	0	$\frac{2\alpha g[\alpha(k-k^B)-\omega+\mu]}{(-1+\alpha)^2} > 0$

5. Extended models

5.1. Marginal cost of adopting BCT

In the models above, we assume the cost of BCT is a lump sum neglecting the marginal cost of BCT to acquire and store data, which may not be accurate in practice. Thus, we extend the blockchain models considering the marginal cost of adopting BCT denoted by c. We verify the robustness of our findings by exploring two cases that (i) blockchain-embedded satellite launch supply chain with insurance (Model B-c) (ii) blockchain-embedded satellite launch supply chain with government-subsidized insurance (Model BG-c).

5.1.1. Model B-c

According to the setting, the market demand of Model B-c can be written as follows:

$$D^{B-c} = 1 \int_{p^{B-c}-b}^{1} f(u)\,\mathrm{d}u = 1 - p^{B-c} + b \tag{21}$$

Therefore, the members' payoffs can be measured as follows:

$$\begin{aligned}
&\pi_S^{B-c} = e(p-c)D^{B-c} - [\alpha + e(1-\alpha)]l - (r-g)(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB},\\
&\pi_I^{B-c} = r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l),\\
&\pi_V^{B-c} = [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB},\\
&s.t.\ \pi_V^{B-c} \geq 0.
\end{aligned} \tag{22}$$

Note, the only difference between Model B-c and Model B is that the BCT's marginal cost occurs to SO. We solve the derivation and summarize the outcomes in Table 16.

To explore the effect of blockchain marginal cost on the equilibrium outcomes, we compare Model B-c with Model B and obtain Proposition 5.1.

Proposition 5.1. *Under Model B-c, the satellite launch supply chain adopts the BCT with insurance considering the marginal cost of BCT.*

Compared with Model B, (i) when $c_V < H(\alpha)$, (a) $e^{B-c} < e^B$, $l^{B-c} < l^B$, $r^{B-c} > r^B$, $p^{B-c} > p^B$; (b) if $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\eta}{1-\alpha}}$, $\pi_S^{B-c} > \pi_S^B$; otherwise, $\pi_S^{B-c} \leq \pi_S^B$; if $0 < c < 1 + b -$

Table 16: The equilibrium outcomes in Model B-c.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting e^*	$\frac{\eta-C}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price l^*	$l^* = l_S = \frac{\eta-8\theta(1-\alpha)-C}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1+b+c}{2}$	$\frac{1+b+c}{2}$
Premium rate r^*	$\beta(1-\frac{\eta-C}{16(1-\alpha)k^B})$	$\beta\frac{k^B-\mu}{(1-\alpha)k^B}$
SO's profit π_S^{B-c}	$\frac{\eta^2-C(C-2\eta)}{128(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$	$\frac{(\mu-\alpha k^B)(\eta+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$
VM's profit π_V^{B-c}	$\frac{\eta^2+32\alpha k^B\eta-C(C-2\eta-32\alpha k^B)}{256(1-\alpha)^2k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus CS^{B-c}	$\frac{(1+b-c)^2}{8}$	$\frac{(1+b-c)^2}{8}$
Social welfare SW^{B-c}	$\frac{3\eta^2+32\alpha k^B\eta-C(3C-6\eta-32\alpha k^B)}{256(1-\alpha)^2k^B} - \theta - c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b-c)^2}{8}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB} + \frac{(1+b-c)^2}{8}$

To avoid complicated writing, we define $\eta = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B$, $\mu = \sqrt{(1-\alpha)^2k^B(c_V+c_{VB}) + \alpha^2{k^B}^2 - (1-\alpha)k^B\theta}$, $C = (1-\alpha)c(2+2b-c)$.

$\sqrt{\frac{(1-\alpha)(1+b)^2-2(\eta+16\alpha k^B)}{1-\alpha}}$, *$\pi_V^{B-c} > \pi_V^B$; otherwise, $\pi_V^{B-c} \leq \pi_V^B$; $CS^{B-c} < CS^B$; if* $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-2(3\eta+16k^B)}{3(1-\alpha)}}$, *$\pi_{SW}^{B-c} > \pi_{SW}^B$; otherwise, $\pi_{SW}^{B-c} \leq \pi_{SW}^B$;*

(ii) when $c_V \geq H(\alpha)$, (a) $e^{B-c} = e^B$, $l^{B-c} = l^B$, $r^{B-c} = r^B$, $p^{B-c} > p^B$; (b) $\pi_S^{B-c} < \pi_S^B$; $\pi_V^{B-c} = \pi_V^B =$ 0*; $CS^{B-c} < CS^B$; $\pi_{SW}^{B-c} < \pi_{SW}^B$.*

Proposition 5.1 indicates the effect of marginal cost of BCT by comparing Model B-c and Model B and give us new findings. It implies that in the case of $c_V < H(\alpha)$, the presence of the BCT marginal cost in the satellite launch supply chain means that SO prefers to pay a lower launch price, the VM exerts less effort to make the launch successful, the SO has to bear higher insurance rates, and consumers suffer a higher retail price. Since the marginal cost of BCT can lead to both an increase in retail price and a decrease in market demand, there exists thresholds regarding c for comparing members' profits between Model B-c and Model B. The tradeoff between the higher retail price and the lower market demand affects the change in total profit eventually. In the first case ($c_V < H(\alpha)$), when the marginal cost is low, the supply chain participants in Model B-c have higher returns. Once the marginal cost exceeds a certain threshold, the payoffs of participants in Model B-c are lower than those in Model B. For consumers, once the marginal cost exists, consumer surplus is impaired because they need to pay a higher retail price.

However, when the SO chooses an expensive vehicle ($c_V \geq H(\alpha)$), only the retail price is higher than that in Model B, and the others are equal to that in Model B, which do not affect by c. This is because the VM sets the launch price instead of the SO in this scenario. Therefore, transferring the marginal cost of BCT to consumers is the only way for the SO to make a profit. This treatment is similar to transferring the variable price per product unit in a traditional supply chain. For the payoff, all participants except the VM suffer a loss of profits due to the presence of marginal costs. The VM only maintains break-even in this scenario, the same as Model B.

Further, to explore whether the value of BCT to the launch supply chain changes after considering marginal costs, i.e., to verify the robustness of Proposition 4.1 and Proposition 4.2, we conduct comparison between Models B-c and Model I nextly.

Proposition 5.2. *Under Model B-c, the satellite launch supply chain adopts the BCT with insurance considering the marginal cost of BCT.*

Compared with Model I, (i) when $c_V < H(\alpha)$, *(a) if* $0 < c < 1 + b - \sqrt{\frac{(1+4\theta)k^B}{k} - 4\theta}$, $e^{B-c} > e^I$, $r^{B-c} < r^I$; *otherwise,* $e^{B-c} \leq e^I$, $r^{B-c} \geq r^I$; *if* $0 < c < 1 + b - \sqrt{1 - \frac{8\alpha(k-k^B)}{1-\alpha}}$, $l^{B-c} > l^I$; *otherwise,* $l^{B-c} \leq l^I$; *if* $0 < c < b$, $p^{B-c} > p^I$, *otherwise,* $p^{B-c} \leq p^I$ *(b) if* $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2 - 2\eta}{1-\alpha}}$ *and* $c_{SB} < \frac{k\eta^2 - k^B\phi^2}{128kk^B(1-\alpha)^2}$, $\pi_S^{B-c} > \pi_S^I$; *otherwise,* $\pi_S^{B-c} \leq \pi_S^I$; *if* $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2 - 2\eta - 32\alpha k^B}{1-\alpha}}$ *and* $c_{VB} < \frac{k\eta^2 - k^B\phi^2 + 32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2}$, $\pi_V^{B-c} > \pi_V^I$; *otherwise,* $\pi_V^{B-c} \leq \pi_V^I$; *if* $0 < c < b$, $CS^{B-c} > CS^I$; *otherwise,* $CS^{B-c} \leq CS^I$; *if* $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2 - 6\eta - 32\alpha k^B}{3(1-\alpha)}}$ *and* $c_{SB} + c_{VB} < \frac{3k\eta^2 - 3k^B\phi^2 + 32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$, $SW^{B-c} > SW^I$; *otherwise,* $SW^{B-c} \leq SW^I$.

(ii) when $c_V \geq H(\alpha)$, *(a)* $e^{B-c} > e^I$, $l^{B-c} > l^I$, $r^{B-c} < r^I$; *if* $0 < c < b$, $p^{B-c} > p^I$; *otherwise,* $p^{B-c} \leq p^I$; *(b) if* $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta - 8(\mu-\alpha k^B)] - k^B(\omega-\alpha k)[\phi - 8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$, $\pi_S^{B-c} > \pi_S^I$; *otherwise,* $\pi_S^{B-c} \leq \pi_S^I$; $\pi_V^{B-c} = \pi_V^I = 0$; *if* $0 < c < b$, $CS^{B-c} > CS^I$; *otherwise,* $CS^{B-c} \leq CS^I$; *if* $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta - 8(\mu-\alpha k^B)] - k^B(\omega-\alpha k)[\phi - 8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$ *and* $0 < c < b$, $\pi_{SW}^{B-c} > \pi_{SW}^I$; *otherwise,* $\pi_{SW}^{B-c} \leq \pi_{SW}^I$.

Proposition 5.2 shows that when the BCT variation cost is within a certain interval, comparing Model B-c and Model I, the launch success probability increases, the launch price increases, the retail price increases, and the insurance rate decreases. This result is the same as the outcomes in Proposition 4.1 (comparing Model B with Model I).

Moreover, by comparing the members' profits in Model B-c and Model I, we also find that when the marginal cost c under a threshold and the cost of BCT is low, all the members will benefit from adopting BCT.

Therefore, by comparing Model B-c and Model I in Proposition 5.2, our findings on the value of BCT are proved to be robust.

5.1.2. Model BG-c

Similar to Model BG, we build Model BG-c considering the marginal cost of BCT, which can be written as follows:

$$D^{BG-c} = 1 \int_{p^{BG-c}-b}^{1} f(u)\,\mathrm{d}u = 1 - p^{BG-c} + b \tag{23}$$

Therefore, the members' payoffs can be measured as follows:

$$\begin{aligned}
&\pi_S^{BG-c} = e(p-c)D^{BG-c} - [\alpha + e(1-\alpha)]l - (r-g)(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB},\\
&\pi_I^{BG-c} = r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l),\\
&\pi_V^{BG-c} = [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB},\\
&s.t.\ \pi_V^{BG-c} \geq 0.
\end{aligned} \tag{24}$$

Note, the only difference between Model BG-c and Model BG is that the BCT's marginal cost occurs to SO. We solve the derivation and summarize the outcomes in Table 17.

To explore the effect of blockchain marginal cost on the equilibrium outcomes under government subsidies, we compare model BG-c with Model BG and obtain Proposition 5.3.

Proposition 5.3. *Under Model BG-c, the satellite launch supply chain adopts the BCT with government-subsidies insurance considering the marginal cost of BCT.*

Compared with Model BG, (i) when $c_V < H(\alpha)$, (a) $e^{BG-c} < e^{BG}$, $l^{BG-c} < l^{BG}$, $r^{BG-c} > r^{BG}$, $p^{BG-c} > p^{BG}$; (b) if $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda}{1-\alpha}}$, $\pi_S^{BG-c} > \pi_S^{BG}$; otherwise, $\pi_S^{BG-c} \leq \pi_S^{BG}$; if $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2(\lambda+16\alpha k^B)}{1-\alpha}}$, $\pi_V^{BG-c} > \pi_V^{BG}$; otherwise, $\pi_V^{BG-c} \leq \pi_V^{BG}$; $CS^{BG-c} < CS^{BG}$; if $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-6\lambda-32k^B}{3(1-\alpha)}}$, $\pi_{SW}^{BG-c} > \pi_{SW}^{BG}$; otherwise, $\pi_{SW}^{BG-c} \leq \pi_{SW}^{BG}$; (ii) when $c_V \geq H(\alpha)$,

Table 17: The equilibrium outcomes in Model BG-c.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting e^*	$\frac{\lambda - C}{16(1-\alpha)k^B}$	$\frac{\mu - \alpha k^B}{(1-\alpha)k^B}$
Launch price l^*	$l^* = l_S = \frac{\lambda - 8\theta(1-\alpha) - C}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu - 2\alpha k^B - (1-\alpha)\theta}{(1-\alpha)^2}$
Retail price p^*	$\frac{1+b+c}{2}$	$\frac{1+b+c}{2}$
Premium rate r^*	$\beta(1 - \frac{\lambda - C}{16(1-\alpha)k^B})$	$\beta \frac{k^B - \mu}{(1-\alpha)k^B}$
SO's profit π_S^{B-c}	$\frac{\lambda^2 - C(C-2\lambda)}{128(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB}$	$\frac{(\mu - \alpha k^B)(\lambda + 8\alpha k^B - 8\mu - C)}{4(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_S$
VM's profit π_V^{B-c}	$\frac{\lambda^2 + 32\alpha k^B \lambda - C(C - 2\lambda - 32\alpha k^B)}{256(1-\alpha)^2 k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus CS^{B-c}	$\frac{(1+b-c)^2}{8}$	$\frac{(1+b-c)^2}{8}$
Social welfare SW^{B-c}	$\frac{3\lambda^2 + 32\alpha k^B \lambda - C(3C - 6\lambda - 32\alpha k^B)}{256(1-\alpha)^2 k^B} - \frac{\theta[1-(1-g)\alpha]}{1-\alpha} - (1-g)c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b-c)^2}{8}$	$\frac{(\mu - \alpha k^B)(\phi + 8\alpha k^B - 8\mu - C)}{4(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB} +$

To avoid complicated writing, we define $\lambda = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B$, $\mu = \sqrt{(1-\alpha)^2 k^B (c_V + c_{VB}) + \alpha^2 k^{B^2} - (1-\alpha)k^B\theta}$, $C = (1-\alpha)c(2+2b-c)$.

(a) $e^{BG-c} = e^{BG}$, $l^{BG-c} = l^{BG}$, $r^{BG-c} = r^{BG}$, $p^{BG-c} > p^{BG}$; *(b)* $\pi_S^{BG-c} < \pi_S^{BG}$; $\pi_V^{BG-c} = \pi_V^{BG} = 0$; $CS^{BG-c} < CS^{BG}$; $\pi_{SW}^{BG-c} < \pi_{SW}^{BG}$.

Proposition 5.3 indicates the effect of marginal cost of BCT under government subsidies by comparing Model BG-c and Model BG, which is similar to.

Proposition 5.3 shows that the impact of BCT marginal cost under government subsidies derived by comparing model BG-c with model BG. It can be seen that the results are very similar to Proposition 5.1, the only difference being that the specific threshold of marginal cost becomes higher with government subsidies. That means the affordability of marginal costs is enhanced with the support of government subsidies.

Moreover, we compare Model BG-c with Model BG to explore whether the marginal cost changes the value of BCT under government subsidies, i.e., to verify the robustness of Proposition 4.3 and Proposition 4.4.

Proposition 5.4. *Under Model BG-c, the satellite launch supply chain adopts the BCT with government-subsidies insurance considering the marginal cost of BCT.*

Compared with Model IG, (i) when $c_V < H(\alpha)$, *(a) if* $0 < c < 1 + b - \sqrt{\frac{(1+4\theta)k^B}{k} - 4\theta}$, $e^{BG-c} > e^{IG}$, $r^{BG-c} < r^{IG}$; *otherwise,* $e^{B-c} \leq e^I$, $r^{BG-c} \geq r^{IG}$; *if* $0 < c < 1 + b - \sqrt{1 - \frac{8\alpha(1-g)(k-k^B)}{1-\alpha}}$, $l^{BG-c} > l^{IG}$;

otherwise, $l^{BG-c} \leq l^{IG}$*; if* $0 < c < b$*,* $p^{BG-c} > p^{IG}$*, otherwise,* $p^{BG-c} \leq p^{IG}$ *(b) if* $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda}{1-\alpha}}$ *and* $c_{SB} < \frac{k\lambda^2-k^B\psi^2}{128kk^B(1-\alpha)^2}$*,* $\pi_S^{BG-c} > \pi_S^{IG}$*; otherwise,* $\pi_S^{BG-c} \leq \pi_S^{IG}$*; if* $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda-32\alpha kk^B}{1-\alpha}}$ *and* $c_{VB} < \frac{k\lambda^2-k^B\psi^2+32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2}$*,* $\pi_V^{BG-c} > \pi_V^{IG}$*; otherwise,* $\pi_V^{BG-c} \leq \pi_V^{IG}$*; if* $0 < c < b$*,* $CS^{BG-c} > CS^{IG}$*; otherwise,* $CS^{BG-c} \leq CS^{IG}$*; if* $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-6\lambda-32\alpha kk^B}{3(1-\alpha)}}$ *and* $c_{SB} + c_{VB} < \frac{3k\lambda^2-3k^B\psi^2+32\alpha kk^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$*,* $SW^{BG-c} > SW^{IG}$*; otherwise,* $SW^{BG-c} \leq SW^{IG}$*.*

(ii) when $c_V \geq H(\alpha)$*, (a)* $e^{BG-c} > e^{IG}$*,* $l^{BG-c} > l^{IG}$*,* $r^{BG-c} < r^{IG}$*; if* $0 < c < b$*,* $p^{BG-c} > p^{IG}$*; otherwise,* $p^{BG-c} \leq p^{IG}$*; (b) if* $c_{SB} < \frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$*,* $\pi_S^{BG-c} > \pi_S^{IG}$*; otherwise,* $\pi_S^{BG-c} \leq \pi_S^{IG}$*;* $\pi_V^{BG-c} = \pi_V^{IG} = 0$*; if* $0 < c < b$*,* $CS^{BG-c} > CS^{IG}$*; otherwise,* $CS^{BG-c} \leq CS^{IG}$*; if* $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$ *and* $0 < c < b$*,* $\pi_{SW}^{BG-c} > \pi_{SW}^{IG}$*; otherwise,* $\pi_{SW}^{BG-c} \leq \pi_{SW}^{IG}$*.*

The results in Proposition 5.4 are similar to Proposition 5.2 that comparing Model BG-c and Model G,the launch success probability increases, the launch price increases, the retail price increases, and the insurance rate decreases with the BCT variation cost in a certain interval. This result is the same as the outcomes in Proposition 4.3 (comparing Model BG with Model IG).

Besides, by comparing members' profits in Model BG-c and Model IG, we also find that when the marginal cost c under a threshold and the cost of BCT is low, all the members will benefit from adopting BCT under government subsidies.

Therefore, by comparing Model BG-c and Model IG, our findings in Proposition 4.3 and Proposition 4.4 about the value of BCT with the government subsidy are proved to be robust.

5.2. Alliance

Inspired by alliances in the real-world alliances, such as U.S. Space Enterprise Consortium and China Commercial Space Alliance, we extend the models to explore if an alliance strategy is a better to improve the effective of satellite launch supply chain in this section. On the basis of the main cases, we build three models: (i) the VM and SO form an alliance with launch insurance (Model IA); (ii) the VM and SO form an alliance with launch insurance under government subsidies(Model GA); (iii) the VM and SO form an alliance with blockchain-embedded launch insurance (Model BA); (iv) the VM and SO form an alliance with blockchain-embedded launch insurance under government subsidies (Model BGA).

In the above models, the VM and the SO attempt to maximize their respective benefits, VM by deciding the effort to be paid, and SO by determining the launch service price and retail price. However, in the alliance strategy, VM and SO will act as a whole alliance to decide the efforts exert and the retail price. Thus the market demand and payoff functions of Model IA can be written as follows:

$$D^{IA} = 1\int_{p^{IA}}^{1} f(u)\,\mathrm{d}u = 1 - p^{IA} \tag{25}$$

$$\begin{aligned} \pi_{SC}^{IA} &= epD^{IA} - (1-e)\theta - rc_S + (1-e)\beta c_S - c_S - c_V, \\ \pi_{I}^{IA} &= rc_S - (1-e)\beta c_S. \end{aligned} \tag{26}$$

The functions of Model GA, Model BA, and model BGA are similar to Model IA which we omit here. By inverse solving, we obtain the equilibrium outcomes which are summarized in Table 18 and Table 19

Table 18: The equilibrium outcomes in Model IA and Model GA.

	Model IA	Model GA
Effort of SC exerting e^*	$\frac{1+4\theta-4\beta c_S}{8k}$	$\frac{1+4\theta-4\beta c_S}{8k}$
Retail price p^*	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate r^*	$\beta(1-\frac{1+4\theta-4\beta c_S}{8k})$	$\beta(1-\frac{1+4\theta-4\beta c_S}{8k})$
SC's profit π_{SC}	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - c_S - c_V$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - (1-g)c_S - c_V$
Consumer surplus CS	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare SW	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - c_S - c_V + \frac{1}{8}$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - (1-g)c_S - c_V + \frac{1}{8}$

The outcomes above imply a difference that the optimal decisions are effected by the insurance market instead of the prepay rule. That means, as the VM and SO form an alliance, the motivation of VM to improve the successful launch probability changes from the prepay ratio (α) to the insurance claim (βc_S). Thus, the less insurance covers, the more effort VM exerts. By comparing Model IA and Model I, model GA and Model IG, Model BA and Model B, Model BGA and Model BG, we get Proposition 5.5.

Table 19: The equilibrium outcomes in Model BA and Model BGA.

	Model BA	Model BGA
Effort of SC exerting e^*	$\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B}$	$\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B}$
Retail price p^*	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate r^*	$\beta(1-\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B})$	$\beta(1-\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B})$
SC's profit π_{SC}	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B}-\theta-c_S-c_V-c_{SB}-c_{VB}$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B}-\theta-(1-g)c_S-c_V-c_{SB}-c_{VB}$
Consumer surplus CS	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare SW	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B}-\theta-c_S-c_V-c_{SB}-c_{VB}+\frac{(1+b)^2}{8}$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B}-\theta-(1-g)c_S-c_V-c_{SB}-c_{VB}+\frac{(1+b)^2}{8}$

Proposition 5.5. *When the VM and the SO form an alliance,*

(i) comparing Model IA and Model I, if $\beta c_S < \frac{(1-\alpha)(1+4\theta)+8\alpha k}{8(1-\alpha)}$*, then* $e^{IA} > e^I$ *and* $SW^{IA} > SW^I$*;*

(ii) comparing Model GA and Model G, if $\beta c_S < \frac{(1-\alpha)(1+4\theta)+8\alpha k(1-g)}{8(1-\alpha)}$*, then* $e^{GA} > e^{IG}$*; if* $(\beta c_S)^2 < \frac{[(1-\alpha)(1+4\theta)+8\alpha k(1-g)]^2+32\alpha kg[(4\theta-1)(1-\alpha)+8\alpha k(1-g)]}{[8(1-\alpha)]^2}$*, then* $SW^{GA} > SW^{IG}$*;*

(iii) comparing Model BA and Model B, if $\beta c_S < \frac{(1-\alpha)[(1+b)^2+4\theta]+8\alpha k^B}{8(1-\alpha)}$*,* $e^{BA} > e^B$ *and* $SW^{BA} > SW^B$*;*

(iv) comparing Model BGA and Model BG, if $\beta c_S < \frac{(1-\alpha))[(1+b)^2+4\theta]+8\alpha k^B(1-g)}{8(1-\alpha)}$*,* $e^{BGA} > e^{BG}$*; if* $(\beta c_S)^2 < \frac{\{(1-\alpha)[(1+b)^2+4\theta]+8\alpha k^B(1-g)\}^2+32\alpha k^B g\{[4\theta-(1+b)^2](1-\alpha)+8\alpha k^B(1-g)\}}{[8(1-\alpha)]^2}$*,* $SW^{BGA} > SW^{BG}$*.*

Proposition 5.5 gives the specific insurance claim thresholds for the adoption of the alliance strategy under four scenarios. Note that the retail price paid by the consumer and the consumer surplus remain the same, so the increased social welfare mainly comes from the increase in supply chain profits.

Therefore, when the insurance market is soft, it would be a wise idea to pursue an alliance strategy in the satellite launch supply chain. It will contribute to an increase in the probability of successful launches as well as to the improvement of social welfare.

6. Conclusions

6.1. Remarkable findings

Nowadays, with the prosperity of commercial launches, more and more research is being conducted in the operation management of space. Motivated by the real-world government-subsidized launch insurance project, we explored the operations of the satellite launch supply chain with government-subsidized insurance. Firstly, we established the traditional insurance model (Model I) and the government-subsidized insurance model (Model IG). By deriving analytical results, we demonstrate the optimal decisions for each participant. We have further uncovered the effect of the subsidies on different variables. Finally, we built value models to investigate the benefit of subsidies, especially revealing the conditions under which one model outperforms the other.

However, we find that if only the government provides subsidies, the customers cannot benefit. So we investigate the blockchain applications in the space launch supply chain by building a blockchain-embedded insurance model (Model B), which has also been implemented in the real world. Besides, considering the high blockchain costs, we explored the scenario of adopting blockchain under government subsidies (Model BG). At last, in order to measure the value of blockchain under different scenarios, we compare Model B with Model I and Model BG with Model IG. And we analyzed the change of blockchain impact under the government subsidy scenario.

As a concluding remark, we highlight the answers as follows:

(1) Government subsidized launch insurance can achieve win-win in satellite launch supply chain and improve the social welfare. However, it is not always preferred to implement the government subsidy in all cases. When the government provides subsidies, it is necessary to screen satellite vendors, and only by subsidizing satellite launch activities with inexpensive vehicles can it effectively promote the development of the launch market. Otherwise, subsidies can only increase the profit of satellite operators but can not promote the launch success rate, which is not conducive to the optimal allocation of government funds.

(2) The government subsidies have helped to establish positive feedback for the satellite launch market; that is, the satellite vendor is more willing to pay high launch price, so that the vehicle manufacturer is motivated to increase the probability of successful launches.

(3) Once the government subsidy project is launched, the satellite operator will always get more from it than before. But for the vehicle manufacturer, only when the cost of vehicle is relatively low, his income will increase compared to before; otherwise, he cannot benefit from

the subsidy program. For consumers, there is no change in consumer surplus. Therefore, the overall social welfare as the sum of the profit of the various subjects will increase.

(4) In the blockchain-embedded model, the values that blockchain bring to the optimal decisions are similar to the government subsidy brings. However, there is one difference to claim that the retail price has been increased and the market demand also increases.

(5) Moreover, for the satellite, she will always benefit from the adoption of blockchain if its cost is relatively low.

(6) However, the profitable condition for the vehicle to decide whether use the blockchain is not only the cost of blockchain is expensive but also the cost of vehicle manufacturing is low.

(7) Significantly, the use of the blockchain launch platform will make the consumer surplus increase no matter in which situation.

(8) Interestingly, the adoption of blockchain can increase the benefits of government subsidies. Besides, when the supply chain obtains the government subsidies, both the satellite operator and the vehicle manufacture can enhance the affordability of blockchain costs.

6.2. Managerial implications

Analyzing the derived findings, we further propose the following managerial implications, which help form action plans for satellite operators, vehicle manufacturers, and the government.

Satellite operator: It is the most effective to improve profit by applying for government insurance subsidies. Moreover, the adoption of the blockchain-embedded launch platform will also enhance the profit when the cost of blockchain is low.

Vehicle manufacturer: Only when vehicle costs are low can manufacturers indirectly enjoy the benefits of government subsidies. Otherwise, the manufacturer will be nonprofitable. However, it is worth noting that adopting blockchain technology to provide launch services is always beneficial for vehicle manufacturers, as it can increase the probability of a successful launch. Besides, when the blockchain and vehicle manufacturing costs are low, adopting blockchain technology is the best strategy for the manufacturer, which will improve his profitability.

Government: Intuitively, government provision of insurance subsidies can improve social welfare. However, the excellent way to optimally allocate the limited subsidy funds is to disburse the subsidies to satellite operators who choose cost-effective vehicles. This is because it is in this condition that the probability of a successful launch is increased, and a virtuous closed-loop commercial satellite launch market is promoted. Finally, this results in a win-win situation in the supply chain. However, it is worth noting that when the government provides subsidies to blockchain technology embedded launch activities, it will maximize the funds' effectiveness, achieving all-win among the satellite operator, the vehicle manufacturer, and customers.

6.3. Future research

For the future studies, we suggest several probable future directions. First, the risk attitude of different participants can be taken into account which will effect the optimal decisions. Second, the JIT operation management with the supported of blockchain in launch supply chain can be promising directions for future research. Last but not least, multi-tier supply chain or supply chain network will be interesting to investigate, which involve more members such as the rideshare broker in piggyback launch and rideshare or cluster launch (Barschke, 2020).

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