Coordination of insured satellite launch supply chain: government subsidy or blockchain implementation?

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Abstract

The commercial launch industry is booming but abounds enormous-loss risks, which is similar to the disruption risk in the supply chain. Traditionally, launch insurance is the commonly used financial tool to hedge such risks. And lots of governments have implemented the measures for subsidizing the insurance fee for commercial space launches in order to promote the development of the commercial space industry, stimulate the innovation vitality of enterprises and accelerate the promotion of manufacturing in the commercial aerospace field. Nowadays, with the development of blockchain technology, it also is implemented to decrease launch risks from a technical perspective. However, the cost of both launch insurance and blockchain technology stop lots of satellite owners who think they are not cost-effective. In this paper, we apply a game-theoretic approach to study the fintech launch contract supported by government subsidy or blockchain for solving the trade-off between high risk and high cost. More precisely, we consider a Stackelberg strategy in a space launch supply chain and build math models to examine the cases with launch insurance (Model I), with government-subsidy(Model IG) and with blockchain-embedded (Model IB). From a theoretical perspective, we investigate the optimal launch price and the optimal effort (for improving launch success probability) expressions. We find that if the government wants to form a virtuous circle and optimize the allocation of funds, it should screen when subsidizing satellite companies, rather than unconditional subsidies. In addition, we also find that the

subsidy do not benefit consumers, but blockchain can. Once the blockchain technology is adopted, contract prices go up, VM exerts more effort, and the premium rate always is lower as the launch missions become more efficient and believable. Moreover, when the satellite owner choose an inexpensive vehicle for launch, the cost-advantage BEL platform is beneficial to all participants. Finally, coupling with 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

Due to Earth's insatiable need for information and communication, the artificial satellite industry is booming. The ability of satellites to collect signals and data extensively, even from places hard to reach, allows for a variety of functions such as providing satellite telecommunication, satisfying weather and climate monitoring, supporting satellite television (BskyB, Direct TV, SkyTV and Dish), meeting Global Positioning System (GPS) needs, and serving for military and scientific. Since the 1980s, with the privatization of telecommunication organizations as well as the development of space laws and regulatory regimes, commercial space has begun to sprout (OECD, 2014). Furthermore, SpaceX Falcon 9 delivering the SES-8 satellite into orbit marks on Dec.3th, 2013, marks the rise of the private space launch market (Tariq, 2013). Space is no longer confined to government and military agencies like NASA and its contractors but expanding rapidly via private commercial companies like SpaceX, Blue Origin, Cloud Constellation Corporation, and more. According to Report (2021), the space economy grew 176% during the last 15 years, reaching 447 billion dollars in 2020. It is worth noting that 80% of the total income is contributed by the commercial space. In addition, there are more than 1,100 SmallSats launched in 2020, which is twice in average size over the same period. Thus the space launch market gradually plays a pivotal part in modern societies and economic growth. In parallel, the vigorous development of the space economy also points that the needs of operation management implanting in the space launch market are increasing (Kucukcay, 2018).

While the successful SpaceX mission has created new enthusiasm for commercial satellite launching, there are still many risks that should not be ignored in satellite launch services, such as the responsibility of the vehicle, the indicators of the satellite, the condition of the launch activity so on. In addition, many private investors are hesitant about investing in space businesses because of the costly infrastructure and extended timelines. From the perspective of private companies, once the launch fails, the loss for both satellite owner and launch servicer is enormous. While governmental and military satellites are usually self-insured, commercial satellite owners often require insurance to be in place.

In order to hedge launch risks, space insurance emerged. Insurance companies like Global Aerospace have been providing insurance for space initiatives since the first commercial satellites and launch vehicles required financial support to cover their risk. New concepts and technologies such as prominent constellations of satellites have distinctive risk profiles requiring unique coverages. According to the satellite launch project process, space insurance is roughly divided into four types of coverage which reflect the various phases of most satellite projects - pre-launch insurance [1], launch insurance [2], in-orbit insurance [3], and launch plus life insurance [4]. The launch insurance is usually the most widely focused (Suchodolski, 2018) because the launch is the riskiest part of any space activity, and the damage is often catastrophic. (Gould & Linden, 2000; Kunstadter, 2020).

In addition to compensating for risk financially, reducing the launch failure rate on the technical side is also an available way for commercial space companies. While commercialized space projects have braved all the challenges, they are still involved in conventional economic models that may hamper their growth and success. Luckily, blockchain technology supports building smart contracts and tracking data, considered a disruptive technology that facilitates data flow. In the real world, companies are emerging to implementing blockchain technology specifically for space launches, such as SpaceChain, IBM and Cloud Constellation Corporation. The blockchain is used to deal with the above complexities such as contracts, order tracking, parts assembly, shipments, design and test documents, test results data,

[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.

near real-time data, workflows for approvals, auditing, launch, and control, which make the project more visible, responsive and mitigate costly interruptions during the launch, in other words, it increases the probability of successful launch (Zheng et al., 2021). Here are the main features in details of blockchain about supporting space launch:

(1) Reliability: The verified data on the blockchain launch platform is reliable, which cannot be changed based on decentralizing electronic record-keeping.

(2) Efficiency: Blockchain supports the smart contract to build an efficient network between the participants who get a node to share, add and update information.

Despite the ideas given above being excellent, both space insurance and blockchain technology are high-cost, which make lots of private space companies hesitate to adopt them. Considering the trade-off between handling risk and considerable cost, we examine the contract price problem. From the perspective of operation management, we refer to the participants as supply chain members and simplify the question as a two-echelon supply chain consisting of a satellite owner and vehicle manufacturer who provide the launch service. We examine how the insurance contract and blockchain technology to help improve the supply chain value and how it affects the contract price in the supply chain. We consider two modes: 1) the satellite owner contract with the vehicle manufacturer under insurance; 2) the satellite owner contracts with the vehicle manufacturer under blockchain-embedded insurance.

1.2. Research questions and key findings

Motivated by the application of fintech and the importance of space launching operation management in the real world, we theoretically study the research questions listed below:

RQ1. How to analytically build the mathematical models under traditional launch insurance and blockchain-embedded launch insurance, respectively? How to price the launch service contract for the satellite owner? Furthermore, how to make the optimal decision for the vehicle manufacturer?

RQ2. When will the blockchain launch platform be feasible and how does it affect the optimal decisions?

RQ3. What are the blockchain values for the satellite owner and the vehicle manufacturer, respectively? When will the presence of the blockchain launch platform achieve a win-win in which both the satellite owner, and the vehicle manufacturer are beneficial?

To address the above research questions, we conduct a game-theoretic analytical study by building math models. By arithmetic derivation and analysis, we obtain the following results: (1) When the anti-risk ability of the satellite owner is enhanced, the profits of both the satellite owner and the vehicle manufacturer will increase. Significantly, the implementation of the blockchain launch platform will make this effect more pronounced. Moreover, the adoption of blockchain will decrease the threshold of the satellite owner to set the optimal price. (2) Particularly, the optimal effort the vehicle manufacturer exert will increase and the contract price as well as the premium rate will decrease with the support of blockchain. (3) Via analyzing the value of blockchain, we note that the blockchain launch platform will always benefit the satellite owner no matter how weak her risk resistance is. However, it is profitable for the vehicle manufacturer to implement cost-advantage blockchain technology only when the satellite owner has a strong capacity for risk.

2. Literature review

Our paper is closely related to three research streams: supply chain insurance, space supply chain management and blockchain. We review them as follows.

2.1. Supply chain insurance

Our paper is closely related to the topic of insurance adopted to manage disruptive risk, which is a stream of supply chain finance. For a comprehensive overview, we refer readers to read Wang et al. (2021a), Chakuu et al. (2019), Xu et al. (2018), Gelsomino et al. (2016), Zhao & Huchzermeier (2015), and Gomm (2010). As a financial derivative instrument of risk aversion, insurance contracts can be seen as hedging at the expense of current profits and improving the risk tolerance by compensating the economic losses of enterprises when the supply chain disrupt caused by internal (e.g., the quality of products, the interruption of funds, and the disruption of logistic) or external (e.g., the change of weather, the pandemic of COVID-19, and the change of market) risks (Sodhi et al., 2012; Heckmann et al., 2015).

According to the type of risks, the literature of supply chain insurance contracts can be reducible to two categories. (1) One is to hedge internal risks by combining insurance contracts with supply chain contracts. As insurance contracts could coordinate the supply chain (Lin et al., 2010), researchers compared it with the revenue sharing contract according to different agents' risk aversion based on the newsvendor model. Besides, Wang et al. (2021b) also discussed which contract is better for the supply chain partners between the advanced payment contract, penalty contract, and time insurance contract in the express delivery supply chain.

(2) Another is to study the trade-off between high commercial insurance and the substantial economic losses caused by external risks. The typical market risk of demand uncertainty is a thorny question that the newsvendor model faces thus Lodree Jr & Taskin (2008) design an insurance policy framework to quantify the risks and benefits, which give decision-makers a practical approach to prepare for supply chain disruptions. Moreover, Yu et al. (2021) considered the interrupt probability of the supply chain and illustrate the value of business interruption insurance which increases the profit of each participant. Brusset & Bertrand (2018) constructed a weather index through case studies that transfer entrepreneurial risk to other risk-takers through insurance or options contracts. Similar to these researches, our paper also adopts the insurance contract to hedge the interrupt risk while the focal point is in the space launch supply chain, which is remarkable for technical complexity, high quality & reliability requirements, and colossal failure losses.

2.2. Space supply chain management

At present, supply chain management in space era is initiated by research institutes, universities and researchers. Such as China Aerospace Industry Corporation, European Space Agency and Indian Space Research Organisation conducted a series of research on space supply chain management (Kucukcay, 2018). Moreover one of the famous works is the Interplanetary Supply Chain Management and Logistics Architectures project from MIT, which develops an integrated supply chain management framework for space logistics.

According to the types of existing studies in this topic, they can be reducible to two categories:

(1) One kind of research focuses on optimizing the operating system to improve the efficiency from mathematical models and simulation. Galluzzi et al. (2006) regarded supply chain management as a critical piece of framework in the aerospace industry, and they elaborated the pattern operation in this area. Taylor et al. (2006) also designed and evaluated the operating system in the space supply chain, but they primarily engaged in optimizing delivery operation, which sustains the exploration initiative. Moreover, Gralla et al. (2006) gave a comprehensive model and simulation of the supply chain management implemented in the aerospace industry, which is low-volume and schedule-driven compared to the high-volume and market demand-driven SCM in the commercial sector.

(2) Another type of study starred in analyzing the business problem in supply chain management. The research on this topic is relatively few. Wooten & Tang (2018) examined the space industry's operation management, which involves manufacturing operations, supply chain management, and sustainable operations. Besides, they also outlined the challenges and essential questions related to stakeholders. Raghunath & Kang (2021) discussed the challenges that commercial space operation faces from a business perspective. Furthermore, Guo et al. (2021) comprehensively analyzed the global aerospace industry's current situation and future development from the upstream supply chain, midstream production chain, and downstream application chain. In addition, Donelli et al. (2021) considered the profitability and efficiency during the aircraft manufacturing and supply chain. The paper proposed a model-based approach to optimal the multiple-choice. Furthermore, Dewicki et al. also based on operational management analyze the business model in commercial space.

As review literature, most papers target SCM in space give the mathematical model from optimizing logistics, even the system flow. While our paper builds models from the business angle, we concentrate on the game theory between participants during the launch activity.

2.3. Blockchain technology support 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 (2020); 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, 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. Adhikari & Davis (2020) gave a clearly analysis on the implementation of blockchain in the area of space cybersecurity framework against global positioning system spoofing. 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. However, different from them, this article's focal point is on launching a service supply chain supported by fintech (blockchain-embedded insurance) to facilitate launching risks and contract pricing.

2.4. Summary

Supply chain insurance and blockchain technology adoption are essential topics in space launch operation management. Motivated by real-world blockchain application such as IBM and Cloud Constellation Corporation are working together to build a blockchain-based platform in the space launch supply chain, this paper theoretically investigates the blockchain-embedded insurance model operations. The insights not only contribute to the literature in operation management but also advance the industrial knowledge regarding blockchain launch platforms.

The following parts in this paper are organized as: Section 3 establishes the main models and investigates corresponding optimal decisions, one for insurance model (model I) and the other for blockchain-embedded insurance model (Model B). Section ?? further demonstrates the effect on optimal decisions and value for participants brought by the blockchain-embedded launch platform. Section 5 concludes this study and gives analytical insights.

3. Without blockchain technology

Consider a make-to-order supply chain consisting of one vehicle manufacturer (VM, he), one satellite owner (SO, she) and an insurance company (IC, it). As shown in Figure 1, to launch the satellite successfully, the SO usually conducts a series analyses to choose the vehicle and design the launch service contract with launch price l and prepay ratio α. Once the satellite is on-track, the SO will pay VM last part $(1-\alpha)p$ and she will obtain income from sailing satellite data. Without loss generality, consumers 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 with a rage of $0-1$, denoted by $U[0,1]$. To avoid facing messy mathematics, we normalize the consumer population as 1.

As common in launch activity, our models capture two typical features in the space supply chain. First, the launch activity is risky, which means there is a probability for the satellite operating in its final orbital position. The VM can improve the probability of mission success (aka reliability) by exerting costly efforts (e.g., improving technologies, equipment or processes) (Bailey, 2020; Kunstadter, 2020). 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 disutility (cost of effort) ke^2 with $k > 0$. The setting of such a disutility is common in many models.

Notedly, a launch failure is costly to all involved parties. For the SO, she will lost her satellite and the income. For the VM, what he will face is 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 the profit function. Considering the launch risk, it is natural that SO attempts to purchase launch insurance before launching to hedge risks. IC designs the launch insurance according to the analyses of conducting serious technological analyses of satellite and the VM. Once the launch fails, the IC usually pays pro rata compensation. We assume the claim covers β of the whole loss including the cost of satellite and the prepay price. references

We summarize the notation used throughout the paper in Table 1.

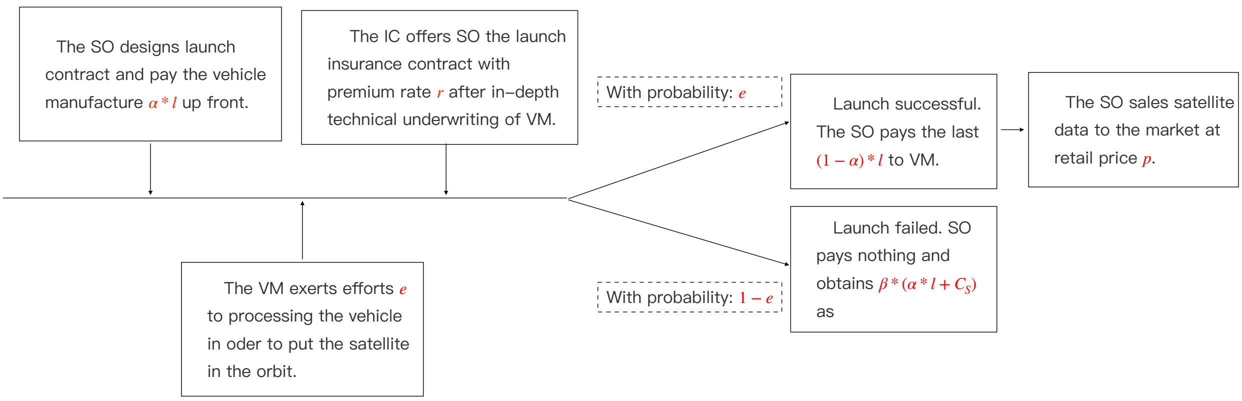

Figure 1: Sequence of events. SO :the satellite owner; VM: the vehicle manufacture; IC: the insurance company.

3.1. Model I: Satellite launch supply chain with insurance

Acting as the Stackelberg leader, the SO sets the contract terms and the VM, as the follower, decides whether to accept the contract. Without loss of generality, we focus on the following contract: the SO pays the VM a certain α of launch price l upfront when launch

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
d	The benefit of satellite data brought to customers
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
g	The government-subsidized launch insurance premium rates
c_i	The cost of VM ($i = V$) or SO ($i = S$)
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 owner ($i = S$) or insurance company ($i = I$)
CS	The consumer surplus
SW	The social welfare

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

[b] Superscript I, IG, B and BG to describe function and decisions in model I, model IG, model B and model BG respectively.

services are procured. (Andrews & Bonnema, 2011; Barschke, 2020) Furthermore, when the launch is successful, the VM then receives the balance of the payment $(1-\alpha)*l$ for services or 0 otherwise. Concerning risk, the SO buys the launch insurance with the premium rate r to compensate the loss if the launch failed. Figure 1 shows the sequence of events corresponding to the game model. Therefore, the market demand and payoff function, D^I and π_S^I, faces by the SO can be measured as follows:

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

$$\max_{l,p} \mathbb{E}[\pi_S^I(l,p,e,r)] = epD - [\alpha + e(1-\alpha)]l - r(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S, \tag{2}$$

As shown, π_S^I consists of five parts: (1) the income she can obtain once the satellite works in orbit epD; (2) the expect launch service price $[\alpha + e(1-\alpha)]l$; (3) the premium for the launch insurance $r(c_S + \alpha l)$; (4) the compensate she will get once the launch failed $(1-e)\beta(c_S + \alpha l)$. (5) the cost of building the satellite c_S. Without loss of generality, the satellite income covers its building and launch cost; i.e., the SO sets a contract only when $pD \geq c_S + l$.

As depicted in Figure 1, the VM accepts a contract with price l and receives the pre-payment $\alpha * l$ from the SO, then he manufactures the rocket which cost c_v. If the vehicle launch successfully, he receives the last $(1-\alpha)*l$ from the SO. If launching is failed, the VM not only receives no payment but also suffers penalty which monetized as θ . Therefore, the VM's objective is to maximize his expected payoff π_V^I as follows:

$$\begin{aligned} \max_{e} \mathbb{E}[\pi_V^I(l,p,e)] &= [\alpha + e(1-\alpha)]l - (1-e)\theta - (ke^2 + c_V), \\ s.t.\ \pi_V^I &\geq 0 \end{aligned} \tag{3}$$

As shown, π_V^I consists of three parts: (1) the prepaid income and expected gain upon successful launch $[\alpha + e(1-\alpha)]l$, (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 non-negative profit constraint ensures the profitability of launch successfully; otherwise, the VM will quit the cooperation.

3.1.1. The VM's effort

We now solve the Stackelberg game as depicted in Figure 1 using backward induction. First, given any launch price l, by considering the first-order condition of Equation (3), the VM's best response is given as:

$$e(l) = \frac{(1-\alpha)l+\theta}{2k}, \tag{4}$$

$$s.t. \quad 0 < e \leq 1. \tag{5}$$

By substituting Equation (4) into the VM's payoff π_V^I given in Equation (3), it can be obtained that:

$$\pi_V^I = \frac{[(1-\alpha)l+\theta]^2}{4k} + \alpha l - \theta - c_V \tag{6}$$

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

$$l \geq l_{VA} \equiv \frac{2\omega - 2\alpha k - (1-\alpha)\theta}{(1-\alpha)^2}, \tag{7}$$

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

3.1.2. The IC's premium rate

Observing the contract price l selected by the SO, the insurance company can anticipate the VM's effort $e(l)$ as given in (4). Operating in a competitive market, the insurer sets its rate r to break-even 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, $(1-e)\beta(c_S + \alpha l)$. Thus IC's profit function and the premium rate can be written as:

$$\begin{aligned} \pi_i^I &= r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\ r(l) &= \beta[1 - \frac{(1-\alpha)l+\theta}{2k}]. \end{aligned} \tag{8}$$

3.1.3. The SO's optimal price

Anticipating the VM's best response e given in (4) and the premium rate (8), the SO's payoff given in Equation (2) can be rewritten as:

$$\max_{p} \mathbb{E}[\pi_S^I(l,p)] = \frac{[pD-(1-\alpha)l]*[(1-\alpha)l+\theta]}{2k} - \alpha l - c_S, \qquad l \geq l_{VA}. \tag{9}$$

Checking the Hessian matrix of SO's payoff, we find π_S^I is concave in l and p jointly when $0 < k < \frac{(1-\alpha)[(1+d)^2+\theta]}{8\alpha}$. In this paper, we focus on the case when the condition is met. According to the assume, we can get the optimal launch price and optimal retail price for her which are $l_S = \frac{\phi-8\theta(1-\alpha)}{8(1-\alpha)^2}$ and $p^* = \frac{1+d}{2}$, where $\phi = (1-\alpha)(1+d)^2 + (1-\alpha)4\theta - 8\alpha k$. Consider the constraints, the SO aims to select the optimal contract price $l^* = \max(l_S, l_{VA})$ that maximizes her payoff, given in Equation (9). The optimal contract and corresponding equilibrium outcomes are given in Lemma 3.1.

According to the above derivation, we can also obtain the consumer surplus and social welfare as follows:

$$CS^I = 1\int_{p-d}^{1} [u-(p-d)]f(u)\,\mathrm{d}u = \frac{(1+d)^2}{8}, \qquad SW^I = \pi_S^I + \pi_V^I + CS^I. \tag{10}$$

By denoting all of the functions, we obtain Lemma 3.1.

Lemma 3.1. The equilibrium outcomes of Model I are shown in Table 2.

Note that there are two cases in our equilibrium result that $c_V < H(\alpha)$ and $c_V \geq H(\alpha)$, where $H(\alpha) = \frac{(1+d)^4(1-\alpha)^2+(1+d)^2+8(1-\alpha)[2\alpha k+\theta(1-\alpha)]+16\theta^2(1-\alpha)^2-192\alpha^2k^2-64\theta k(1-\alpha)(4-\alpha)}{256(1-\alpha)^2 k}$. This is due to the launch price $l^* = \max(l_S, l_{VA})$. In the first case, the optimal launch price l_S fixed by the SO is higher than l_{VA}, which means the contract launch price l^* is l_S equaling $c_V < H(\alpha)$. In the second case, SO's optimal launch price l_S is lower than l_{VA}, so she has to fix the contract price l^* as l_{VA} to avoid the profit of VM being negative; otherwise the VM will quit the cooperation.

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^*	$\frac{1+d}{2}$	$\frac{1+d}{2}$
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	$\frac{(1+d)^2}{8}$	$\frac{(1+d)^2}{8}$
Social welfare SW	$\frac{3\phi^2+32\alpha k\phi}{256(1-\alpha)^2k} - \theta - c_S - c_V + \frac{(1+d)^2}{8}$	$\frac{(\omega-\alpha k)(\phi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{\alpha\theta}{(1-\alpha)} - c_S + \frac{(1+d)^2}{8}$

To avoid complicated writing, we define $\phi = (1-\alpha)(1+d)^2 + 4(1-\alpha)\theta - 8\alpha k$, $\omega = \sqrt{(1-\alpha)^2kc_V + \alpha^2k^2 - (1-\alpha)k\theta}$.

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

Firstly, we examine how the benefit of satellite data brought to customers affects the optimal VM' effort, premium rate, launch price, and retail price. We have the following findings: if the benefit of satellite data brought to customers d increases, (a) when the manufacturing cost of the vehicle c_V is satisfied with $c_V < H(\alpha)$: (i) the effort of VM exerting e^*, the launch price l^*, and the retail price p^* will all monotonically increase; (ii) the premium rate r^* will decrease monotonically; (b) when $c_V \geq H(\alpha)$: (i) the retail price p^* will increase; (ii) but the effort of VM exerting e^*, the launch price l^*, and the premium rate r^* do not change. In the first situation that the cost of the vehicle is satisfied with $c_V < H(\alpha)$ (i.e. $l^* = l_S$), intuitively, when customers benefit more from the satellite data, the retail price p set by SO will increase. Furthermore, she will be willing to pay more for VM, which leads to a high launch price l. Then the VM' s motivation to increase the probability of a successful launch will also increase. The insurance premium rate r will also decrease based on the successful launch probability increase. In the second situation $c_V \geq H(\alpha)$ (i.e. $l^* = l_{VA}$), the launch price just satisfied the VM's acceptance line . The launch price l and the effort e are depend on the VM instead of the SO, so they are not affect by the benefit brought to customers d. As the premium rate r is set according to the effort e, thus it also does not change with d in this situation. However, the retail price p steal increases because it is relative to the customers closely.

Nextly, we explore how the cost coefficient of effort k affects the equilibrium outcomes mentioned above. If the cost coefficient of effort k increases, (a) no matter what the manufacturing cost of the vehicle c_V is, (i) the effort exerted by the VM e and the launch price l will always decrease; (ii) the premium rate r will always increase; (iii) the retail price p does not change all the time; (b) however, the effects on launch price l are different in the two situations; (i) when $c_V < H(\alpha)$ (i.e. $l^* = l_S$), the launch price l will decrease; (ii) otherwise, it will increase. As the cost coefficient of effort k increases, the VM will exert less effort. So no matter the situation, the effort e always decreases with the increase of k. However, the changes in launch price l are different when c_V satisfies different conditions. That is because the body that determines the launch price has changed. When $c_V < H(\alpha)$, it is the SO to decide the launch price that she will decrease the contract price according to the decrease of effort e. But when $c_V \geq H(\alpha)$, the launch price is the VM's acceptance line, which means it is the VM to decide the launch price l, so he will increase the contract price to compensate for the increase of 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. As the retail price is not relative to the effort cost coefficient, there is no change in retail price p.

Then we analyze how penalty cost θ affects these optimal outcomes. If the failed-launch penalty θ increases, (a) no matter what the manufacturing cost of the vehicle c_V is, (i) the effort exerted by the VM e and the launch price l will always increase; (ii) the premium rate r will always decrease; (iii) the retail price p does not change all the time; (b) however, the effects on launch price l are different in the two situations; (i) when $c_V < H(\alpha)$ (i.e. $l^* = l_S$), the launch price l will decrease; (ii) otherwise, it will increase. Noted, the effect of θ to e is similar to k, but the change is the opposite: no matter the situation, the effort e always increases with the increase of θ. That is because the VM has to exert more effort to increase the successful launch probability to avoid the expensive failed-launch penalty θ. The change of launch price l in these two situations is the same as k affects it. However, the internal cause of its change is different. When $c_V < H(\alpha)$, it is the SO to decide the launch price that she don't need to increase the launch price l as the VM will increase effort e spontaneously with the increasing of θ. But when $c_V \geq H(\alpha)$, the launch price is the VM's acceptance line, which means it is the VM to decide the launch price l, so he will 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. As the retail price is not relative to the penalty cost, there is no change in retail price p.

Under model I, by deriving different factors' sensitivity analyses on payoffs we have following findings: (a) When the benefit satellite data brings to customers increases, both SO's and VM's profits increase. Noted, the consumer surplus CS also increases which is the only one condition that can benefit the customers. Therefore, we will not analyze the impact of other factors on consumer surplus CS. As a result, the social welfare SW, the sum of the three parts, will increases with d naturally. (b) If the cost coefficient of effort k increases, (i) VM's profit and social welfare always decrease; (ii) for the SO, in the situation $c_V < H(\alpha)$, her profit will increase when $k < k_1$, where $k_1 = \frac{(1-\alpha)[(1+d)^2+4\theta]}{8\alpha}$, otherwise π_S^I will decrease when $k \geq k_1$; in the other situation $c_V \geq H(\alpha)$, SO's profit decreases. (c) As the increasing of θ, (i) SO's profit always increases; (ii) for the VM and 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 $\theta_{V1} = \frac{32k-(1-\alpha)(1+d)^2-8\alpha k}{4(1-\alpha)}$ and $\theta_{W1} = \frac{32k-3(1-\alpha)(1+d)^2-24\alpha k}{12(1-\alpha)}$, 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 practical observation of the real world, we build model IG in which we consider the situation that the government, aiming to promote the development of the commercial space industry, launches the commercial space launch insurance subsidy program. The event sequence is similar to the model I which is illustrated in Figure 2, but there is a change: after the IC decides the premium rate r, the government will determine a subsidized rate g. So the only difference between model I and model IG is that the SO will obtain an insurance subsidy g.

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

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

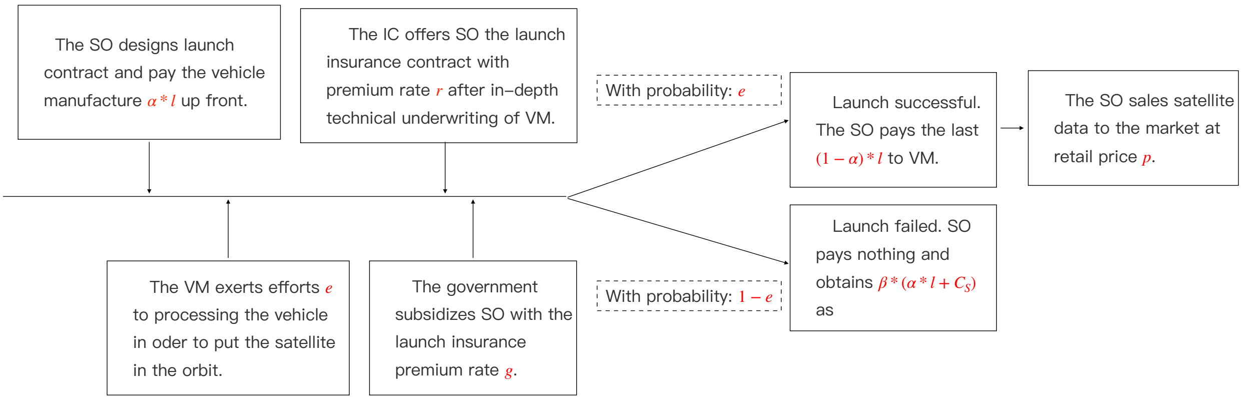

Figure 2: Sequence of events. SO :the satellite owner; VM: the vehicle manufacture; IC: the insurance company.

Thus the market demand is given as follows:

$$D^{IG} = 1 \int_{p^{IG}-d}^{1} f(u)\,\mathrm{d}u = 1 - p^{IG} + d \tag{11}$$

Then the members' payoffs can be measured as follows:

$$\begin{aligned} \pi_S^{IG} &= epD - [\alpha + e(1-\alpha)]l - (r-g)(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S, \\ \pi_i^{IG} &= r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\ \pi_V^{IG} &= [\alpha + e(1-\alpha)]l - (1-e)\theta - (ke^2 + c_V), \\ s.t.\ \pi_V^{IG} &\geq 0 \end{aligned} \tag{12}$$

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

Lemma 3.2. The equilibrium outcomes of Model IG are shown in Table 4.

Observing the optimal decisions of model IG are similar to that of model I, but there are three points worthy of notice. (i) When $c_V < H(\alpha)$, 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, affected by government subsidy. (ii) When $c_V \geq H(\alpha)$, the successful launch probability, launch price, and the premium rate do not affect by the 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^*	$\frac{1+d}{2}$	$\frac{1+d}{2}$
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}	$\frac{(1+d)^2}{8}$	$\frac{(1+d)^2}{8}$
Social welfare SW^{IG}	$\frac{3\psi^2+32\alpha k\psi}{256(1-\alpha)^2k} - \frac{\theta[1-(1-g)\alpha]}{1-\alpha} - (1-g)c_S - c_V + \frac{(1+d)^2}{8}$	$\frac{(\omega-\alpha k)(\psi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{(1-g)\alpha\theta}{(1-\alpha)} - (1-g)c_S + \frac{(1+d)^2}{8}$

To avoid complicated writing, we define $\psi = (1-\alpha)(1+d)^2 + 4(1-\alpha)\theta - 8\alpha k(1-g)$, $\omega = \sqrt{(1-\alpha)^2kc_V + \alpha^2k^2 - (1-\alpha)k\theta}$.

(iii) No matter the situation, the retail price doesn't change, which means the government subsidy program doesn't affect the market retail price. We will talk about the difference between model I and model IG in detail in Section 3.3.

We now report the sensitivity analysis performing as shown in Table 3. We find that the results of Model IG and Model I were very similar, but with three difference.

Firstly, 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 $g = 1$, which means the subsidy wholly covers the insurance, 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 $k_2 = \frac{(1-\alpha)[(1+d)^2+4\theta]}{8\alpha(1-g)}$.

Secondly, 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 $\theta_{V2} = \frac{32k-(1-\alpha)(1+d)^2-8\alpha k(1-g)}{4(1-\alpha)}$ and $\theta_{W2} = \frac{32k-3(1-\alpha)(1+d)^2-24\alpha k(1-g)}{12(1-\alpha)}$. That means the VM and society can bear a higher penalty when the government launch the subsidy program.

Thirdly, 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.

3.3. Values of government subsidies

In order to better explore the value of government subsidies, we explored VSO, VVM, CS, and SW as following, which represent the benefits that government subsidies bring to the SO, the VM, customers, and the society, respectively.

$$\begin{aligned} VSO &= \pi_S^{IG} - \pi_S^I \\ VVM &= \pi_V^{IG} - \pi_V^I \\ VCS &= CS^{IG} - CS^I \\ VSW &= SW^{IG} - SW^I \end{aligned} \tag{13}$$

We report the results in Table 5 by comparing the equilibrium outcomes between model I and model IG. After analyzing the results, we obtain Proposition 3.1 and Proposition 3.2.

Table 5: Values of government subsidies.

	Situation	Δe^*	Δr^*	Δl^*	Δp^*	VSO	VVM	VCS	VSW
Value	$c_V < H(\alpha)$	$\frac{8\alpha g}{16(1-\alpha)}$	$\frac{-8\beta\alpha g}{16(1-\alpha)}$	$\frac{\alpha g}{(1-\alpha)^2}$	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 d, k, θ: $e^{IG} > e^I$, $r^{IG} < r^I$, $l^{IG} > l^I$ if and only if $c_V < H(\alpha)$.

Proposition 3.1 indicates three points. Firstly, for given d, k, θ, the launch insurance subsidy provided by the government can help to improve the successful launch probability e which is definitely helps to promote the benign development of the commercial satellite industry. Secondly, when the subsidy also helps to decrease the launch insurance rate r. This is because insurance companies set insurance rates based on break-even, so the larger the e, the smaller the r. From a market perspective, government subsidies help soften the insurance market. Thirdly, the launch price in model IG also higher than that in model

I. This is attributed to the fact that SO is more willing to pay higher launch fees after receiving subsidies. Higher launch fees also give VM an incentive to increase the probability of successful launches, thus forming a virtuous circle that helps to promote the development of the commercial satellite launch market.

Note, the above phenomenon occurs only in condition $c_V < H(\alpha)$ which means that when the SO chooses an expensive vehicle, $c_V > H(\alpha)$, government subsidies will not be able to form the above positive feedback closed loop in the market.

Proposition 3.2. (i) Given d, k, θ: $\pi_S^{IG} > \pi_S^I$, $SW^{IG} > SW^I$.
(ii) Given d, k, θ: $\pi_V^{IG} > \pi_V^I$ if and only if $c_V < H(\alpha)$.

Proposition 3.2 indicates two points. Firstly, for given d, k, θ, the profit of SO and the social welfare in model IG are always higher than in model I. This means that when the launch insurance subsidy program is implemented, satellite owners and society always benefit. Mainly because the satellite owner is a direct beneficiary. Her earnings decided by the tradeoff between higher launch fees and higher launch success rates. Secondly, the profit of VM in model IG is higher than in model I if and only if $c_V < H(\alpha)$. The change of VM's profit depends on the tradeoff between higher effort cost and higher launch service income. However, when the cost of vehicle is quite high, VM will not benefit from the government subsidy.

As a remark, 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 effectively promote the benign development of the launch market. Otherwise, subsidies can only increase the profit of satellite owners, but can not promote the launch success rate, which is not conducive to the optimal allocation of government funds.

4. With blockchain technology

After exploring model I and model IG, we find that government subsidies for launch insurance do not benefit customers that the data demand D and retail price p remain unchanged in these two models. However, the implementation of innovative technology, blockchain technology (BCT), injects new blood into the commercial space industry in two aspects: on one hand, BCT can enhance the security of satellite data; on the other hand, blockchain technology helps to improve the workflow efficiency of launch activities which helps to reduce the error rate, and thus increases the probability of successful launch. In this section, we analytical exploring how BCT improve the performance of the satellite launch supply chain.

In the real world, as depicted in Figure 3, the launching workflow is supported by BCT to deal with the complexities such as contracts, order tracking, parts assembly, shipments, design and test documents, test results data, near real-time data, workflows for approvals, auditing, launch and control. That means it will improve the data flow between different participants and capture the problem in time during the process. In other words, when information is shared adequately in the whole supply chain, it will help VM to save the effort cost to reach the ideal launch success probability, which is related to the symmetric and transparent information. (such as IBM and Cloud Constellation Corporation are working together to build a range of prototype solutions from Edge Computing in Space to exploring how blockchain can optimize the logistics and supply chain for the space tech industry (Altaf, 2019).

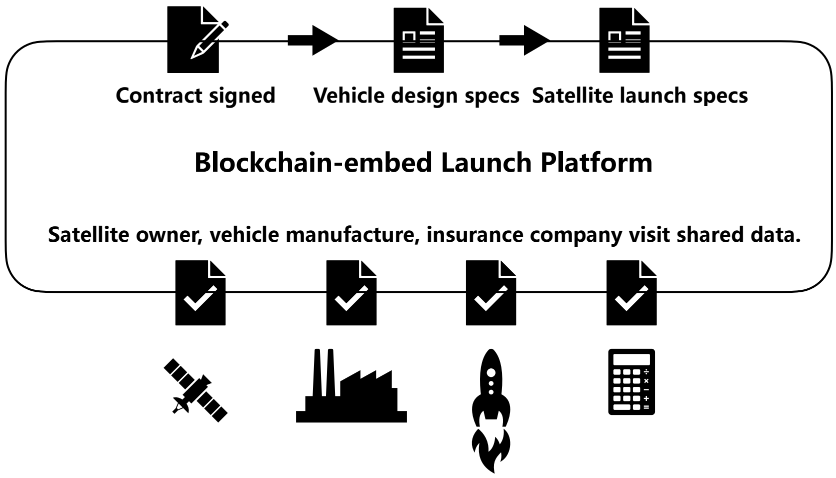

Figure 3: Satellite launch supported by blockchain platform.

Altaf (2019)

4.1. Model IB: Blockchain-embedded satellite launch supply chain with insurance

Compared to the case under Model I, all these parties will work together on the blockchain platform and the workflow will be more efficient which will be like (i) Launch data is made accessible via application program interfaces (APIs) for each of the participants on the nodes, and all interactions such as data download are tracked. (ii) All of the above activity is logged in the form of transactions in an immutable ledger database for auditing purposes to all the authorized interested participants. (iii) The data collected by the satellite will also record on BCT which cannot be tampered with. Figure 3 shows the whole launch success process in the avail of blockchain. Thus, the obvious advantage over Model I is that the transform data flow will decrease the effort cost and enhance the trust of customers. In other words, for the members in the supply chain, for the effort cost VM exerting to improve the launch successfully probability (denoted by $k^B e^2$ for the case under Model IB), it will be lower under Model B than under Model I. We assume the blockchain platform provided by the third party which will charge SO and VM for c_{SB} and c_{VB} respectively. For customers, the benefits brought by BCT are characterized by factor b which will increase their utility. To be specific, the market demand can be written as follows:

$$D^B = 1\int_{p^B-d-b}^{1} f(u)\,\mathrm{d}u = 1 - p^B + d + b \tag{14}$$

Similar to Section 3.1, as the Stackelberg leader, SO sets the contract terms and the VM, as the follower, decides whether to accept the contract. Once the cooperation is signed, each of the participants gets a node which has a copy of ledger and smart contracts. As in Section 3.1, the SO prepays the supplier part of the contract price $\alpha * l$ ahead. After launching, she will pay $(1-\alpha) * l$ upon successful delivery and pays 0 otherwise. Concerning risk, SO buy the launch insurance with premium rate r to compensate the damage if launch failed. Therefore, the members' payoffs can be measured as follows:

$$\begin{aligned}
&\pi_S^B = epD - [\alpha + e(1-\alpha)]l - r(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB},\\
&\pi_i^B = r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l),\\
&\pi_V^B = [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB},\\
s.t.\ &\pi_V^B \geq 0
\end{aligned} \tag{15}$$

As shown, π_S^B consists of five parts: (1) the income she will obtain once the satellite works in orbit (epD), (2) the launch service price ($[\alpha + e(1-\alpha)]l$), (3) the premium SO pays for launch insurance($r^B(c_S + \alpha l)$), (4) the compensate she will get once the launch failed($(1-e)\beta(c_S + \alpha l)$), (5) the cost of satellite and blockchain service, c_S and c_{SB}.

After receiving a contract with price l that is acceptable to VM, the cooperation is reached and a smart contract will be built. Then VM gets the node of checking the contract, which captures serious details to direct the conduction design, development, test and evaluation efficiently which cost $c_V + c_{VB}$. Also, he will get the prepayment $\alpha * l$ from the SO. If the vehicle launch successfully, he receives the last $(1-\alpha) * l$ from the SO. If launching is not successful, the VM receives no payment. As shown, π_V^B consists of three parts: (1)the prepaid income and expected gain upon successful launch $[\alpha + e(1-\alpha)]l$, (2)the expected loss of failure penalty in the event of launch failure $(1-e)\theta$, (3)the whole cost $k^B e^2 + c_V + c_{VB}$. The non-negative profit constraint ensures the profitability of launch; otherwise, the VM will reject such a contract.

After a backward induction similar to the 3.1, we obtain Lemma 4.1.

Lemma 4.1. The equilibrium outcomes of Model IB are shown in Table 6.

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^*	$\frac{1+d+b}{2}$	$\frac{1+d+b}{2}$
Premium rate r^*	$\beta(1-\frac{\eta}{16(1-\alpha)k^B})$	$\beta\frac{k-\mu}{(1-\alpha)k^B}$
SO's profit π_S^B	$\frac{\eta^2}{128(1-\alpha)^2k^B}+\frac{\alpha\theta}{(1-\alpha)}--c_{SB}$	$\frac{(\mu-\alpha k^B)(\eta+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B}+\frac{\alpha\theta}{(1-\alpha)}-c_S-c_{SB}$
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	$\frac{(1+d+b)^2}{8}$	$\frac{(1+d+b)^2}{8}$
Social welfare SW^B	$\frac{3\eta^2+32\alpha k^B\eta}{256(1-\alpha)^2k^B}-\theta-c_S-c_V-c_{SB}-c_{VB}+\frac{(1+d+b)^2}{8}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu)}{4(1-\alpha)^2k^B}+\frac{\alpha\theta}{(1-\alpha)}-c_S-c_{SB}+\frac{(1+d+b)^2}{8}$

To avoid complicated writing, we define $\eta=(1-\alpha)(1+d+b)^2+4(1-\alpha)\theta-8\alpha k^B$, $\mu=\sqrt{(1-\alpha)^2k^Bc_V+\alpha^2k^{B2}-(1-\alpha)k^B\theta}$.

Outcomes in Lemma 4.1 are neat and similar to Lemma 3.1. There are two differences worth knowing. (i) First, when $c_V < H(\alpha)$,as k^B is less than k, leading to $\eta > \phi$, thus the successful launch probability, the launch price are higher than in model I; and the premium rate is lower than in Model I. (ii) When $c_V \geq H(\alpha)$, the equilibrium outcomes are not neat and cannot be directly compared which we will conduct analyze in detail in Section 4.2. (iii) Although the retail price is higher compared with model I, the consumer surplus in increase with the implementation of BCT. Notedly, the consumer surplus is only related to b, not to the cost of the blockchain. Therefore, as long as blockchain technology is adopted, the consumer surplus can be improved.

As the sensitivity outcomes shown in Table 3 we now conduct the analysis.

By comparing the sensitivity analysis results of model IB and model I, we find three differences: (i) Firstly, if the effort cost coefficient increase, when $c_V < H(\alpha)$, there there exist a threshold k_3, where $k_3 = \frac{(1-\alpha)[(1+b+d)^2+4\theta]}{8\alpha}$. Thus SO's profit decreases as k^B increasing when $k^B < k_3$, otherwise π_S^{IG} decreases. Note $k_3 > k_2$, which means BCT raises the threshold of the

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

	Model	Situation	e^*	r^*	l^*	p^*	π_S	π_V	CS	SW
$d\uparrow$	Model I	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	-	-	-	$\uparrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$
	Model IB	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	-	-	-	$\uparrow$	$\uparrow$	$-$	$\uparrow$	$\uparrow$
$k\uparrow$	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 IB	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	$-$	$\downarrow$: $k < k_3$	$\downarrow$	$-$	$\downarrow$
							$\uparrow$: $k \geq k_3$			
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	$-$				
$\theta\uparrow$	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 IB	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	$-$	$\uparrow$	$\uparrow$: $\theta < \theta_{V3}$	$-$	$\uparrow$: $\theta < \theta_{W3}$
								$\downarrow$: $\theta \geq \theta_{V3}$		$\downarrow$: $\theta \geq \theta_{W3}$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
$b\uparrow$	Model IB	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	$-$	$-$	$-$	$\uparrow$	$-$	$-$	$\uparrow$	$\uparrow$

SO to change the trend of her profits. (ii) Secondly, if the failed-launch penaltyθ increase, when $c_V < H(\alpha)$, the thresholds of VM's profit θ_{V3} and social welfare θ_{W3} also change, where $\theta_{V3} = \frac{32k^B-(1-\alpha)(1+d+b)^2-8\alpha k^B}{4(1-\alpha)}$ and $\theta_{W3} = \frac{32k^B-3(1-\alpha)(1+d+b)^2-24\alpha k^B}{12(1-\alpha)}$. 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. (iii) If the benefits that blockchain brings to consumers b increases, (a) when $c_V < H(\alpha)$, the successful launch probabilit, launch price, retail price, member's profits, consumer surplus, and social welfare will all increase; the premium rate will decrease; (b) when $c_V < H(\alpha)$, although the retail price increase and the consumer surplus obtain for the customers will increase at all.

In order to figure out the conditions for implementing BCT, we conduct the value study in Section 4.2.

4.2. Values of implying BCT

After deriving the equilibrium decisions in the supply chains under Models I and B, we now explore the values of blockchain technology. By comparing the equilibrium outcomes model I and model IB, we obtain the following results:

$$\begin{aligned} VSO^B &= \pi_S^B - \pi_S^I \\ VVM^B &= \pi_V^B - \pi_V^I \\ VCS^B &= CS^{IB} - CS^I \\ VSW^B &= SW^{IB} - SW^I \end{aligned} \tag{16}$$

We report the results in Table 8 and Table 9 by comparing the equilibrium outcomes between model I and model IB. After analyzing the results, we obtain Proposition 4.1 and Proposition 4.2.

Proposition 4.1. Given d, k^B, k, θ: $e^{IB} > e^I$, $r^{IB} < r^I$, $l^{IB} > l^I$, $p^{IB} > p^I$.

Proposition 4.1 gives us four claims. Firstly, the optimal effort exerted by VM is higher after applying blockchain technology, which leads to a higher launch success probability

Table 8: Values of BCT.

	Situation	Δe^*	Δr^*	Δl^*	Δp^*
Value	$c_V < H(\alpha)$	$\frac{k\eta - k^B\phi}{16kk^B(1-\alpha)} > 0$	$-\beta \frac{k\eta - k^B\phi}{16kk^B(1-\alpha)} < 0$	$\frac{k\eta - k^B\phi + 8\theta(1-\alpha)(k^B - k)}{16kk^B(1-\alpha)} > 0$	$\frac{b}{2} > 0$
	$c_V \geq H(\alpha)$	$\frac{k\mu - k^B(\omega-\alpha)}{kk^B(1-\alpha)} > 0$	$-\beta \frac{k\mu - k^B\omega}{kk^B(1\alpha)} < 0$	$\frac{2(\mu-\omega)+2\alpha(k-k^B)}{(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$

Table 9: Values of BCT.

	Situation	VSO^B	VVM^B	VCS^B	VSW^B
Value	$c_V < H(\alpha)$	$\frac{k\eta^2 - k^B\phi^2}{128kk^B(1-\alpha)^2} - c_{SB}$	$\frac{k\eta^2 - k^B\phi^2 + 32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} - c_{VB}$	$\frac{b^2+2b(1+d)}{8}$	$\frac{3k\eta^2 - 3k^B\phi^2 + 32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b(1+d)}{8} - c_{SB} - c_{V}$
	$c_V \geq H(\alpha)$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} - c_{SB}$	0	$\frac{b^2+2b(1+d)}{8}$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b(}{8}$

directly. That also implies that blockchain technology helps to improve the work efficiency. Secondly, premium rate is going down. This is because the successful launch probability increase which is beneficial for SO. Thirdly, the launch price is higher with the support of BCT, mainly because the probability of successful launch increases, and the SO is willing to pay higher fees Fourthly, as shown the change of e, r, and l are similar to 13, however, the retail price in model B increases after implementing BCT which is different from 13. It is due to the higher utility that BCT bring to customers, so they are more willing to pay a higher retail price.

Proposition 4.2. Given d, k^B, k, θ:

(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: $VSO^B \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$;

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

(iii) $VCS^B > 0$

Proposition 4.2 shows three neat findings.

Firstly, it gives the threshold of blockchain cost, which indicate that if the cost of implementing blockchain technology is high, then launching through the BCT platform is not profitable for the SO. That is because the loss of paying for blockchain cannot be offset by the benefits of improving the quality of data flow. Actually, there are two thresholds for the SO to decide whether implement BCT in two situations. However, once the cost of BCT is quite low, it is always profitable for the SO to use blockchain.

Secondly, it also gives the threshold for VM using blockchain. When $c_V < H(\alpha)$, if the cost of BCT is low, there is space for VM to make profit. However, when c_V is high, it is no use for VM to apply BCT. It lies in the launch price SO offering only matches VM's acceptance level and his payoff being zero in this situation.

Thirdly, with the help of BCT, the consumer surplus increase which means customers will benefit more although they have to pay higher retail price.

5. Conclusions

Nowadays, with the prosperity of commercial launch, more and more research study the operation management in 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 and the government-subsidized insurance model. 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 launch subsidy program the customers cannot be benefit . So we investigate the blockchain applications in the space launch supply chain by building blockchain-embedded insurance model which is also be implemented in the real world.

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

(1) When government subsidies for the selection of satellite owners for low-cost vehicle launches, it helps to form positive feedback in the commercial satellite market, that is, the satellite vendor is more willing to pay high launch prices, so that the vehicle

manufacture have the motivation to increase the probability of successful launches.

(2) Once the government subsidy project is launched, the satellite owner 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.

(3) 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.

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

(5) 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.

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

6. 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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