Transportation Research Part E 128 (2019) 17–29

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains☆

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ARTICLE INFO

Keywords:
Blockchain technology
Luxury supply chain
Fashion accessories
Platform operations
Diamond authentication and certification

ABSTRACT

The blockchain technology is very useful in many industries. One current application is on diamond authentication and certification, which is important in many luxury supply chains. In this paper, we explore different consumer utility driven operations models and highlight the values of blockchain technology supported (BTS) platforms for diamond authentication and certification. We build models and analytically examine both the traditional retail network operations (Model R) and the BTS selling platform (Model PL). We further extend the analysis to study the case with the BTS certification platform (Model BCR). We reveal the conditions under which one model outperforms the others. In particular, we note that the shopping convenience utility offered by the traditional retailers is a critical factor determining which model is the best. Finally, for the BTS platform operations, we study the blockchain-technology-based diamond authentication and certification (BDAC) cost and reveal that reducing it is beneficial to all parties in the luxury supply chain.

1. Introduction

1.1. Background and motivation

Platform operations are very common nowadays. In the luxury industry, platforms are emerging as an important player. For instance, for fashion product rental services of products like luxury handbags, platforms are critical (Choi and He 2019). Nowadays, with the advance of blockchain technology, many new applications can be offered by the platform. One example is diamond authentication and certification (with provenance information disclosure).

Consumers purchasing diamonds (including diamond rings, necklaces, etc) all have concerns about the authenticity, sources as well as quality of the diamond. The traditional way of certifying the diamonds is to issue some paper certificates which specify many details. However, these paper documents involve a few problems. First, they can be faked. A real certificate can be used for a "fake"[1] diamond, or a "fake" (and manipulated) certificate is issued for a diamond. Second, the sourcing information is less clear. Noting that for diamonds, every involved step can make a difference and craftsmanship is also critical. It is important to have clear details of the whole diamond from origin, sourcing to every single involved step. Moreover, when consumers stop by jewelry retail stores to buy diamonds, it takes a very long time for the sales associates to present the details, demonstrate the authenticity of the diamonds by using a piece of lens and explain this and that. This incurs a "non-trivial shopping cost" to consumers and is a hurdle to purchasing for those consumers who are impatient to wait for this and that. Unfortunately, in the past, these challenges were difficult to address.

☆ I sincerely thank the editor, associate editor and three anonymous reviewers for their kind and helpful comments on this paper.
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[1] "Fake" here means the one which is misidentified or with wrong details.

https://doi.org/10.1016/j.tre.2019.05.011
Received 2 April 2019; Received in revised form 30 April 2019; Accepted 15 May 2019

However, nowadays, with the use of blockchain technology, platforms (and information systems solution providers) like Everledger[2] are providing a unique digital thumb-print for each diamond (DHL Trend Research, 2018). With this digital thumb-print, every diamond's details (from the source in mine, rough sorting, to certification, store, and then consumers[3]), including cutting, weight, "clarity" and color are all well defined and described by using scientific methods. This digital thumb-print system is implemented by using laser technology. With this blockchain technology supported digital thumb-print system, the digital thumb-print of every certified diamond can be made available to everybody permanently. Thus, consumers purchasing the blockchain technology supported digital thumb-print certified diamonds will hence have full product knowledge, including full provenance (Montecchi et al. 2018) and authenticity of the diamond products. See Figs. 1, 2 and 3 for more details of Everledger's blockchain technology supported (BTS) "Diamond Time-Lapse" program and the sample reports (all downloaded or screen-captured from Everledger's webpage).[4]

Note that the blockchain technology is a distributed ledger which has the features of being able to keep permanent record of reliable data. It is hence a great technology, which has been implemented in practice, for diamond authentication and certification. Table 1.1 shows the features of the blockchain technology, which make it an excellent technology for diamond authentication and certification.

1.2. Research questions and major findings

Even though the use of blockchain technology supported (BTS) platform for diamond authentication and certification is already present in practice, in terms of operations management, many issues arise and remain open:

1. Compared to the traditional jewelry retail stores based operations, does the sales channel via the BTS platform help generate more benefit to the manufacturer and the consumers? Are there any tradeoffs governing this comparison result?
2. If both the traditional jewelry retail stores based operations and the BTS platform have their benefits, is it a wise measure to combine them together? Will that do more harm than good?
3. If the BTS platform incurs a significant unit operations cost called the blockchain-technology-based diamond authentication and certification (BDAC) cost (e.g., creating the digital thumb-print and the respective online digital certification), how would it affect the performance of BTS platforms?

This paper aims to address the above three main research questions by conducting a game-theoretic analytical study. To be specific, we build stylized consumer utility driven analytical models. Among many findings, we show the following results: Compared to the traditional jewelry retail stores based operations, the sales channel via the BTS platform can help generate more benefit to the manufacturer and the consumers if the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification is higher than the unit net benefit brought of shopping convenience brought by the retailers (i.e., the shopping convenience utility enjoyed by consumers), then it is beneficial to both the manufacturer and the consumers if the manufacturer switches from the traditional jewelry retail network sales channel to the BTS selling platform. The tradeoff between these two factors is very clear. If both the traditional jewelry retail stores based operations and the BTS platform have their benefits, a new model, denoted by Model BCR emerges. On one hand, Model BCR possesses the benefit of BTS-platform for diamond authentication and certification, and also the shopping convenience offered by the presence of traditional jewelry retail stores. On the other hand, the supply chain is longer which may turn out to be less efficient than a shorter supply chain. Our analytical findings have uncovered that depending on the value of shopping convenience utility offered by the retailers, the social welfare under Model BCR can be larger than or smaller than the ones under the model with traditional jewelry retailers, and the model with the BTS selling platform. We also prove that if the utility derived from shopping convenience is bounded between two critical thresholds, then Model BCR is the optimal choice from the perspective of social welfare. Finally, if the BTS platform incurs a significant unit operations cost called the blockchain-technology-based diamond authentication and certification (BDAC) cost (which supports the digital thumb-print), we analytically uncover that the presence of the BDAC cost will reduce the benefits of all involved parties in the supply chain. As a result, it is critically important to reduce the BDAC cost as this act will benefit all parties involved in the supply chain.

1.3. Contribution statements and paper structure

To the best of our knowledge, this paper is the first analytical study in operations management (OM) devoted to exploring supply chain operations with BTS platforms for diamond authentication and certification. Given that diamond authentication and certification using the blockchain technology is a recent real world practice, the findings of this paper not only contribute to the related literature but also provide novel managerial insights to practitioners on the value of blockchain technology for diamond authentication and certification. Some important implications are also derived which provide a significant guidance to operations managers on how to properly implement the BTS platform.

This paper is organized as follows. Section 2 presents the related literature. Section 3 shows the basic analytical models, one for the traditional jewelry retail (TJR) network based operations and one for the BTS selling platform based operations. Section 4

[2] https://diamonds.everledger.io/ [accessed on 29 March 2019].
[3] http://www.mydtl.io/#main [accessed on 29 March 2019].
[4] https://diamonds.everledger.io/search/QSLIS013 [accessed on 31 March 2019].

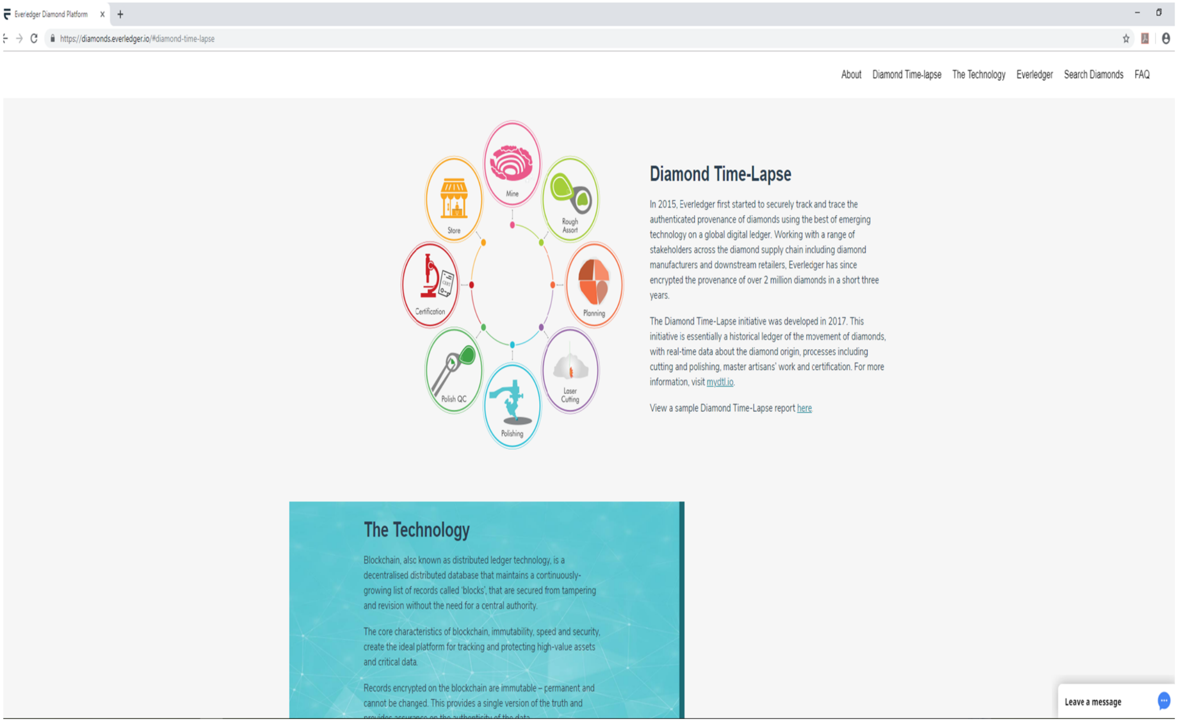

Fig. 1. The screen capture of “Diamond Time-Lapse” program by the BTS platform Everledger.

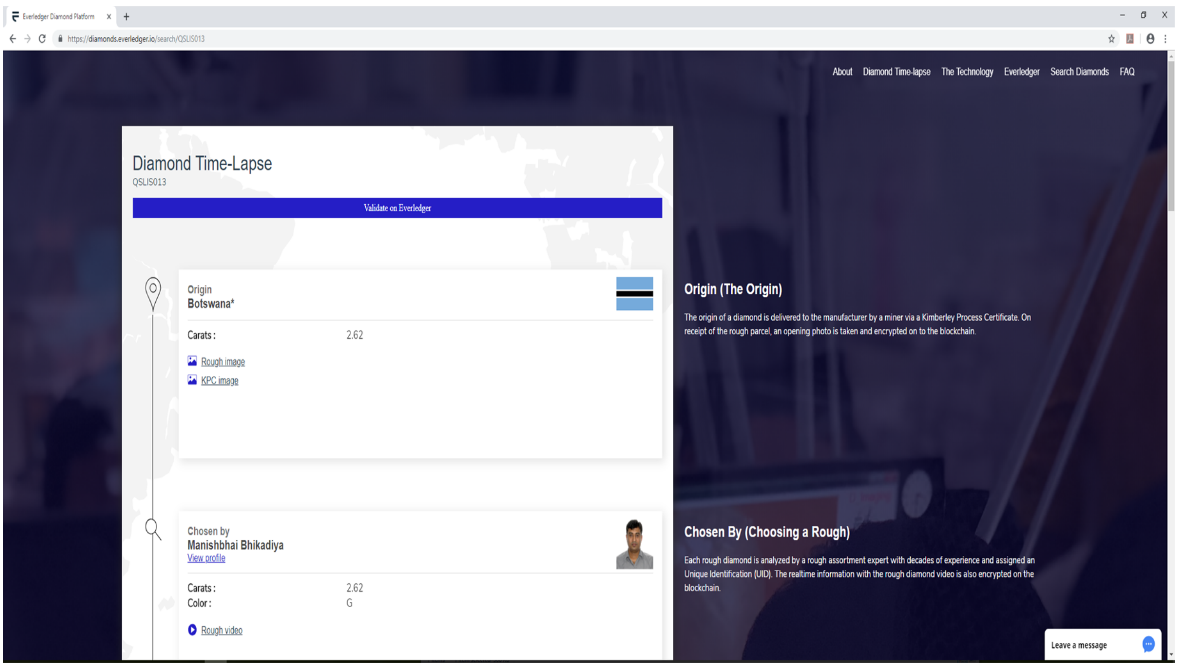

Fig. 2. The sample report on the origin, and people involved with the diamond under the “Diamond Time-Lapse” program by the BTS platform Everledger.

compares the two models and uncovers the values of the BTS selling platform. Section 5 reports two extended analyses which respectively investigate an operations model combining the TJR network with the BTS platform for authentication and certification only, and the presence of the BDAC cost for the deployment of blockchain technology for diamond authentication and certification. Section 6 concludes this study with a discussion on managerial implications. To enhance exposition, we present all proofs in Appendix A and a list of notation in Table 2.1.

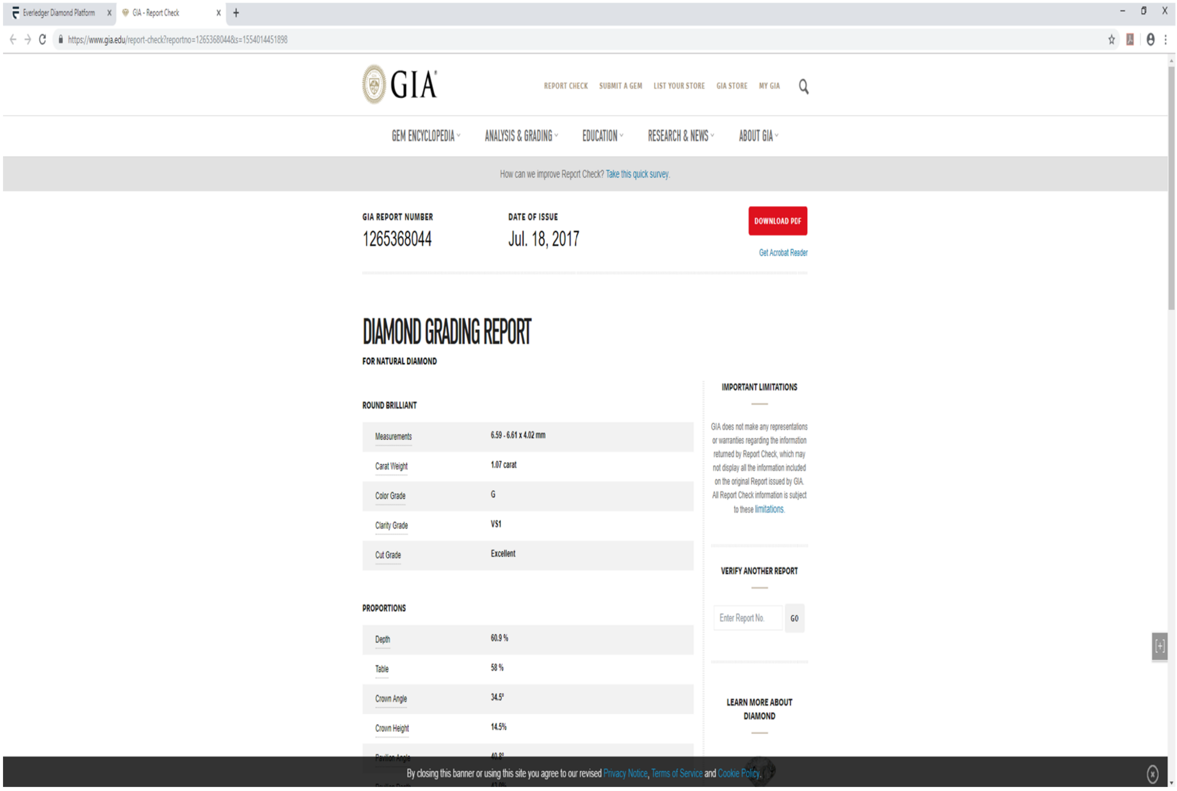

Fig. 3. The sample report for the diamond grading report under the "Diamond Time-Lapse" program by the BTS platform Everledger.

Table 1.1
Features of the blockchain technology for diamond authentication and certification.

Features	Details
Full details and identification	All the detailed product features which help with identification can be stored. Identification can be achieved by using digital "thumb-print"
Permanent record	The information cannot be changed without the consent of all related members
Data reliability	The blockchain technology keeps and shares the reliable data publicly which facilitate checking and verification

2. Related literature

2.1. Product authentication

In OM, it is known that problems with product authenticity exist. In particular, the counterfeiting problems are non-trivial. In the literature, Cho et al. (2015) study counterfeiters in two categories, namely the deceptive type, and the non-deceptive type. The

Table 2.1
Definitions of some important notation.

Notation	Definitions
BTS	Blockchain technology supported
Superscript (R)	Notation and expression for Model R
Superscript (PL)	Notation and expression for Model PL
Superscript (BCR)	Notation and expression for Model BCR
Superscript (PL-k)	Notation and expression for Model PL-k
Superscript (BCR-k)	Notation and expression for Model BCR-k
Model R	The operations model with the traditional jewelry retail stores and there is no blockchain
Model PL	The operations model with the BTS selling platform and traditional jewelry retail stores are absent
Model BCR	The operations model with both the traditional jewelry retail stores and the BTS platform for diamond authentication and certification
Model PL-k	Model PL with the consideration of BDAC cost
Model BCR-k	Model BCR with the consideration of BDAC cost
BDAC cost	Blockchain-technology-based authentication and certification cost (per unit), which also includes the use of laser technology

authors argue that by quality improvement, the real branded company can fight against the non-deceptive counterfeiter and enhance its own profit. It is interesting to note that the authors also prove that this strategy will not work against the counterfeiter who is deceptive. Stevenson and Busby (2015) conduct a study on supply chain operations strategies to deal with counterfeiting. The authors establish a theoretical framework regarding the impacts of "counterfeiting". They propose measures to deal with it and explain the implications by using the resource-based-view theory and the signaling theory. This paper also addresses the product authentication issue but it focuses on the use of blockchain technology, which is totally different from the existing studies.

2.2. Information technologies supported operations

OM has entered the digital era. In the past, we had the RFID technology (Lee and Ozer 2007). Now, we have big data (Choi et al. 2018; Fisher and Raman 2018) and disruptive technologies like blockchain (Michelman 2017) and 3D printing. Information technologies help in many ways, from learning (Li et al. 2015) to decision supports (Choi 2018). As a result, many related studies have appeared in recent years. For example, Choi (2018) explores how social media observations, in the big data era, can be put into fashion supply chains to address the bounded rationality issue. The author shows how a win-win situation can be attained when lead time is shortened under quick response. He also proposes how manipulating the social media data (i.e., comments) may bring benefits to the manufacturer under different supply contracts. Basole and Nowak (2018) investigate the deployment of tracking technology in supply chain systems. The authors employ the transaction cost theory and the institutional theory to highlight how factors like the product features and supply chain structure would affect the application of the tracking technology.

In the context of blockchain technology, Babich and Hilary (2018) propose how the blockchain technology may apply in operations management. Chod et al. (2018) study the use of blockchain in financing supply chains. Wang et al. (2019a) propose how blockchain may change the operations of supply chain systems. The authors employ the theory of sense-making, and conduct personal interviews with various practitioners and experts in supply chain operations. They highlight how the theory of sense-making can help uncover the behaviors of managers towards the adoption of new technologies. Recently, Saberi et al. (2019) examine the smart contracting mechanism of blockchain technology for establishing a sustainable supply chain system. The authors also propose future research agenda with the use of blockchain technology for better management of supply chains. This paper also explores the use of blockchain technology while the detailed models and application domains are different from the above reviewed studies.

2.3. Platform operations

Platforms exist in all kinds of industries. Nowadays, with the emergence of the sharing economy (Choi et al. 2019) as well as "mobile apps" (Wang et al. 2018) technologies, platforms play a very critical role. Wang et al. (2016) study the optimal pricing decisions for a service platform for calling taxi. Kung and Zhong (2017) investigate the pricing decisions of a two-side platform with the delivery service considerations. Benjaafar et al. (2018) study the P2P (peer to peer) sharing scheme for products. The authors explore the impacts of P2P product exchanges on social welfare. Cheng et al. (2019) explore the crowdsourcing platform via building the analytical auction model. The authors investigate various strategies and uncover that the fixed schedule approach tends to yield the maximum profit for the platform. Choi and He (2019) study the fashion rental platform operations with the considerations of P2P collaborative consumption. They prove that the presence of P2P collaborative consumption is beneficial to both the fashion brand and the consumers. Liu et al. (2019) examine the pricing decisions for service platforms. The authors highlight the importance of value added services (VASs) and argue that developing the VASs will yield a higher profit for the platform. Choi et al. (2019) investigate the platform operations for managing food product leftover. They find that a proper use of the proposed platform can achieve all win and enhance social welfare. Most recently, Vatankhah Barenji et al. (2019) explore a smart platform for e-commerce based logistics services. The authors propose two types of communication schemes to better integrate data for the platform operations. In this paper, we also examine the platform operations. However, the platform under investigation in this paper is one for diamond authentication and certification, which has never been examined in other studies in the OM literature.

2.4. Luxury supply chains

Diamonds are important components for many luxury products. Thus, this paper also relates to luxury supply chain management. In the literature, Castelli and Sianesi (2015) empirically study different strategies in luxury supply chains in the fashion industry. The authors argue that the decisions made in the luxury fashion supply chain significantly affect the chance of success of the luxury fashion brand. They also suggest ways to determine the critical success factors for luxury fashion business operations. Brun et al. (2017) conduct an empirical study on luxury fashion supply chains. The authors propose that the right luxury supply chain management measures should be designed with respect to the firm's luxury positioning, the sales channel, as well as product and brand features. Shen et al. (2017) analytically explore the channel coordination challenge when a luxury fashion brand sells online. The authors consider the effects of social influences. They determine the optimal pricing decisions and analytically propose how three commonly seen contracts can coordinate the luxury fashion supply chain with social influence considerations. This paper is an analytical study. Similar to the above examined papers, this paper's topic is related to luxury supply chains as diamonds are commonly used in, e.g., luxury fashion accessories. However, this paper focuses on BCT and the product authentication and certification issues, which have never been covered by the above reviewed studies. Obviously, this paper is positioned in the operations-marketing interface and aims to uncover the values and applicability of BTS platform for diamond authentication and certification.

3. Basic Models

3.1. Traditional jewelry retail network (Model R)

Consider the case when a manufacturer sells a diamond based fashion accessory product (e.g., a diamond ring) or simply "diamond"[5] through a traditional jewelry retail (TJR) network with K retailers located in geographically dispersed markets, where $K > 1$. Owing to geographical distances, these retailers would only serve their own "market zones" and there is no market competition. There is also no blockchain technology in place. For Retailer i, where $i = 1, ...,K$, the respective market includes n_i consumers who may be interested in the product. These consumers have heterogeneous valuation v_i towards the product, in which v_i follows a distribution $f_i(\cdot)$. Following the extant literature and to enhance analytical tractability, we consider in this paper the case when $f_i(\cdot)$ is the uniform distribution in the range of 0 and 1, for all $i = 1, ...,K$. Plus, to focus on our core exploration areas with respect to the use of blockchain technology, we consider the case when the retailers are homogeneous, except for the market size that they are facing. When consumers judge whether to buy the product or not, they will consider a few main factors: (i) the product's retail selling price p_i, (ii) the authenticity of the diamond (measured by the chance of having a fake certification $1 - a$, where a represents the chance of having a real and accurate certification), (iii) the time it takes in checking and evaluating the diamond (t), and (iv) the shopping convenience utility enjoyed by the consumers when they buy from the TJR network, e.g., retail store's location and support (s). The dis-utilities associated with the fake certification $(1 - a)$ and the time of checking (t) are scaled by the coefficients β and γ, respectively. Thus, the number of consumers who will buy from Retailer i, where $i = 1, ...,K$, is given by the following:

$$d_i^{(R)} = n_i \int_{p_i+\beta t+(1-a)\gamma-s}^{1} f(v_i)dv_i = n_i(1 - (p_i + \beta t + (1 - a)\gamma - s)). \tag{3.1}$$

Note that we use the superscript (R) to represent the functions and optimal decisions under Model R.

Under Model R, the product is supplied by the manufacturer to the retailers at a unit wholesale price c. The unit product cost for the manufacturer is m. In the supply chain, the manufacturer determines the wholesale price and each Retailer i decides its own retail selling price. Thus, the profit functions of Retailer i, where $i = 1, ...,K$, and the manufacturer are given as follows:

$$\Pi_i^{(R)}(p_i) = (p_i - c)d_i = (p_i - c)n_i(1 - (p_i + \beta t + (1 - a)\gamma - s)), \tag{3.2}$$

$$\Pi_M^{(R)}(c) = \sum_{i=1}^{K} (c - m)d_i. \tag{3.3}$$

It is straightforward to derive that $\Pi_i^{(R)}(p_i)$ is concave in p_i (P.S.: $\partial^2\Pi_i^{(R)}(p_i)/\partial p_i^2 < 0$). Thus, for a given c, the optimal retail price for Retailer i, where $i = 1, ...,K$, is:

$$p_i^*|_c = (1 + c + s - \beta t - (1 - a)\gamma)/2. \tag{3.4}$$

Put (3.4) into (3.1) yields the demand at Retailer i's optimal price (for a given c):

$$d_i^{(R)}(p_i^*|_c) = n_i(1 - (\beta t + (1 - a)\gamma - s) - [(1 + c + s - \beta t - (1 - a)\gamma)/2]) = \frac{n_i(A - c)}{2}, \tag{3.5}$$

where $A = (1 + s - \beta t - (1 - a)\gamma)$.

With (3.5), we can rewrite the profit function of the manufacturer as follows:

$$\Pi_i^{(R)}(c; p_i^*|_c) = \sum_{i=1}^{K} \frac{n_i}{2}(A - c)(c - m). \tag{3.6}$$

It is easy to check that $\Pi_i^{(R)}(c; p_i^*|_c)$ is concave in c and optimizing it yields the optimal[6] wholesale price. Put it into (3.4) yields the unconditional optimal retail price. We summarize the results in Lemma 3.1.

Lemma 3.1. *Under Model R, at the Stackelberg equilibrium, the retail price set by Retailer i, where* $i = 1, ...,K$, *is:* $p_i^{(R)*} = \frac{3A + m}{4}$, *and the wholesale price set by the manufacturer is:* $c^{(R)*} = \frac{A + m}{2}$, *where* $A = (1 + s - \beta t - (1 - a)\gamma)$.

Lemma 3.1 gives the neat expressions of the optimal decisions in the supply chain under Model R at the equilibrium. The result is also intuitive, e.g., if the product cost m increases, both the wholesale price and retail price under Model R will increase. For the parameter A, it captures how different major parameters in the consumer utility driven demand model affect the wholesale price and retail price. In particular, when the shopping convenience utility increases (s), the consumer disutility with respect to fake certification (γ) increases, or the consumer disutility associated with checking time (β) increases, we know from Lemma 3.1 that A increases which also implies a higher wholesale price and a higher retail selling price.

In addition to the profits of the retailers and the manufacturer, we also examine the consumers and social welfare. In the market,

[5] If we focus on the practices of platforms like Everledger, the product is simply "diamond" but it is obvious that the application can be extended to cover products with which diamonds are the major component (e.g., diamond rings).

[6] In this paper, we use the term optimal and equilibrium interchangeably. When we use the term "optimal", we try to highlight that the respective decision is the "best" one.

the (total) consumer surplus under Model R is given as follows:

$$CS^{(R)} = \sum_{i=1}^{K} n_i \int_{p_i+\beta t+(1-a)\gamma-s}^{1} (v_i - [p_i + \beta t + (1-a)\gamma - s]) f(v_i) dv_i$$
$$= \sum_{i=1}^{K} \frac{n_i}{2} (1 - \beta t - (1-a)\gamma + s - p_i). \tag{3.7}$$

Note that for the social welfare, by definition, it is equal to the following:

$$SW^{(R)} = CS^{(R)} + \Pi_M^{(R)}(c) + \sum_{i=1}^{K} \Pi_i^{(R)}(p_i). \tag{3.8}$$

Define the total profit of all retailers in the TJR network together as follows:

$$\Pi_R^{(R)} = \sum_{i=1}^{K} \Pi_i^{(R)}. \tag{3.9}$$

From Lemma 3.1, we have the optimal decisions, and hence we can derive the manufacturer's profit, retailers' profits, consumer surplus, and the social welfare at the optimal decisions. The results are summarized in Proposition 3.1.

Proposition 3.1. *Under Model R, at the Stackelberg equilibrium, the manufacturer's profit, retailers' total profit, consumer surplus, and social welfare are given as follows:* $\Pi_M^{(R)*} = \frac{N(A-m)^2}{8}$, $\Pi_R^{(R)*} = \frac{N(A-m)^2}{16}$, $CS^{(R)*} = \frac{N(A-m)^2}{32}$, $SW^{(R)*} = \frac{7N(A-m)^2}{32}$, *where* $N = \sum_{i=1}^{K} n_i$.

Proposition 3.1 reveals various important messages. First of all, $(A - m)$ and N are two critical terms which deserve our attention. When the total market size N increases, or $(A - m)$ increases, the manufacturer's profit, retailers' total profit, consumer surplus, and social welfare all increase. This feature is important as we know clearly that when these two critical terms vary, the effects to the manufacturer, the retailers, the consumers, and the social welfare are the same. Second, as we will see later on, this feature appears in Model R as well as all the subsequent models we will examine in this paper.

3.2. Blockchain technology supported (BTS) selling platform (Model PL)

After exploring Model R, we now consider Model PL in which the manufacturer simply sells the diamond based fashion accessory product via the BTS selling platform.[7] This BTS selling platform is supported by blockchain technology (such as those with the certification by Everledger) and it also directly sells to consumers. In other words, the BTS platform has two main functions: Providing product authentication as well as selling to the consumers. As it does not involve another layer of retailers, its presence will not lengthen the supply chain. Compared to the case under Model R, consumers will perceive some differences: (i) For the authenticity of the diamond, as blockchain technology is implemented, all the details are clearly shown and can always be verified, the chance of having a fake certification is set to be zero. (ii) For the time it takes to check and evaluate the diamond (denoted by T for the case under Model PL), it will be shorter under Model PL than under Model R because consumers no longer need to use the lens to physically check this and that, and hence we have $T < t$. For the shopping convenience utility, as the BTS selling platform does not provide the shopping convenience utility (like convenient location) s to consumers.

We assume in this paper that the numbers of consumers in the market who are interested in the diamond product are the same under Model R and Model PL. The only differences are the way the product is sold and the presence of the BTS platform for diamond authentication and certification. Thus, the number of consumers who will buy from the BTS selling platform is given by the following (P.S.: The superscript (PL) is employed to represent the functions and optimal decisions under Model PL):

$$d^{(PL)} = N(1 - (p^{(PL)} + \beta T)). \tag{3.10}$$

Moreover, the profit functions of the BTS selling platform and the manufacturer are given as follows:

$$\Pi_{PL}^{(PL)} = (p^{(PL)} - c^{(PL)}) d^{(PL)}, \tag{3.11}$$

$$\Pi_M^{(PL)} = (c^{(PL)} - m) d^{(PL)}, \tag{3.12}$$

where $p^{(PL)}$ and $c^{(PL)}$ are the unit retail price and the unit wholesale price of the product respectively.

We can also derive the consumer surplus and social welfare functions under Model PL as follows:

$$CS^{(PL)} = N(B - p^{(PL)})^2, \tag{3.13}$$

where $B = (1 - \beta T)$.

$$SW^{(PL)} = CS^{(PL)} + \Pi_M^{(PL)} + \Pi_{PL}^{(PL)}. \tag{3.14}$$

[7] This platform operates in a single location, which may be online or offline. In the extended model, we consider another scenario when there are multiple selling points, via the retailers, and the BTS platform serves as the certification platform only.

Following the similar approach as in Section 3.1, we have the equilibrium decisions and results as summarized in Proposition 3.2.

Proposition 3.2. *Under Model PL, at the Stackelberg equilibrium: (a) The retail price set by the BTS selling platform is:* $p^{(PL)*} = \frac{3B+m}{4}$*, and the wholesale price set by the manufacturer is:* $c^{(PL)*} = \frac{B+m}{2}$*. (b) The manufacturer's profit, the BTS selling platform's profit, consumer surplus, and social welfare are given as follows:* $\Pi_M^{(PL)*} = \frac{N(B-m)^2}{8}$, $\Pi_{PL}^{(PL)*} = \frac{N(B-m)^2}{16}$, $CS^{(PL)*} = \frac{N(B-m)^2}{32}$, $SW^{(PL)*} = \frac{7N(B-m)^2}{32}$.

Proposition 3.2 is very similar to Proposition 3.1. There are two differences. First, in Proposition 3.2, as the traditional retailers are absent, we only have the BTS selling platform's profit and optimal pricing decision (but no profit for any retailers in the TJR network). Second, in Proposition 3.2, the critical term is $(B - m)$, which is different from Proposition 3.1 in which the critical term is $(A - m)$. Similar to Proposition 3.1, we observe that when the total market size N increases, or $(B - m)$ increases, the manufacturer's profit, the retailers' total profit, the consumer surplus, and the social welfare all increase.

4. Values of the BTS selling platform

After deriving the equilibrium decisions and performance measures in the supply chains under Models R and PL, we now explore the values of blockchain technology. We define the following, which respectively represent the values of blockchain technology (VBTs) for the manufacturer, the consumers, and the social welfare when Model PL is adopted (compared to Model R, i.e., the traditional operations model in the presence of the TJR network):

$$VBT_M^{(PL)} = \Pi_M^{(PL)*} - \Pi_M^{(R)*}, \tag{4.1}$$

$$VBT_{CS}^{(PL)} = CS^{(PL)*} - CS^{(R)*}, \tag{4.2}$$

$$VBT_{SW}^{(PL)} = SW^{(PL)*} - SW^{(R)*}. \tag{4.3}$$

We have Proposition 4.1.

Proposition 4.1. *If* $s \begin{pmatrix} < \\ = \\ > \end{pmatrix} \beta(t - T) + (1 - a)\gamma$*, then we have:* $VBT_l^{(PL)} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$*, for* $l \in \{M, CS, SW\}$.

Proposition 4.1 shows a very neat and clean result on the values of the BTS selling platform. In particular, we highlight that $\beta(t - T) + (1 - a)\gamma$ and s are both critical because depending on their relative values, the VBTs derived from the deployment of the BTS selling platform will be different. In fact, these two terms carry very good physical meanings. To be specific, $\beta(t - T) + (1 - a)\gamma$ represents the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification, and s denotes the unit net benefit of shopping convenience (i.e. the shopping convenience utility) brought by the retailers. Proposition 4.1 indicates that if $\beta(t - T) + (1 - a)\gamma$ is larger than s, then the VBTs for the manufacturer, the consumers and the social welfare will all be positive, which means that Model PL outperforms Model R. However, the opposite can also appear if $\beta(t - T) + (1 - a)\gamma$ is smaller than s, then the VBTs for the manufacturer, the consumers and the social welfare will all be negative which implies that Model R performs better than Model PL. We summarize the managerial insights in Theorem 4.1.

Theorem 4.1. *If the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification (i.e.,* $\beta(t - T) + (1 - a)\gamma$*) is higher than the unit net benefit brought of shopping convenience brought by the retailers (i.e., the shopping convenience utility* s*), then it is beneficial to both the manufacturer and the consumers if the manufacturer switches from the traditional jewelry retail (TJR) network sales channel to the BTS selling platform.*

Note that in Theorem 4.1, the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification will be larger if T is smaller, a is smaller, β is larger or γ is larger. These conditions imply that if the time it takes to check and evaluate the diamond with BTS supported platform is smaller, the accuracy in terms of diamond authentication and certification without the use of blockchain is lower, the importance of checking time to consumers is higher, or the importance of diamond authentication and certification is higher, then the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification will be larger which implies that the likelihood of generating a positive VBT via using the BTS selling platform will also be higher. Moreover, Theorem 4.1 shows one important thing, which is, if the use of the BTS selling platform is good for the manufacturer, it will also be good for the consumers and the social welfare. The same pattern appears for the case if the BTS selling platform is bad to the manufacturer, it will also be bad to the consumers and the social welfare. Moreover, Theorem 4.1 further uncovers one important point: If the TJR network sales channel and the BTS platform both carry good values, is it wise and beneficial to combine them together and form another operations model in the luxury supply chain? We will explore it in Section 5.1.

5. Extended models

5.1. The BTS-certification-platform (model BCR)

In Sections 3 and 4, we explore and compare the traditional jewelry retail network based operations model and the BTS selling platform operations model. However, one natural proposal is to combine the niche of them and develop a new model in which consumers can enjoy: (i) the benefits brought by blockchain technology supported authentication and certification, and (ii) the shopping convenience utility offered by the traditional jewelry retail network. In this section, we explore it by establishing a new operations model called Model BCR.[8]

Under Model BCR, the manufacturer first supplies the product to the BST certification platform at a price $c^{(BCR)}$. The BST certification platform offers the blockchain technology based solution and provides all those details for the diamond similar to what the "Diamond Time-Lapse" program that Everledger is offering.[9] The BST certification platform supplies the blockchain technology processed and equipped product to the retailers at a wholesale price $w^{(BCR)}$. As a service provider, we consider the case when the BST certification platform also charges a certain fixed fee from the manufacturer, denoted by $F_M^{(BCR)}$. It also charges each Retailer i, where $i = 1, ..., K$, a certain fixed fee of $F_{R,i}^{(BCR)}$. Finally, the product is sold to the market via the traditional jewelry retail network. Obviously, under Model BCR, the supply chain is longer than the supply chains under Model R and Model PL. This is just the opposite to the proposal of dis-intermediation. In the presence of one more intermediary supply chain member, whether the manufacturer and the consumers are benefited is unclear.

Similar to the derivations and analyses conducted for Models R and PL, under Model BCR, we can derive the respective equilibrium decisions

Proposition 5.1. *Under Model BCR, at the equilibrium: (a) The retail price set by Retailer i, where i* $= 1, ..., K$, *is:* $p_i^{(BCR)*} = \frac{7G+m}{8}$, *the wholesale price set by the BTS certification platform is:* $w^{(BCR)*} = \frac{3G+m}{4}$, *and the product offering price set by the manufacturer is:* $c^{(BCR)*} = \frac{G+m}{2}$, *where* $G = (1 + s - \beta T)$. *(b)The manufacturer's profit, the Retailer i's profit, the BTS certification platform's profit, the consumer surplus, and the social welfare are given as follows:* $\Pi_M^{(BCR)*} = \frac{N(G-m)^2}{16} - F_M^{(BCR)}$, $\Pi_{PL}^{(BCR)*} = \frac{N(G-m)^2}{32} + F_M^{(BCR)} + \sum_{i=1}^K F_{R,i}^{(BCR)}$, $\Pi_{R,i}^{(BCR)*} = \frac{n_i(G-m)^2}{64} - F_{R,i}^{(BCR)}$, $CS^{(BCR)*} = \frac{N(G-m)^2}{128}$, $SW^{(BCR)*} = \left(\frac{27N}{128}\right)(G-m)^2$.

Proposition 5.1 is very similar to Proposition 3.1 and Proposition 3.2. One major difference is on the critical term $(G - m)$ in Proposition 5.1 (for Model BCR) whereas the terms are $(A - m)$ and $(B - m)$ for Models R and Pl, respectively. The other major difference is the presence of service fees (fixed). We summarize the equilibrium details of different models in Table 5.1.

For a notational purpose, we define two critical thresholds (which are important to reflect the conditions under which Model BCR outperforms other models) as follows:

$$\hat{s}_{BCR-PL} = \left(\frac{\sqrt{28} - \sqrt{27}}{\sqrt{27}}\right)(1 - \beta T - m),$$

$$\hat{s}_{BCR-R} = m - 1 + \left(\frac{\sqrt{28}\,(\beta t + (1-a)\gamma)}{\sqrt{28} - \sqrt{27}}\right) - \left(\frac{\sqrt{27}\,\beta T}{\sqrt{28} - \sqrt{27}}\right).$$

Now, we would like to proceed to explore the performance of Model BCR. Note that under Model BCR, as the presence of fixed service fees $F_M^{(BCR)}$ and $F_{R,i}^{(BCR)}$ would allow the flexibility[10] of dividing the total benefit derived from the supply chain, we focus on exploring the total systems benefit, i.e. the social welfare. If the social welfare achieved under Model BCR is higher than the other models, then we say that Model BCR performs better, or vice versa. Proposition 5.2 tells us the insights.

Proposition 5.2. *(a)* $SW^{(BCR)*}\begin{pmatrix}>\\=\\<\end{pmatrix}SW^{(PL)*}$ *if and only if* $s\begin{pmatrix}>\\=\\<\end{pmatrix}\hat{s}_{BCR-PL}$. *(b)* $SW^{(BCR)*}\begin{pmatrix}>\\=\\<\end{pmatrix}SW^{(R)*}$ *if and only if* $s\begin{pmatrix}<\\=\\>\end{pmatrix}\hat{s}_{BCR-R}$.

Proposition 5.2 uncovers that depending on the value of shopping convenience utility offered by the retailers, the social welfare under Model BCR can be larger than or smaller than the ones under Model PL and Model R. To be specific, when the shopping convenience utility is sufficiently high ($s > \hat{s}_{BCR-PL}$), the use of Model BCR (i.e. using blockchain for diamond certification only) outperforms Model PL (i.e. using blockchain for both diamond certification and sales). This finding can be explained by the fact that if the shopping convenience utility is sufficiently high, the value of having the TJR network in the supply chain will be high and their presence will bring more benefit to the total system (i.e. social welfare). On the contrary, when we compare Model BCR and Model R, when the shopping convenience utility is sufficiently low ($s < \hat{s}_{BCR-R}$), the use of Model BCR (i.e. using the traditional jewelry retailers to sell while using blockchain for diamond certification only) outperforms Model R (i.e. using the traditional jewelry retailers to sell, without using blockchain at all). This finding highlights another side of the comparison: Under Model BCR, both blockchain and traditional retailers are present. If the shopping convenience utility is very high, then Model R will outperform Model BCR and the use of blockchain is unimportant. However, when the shopping convenience utility is sufficiently low, then relatively speaking, the value of blockchain is higher and hence Model BCR outperforms Model R. When we compare the conditions, we also identify that it is possible for Model BCR to outperform both Model PL and Model R. We summarize it in Theorem 5.1.

Theorem 5.1. *From the social welfare perspective, among all three models, namely Model R, Model PL and Model BCR, Model BCR yields the largest social welfare if and only if* $\hat{s}_{BCR-PL} < s < \hat{s}_{BCR-R}$.

Theorem 5.1 is implied by Proposition 5.2. It shows that a bit counter-intuitively, a longer supply chain (Model BCR) can be

[8] Here, B, C, and R represent "blockchain", "certification", and "(traditional) retailer" respectively.
[9] http://www.mydtl.io/#mining [accessed on 29 March 2019],
[10] Note that the fixed costs can be positive or negative. If they are positive, they are charges. If they are negative, they become sponsors. Allowing the fixed costs to be positive or negative grants the supply chain members a way to flexibly divide the supply chain profit among members.

Table 5.1
Equilibrium results under Models R, PL and MCR.

Models	Benefits			
	Manufacturer	Intermediaries		Consumers
		Retailers	Platform	
R	$\frac{N(A-m)^2}{8}$	$\frac{N(A-m)^2}{16}$	Not applicable	$\frac{N(A-m)^2}{32}$
PL	$\frac{N(B-m)^2}{8}$	Not applicable	$\frac{N(B-m)^2}{16}$	$\frac{N(B-m)^2}{32}$
BCR	$\frac{N(G-m)^2}{16} - F_M^{(BCR)}$	$\frac{N(G-m)^2}{64} - \sum_{i=1}^{K} F_{R,i}^{(BCR)}$	$\frac{N(G-m)^2}{32} + F_M^{(BCR)} + \sum_{i=1}^{K} F_{R,i}^{(BCR)}$	$\frac{N(G-m)^2}{128}$

beneficial to the social welfare compared to the shorter supply chain models (Model R and Model PL). In addition, if $\hat{s}_{BCR-PL} < s < \hat{s}_{BCR-R}$, Theorem 5.1 implies that the combination of traditional jewelry retail networks and the blockchain technology supported platform can yield the optimal performance among all three scenarios under Model R, Model PL, and Model BCR. This is an important finding.

5.2. BDAC cost for BTS diamond authentication and certification

In the model analysis above, we assume that there is no (significant) additional cost incurred during the process of having the blockchain technology certification. However, it may not be true in practice. This section explores the presence of this cost, which specifically refers to the BDAC cost (e.g., for establishing the digital thumb-print and the authentication certification). In fact, the use of laser technology for creating digital thumb-print for diamonds has been well-established. A well-known company called Gemprint.com[11] is already implementing it. It is known that a machine for creating the authentication and certification digital thumb-print for diamonds using laser technology would cost the company US$14000.[12] Creating the digital thumb-print for a diamond using such an expensive device definitely would incur a substantial fee. In addition, after creating the digital thumb-print, each data record would cost the user US$50 for registration.[13]

Benchmarking with the above industrial data, suppose that for the BTS platform to provide the digital thumb-print on each diamond, there is a BDAC cost incurred and we denote it as k. Then, for Model PL, we have to include this BDAC cost there and we rename it as Model PL-k. We have Proposition 5.3.

Proposition 5.3. *Under Model PL-k, at the Stackelberg equilibrium: (a) The retail price set by the BTS selling platform is* $p^{(PL-k)*} = \frac{3B+m+k}{4}$*: and the wholesale price set by the manufacturer is:* $c^{(PL-k)*} = \frac{B+m-k}{2}$*. (b) The manufacturer's profit, the BTS selling platform's profit, the consumer surplus, and the social welfare are given as follows:* $\Pi_M^{(PL-k)*} = \frac{N(B-m-k)^2}{8}$, $\Pi_{PL}^{(PL-k)*} = \frac{N(B-m-k)^2}{16}$, $CS^{(PL-k)*} = \frac{N(B-m-k)^2}{32}$, $SW^{(PL-k)*} = \frac{7N(B-m-k)^2}{32}$.

Proposition 5.3 indicates how the presence of BDAC cost affects the equilibrium decisions and performance measures in the supply chain. Compared to Model PL, the presence of BDAC cost (i.e., k) under Model PL-k implies that the retail price increases by k whereas the product wholesale price decreases by k. It means that in the supply chain, under the Stackelberg game, the presence of BDAC cost will imply a "share of cost" in which the manufacturer suffers with a lower wholesale price, and the consumers suffer with a higher retail price. All involved members also suffer a drop of benefit.

Similarly, when we consider the presence of BDAC cost in Model BCR, we have a new model called Model BCR-k, and we can derive Proposition 5.4.

Proposition 5.4. *Under Model BCR-k, at the equilibrium: (a) The retail price set by Retailer i, where* $i = 1, \ldots, K$*, is:* $p_i^{(BCR-k)*} = \frac{7G+m+k}{8}$*, the wholesale price set by the BTS certification platform:* $w^{(BCR-k)*} = \frac{3G+m+k}{4}$*, and the product offering price set by the manufacturer is:* $c^{(BCR-k)*} = \frac{G+m-k}{2}$*, where* $G = (1+s-\beta T)$*. (b)The manufacturer's profit, the Retailer i's profit, the BTS certification platform's profit, consumer surplus, and social welfare are given as follows:* $\Pi_M^{(BCR-k)*} = \frac{N(G-m-k)^2}{16} - F_M^{(BCR)}$, $\Pi_{PL}^{(BCR-k)*} = \frac{N(G-m-k)^2}{32} + F_M^{(BCR)} + \sum_{i=1}^{K} F_{R,i}^{(BCR)}$, $\Pi_{R,i}^{(BCR-k)*} = \frac{n_i(G-m-k)^2}{64} - F_{R,i}^{(BCR)}$, $CS^{(BCR-k)*} = \frac{N(G-m-k)^2}{128}$, $SW^{(BCR-k)*} = \left(\frac{27N}{128}\right)(G-m-k)^2$.

Proposition 5.4 shows similar results as the ones explained for Proposition 5.3. Combining Proposition 5.3 and Proposition 5.4, we have Theorem 5.2.

Theorem 5.2. *(a) Comparing between "Model PL and Model PL-k", and "Model BCR and Model BCR-k", we clearly reveal that the presence*

[11] http://www.gemprint.com/ (accessed 30 April 2019).
[12] https://www.nationaljeweler.com/independents/retail-profiles/2451-retailer-talk-two-tools-that-changed-my-year (accessed 30 April 2019).
[13] https://register.gemprint.com/pages/safe_register/gemprint_registry/safe_register.aspx (accessed 30 April 2019).

of the BDAC cost for blockchain technology certification will reduce the benefits of all involved parties in the supply chain (i.e., the manufacturer, the platform (i.e the BTS selling platform under Model PL-k, or the blockchain technology certification platform under Model BCR-k), the retailers (for Model BCR-k only), the consumers, and the social welfare). (b) Under both Model PL-k and Model BCR-k, a larger BDAC cost for blockchain technology certification for diamond authentication and certification k is harmful to all involved parties in the supply chain.

Theorem 5.2 gives the key insight that the presence of BDAC cost k reduces the benefits of all members under both the scenario when the blockchain technology is used for diamond authentication, certification and sales, and the scenario when the blockchain technology is used for diamond authentication and certification only. Plus, a larger BDAC cost also implies a bigger harm to all involved parties in the supply chain. As a result, it benefits all members in the supply chain if this BDAC cost can be reduced.

6. Conclusion

6.1. Concluding remarks and answers to research questions

Nowadays, the blockchain technology is developing as a critical tool for many important industrial applications. Motivated by the widely reported real world application of the blockchain technology for diamond authentication and certification, we have built formal analytical models to explore the values of blockchain technology. We have considered a few different models. First, we have examined both the traditional jewelry retail (TJR) network operations (Model R) and the blockchain technology supported (BTS) selling platform (Model PL). We have further extended the analysis to explore the case with the BTS certification platform (Model BCR). We have derived the conditions under which one model outperforms the others.

As a concluding remark, we highlight the answers we have derived with respect to the research questions:

1. Compared to the traditional jewelry retail stores based operations, the sales channel via the BTS platform can help generate more benefit to the manufacturer and the consumers if the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification (i.e., $\beta(t - T) + (1 - a)\gamma$) is higher than the unit net benefit brought of shopping convenience brought by the retailers (i.e., the shopping convenience utility s). The tradeoff between these two factors is very clear.
2. If both the traditional jewelry retail stores based operations and the BTS platform have their benefits, a new model, denoted by Model BCR emerges. On one hand, Model BCR possesses the benefit of BTS-platform for diamond certification and also the shopping convenience offered by the presence of traditional jewelry retail stores. On the other hand, the supply chain is longer which may turn out to be less efficient than a shorter supply chain. Our analytical findings have uncovered that Model BCR may or may not outperform Model R and Model PL. To be specific, depending on the value of shopping convenience utility offered by the retailers, the social welfare under Model BCR can be larger than or smaller than the ones under Model PL and Model R. In particular, we have derived the analytical condition which shows that if the utility derived from shopping convenience is bounded between two critical thresholds (i.e., $\hat{s}_{BCR-PL} < s < \hat{s}_{BCR-R}$), then the combination of traditional retail networks and the blockchan technology supported platform can yield the optimal performance among all three scenarios under Model R, Model PL, and Model BCR.
3. If the BTS platform incurs a significant unit operations cost called the BDAC cost for the digital thumb-printing, authentication and certification with the use of blockchain, we have proven analytically that the presence of BDAC cost will reduce the benefits of all involved parties in the supply chain. Thus, BDAC cost brings harms to all involved parties in the supply chain. As a result, it is beneficial to all members in the supply chain if this BDAC cost can be reduced.

Note that this paper is motivated by the real world application of blockchain for diamond authentication and certification. Thus, the results are directly relevant to the case with diamonds, which includes the findings with respect to the use of laser technology and the respective BDAC cost. Having said that, some findings may be generalizable to cover other industrial products. For example, in the luxury fashion industry (Chiu et al. 2018), luxury handbags may exhibit many similar features and the blockchain technology should also be applicable to help provide authentication and certification services to them.

6.2. Future studies

In this paper, we have not considered the competition between the traditional jewelry retailers and the BTS platforms for selling diamond related products. For further studies, the role played by blockchain technology will be interesting as it can be a strategic decision for these related parties under competition. Another probable future research direction is to investigate how the risk averse attitudes of supply chain members (Asian and Nie 2014) may affect the deployment of BTS platforms for diamond authentication and certification. When the presence of BTS platform implies the establishment of a new channel, how would the supply chain members choose the optimal channel structure (Wei et al., 2018; Wang et al., 2019b) and the respective optimal pricing decisions all deserve deeper investigation in the future. Last but not least, it will also be interesting to extend the analysis to cover the situation when there are multiple manufacturers in the supply chain system.

Acknowledgment

This research is partially supported by The Hong Kong Polytechnic University (grant number: G-YBV5).

Appendix A. All proofs

Proof of Lemma 3.1. Under Model R, the number of consumers who will buy from Retailer i, where $i = 1, ..., K$, is given by the following: $d_i^{(R)} = n_i \int_{p_i+\beta t+(1-a)\gamma-s}^{1} f(v_i)dv_i = n_i(1-(p_i+\beta t+(1-a)\gamma-s))$. The profit function of Retailer i, where $i = 1, ..., K$, is given as follows: $\Pi_i^{(R)}(p_i) = (p_i - c)d_i = (p_i - c)n_i(1-(p_i+\beta t+(1-a)\gamma-s))$. Checking the 2nd order derivative shows that $\partial^2\Pi_i^{(R)}(p_i)/\partial p_i^2 < 0$). Thus, for a given c, the optimal retail price for Retailer i, where $i = 1, ..., K$, is:
$p_i^*|_c = (1+c+s-\beta t-(1-a)\gamma)/2$. The manufacturer's profit function becomes:

$$\Pi_i^{(R)}(c; p_i^*|_c) = \sum_1^K \frac{n_i}{2}(A-c)(c-m).$$

Since $\partial^2\Pi_i^{(R)}(c; p_i^*|_c)/\partial c^2 < 0$, we know that $\Pi_i^{(R)}(c; p_i^*|_c)$ is concave in c and optimizing it yields the optimal wholesale price $c^{(R)*} = \frac{A+m}{2}$, where $A = (1+s-\beta t-(1-a)\gamma)$. Then, with $c^{(R)*}$, we can easily find the optimal retail price $p_i^{(R)*} = \frac{3A+m}{4}$. □

Proof of Proposition 3.1. Under Model R, at the Stackelberg equilibrium, by putting the optimal wholesale pricing and retail pricing decisions into the manufacturer's profit, retailers' total profit, consumer surplus, and social welfare functions, we have: $\Pi_M^{(R)*} = \frac{N(A-m)^2}{8}$, $\Pi_R^{(R)*} = \frac{N(A-m)^2}{16}$, $CS^{(R)*} = \frac{N(A-m)^2}{32}$, $SW^{(R)*} = \frac{7N(A-m)^2}{32}$, where $N = \sum_1^K n_i$. □

Proof of Proposition 3.2. Similar to the proofs of Lemma 3.1 and Proposition 3.1, note that the supply chain operates as a Stackelberg game under Model PL. Then, at the Stackelberg equilibrium: (a) We can determine the equilibrium decisions by standard calculus: The optimal retail price set by the BTS selling platform becomes: $p^{(PL)*} = \frac{3B+m}{4}$, and the wholesale price set by the manufacturer is: $c^{(PL)*} = \frac{B+m}{2}$. (b) Substituting the optimal pricing decisions into the manufacturer's profit, the BTS selling platform's profit, consumer surplus, and social welfare functions, we have: $\Pi_M^{(PL)*} = \frac{N(B-m)^2}{8}$, $\Pi_{PL}^{(PL)*} = \frac{N(B-m)^2}{16}$, $CS^{(PL)*} = \frac{N(B-m)^2}{32}$, $SW^{(PL)*} = \frac{7N(B-m)^2}{32}$. □

Proof of Proposition 4.1. By definition, from (4.1), (4.2) and (4.3), we have:

$$VBT_M^{(PL)} = \Pi_M^{(PL)*} - \Pi_M^{(R)*},$$

$$VBT_{CS}^{(PL)} = CS^{(PL)*} - CS^{(R)*},$$

$$VBT_{SW}^{(PL)} = SW^{(PL)*} - SW^{(R)*}.$$

Then, checking each VBT, we will find that if $s \begin{pmatrix} < \\ = \\ > \end{pmatrix} \beta(t-T)+(1-a)\gamma$, then $VBT_l^{(PL)} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$ is true, for $l \in \{M, CS, SW\}$. □

Proof of Theorem 4.1. From Proposition 4.1, we have: If $s \begin{pmatrix} < \\ = \\ > \end{pmatrix} \beta(t-T)+(1-a)\gamma$, then $VBT_l^{(PL)} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0$ holds. From this important result, the following finding is implied: If the unit net benefit to consumers brought by the blockchain technology for diamond authentication and certification (i.e., $\beta(t-T)+(1-a)\gamma$) is higher than the unit net benefit brought of shopping convenience [brought by the retailers (i.e., the shopping convenience utility s)], then it is beneficial to both the manufacturer and the consumers if the manufacturer switches from the traditional jewelry retail network sales channel to the BTS selling platform. □

Proof of Proposition 5.1. Similar to the proof of Proposition 3.2, note that the supply chain operates as a Stackelberg game under Model BCR. Then, at the Stackelberg equilibrium: (a) We can determine the equilibrium decisions by standard calculus: The retail price set by Retailer i, where $i = 1, ..., K$, is: $p_i^{(BCR)*} = \frac{7G+m}{8}$, the wholesale price set by the BTS certification platform: $w^{(BCR)*} = \frac{3G+m}{4}$, and the product offering price set by the manufacturer is: $c^{(BCR)*} = \frac{G+m}{2}$, where $G = (1+s-\beta T)$. (b) Substituting the optimal pricing decisions into the manufacturer's profit, the Retailer i's profit, the BTS certification platform's profit, the consumer surplus, and the social welfare functions yields: $\Pi_M^{(BCR)*} = \frac{N(G-m)^2}{16} - F_M^{(BCR)}$, $\Pi_{PL}^{(BCR)*} = \frac{N(G-m)^2}{32} + F_M^{(BCR)} + \sum_{i=1}^K F_{R,i}^{(BCR)}$, $\Pi_{R,i}^{(BCR)*} = \frac{n_i(G-m)^2}{64} - F_{R,i}^{(BCR)}$, $CS^{(BCR)*} = \frac{N(G-m)^2}{128}$, $SW^{(BCR)*} = \left(\frac{27N}{128}\right)(G-m)^2$. □

Proof of Proposition 5.2. Proposition 5.2 is a direct result from simple algebraic manipulation of the social welfare terms. With the definitions of the following two critical thresholds,

$$\hat{s}_{BCR-PL} = \left(\frac{\sqrt{28}-\sqrt{27}}{\sqrt{27}}\right)(1-\beta T-m),$$

$$\hat{s}_{BCR-R} = m - 1 + \left(\frac{\sqrt{28}\,(\beta t + (1-a)\gamma)}{\sqrt{28} - \sqrt{27}}\right) - \left(\frac{\sqrt{27}\,\beta T}{\sqrt{28} - \sqrt{27}}\right),$$

it is straightforward to prove that $SW^{(BCR)*}\begin{pmatrix} > \\ = \\ < \end{pmatrix}SW^{(PL)*}$ if and only if $s\begin{pmatrix} > \\ = \\ < \end{pmatrix}\hat{s}_{BCR-PL}$, and $SW^{(BCR)*}\begin{pmatrix} > \\ = \\ < \end{pmatrix}SW^{(R)*}$ if and only if $s\begin{pmatrix} < \\ = \\ > \end{pmatrix}\hat{s}_{BCR-R}$. □

Proofs of Proposition 5.3 and Proposition 5.4. Similar to the proofs of Proposition 3.2 and Proposition 5.1, respectively. □

Proof of Theorem 5.2. Implied by Propositions 5.3 and 5.4. □

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