Transportation Research Part E 145 (2021) 102162

Contents lists available at ScienceDirect

Transportation Research Part E

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

How should a capital-constrained servicizing manufacturer search for financing? The impact of supply chain leadership

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ARTICLE INFO

Keywords:
Servicization
External financing
Internal financing
Stackelberg game

ABSTRACT

Servicization is an emerging business paradigm that entails selling services along with physical goods. Money is paid for the utility value derived from using the product. To ensure the product runs well, the servicizing manufacturer bears the cost for operating it. We establish a Stackelberg game to investigate the interaction between a manufacturer and an operator using the product provided by the manufacturer. As a servicizing firm, the manufacturer is more likely to be capital-constrained. When the manufacturer has to raise funds for the production, it has two channels: external financing, which means raising funds from a bank, and internal financing, which means raising funds from the operator. Both the manufacturer and the operator may act as the leader under external financing, while under internal financing, the operator always moves first. We find that under external financing, moving first is not always beneficial. Also, high operating efficiency benefits both chain members when the manufacturer is the leader, but both are hurt when the operator leads. We find that it can be optimal to provide a subsidy not only when the operating efficiency is low but also when it is very high. Furthermore, when the per-unit price is high, the manufacturer should accept a high interest rate to facilitate earning more profit.

1. Introduction

Currently, the world is witnessing a big change for the manufacturing industry, a shift from producing for selling to producing for servicing. The underlying reason is a change in the buyers, viz., more and more buyers are focusing on the functionality of a product rather than simply owning it. Unlike traditional service, servicization depends on physical goods since manufacturers need products to deliver their services. The value of these services, therefore, relies on the performance of both the products and the services themselves.

Many manufacturers sell services along with products, but if they only sell services, we call their business strategy servicization. The biggest difference between these two systems is who retains ownership of the product. Servicization is also different from leasing because of who pays for the operating cost. Under servicization, the buyers pay for the service time while the manufacturers bear all costs for production and operation. Rolls Royce and its contractual partners share the power-by-hour contracts where Rolls Royce owns engines and maintains them regularly, but the customers pay for the number of hours they use the vehicle. Many high-end hotels are also charged for using carpets produced by Desso, and Desso is responsible for daily cleaning and maintenance (Agrawal et al., 2019). A

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https://doi.org/10.1016/j.tre.2020.102162
Received 30 April 2020; Received in revised form 3 November 2020; Accepted 6 November 2020
Available online 11 December 2020
1366-5545/

company called Bundles from the Netherlands purchases categories of appliances from other companies and then, rather than selling them, charges its customers based on their usage time.

A manufacturer using servicization is more likely to be capital-constrained because it charges fees based on time. Unlike a selling strategy, money (in particular, money to cover the production cost) is not paid upfront when adopting servicization. This is a definite problem since the products serviced for the customers are usually durable goods and generally require a large amount of investment to produce. When the manufacturer does not have enough money to do so, financing becomes of cardinal significance. Traditionally, when facing financial constraints, the manufacturer usually gets loans from banks or other financial institutions, a process we call external financing. Another format of financing is from buyers, which we call internal financing or buyer financing. The buyers can pay in advance or provide funds directly when required. As Buzacott and Zhang (2004) reports, BMW and PSA pay suppliers in advance for parts, and Ford provides loans to suppliers.

In our model, we assume a manufacturer offers equipment with a servicization strategy, and an operator is charged for the equipment's use time. The operator utilizes the product for further production or to serve other customers. For example, Rolls Royce (as an engine manufacturer) offers power-by-hour contracts for flight companies (as operators of flight services). We consider the price of per-unit use being exogenous, because it is impacted by existing firms producing similar products with a selling or leasing strategy in the market. For instance, BMW has entered the car sharing business. Rather than selling cars, the customers are charged by the duration of use or driving miles, the price of which is based on the existing price in the market. Because the price for per-unit use is exogenous, there is a risk that a deal may not happen because that price may be too high for the operator to afford the service or too low for the manufacturer to offer the service.

Comparisons between the selling and servicization strategies have been provided by Agrawal et al. (2012) and Agrawal and Bellos (2016). Similarly, Bhaskaran and Gilbert (2005, 2009) studied leasing and selling strategy for durable goods. These works show that servicization has many advantages, leading more manufacturers to adopt this emerging paradigm. With a servicization strategy, the choice of quality is very important, as the manufacturer has to bear production cost and operating cost, and both of these are closely related to the quality. For example, when entering the car-sharing market, BMW and GM offered a narrower set of models compared to the selling market (Bellos et al., 2017). The design and choice of vehicle models for a servicization market greatly impact the manufacturer's profitability.

With servicization, the operating cost is borne by the manufacturer, and it must take more responsibility for the product. As the unit maintenance cost increases with the use time, the manufacturer will incur increasing operating expenses. Specifically, if the product quality is low and the buyers desire a long use duration, the manufacturer will have to bear very high operating costs. Besides, because the use efficiency decreases with the growth of use duration, the low quality reduces the use utility of the buyer rapidly. In contrast, a high-quality product used for only a short duration is a waste of resources because of not taking full advantage of the value that high quality brings. Without any doubt, the decisions of quality and usage are closely interconnected. We intend to answer the following research questions in this work:

1. What are the optimal decisions for the manufacturer and operator under different leadership assumptions and different financing formats?
2. How do supply chain leadership and different financing formats affect the benefits of the manufacturer and the operator?
3. Under what circumstances will external financing or internal financing be preferred?

We use a Stackelberg game to analyze the interaction between the manufacturer ("he") and operator ("she") under different financing formats. Under external financing, both the manufacturer and the operator have a chance to move first. We find the impact of the operating efficiency on their benefits and decisions could be opposite under different leadership. When the manufacturer moves first, a high operating efficiency leads to a high quality level and a long use duration. The manufacturer's leading also improves both sides' benefits. However, when the operator moves first, the high operating efficiency may unexpectedly damage both parties' benefits. Under internal financing, the operator does not always prefer a high interest rate for the loan to the manufacturer. She may even give a subsidy to the manufacturer by lowering the interest rate to less than zero. In addition to the case of low operating efficiency, a subsidy may also be optimal when the operating efficiency is high. If the per-unit price is high, the manufacturer will accept a high interest rate to increase both parties' benefits.

If a choice between internal and external financing is needed, whether the manufacturer moves first under external financing impacts the decision because the manufacturer is always the follower under internal financing. Under internal financing, the operator can grab some of the manufacturer's profit by increasing the interest rate, but we find that, following the manufacturer under external financing, the operator usually gets higher benefits when a high operating efficiency exists.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. In Section 3, we formulate the model with an introduction of notations and assumptions. In Section 4, we present the equilibrium decisions of the manufacturer and operator under different leadership assumptions and different financing formats, examining the impact of these differences on the manufacturer's profit and the operator's utility. In Section 5, we compare the benefits under different financing formats. We show some managerial implications in Section 6. In Section 7, concluding remarks are provided. All proofs are relegated to the online Appendix A.

2. Literature review

Servicization is a stream of research studying the impact of servicizing strategies on the profitability (White et al., 1999; Rothenberg, 2007; Drake et al., 2016; Li et al., 2019) and social responsibility of firms (Plambeck and Wang, 2009; Atasu and Subramanian, 2012). Specifically, Agrawal et al. (2019) introduce the prospects and advantages of servicization. Avci et al. (2014) study the adoption of electric vehicles when consumers are charged according to miles driven rather than buying the ownership of the battery. Agrawal and Bellos (2016) examine the impact of servicization with or without resource pooling. These papers assume the use duration is predetermined. Although Örsdemir et al. (2019) offer a menu of choices for the use duration, the buyers (operators) still cannot determine their optimal use duration unilaterally. In our paper, we allow the operator to decide use duration purely based on her best utility.

Our study is related to the growing stream of research on supply chain finance. Much research about the interface of operations and finance decisions has been done (Chao et al., 2008; Xu and Birge, 2004), focusing on the impact of financial constraints on operational decisions. A well-chosen financing method can increase both the profit of the suppliers and the efficiency of the whole supply chain (Kouvelis and Zhao, 2012; Yang and Birge, 2018; Jing et al., 2012; Deng et al., 2018). Tang et al. (2018) and Deng et al. (2018) compare internal financing to special external financing, finding internal financing is better in certain cases. Tunca and Zhu (2017) study buyer-intermediated financing, and they find this financing format can significantly benefit both supply chain participants. Deng et al. (2018) and Kouvelis and Zhao (2012) show that it can be optimal to sacrifice financing profit by charging the minimal interest rate.

With servicization, the manufacturer is more likely to be underfunded because his capital return is based on the service time of the product instead of payment in full, as happens when using the selling strategy. Zhen et al. (2020) study the financing strategy of a capital-constrained manufacturer in a dual-channel supply chain and show that the manufacturer is more likely to prefer the internal financing strategy as the channel competition increases. Li et al. (2020) are the first to investigate the co-opetition-type dual-channel supply chain with capital constraint. They illustrate a competitive supplier and a capital-constrained manufacturer's preference structures regarding trade credit, bank loans, and hybrid financing. Huang et al. (2020) investigate the effect of subsidy offered by the government when the manufacturer is capital-constrained. Tang and Yang (2020) investigate a low-carbon supply chain consisting of a capital-constrained manufacturer and a capital-abundant retailer. They find that early payment can produce lower carbon emissions and higher social welfare in the retailer-led power structure. Our current servicization model is one of the first to involve financing in the research of servicization. Our analysis concludes that it may benefit both parties when the operator provides the manufacturer with a subsidy by lowering the interest rate below zero.

Continuing our literature review, Buzacott and Zhang (2004) and Dada and Hu (2008) apply a Stackelberg game to study supply chain financing. They discuss the interaction between a capital-constrained firm and a bank. In our servicization paper, we study the relationship between a capital-constrained manufacturer and an operator who uses the product provided by the manufacturer and may offer him a loan. Agrawal and Bellos (2016) formulate a sequential firm-customer game. In their model, the firm determines the product property and then chooses between selling or using a servicization strategy. Subsequently, the pay-per-use price is set, and the customers make their usage decisions. In our paper, the use duration can be decided first, after which the manufacturer decides based on the usage time that has been selected. Örsdemir et al. (2019) solve their problems from the manufacturer's angle, using the utility of customers as a constraint. In our paper, the quality level may be determined based on a use duration that has already been decided, and, when they make decisions of financing format, the firms have to take account of the price risk.

In the contracting literature, some papers study the impact of performance-based contracts on supply chains (Guajardo et al., 2012; Guan et al., 2016; Kim et al., 2007; Kim et al., 2010; Li and Mishra, 2017). Chu et al. (2020) find that the optimal ex ante contract among collusive principals is a profit-sharing contract. Rothenberg (2007) points out that car sharing can be viewed as a servicizing business. For contracts in the sharing economy, Corbett and DeCroix (2001) examine shared-savings contracts for materials. Bellos et al. (2017) focus on choosing the best combination of car models for car-sharing contracting. Seung and Taesu (2018) investigate several incentive mechanisms for collaborative product quality improvement with a focus on buyer-driven supply chains. Differently, we focus on the final product itself not only in a buyer market but also in a seller market by endogenizing the product quality. Meanwhile, we enrich the research by introducing financing and allowing the chain members to make preference decisions.

3. Model setup

We consider a capital-constrained manufacturer ("he") servicizing his product to an operator ("she"). The operator may produce other goods or offer services for other customers by using the equipment and pays for the value derived from the use of the equipment. For production purposes, the manufacturer can finance either from outside (e.g., banks) or inside the chain (i.e., the operator).

3.1. Operator and manufacturer concerns

We assume the utility per unit time derived from the use of the product deteriorates with the use time, and its initial value is θ. The deterioration rate depends on the quality, δ; a higher level can slow down the deterioration of the utility (Iravani and Duenyas, 2002; Örsdemir et al., 2019). This assumption also aligns with the consensus in the durable-goods literature that high-quality products deteriorate more slowly (Desai and Purohit, 1998).

The operating cost, including the maintenance cost and other factors, is paid to keep the product running well. The maintenance becomes more frequent and less efficient as the use time increases (Iravani and Duenyas, 2002; Deshpande et al., 2006). We further assume the operating cost is decreasing in product quality δ, and with the increase of use time, a product requires more frequent repairs (Desai and Purohit, 1998). Given time t, the marginal operating cost is assumed to be $m\frac{t}{\delta}$ (Örsdemir et al., 2019). Herein, we employ m to denote operating inefficiency (opposite of efficiency), so a larger value of m corresponds to a lower operating efficiency.

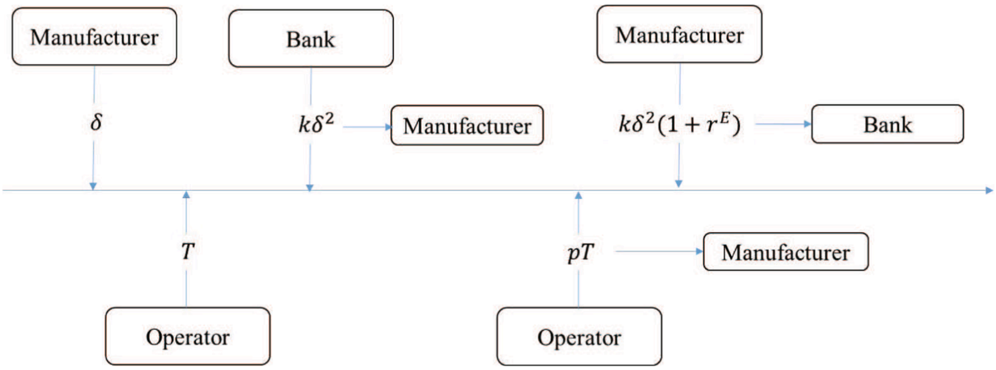
The operating efficiency not only relates to the manufacturer's maintenance efficiency but also depends on how properly the operator uses the product. Bardhi and Eckhardt (2012) point out that the ownership of a product significantly impacts people's usage behavior. When buyers own the product, they use it properly to reduce the maintenance cost. Under servicization, the manufacturer bears the maintenance cost, and hence buyers have less incentive to use it carefully, which may then incur higher operating expenses. The whole use duration, which is the operator's decision, is referred to as T. Then, the total operating cost is $\int_0^T m\frac{t}{\delta}dt = \frac{mT^2}{2\delta}$ (Örsdemir et al., 2019). We use p to denote the per-unit price, which is exogenous in our paper. The operator pays the manufacturer pT for the service along with the product. Given any time t over the whole use duration, the operator's marginal utility for the per-unit use is $\theta - \frac{t}{\delta} - p$. All the exogenous parameters are public information in our model. In addition, when making decisions, the manufacturer and the operator must ensure that the benefit of each party is nonnegative.

3.2. External financing

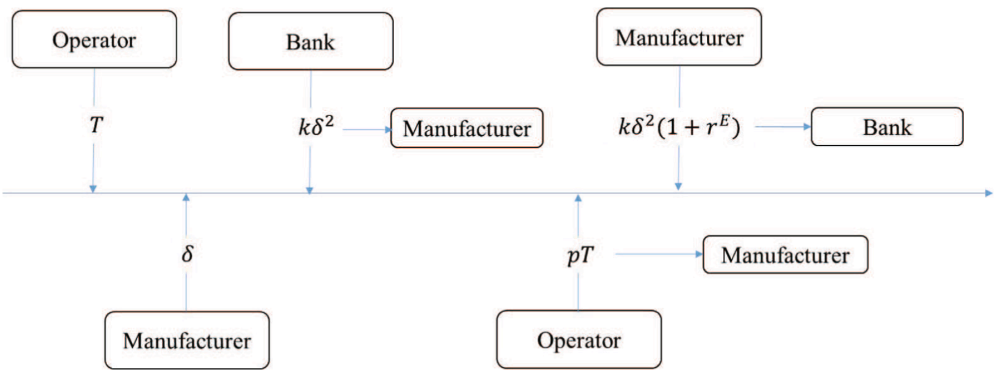
Under external financing, either the manufacturer or the operator may move first. Dominant operators, like airlines (i.e., the operator is the leader) propose the requirements first, and the aircraft manufacturers produce the accepted product. However, huge manufacturers, like automakers, determine the level of quality by themselves. In fact, the position of the leader in a supply chain could change based on changes in the market.

We use subscript $i = M, O$ to represent who moves first in this game. For example, δ_M and T_M denote the valuations of product quality and use duration when the manufacturer is the leader, while δ_O and T_O are the valuations when the operator decides first. In addition, Π_{ij}^E is the payoff of the manufacturer or the operator, where $j = m, o$ denotes the manufacturer's profit and the operator's utility, respectively, and E indicates external financing.

The difference of Fig. 1a) and and Fig. 1(b) hinges on who moves first in this game. After the quality level and use duration are settled, the remaining events are the same in both cases. Considering the situation when the manufacturer has no initial capital to produce, we assume the funds should fully cover his production cost. Finally, the operator pays for the use of the product, and the manufacturer pays back both the principal and interest to the outside creditor. (see Fig. 2).



(a) The manufacturer is the leader



(b) The operator is the leader

Fig. 1. Timeline of the game under external financing.

We assume that the production cost is increasingly convex in product quality and is equal to $k\delta_i^2$, where k is a positive scaling parameter. The quality of the product here is viewed in a twofold sense: functionality and durability. Due to the development of intelligent manufacturing and module production, a servicing firm can usually make a quick response to the operator's request. Accordingly, we ignore the time required to design the product.

After a period of time, the manufacturer will pay back both the principal and interest. We use r^E ($r^E > 0$) to denote the interest rate for the loan. Regardless of the leadership, the manufacturer determines the quality level δ_i to maximize his profit as follows:

$$\Pi_{im}^E = \max_{\delta_i \geqslant 0}\left[pT_i - \frac{mT_i^2}{2\delta_i} - k\delta_i^2(1+r^E)\right]. \tag{1}$$

The decision of δ_i is constrained to guarantee the operator's utility is no less than zero.

On the operator's side, she determines her use duration to maximize utility as below:

$$\Pi_{io}^E = \max_{T_i \geqslant 0}\int_0^{T_i}\left(\theta - p - \frac{t}{\delta_i}\right)dt. \tag{2}$$

We assume there is no residual value and the whole utility is the integral of marginal per-unit use utility over the use time T_i. Based on Eq. 2, the optimal use duration, T_i, is chosen to make the marginal per-unit use utility be zero.

3.3. Internal financing

Under internal financing, we assume the operator is always the leader as she is both customer and creditor to the manufacturer. We use I to denote internal financing. Within this financing format, the operator first determines the length of use duration, T, and the interest rate, r^I, charged to the manufacturer. Following this, the quality level δ is determined by the manufacturer. In this model, we use Π_j^I to denote their respective payoffs. The manufacturer chooses the quality level by maximizing the same objective function as for external financing:

$$\Pi_m^I = \max_{\delta \geqslant 0}\left[pT - \frac{mT^2}{2\delta} - k\delta^2(1+r^I)\right]. \tag{3}$$

Compared to the external financing case, the operator has one more decision r^I. In our internal financing model, r^I is not necessarily greater than zero, which differs from external financing wherein r^E is always positive. A negative r^I means the operator offers the manufacturer a subsidy. We further assume the subsidy cannot be over the unit cost of production, that is $r^I \geqslant -1$. The upper limit of r^I is capped to ensure the profit of the manufacturer is not below zero. The operator determines r^I and T to maximize the utility, and we have:

$$\Pi_o^I = \max_{T \geqslant 0, r^I \geqslant -1}\int_0^T\left(\theta - \frac{t}{\delta}\right)dt - pT + k\delta^2(r^I - r_f). \tag{4}$$

Under internal financing, the utility function has one more term involving the interest rate determined by the operator. As this term depends on r^I and r_f, it may be either positive or negative. We simply assume that when all the money raised by the manufacturer comes from the operator, we have $r_f = 0$. If the money raised by the operator is from banks or other outside financial institutions, we assume $r_f = r^E$. In this case, we assume the manufacturer is unqualified to get loans from banks, and the operator also has no working capital to lend him. The operator must get bank loans first to loan money to the manufacturer. Therefore, the operator has to pay interest to banks, and the interest rate should be the same as when the manufacturer raises funds from banks directly (i.e., r^E).

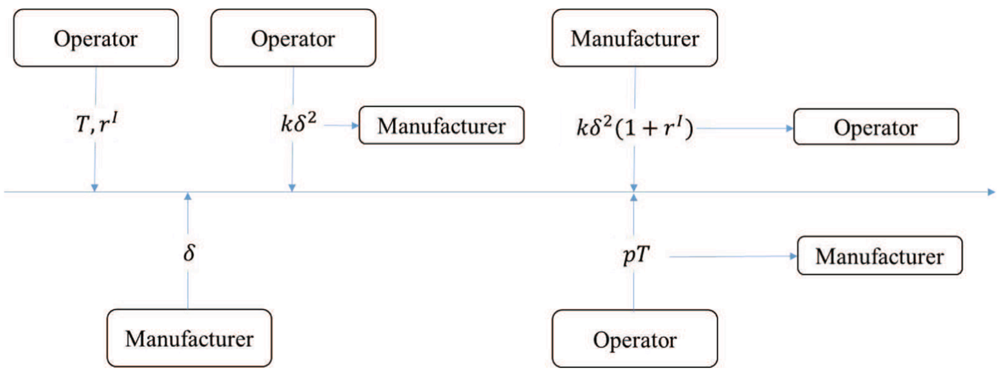


Fig. 2. Timeline of the game under internal financing.

4. Equilibrium analysis

In this section, we first characterize the equilibrium choices of the operator and manufacturer under external and internal financing, respectively. Under external financing, we also explore the impact of different leadership roles on their decisions and benefits. Then, we compare these equilibrium outcomes to determine the impact of different financing formats on their decisions and profits. For the sake of brevity, we let α denote the ratio $\frac{p}{\theta}$. Because $p > 0$ and the deal is viable only when $p < \theta$, the range of α must be $0 < \alpha < 1$. In fact, in our model, the first use utility θ is fixed with respect to the per-unit price p, which is variational according to the market. When considering θ and p in our results, $\theta - p$ is a unique form of existence that can be written as $\theta(1 - \alpha)$. Because θ is fixed, we can use α in our analysis instead of θ and p.

4.1. External financing

In this format, either party could move first, based on market conditions. In our paper, which party leads plays a critical role. When making decisions, the manufacturer considers both production cost and operating cost. These two kinds of costs are both closely related to the product's quality. A higher quality level increases production cost but decreases the operating cost. Moreover, the use duration decided by the operator impacts the manufacturer's profit. For instance, a short use duration reduces the manufacturer's revenue but also lowers his operating cost. If the manufacturer moves first, he may induce the operator to choose a use duration that favors the manufacturer by adjusting the level of quality. However, according to the utility function, the operator always prefers a high-quality product to improve her utility. Hence, if the operator moves first, she tries to induce a high level of quality by her choice of the use duration. The optimal product quality, use duration, profit, and utility under different leadership options are provided in Table 1. The subsections below discuss these results in detail.

4.1.1. Quality and use duration

In this section, we explore how the parties' decisions are made under different leadership options. White et al. (1999) reveal that, because the manufacturer is responsible for product maintenance, servicization encourages firms to invest in quality to reduce the operating cost. Opposing this, analysis by Örsdemir et al. (2019) shows that controlling use duration through pricing may result in a lower quality level. In these papers, the use duration and quality are both decided by the manufacturer. In our work, the usage choice is made by another party, i.e., the operator. Here, we study how the per-unit price and operating efficiency jointly affect the chain members' decisions. We start by focusing on the per-unit price.

Lemma 1. *The relationship between δ_i^*, T_i^* and α is as follows:*

(i) *When the manufacturer is the leader, δ_M^* first increases in α when $\alpha < \frac{m+1}{m+2}$ and then decreases in α when $\alpha > \frac{m+1}{m+2}$; and T_M^* first increases in α when $\alpha < \frac{3m+2}{3m+6}$ and then decreases in α when $\alpha > \frac{3m+2}{3m+6}$.*

(ii) *When the operator is the leader, δ_O^* and T_O^* decrease in α.*

Lemma 1(i) shows that a moderate per-unit price generates a high product quality and a long use duration when the manufacturer is the leader. When there is a low per-unit price, the production cost is low, and choosing a lower quality level could also decrease the operating cost by inducing the operator to determine a shorter use duration. A high per-unit price incurs a low marginal utility for the operator, $\theta(1 - \alpha) - \frac{t}{\delta_O}$, and the use duration is bounded, which makes it meaningless for the manufacturer to produce a high-quality product.

Lemma 1(ii) indicates that only a low per-unit price results in a high quality, which is different from Lemma 1(i). A low per-unit price generates a high marginal utility that incentivizes the operator to choose a long use duration, and the manufacturer has to produce a higher-quality product to control the operating cost. Similarly, a high α also incurs a low marginal utility, and the manufacturer will determine a relatively low quality level.

Interestingly, whoever moves first, a high per-unit price does not incentivize the manufacturer to choose high quality, mainly due to the short use duration that would then be selected by the operator. We next focus on the impact of operating efficiency.

Lemma 2. *The relationship between δ_i^*, T_i^* and m are*

(i) *when the manufacturer moves first, δ_M^* and T_M^* are decreasing in m;*

Table 1
Equilibrium of quality, use duration, profit, and utility.

Leader	δ_i^*	T_i^*	$\Pi_{im}^{E^*}$	$\Pi_{io}^{E^*}$
Manufacturer	$\frac{(\theta-p)[2p-m(\theta-p)]}{4k(1+r^E)}$	$\frac{(\theta-p)^2[2p-m(\theta-p)]}{4k(1+r^E)}$	$\frac{(\theta-p)^2[2p-m(\theta-p)]^2}{16k(1+r^E)}$	$\frac{(\theta-p)^3[2p-m(\theta-p)]}{8k(1+r^E)}$
Operator	$\frac{9m(\theta-p)^2}{16k(1+r^E)}$	$\frac{27m(\theta-p)^3}{32k(1+r^E)}$	$\frac{27m(\theta-p)^3[8p-9m(\theta-p)]}{256k(1+r^E)}$	$\frac{27m(\theta-p)^4}{128k(1+r^E)}$

(ii) when the operator moves first, δ_O^* and T_O^* are increasing in m.

Surprisingly, Lemma 2 shows two opposite results caused only by the different leadership options. Lemma 2(i) shows that when the manufacturer makes the first decision, both parties prefer a high operating efficiency (i.e., low m) that leads to high quality and long use duration. In terms of the profit function alone, if the operating efficiency is high, a long use duration causes a less significant increase in operating cost, and the manufacturer should produce a low-quality product to reduce the production cost. However, the manufacturer's revenue is also affected by the use duration that will be determined subsequently. Therefore, high operating efficiency incentivizes the manufacturer to induce a longer use duration by setting a high quality level.

However, Lemma 2(ii) implies that if the operator is the leader, high quality and long use duration are induced by the low operating efficiency. The operator believes that only a low operating efficiency results in high quality because from her angle, only high m induces the manufacturer to produce high quality in order to reduce the operating cost. High quality leads to high production cost, but if the operating efficiency is low, the decrease in his operating cost outweighs the increase in his production cost when a long use duration has been determined already. However, if the operating efficiency is very high, the operating cost increases only slightly, even with a low quality and a long use duration. Considering that the manufacturer prefers a low-quality product to maximize his profit, the operator has to choose a short use duration. In turn, since a short use duration has been determined, the manufacturer will have no incentive to produce a high-quality product. Therefore, the high operating efficiency incurs a vicious cycle between the manufacturer and the operator.

According to Lemma 1 and 2, the different leadership greatly impacts the optimal decisions. Moving first, the manufacturer believes a high quality will bring him more profit with high operating efficiency. However, when the operator moves first, the operator makes decisions that lead the manufacturer to produce high-quality products with a low operating efficiency.

4.1.2. *The risks of price fluctuation*

The per-unit price is exogenous, which means that the manufacturer may refuse to offer the service if that price is too low, and the operator may not be able to afford the service if it is too high. Therefore, there is an allowed range of α to ensure the service is feasible. If $p > \theta$, then the utility of the operator, $\int_0^{T_i}\left(\theta - p - \frac{t}{\delta_i}\right)dt$, must be negative. Hence, $\alpha = \frac{p}{\theta} \le 1$ (i.e., no matter who moves first, the upper limit of α is 1). Therefore, the allowable range size (i.e., the difference between the upper limit and the lower limit) of α depends on its allowable minimum value. We assume that, with a wider allowable range of α, there is a stronger ability to resist price volatility. The next proposition describes the relationship between the operating efficiency m and the allowable range size of α.

Proposition 1. *The allowable range size of α decreases in m. When the manufacturer moves first, the allowed range of α is wider than when the operator moves first.*

Proposition 1 agrees with the intuition that a low operating efficiency diminishes the ability to counteract risks of market fluctuation. This is also illustrated in Fig. 3, in which the curves denote the minimum value of α for the two leadership options. As m increases (which means the operation efficiency decreases), the minimum value of α increases because only a higher per-unit price can cover both the operating cost and production cost. In addition, Proposition 1 also indicates that the ability to withstand the risk depends on which party leads. As Fig. 3 shows, in Region S2, the manufacturer will offer the service to the operator only when he moves first, so the operator has to follow the manufacturer if she wants to get the service. With a sufficient decrease in α and increase in m, the transaction cannot proceed, which is represented by Region S3.

When the operator moves first, she expects a low operating efficiency to make a long use duration (Lemma 2). If a long duration is

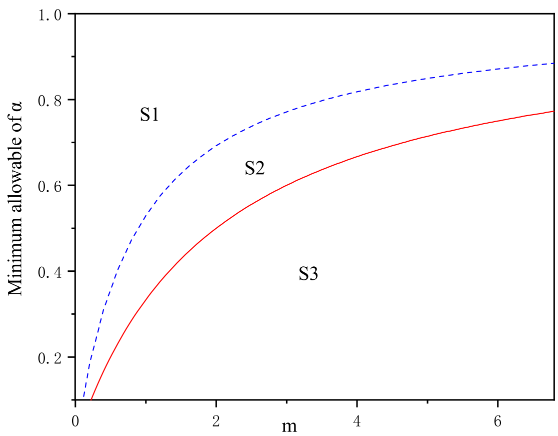


Fig. 3. The feasible range of α as a function of m (the inefficiency) for different leadership options.The dotted line indicates the minimum value of α when the operator moves first, and the solid line means the minimum value of α when the manufacturer moves first. In Region S1, no matter who moves first, the manufacturer will offer the service. In Region S2, the service will be offered only if the manufacturer moves first. In Region S3, the manufacturer never offers the service..

chosen, the manufacturer must improve the quality to reduce the operating cost, but improving the quality also increases the production cost. Although a long use duration increases the manufacturer's revenue, that increase cannot cover the sum of the increase in operating cost and production cost due to a low α and high m, which makes the manufacturer's profit negative. However, if the manufacturer moves first, Lemma 1 and 2 indicate that a low per-unit price and low operating efficiency lead the manufacturer to prefer a low quality, which not only decreases the production cost but also decreases the operating cost by inducing the operator to choose a short use duration. In addition, if the operating efficiency is low enough, even a short use duration will lead to a high operating cost that the manufacturer cannot bear. Therefore, whoever moves first, a lower operating efficiency increases the likelihood of the deal's failure.

4.1.3. Profitability and utility

Next, we focus on how the per-unit price and the operating efficiency impact their benefits under different leadership. In addition, from the above analysis, which party leads affects both members' decisions greatly, so we will also examine whether being a leader always brings more benefits than being a follower.

Proposition 2. *(i) When the manufacturer is the leader, the manufacturer's profit first increases in α when $\alpha < \frac{m+1}{m+2}$ and then decreases in α when $\alpha > \frac{m+1}{m+2}$. The operator's utility first increases in α when $\alpha < \frac{2m+1}{2m+4}$ and then decreases in α when $\alpha > \frac{2m+1}{2m+4}$. (ii) When the operator is the leader, the manufacturer's profit first increases in α when $\alpha < \frac{9m+2}{9m+8}$ and then decreases in α when $\alpha > \frac{9m+2}{9m+8}$, but the operator's utility decreases in α.*

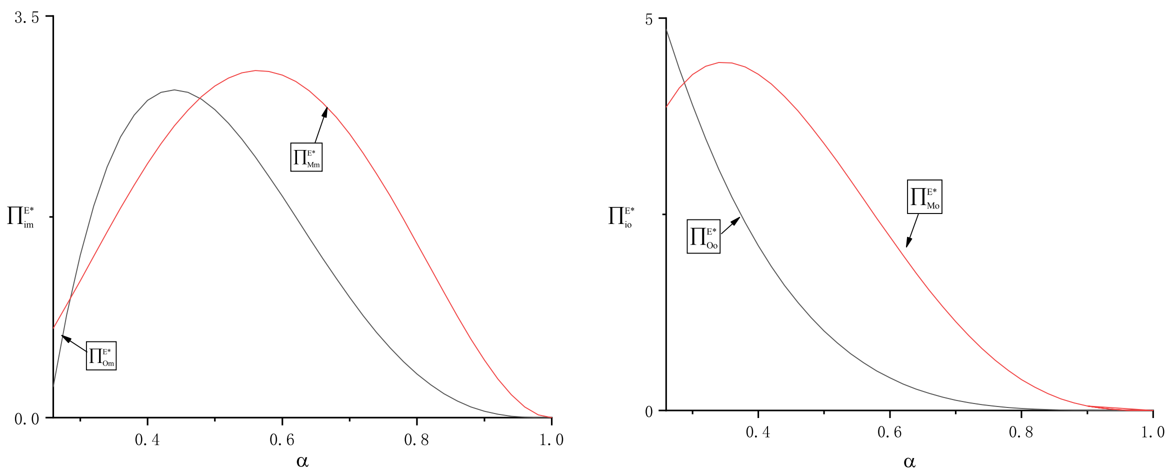
Proposition 2(i) implies that when the manufacturer is the leader, a moderate per-unit price benefits both the operator and the manufacturer. It is obvious that a very low per-unit price hurts the manufacturer's profit, while a high per-unit price also decreases his profit because of the reduction of usage by the operator (Lemma 1). For the operator, a high per-unit price decreases the utility directly, but a low per-unit price decreases the utility because of the low quality that the manufacturer chooses to correspond with the low price.

Proposition 2(ii) indicates that when the operator is the leader, the impact of the per-unit price on the manufacturer's profit is similar to the case when the manufacturer is the leader; the result is illustrated in Fig. 4a. However, the operator obtains a higher utility with a lower per-unit price, which is different from the case when she follows the manufacturer (Fig. 4b). Because a low per-unit price incentivizes the operator to choose a long use duration, accordingly, the manufacturer has to set a high level of quality to reduce the operating cost.

It may be intuitively believed that, no matter who moves first, a high operating efficiency benefits both of them. However, the next proposition delivers a different message.

Proposition 3. *(i) When the manufacturer leads, both the manufacturer's profit and the operator's utility decrease in m. (ii) When the operator leads, the utility increases in m and the manufacturer's profit first increases in m when $m < \frac{4\alpha}{9(1-\alpha)}$ and then decreases in m when $m > \frac{4\alpha}{9(1-\alpha)}$.*

Proposition 3 states that when the manufacturer is the leader, both parties prefer a high operating efficiency (as m rises, the efficiency declines, and their benefits decline). According to Lemma 2, as the operating efficiency decreases, a higher quality level and a longer use duration will be determined, which brings them more benefits. When the operator is the leader, high operating efficiency is not favorable for the manufacturer, and the operator always prefers a low operating efficiency. It is quite a surprising finding that high efficiency damages their benefits. By Lemma 2, assuming a long use duration is determined first, the manufacturer with high operating



(a) The manufacturer's profit (b) The operator's utility

Fig. 4. The manufacturer's profit and the operator's utility as a function of α under different leadership, with $m = 0.3, \theta = 4, r^E = 0, k = 1$.

efficiency prefers to reduce the level of quality to decrease the production cost. Knowing that a low quality inevitably follows a lower production cost, the operator is forced to choose a short use duration when it moves first. As a result, high operating efficiency becomes a stumbling block preventing higher benefits, rather than a stepping stone toward better benefit for all chain members.

Actually, under different leadership, the impact of the operating efficiency on the operator's utility can reverse. When the manufacturer is the leader, high operating efficiency motivates him to produce high-quality products, which benefits both parties. However, when following the operator, high operating efficiency makes the manufacturer more avaricious, and he will lower the quality level, which eventually damages their benefits.

Based on the above result, who moves first significantly impacts all benefits. The next corollary shows that moving first is not always beneficial for both the manufacturer and the operator (also confirmed by Figs. 4 and 5).

Corollary 1. *When the manufacturer moves first and* $\frac{259m^2-12\sqrt{21}m+140m}{259m^2+280m+64} < \alpha < \frac{259m^2+12\sqrt{21}m+140m}{259m^2+280m+64}$, *he earns less profit than he would by following the operator. When the operator moves first and* $\frac{9m}{9m+8} < \alpha < \frac{43m}{32+43m}$, *she earns more profit than she would by following the manufacturer.*

Corollary 1 shows that moving first does not always bring a higher benefit. For the manufacturer, when the per-unit price and operating efficiency are moderate, following the operator brings more profit to him. For the operator, only a low per-unit price brings her a higher utility.

Fig. 6(a) shows that if the per-unit price is high or low, the manufacturer prefers to be the first-mover. This is because if the operator moves first, a high per-unit price incurs a relatively short use duration that reduces the manufacturer's revenue, but a low per-unit generates a very long use duration that increases the operating cost too much (Lemma 1). Analogously, a high operating efficiency also incurs a short use duration, and a low operating efficiency leads to a too-long use duration. Both of these situations damage the manufacturer's profit (Lemma 2). In some extreme cases, the manufacturer clearly understands how to determine an appropriate quality level to obtain a reasonable use duration, but if both the per-unit price and operating efficiency are moderate, the optimal quality level becomes unclear. Thus, a reasonable use duration determined first is vital.

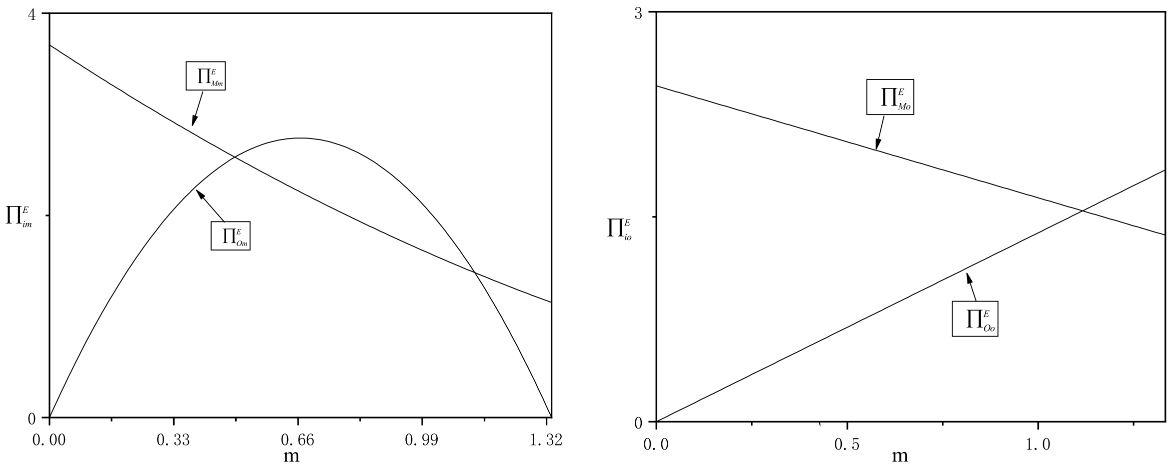
When the operator moves first, she encourages a high level of quality determined by the low operating efficiency, which is detrimental to the manufacturer's profit. Fig.6(b) shows that the operator only gets a higher utility in the middle region. In that region, the bottom line corresponds to $\alpha = \frac{9m}{9m+8}$, where the manufacturer's profit is zero.

4.1.4. Financing

In this section, we examine the case where the capital-constrained manufacturer borrows money from a bank. How does this financing format impact the manufacturer's and operator's benefits? From the equilibrium results, we have the conclusions in Proposition 4:

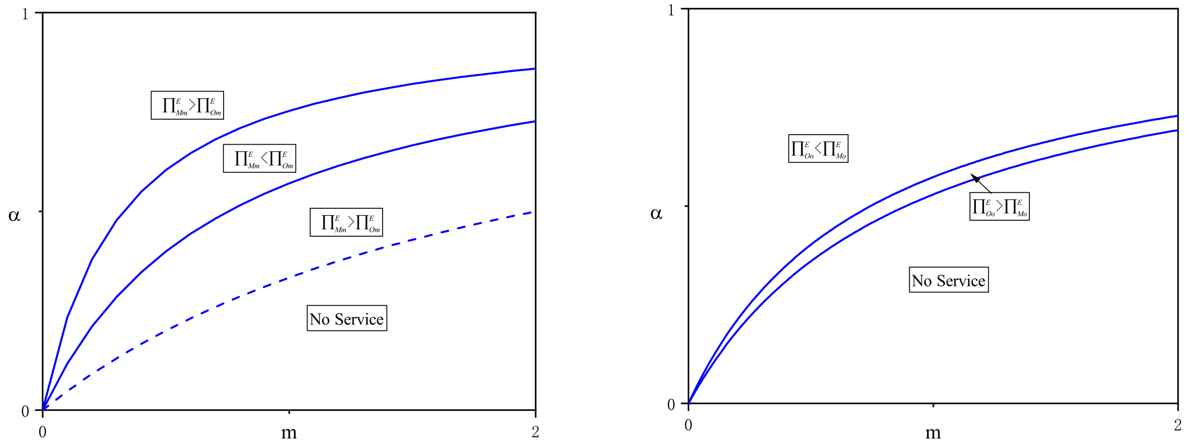
Proposition 4. *External financing reduces both the operator's utility and the manufacturer's profit, and their benefits decrease in the loan's interest rate (i.e.,* r^E*).*

Proposition 4 states that borrowing money from banks damages the chain members' benefits. The financing only happens between the manufacturer and a bank, but because of the equilibrium outcomes, the operator is still affected to the same extent as the manufacturer. It is easy to understand that under external financing, the manufacturer has to pay part of his profit to the bank as loan interest. How is the operator affected by financing? In our model, the interest that the manufacturer pays for the bank relates to quality,



(a) The manufacturer's profit (b) The operator's utility

Fig. 5. The manufacturer's profit and the operator's utility as a function of m (the inefficiency) under different leadership, assuming $\alpha = 0.8, \theta = 4$, $r^E = 0, k = 1$.



(a) The manufacturer's profit (b) The operator's utility

Fig. 6. Comparison of the manufacturer's profit and the operator's utility for different leadership options, with $\theta = 4, r^E = 0, k = 1$..

which means a higher quality incurs a larger amount of interest to pay. Therefore, compared to the case of having no capital constraint, when maximizing the highest profit, the manufacturer tries to lower the level of quality. The operator's utility relates to the level of quality, so a corresponding decrease in the operator's utility is inevitable.

4.2. Internal financing

Based on the previous analysis, external financing causes a loss of benefit for both the manufacturer and operator. If the manufacturer turns to the operator for fund raising, i.e., internal financing is used, does it perform better than external financing? Internal financing is widely used in supply chains, and a variety of benefits have been verified. Many large buyers have recently implemented such a financing approach. In this part, we explore the situation wherein the capital-constrained manufacturer borrows funds from the operator. The key difference from external financing is that the interest rate is endogenous to our model and determined by the operator. The optimal interest rate, product quality, use duration, profit, and utility are provided in Table 2.

4.2.1. Interest rate

Under internal financing, the operator determines the interest rate of the loan to the manufacturer. In our model, we allow the operator to subsidize the manufacturer, which means the interest rate could be less than zero. Comparing to external financing, we find that the interest rate of internal financing brings many changes. Based on the range of operating efficiency, we can determine the operator's optimal interest rate.

Proposition 5. *The value of r^{I^*} depends on m and α as follows:*

(i) *If $m > \frac{4\alpha}{3-\alpha}$, then $r^{I^*} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha} - 1$;*
(ii) *If $m \leqslant \frac{4\alpha}{3-\alpha}$, then $r^{I^*} = -1 + \frac{2m+2mr_f}{2-m}$.*

On the premise that the manufacturer's profit should not be less than zero, we obtain the optimal solution for the interest rate. Proposition 5(i) states the optimal interest rate when the manufacturer's profit is zero; as long as $m > \frac{4\alpha}{3-\alpha}$, the manufacturer obtains no profit. Proposition 5(ii) shows that when $m \leqslant \frac{4\alpha}{3-\alpha}$, the operator gets an optimal solution of r^{I^*}; in this case, the profit of the manufacturer is positive.

Here, we assume $m^I_1 = \frac{2}{3+2r_f}, m^I_2 = \frac{4\alpha}{3-\alpha}$, and $m^I_3 = \frac{8\alpha}{9-4\alpha(1+r_f)-5\alpha}$. As Fig. 7 shows, m^I_1 and m^I_3 are the points when the interest rate is zero, and $m^I_2 = \frac{4\alpha}{3-\alpha}$ plays an important role in our analysis. It is the cut-off point where the manufacturer's profit is at least zero.

Based on the value of r^{I^*}, we indicate the relationship between r^{I^*} and m.

Corollary 2. *The optimal interest rate first increases when $m < m^I_2$ and then decreases when $m > m^I_2$.*

As Fig. 7 shows, when $m = m^I_2$ we have the highest interest rate. Corollary 2 also states that the trend of the optimal interest rate is similar to the manufacturer's profit when the operator moves first under external financing. As the manufacturer's profit increases at first and then decreases along with the growth of m, the operator also adjusts r^{I^*} to grab the manufacturer's profit. Corollary 2 also indicates that a high or low operating efficiency (i.e., low or high inefficiency m, respectively) incurs a low interest rate that may be less than zero. Therefore, we have the following result.

Table 2
Equilibrium of interest rate, quality, use duration, profit, and utility.

r^{I^*}	δ^*	T^*	$\Pi_m^{I^*}$	$\Pi_o^{I^*}$
$\frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}-1(m\geqslant\frac{4\alpha}{3-\alpha})$	$\frac{9m(1+r^{I^*})(\theta-p)^2}{4k[2(1+r^{I^*})-m(r^{I^*}-r_f)]^2}$	$\frac{27m(1+r^{I^*})^2(\theta-p)^3}{4k[2(1+r^{I^*})-m(r^{I^*}-r_f)]^3}$	$\frac{27m(1+r^{I^*})^2(\theta-p)^3\{(1+r^{I^*})[8p-9m(\theta-p)]-4pm(r^{I^*}-r_f)\}}{16k[2(1+r^{I^*})-m(r^{I^*}-r_f)]^4}$	$\frac{27m(1+r^{I^*})^2(\theta-p)^4}{16k[2(1+r^{I^*})-m(r^{I^*}-r_f)]^3}$
$-1+\frac{2m+2mr_f}{2-m}(m<\frac{4\alpha}{3-\alpha})$	$\frac{(\theta-p)^2}{2k(2-m)(1+r_f)}$	$\frac{(\theta-p)^3}{k(2-m)^2(1+r_f)}$	$\frac{(\theta-p)^3(4p+mp-3m\theta)}{2k(2-m)^3(1+r_f)}$	$\frac{(\theta-p)^4}{4k(2-m)^2(1+r_f)}$

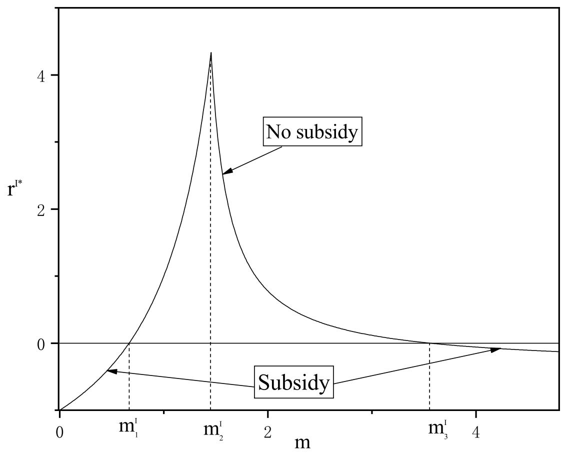


Fig. 7. The optimal interest rate of the loan as a function of m (the inefficiency), with $\alpha = 0.8, r_f = 0$.

Corollary 3. *Subsidies are provided not only when the operating inefficiency m is high, but also when m is very small.*

Usually, a manufacturer should be subsidized when there is an operating difficulty or he has trouble coping with market fluctuation. The firm needs to be subsidized to make a transition or improve its operating efficiency. However, one unexpected finding is shown in Corollary 3, where the operator volunteers to subsidize the manufacturer even the operating efficiency is high (Region S1 of Fig. 8).

In Fig. 7, m_1^I and m_3^I are the points when the operator begins to offer a subsidy. Region S1 of Fig. 8 indicates when $m < m_1^I$ and the operator gives the manufacturer a subsidy even when the operating efficiency and per-unit price are both high. With a higher operating efficiency, the operator has a stronger incentive to provide subsidies. By subsidizing the manufacturer, the operator encourages the manufacturer to produce higher-quality products. Region S2 in Fig. 8 illustrates that the subsidy is provided to ensure the profit of the manufacturer is nonnegative. By Fig. 7, the operator has to give a higher subsidy as the inefficiency m increases when $m > m_3^I$, which is the opposite when m is small ($m < m_1^I$).

Although the subsidies in both cases are used to improve the quality, the reasoning is different. When the operating efficiency is high, the manufacturer is very eager to have the operator subsidize him because when following the operator, the manufacturer prefers a low quality level due to the high operating efficiency (Lemma 2). Therefore, the operator acts to obtain a higher quality level by offering a subsidy, which incurs a higher utility that brings her more gain than the loss due to the subsidy. However, if both the operating efficiency and per-unit price are too low, according to Proposition 1, the service is not viable, which makes the manufacturer turn to the operator for financing.

4.2.2. *The price risk*

Under external financing, when the per-unit price and operating efficiency are both low, the manufacturer's profit may be negative. In this part, we mainly examine how, when facing market fluctuation, the internal financing affects the allowable range of α that guarantees the service is offered.

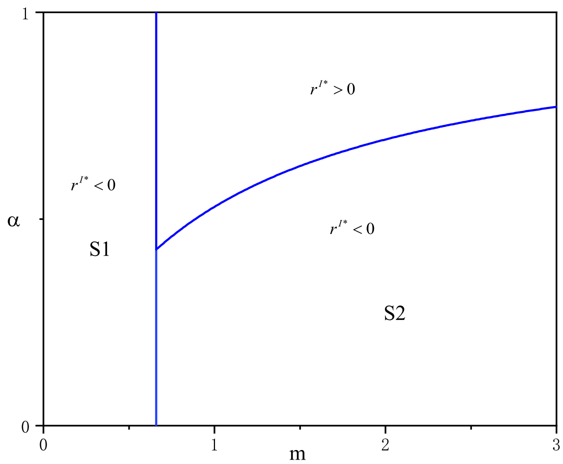


Fig. 8. The conditions for providing subsidies: $r_f = 0$.

Proposition 6. *Theoretically, as long as $0 < \alpha < 1$, the interest rate can be adjusted so that the service is always offered.*

This is illustrated in Fig. 8 in which there is always a solution of r^{I^*} to guarantee the profit of the manufacturer is not negative. Under external financing, if the price is a deal-stopper, internal financing can be a good way to solve this predicament. Under external financing, the interest rate must be above zero. This may lead to a situation where the low per-unit price and operating efficiency bring the manufacturer a negative profit, and he has to refuse the service to the operator. However, under internal financing, the manufacturer obtains a subsidy ($r^I < 0$) to make up his loss when offering the service, so the operator can get the desired product.

4.2.3. Profitability and utility

In this section, we discuss how the operating efficiency and per-unit price impact the benefits of both the manufacturer and operator. Under external financing, the operator's utility is all from the use of the product. Under internal financing, the utility includes two parts: one is also the use utility of the product; the other is income from the manufacturer paying interest. The operator balances these two parts to get her best utility.

Proposition 7. *Under internal financing, the utility of the operator first increases in the inefficiency m when $m < \frac{12\alpha}{9-5\alpha}$ and then decreases in m when $m < \frac{12\alpha}{9-5\alpha}$. In addition, the highest interest rate does not lead to the highest utility.*

Under external financing, when the operator moves first, a lower operating efficiency leads to a higher utility, but under internal financing, Proposition 7 indicates that the operator does not always prefer a low operating efficiency. As Fig. 9(a) shows, the utility of the operator increases in m when $m < m_2^I$; while when $m > m_2^I$, the utility first increases and then decreases in m. It is somewhat surprising that the highest utility is not attained when r^{I^*} reaches the largest valuation.

Under internal financing, the operator's utility contains use utility and interest income. Undoubtedly, a high quality level improves the operator's use utility. Meanwhile, how much interest the operator gets ($k\delta^2(r^I - r_f)$) is determined by the interest rate and the level of quality. With an increase in m, the manufacturer offers a higher quality (Lemma 2) that lets the operator obtain a higher utility. Beyond the point of m that generates the highest r^{I^*}, the interest rate begins to decrease, but the level of quality continues to increase. As a result, the operator does not get her highest utility with the highest interest rate. However, when the operating efficiency is so low that the operator gets only a tiny share of the manufacturer's profit, offering a subsidy to ensure the availability of the service will decrease the operator's whole utility.

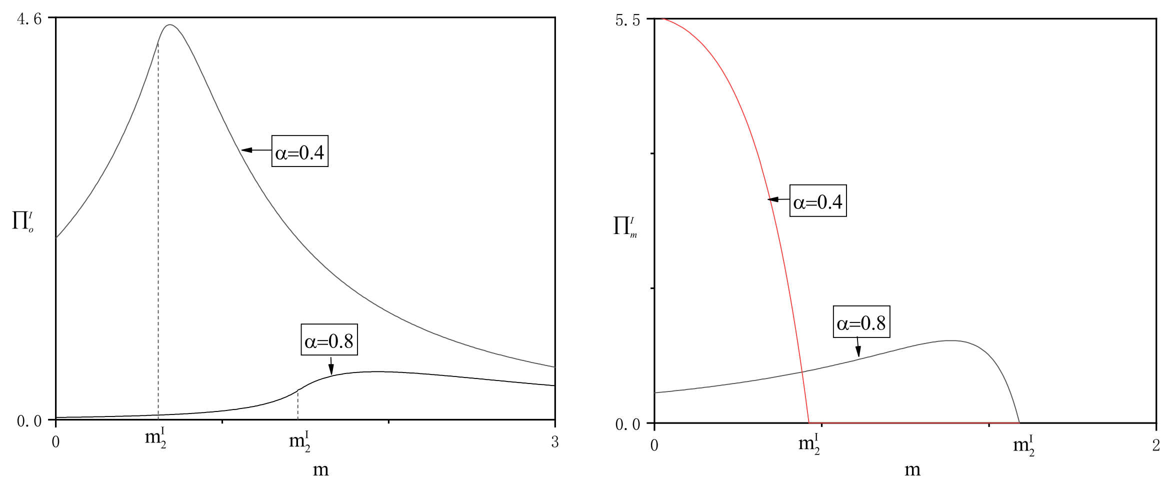
When $m > m_2^I$, the operator extracts all the profit of the manufacturer by adjusting the interest rate. Next, considering the manufacturer's profit, we discuss the case $m < m_2^I$.

Proposition 8. *When ineffiency $m < m_2^I$, based on the value of α, we have:*

(i) *if $\alpha < \frac{3}{7}$, the manufacturer's profit decreases in m;*

(ii) *if $\alpha > \frac{3}{7}$, it first increases in m when $m < \frac{3-7\alpha}{\alpha-3}$ and then decreases in m when $m < \frac{3-7\alpha}{\alpha-3}$.*

Proposition 8(i) shows us if the per-unit price is low, the profit of the manufacturer always decreases in m (Fig. 9b). This result differs from the external financing case because here, the decrease in operating efficiency will increase the manufacturer's profit when the operating efficiency is high. With internal financing, the operator induces the manufacturer to produce high-quality products by providing a subsidy. When the per-unit price is low, the operator can provide a subsidy sufficient to ensure the quality is high enough to



(a)The operator's utility (b) The manufacturer's profit

Fig. 9. The impact m and α on utility and profit, with $r_f = 0, \theta = 4, k = 1$.

make a long use duration optimal. Nevertheless, if the per-unit price is not low, the subsidy for improving the quality level is constrained, which results in a relatively short use duration that decreases the revenue of the manufacturer. However, as the operating efficiency decreases, the manufacturer consciously improves the product quality, which yields a long use duration that increases his revenue despite also increasing his production cost.

5. Comparative analysis

We have derived all the equilibrium outcomes for the two financing formats. A thorough comparison between them will elucidate the impact of financing formats on the performance and identify conditions where one format is preferred. From the previous discussion of interest rates, when the operator gets the highest utility, the manufacturer may get nothing. Therefore, when both financing formats are available to the manufacturer, if $m > m_2^I$, he prefers external financing that ensures his profit more than zero, but if his profit is less than zero under external financing, internal financing is the exclusive choice. When $\alpha = 1$, we get the largest m_2^I.

Next, we will detail the preferences of these two financing formats when $m < 2$ because if $m \geqslant 2$, whatever α is, the manufacturer's profit will be zero under internal financing. Accordingly, external financing is preferred if the per-unit price is not low. If the per-unit price is too low to make the profit negative, internal financing is the only option.

5.1. The manufacturer is the leader under external financing

In this part, we examine the preference for financing formats when the manufacturer is the leader under external financing. If $\Pi_m^{I^*} < \Pi_{Mm}^{E^*}$, then external financing will be adopted by the manufacturer. In contrast, if $\Pi_m^{I^*} > \Pi_{Mm}^{E^*}$, then the manufacturer will turn to borrowing funds from the operator, who decides whether to accept his request. If $\Pi_o^{I^*}$ is also higher than $\Pi_{Mo}^{E^*}$, the operator will offer the funds. If, however, $\Pi_o^{I^*} < \Pi_{Mo}^{E^*}$, the operator will reject the manufacturer's request, and external financing has to be adopted. To summarize, internal financing will be adopted only when both the manufacturer and the operator benefit from it; otherwise, external financing will be chosen.

Fig. 10 illustrates which financing format will be adopted in varying conditions. For better analysis, we discuss the financing preferences separately. We first examine the preference of the manufacturer. Based on Proposition 1, as α decreases and m increases, the service may be unavailable to the operator under external financing, so internal financing is the only choice. The next proposition focuses on the case where the service is available under both financing formats.

Proposition 9. Without considering $\alpha < \frac{m}{m+2}$, where the manufacturer's profit is negative under external financing, if there is (1) a high operating efficiency and a low per-unit price, or (2) a low operating efficiency and a high per-unit price, then the manufacturer prefers internal financing.

If $\alpha < \frac{m}{m+2}$ (i.e., low α and high m), then internal financing is an unavoidable choice, which is illustrated in Region I(a) of Fig. 10. When a low per-unit price and high operating efficiency coincide, following the operator brings the manufacturer more profit, as Region I(b) and E(a_1) of Fig. 10 indicate. The low per-unit price forces the manufacturer to improve the quality level, and a subsidy enables him to produce higher quality products (Fig. 11a). With a great enough increase of α, the subsidy from the operator is insufficient, and a moderate α incurs more profit when the manufacturer is the leader (Proposition 2); in such a case, the manufacturer prefers external financing (Fig. 11b).

A high per-unit price and low operating efficiency lead to an unexpected result that is shown in Fig. 10 (Region I(c) and E(a_2)) and

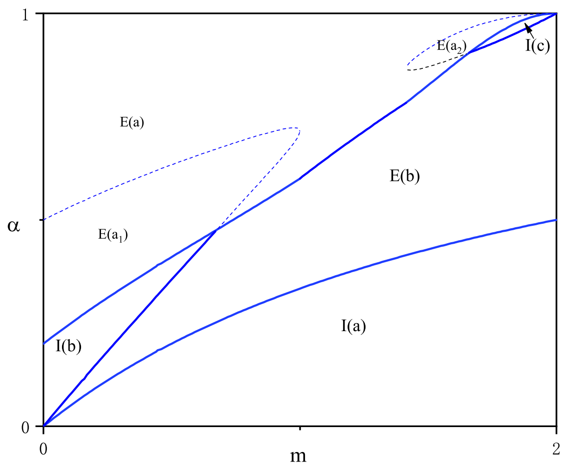


Fig. 10. Financing format preferences when the manufacturer is the leader under external financing, with $r_f = r^E = 0, k = 1, \theta = 4$. E and I denote the financing format.

Fig. 11c.

Corollary 4. If m and α are high, internal financing will still be preferred by the manufacturer, even if there is a high interest rate.

Corollary 4 states that even if the operator sets a high interest rate, the manufacturer still gets a higher profit (Fig. 11c). Differently, under external financing, a high interest rate cannot possibly increase profit. From another perspective, Corollary 4 indicates that internal financing can also be viewed as the manufacturer offering the operator a subsidy by accepting a high interest rate, which induces the operator to choose a longer use duration that benefits both of them. Based on Lemma 1, a short use duration will be decided when the per-unit price is high, which brings less profit to the manufacturer. As a consequence, when the per-unit price is very high, the manufacturer should cede a share of his benefit through accepting a relatively high interest rate, which, in turn, benefits himself. If there is a high operating efficiency, according to Lemma 2, the manufacturer obtains a long use duration by setting a high quality level rather than accepting a high interest rate.

We now focus on the operator's preference for the financing format.

Proposition 10. *If* $\alpha > \frac{m^3-4m^2+4m+2}{m^3-2m^2-4m+10}\frac{1+r^E}{1+r_f}$, *then external financing is preferred. Note that* $(\frac{m^3-4m^2+4m+2}{m^3-2m^2-4m+10}$ *increases in m when* $0 < m < 2$*).*

Proposition 10 shows the operator should be a follower as the operating efficiency and per-unit price increase (E(a,a_1, a_2) in Fig. 10). Under internal financing, the operator not only gets use utility from the product but also interest income from the manufacturer. However, by Proposition 10, by following the manufacturer, the operator may get a higher utility than the overall utility of internal financing. This is also illustrated in Fig. 12; as α increases and m decreases, the operator should follow the manufacturer. If the manufacturer is not eligible for a bank loan, the operator should give up the right to make the first decision when offering the loan, which eventually brings her more utility.

Based on Lemma 1 and 2, by following the manufacturer, the operator can ensure that higher quality will be chosen when α increases and m decreases. As a result, when the operator follows the manufacturer, the increase in her utility is more than the interest she gets from the manufacturer. Therefore, it is not a good approach for the operator to improve utility by raising the interest rate in internal financing when the operating efficiency is high.

5.2. The operator is the leader under external financing

If the operator is the leader under both financing formats, then internal financing is always the operator's preference, because with internal financing, the operator can grab the manufacturer's profit or subsidize the manufacturer by adjusting r^I. Therefore, which format of financing will be chosen completely depends on the manufacturer.

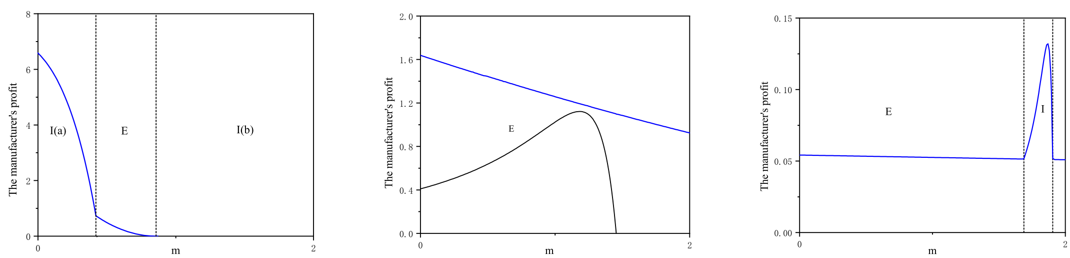
Proposition 11. *If the operator is the leader under both financing formats, then external financing optimal only when the operator grabs too much of the manufacturer's profit.*

This is an intuitive result that is also illustrated in Region E(a) of Fig. 13. As the operating efficiency decreases, the manufacturer consciously improves the level of quality even without a subsidy, and then the operator begins to grab the manufacturer's profit by adjusting the interest rate. As a result, external financing lets the manufacturer earn more profit. In Fig. 13, internal financing performs better except in Region E(a), and we next explore the cases of adopting internal financing.

Corollary 5. *(i) If α is low, internal financing always performs better because of the subsidy; (ii) Similar to Corollary 4, if α is high, then as m increases, the manufacturer will accept a higher interest rate.*

Corollary 5(i) states that when the per-unit price is low, internal financing is better regardless of whether the operating efficiency is high or low; this is illustrated in Fig. 14a. According to the discussion of external financing, with the increase of m, the manufacturer may refuse the service to the operator when the per-unit price is low, so offering a subsidy is the only choice to ensure the operator can access the service (Region I(a) of Fig. 13). Region I(b) of Fig. 13 shows that the operator offers the manufacturer a subsidy even if the per-unit price is high. By Lemma 2, a high operating efficiency prevents the manufacturer from producing high-quality products, which forces the operator to provide the manufacturer a subsidy so that the operator attains a higher utility.

Corollary 5(ii) shows a result similar to Corollary 4: the manufacturer gets higher profit even though he accepts a high interest rate



(a) $\alpha = 0.3$ (b) $\alpha = 0.8$ (c) $\alpha = 0.97$

Fig. 11. Comparison of profit under different financing formats, with $\theta = 4, r_f = r^E = 0, k = 1$.

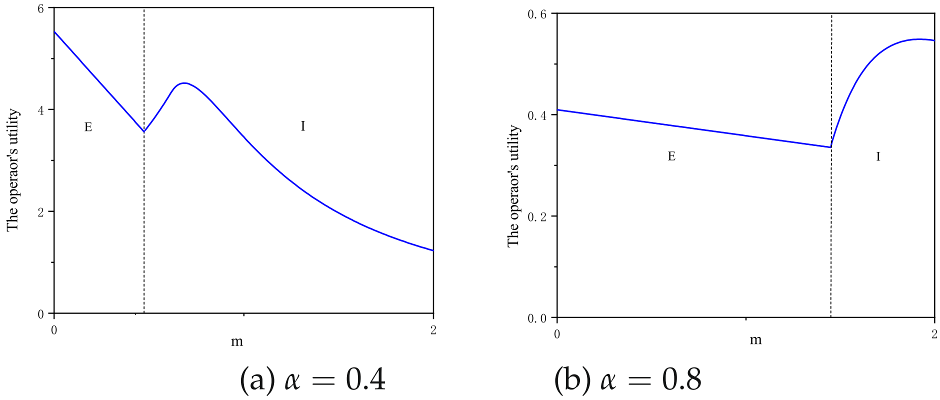


Fig. 12. Comparisons of utility under different financing formats, with $\theta = 4, r_f = r^E = 0, k = 1$.

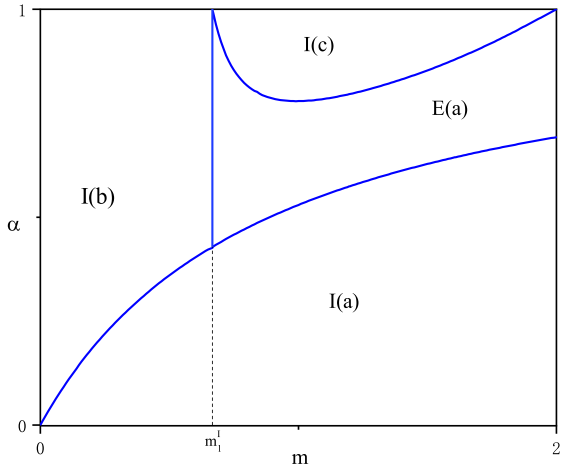


Fig. 13. Financing format preferences when the operator is the leader under external financing, with $r_f = r^E$. E and I denote the financing format.

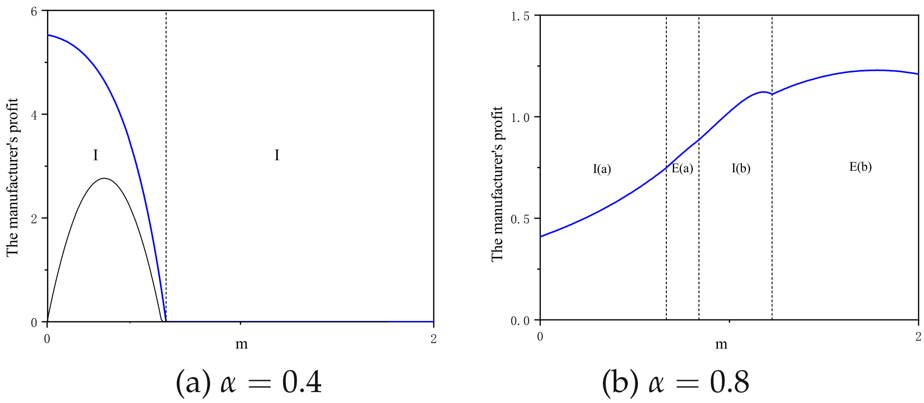


Fig. 14. Comparison of profit under different financing formats, with $\theta = 4, r_f = r^E = 0, k = 1$.

(Region I(c) of Fig. 13 and Region I(b) of Fig. 14b). This acceptance could be regarded as the manufacturer subsidizing the operator by paying more interest. If operating efficiency is high, even though the per-unit price is high, the operator has to provide the manufacturer a subsidy to ensure a higher quality product.

Proposition 9–11 states that if the per-unit price is low and the operating efficiency is high, a subsidy offered by the operator can improve both profit and utility. Although the operator has to sacrifice some utility due to the subsidy, she obtains more use utility as the quality increases. In addition, if we have a high per-unit price and a low operating efficiency, a higher interest rate can also be considered as a subsidy from the manufacturer that benefits him too. Normally, it is self-defeating when the operator improves the utility by enhancing the interest rate. In fact, letting the manufacturer move first benefits both of them when the per-unit price is moderate and the operating efficiency is not low.

6. Managerial implications

The analysis in this paper generates important implications for the decision makers in a servicization supply chain. Both the choice of leadership in the supply chain and the financing formats significantly impact the chain members' decisions and final benefits.

6.1. Impact of different leadership options

Under traditional strategies, being a leader in a supply chain tends to bring more benefits than being a follower. However, this observation may not be right under servicization because the relationships among supply chain members are very close. For example, in our paper, the quality level not only affects the manufacturer's cost (i.e., operating and production cost) but also impacts the operator's marginal utility. The quality determines the use duration that greatly influences the revenue of the manufacturer. Hence, if the manufacturer or the operator always tries to be a leader, they may damage their own interests when optimizing their decisions.

Our findings show that in a stable market, which means the price is moderate, the manufacturer benefits from following the demand side (i.e., operator) rather than being the leade. However, under some extreme cases (e.g., too high or too low per-unit price), the manufacturer should try to be the leader and induce the operator to make choices, which benefits both of them.

Therefore, being a leader in a servicization supply chain is not always good. Under certain conditions, the dominant chain member should give up its leading position to enhance the interests of all the members, including itself.

6.2. Impact of different financing formats

Under external financing, the benefits in the supply chain have to be shared with the third party that provides the funding. However, external financing may still be optimal when a manufacturer with high operating efficiency moves first. This is because internal financing will make the operator move first, which will damage the profit of the manufacturer very much. That is to say, with high operating efficiency, the manufacturer would rather sacrifice some profit to maintain the leadership position than accept internal financing. Under internal financing, the operator is both the buyer and loan provider, which leads to a difficult problem about how to determine the interest rate to the manufacturer. A high interest rate yields more interest returns for the operator, but it may damage the operator's use utility.

In our paper, we indicate that the operator is willing to offer the manufacturer with a high operating efficiency a subsidy to induce him to produce high-quality products. That is to say, in addition to not having to repay the loan, a very competitive manufacturer also gets extra compensation from the fund provider. Besides, in the face of huge market risks, internal financing can make the supply chain more robust by having a chain member control the interest rate.

As a borrower, the manufacturer normally prefers a low interest rate. However, in our paper, we find when the market goes against the operator, the manufacturer should actively help out the operator by accepting a higher interest rate.

7. Concluding remarks

In this paper, we study manufacturer servicization from a financial perspective. We investigate a capital-constrained manufacturer and an operator, who uses the product offered by the manufacturer. A servicizing manufacturer is quite commonly underfunded because they are not paid immediately for providing service or manufacturing the product. Here, we examine two financing formats for the manufacturer raising funds. One is external financing, which means borrowing from banks, and the other is internal financing, which means the operator offers the loan. In our paper, the operator decides the use duration, and the manufacturer decides the quality level. Both of them have a chance to move first under external financing; while under internal financing, the operator is always in the leading position; she decides not only the use duration but also the interest rate of the loan to the manufacturer. We examine the impacts on the manufacturer's profit and the operator's utility under different leadership options, and additionally, investigate which financing format is preferred by the chain members.

Under external financing, the choice of who moves first greatly impacts the decisions and payoffs. A low per-unit price cannot make the manufacturer produce high-quality products when he moves first, but when the operator moves first, the manufacturer prefers to invest more in the quality of the products. In addition, a common belief is that a high operating efficiency benefits firms under servicization, which is indeed true when the manufacturer moves first. However, if the operator moves first, a high operating efficiency may become a stumbling block in the pursuit of the highest profit and utility. Moreover, it is harder for the manufacturer to determine a reasonable quality level to get more profit as a leader than as a follower, when the per-unit price and operating efficiency are moderate. Also, if there is a high per-unit price and high operating efficiency, then the operator gets more benefit by following the manufacturer.

Under internal financing, the operator has one more decision variable: the interest rate of the loan to the manufacturer. The operator could offer a subsidy to the manufacturer by lowering the interest rate to less than zero. We find the operator should subsidize the manufacturer not only in some cases of low operating efficiency, but also in some cases of high operating efficiency.

When the manufacturer has a choice between these two financing formats, internal financing will be accepted only if both of them believe it brings better performance. A low per-unit price and high operating efficiency prompt the operator to offer a subsidy that benefits both members more than external financing. In contrast, a high per-unit price and low operating efficiency lead the manufacturer to accept a high interest rate. Paying high interest is somewhat like the manufacturer offering a subsidy to motivate the operator to choose a long use duration that benefits both of them. Internal financing can mitigate some extreme cases such as too high or too low per-unit price. Generally, adopting external financing and allowing the manufacturer to decide first leads to better performance for both the manufacturer and operator. Under internal financing, however, the operator acquires the manufacturer's profit in addition to the use utility, so the operator still gets less than she would by following the manufacturer. Therefore, sometimes, even if the manufacturer has to turn to the operator for the loan, the operator should give up the leader position.

In our model, we assume that the subsidies from the operator cannot be more than the production cost. If the operator subsidizes more than that, the operating cost is also partially or fully covered by the operator. That possibility needs further study. In our model, we assume no cooperation, but Hong and Guo (2019) show that a supply chain's benefit can increase with the cooperation level. Cooperation may play an important role in decision-making because, with cooperation, a high operating efficiency could improve the chain members' benefits if the operator is the leader. We have not specifically examined how to raise funds from the manufacturer when the operator is capital-constrained, which is also worth further investigation. Moreover, we have established a game with complete information. In practice, it is more reasonable to assume that the operating efficiency depends on asymmetric information between the manufacturer and the operator. Also, our model does not consider the salvage value, which is related to the use duration. Considering the salvage value of the product, the profit function of the manufacturer will change, which may affect the results. This also deserves further study.

8. Highlights

(i) Study the problem in a servicization framework.
(ii) Analyze how different leadership options impact the members' decisions and payoffs.
(iii) Two types of financing formats are analyzed and compared.
(iv) Being a follower in this supply chain can bring more benefit than leading.
(v) Identify managerial implications for the servicization supply chain.

CRediT authorship contribution statement

Zhong-Zhong Jiang: Conceptualization, Supervision, Validation, Visualization, Funding acquisition, Investigation. **Guangqi Feng:** Methodology, Writing - original draft, Formal analysis, Validation, Writing - review & editing. **Zelong Yi:** Supervision, Funding acquisition, Visualization, Validation, Writing - review & editing.

Acknowledgements

This work was partially supported by the National Natural Science Foundation of China (71671033, 71971052, 71801155, 72031004), the Natural Science Foundation of Guangdong Province (No. 2018A030313938), the Fund for Innovative Research Groups of the National Natural Science Foundation of China (71621061), the Major International Joint Research Project of the National Natural Science Foundation of China (71520107004), the Fundamental Research Funds for the Central Universities (N2006006), the Project of Promoting Talents in Liaoning Province (XLYC1807252), and the 111 Project (B16009).

Appendix A

Proof of Table 1. When the manufacturer moves first, we begin by determining the operators optimal usage decision. The utility-maximization problem of the operator is given by $\Pi_{Mo}^{E} = \max_{T_M \geqslant 0} \int_0^{T_M} \left(\theta - p - \frac{t}{\delta_M}\right) dt$, where Π_{Mo}^{E} is strictly concave in T_M. Solving the first-order condition, we obtain $T_M^* = (\theta - p)\delta_M$. The profit-maximization problem of the manufacturer is given by $\Pi_{Mm}^{E} = \max_{\delta_M \geqslant 0}\left[pT_M - \frac{mT_M{}^2}{2\delta_M} - k\delta_M^2\left(1 + r^E\right)\right]$. Π_{Mm}^{E} is strictly concave in δ_M because $\frac{\partial^2 \Pi_{Mm}^{E}}{\partial \delta_M^2} = -2k\left(1 + r^E\right) < 0$. Substituting T_M^* into the profit-maximization function of Π_{Mm}^{E} and solving the first-order condition, we obtain $\delta_M^* = \frac{(\theta-p)[2p-m(\theta-p)]}{4k(1+r^E)}$. We then have the other outcomes (i.e., $T_M^* = \frac{(\theta-p)^2[2p-m(\theta-p)]}{4k(1+r^E)}$, $\Pi_{Mm}^{E^*} = \frac{(\theta-p)^2[2p-m(\theta-p)]^2}{16k(1+r^E)}$ and $\Pi_{Mo}^{E^*} = \frac{(\theta-p)^3[2p-m(\theta-p)]}{8k(1+r^E)}$). When the operator moves first, we begin by determining the manufacturer's optimal quality level. The profit-maximization function is $\Pi_{Om}^{E} = \max_{\delta_O \geqslant 0}\left[pT_O - \frac{mT_O{}^2}{2\delta_O} - k\delta_O^2\left(1 + r^E\right)\right]$. Π_{Om}^{E} is concave in δ_O, we obtain $\delta_O^* = \left(\frac{mT_O^2}{4k(1+r^E)}\right)^{\frac{1}{3}}$ by solving the first-order condition. Substituting δ_O^* into the utility-maximization function (i.e., $\Pi_{Oo}^{E} = \max_{T_O \geqslant 0} \int_0^{T_O} \left(\theta - p - \frac{t}{\delta_O}\right) dt$) and solving the first-order condition in T_O, we obtain $T_O^* = \frac{27m(\theta-p)^3}{32k(1+r^E)}$. We then have the other outcomes (i.e., $\delta_O^* = \frac{9m(\theta-p)^2}{16k(1+r^E)}$, $\Pi_{Om}^{E^*} = \frac{27m(\theta-p)^3[8p-9m(\theta-p)]}{256k(1+r^E)}$ and $\Pi_{Oo}^{E^*} = \frac{27m(\theta-p)^4}{128k(1+r^E)}$.)

Proof of Lemma 1. When the manufacturer moves first, the optimal use duration is $\delta_M^* = \frac{(\theta-p)[2p-m(\theta-p)]}{4k(1+r^E)}$, where δ_M^* is strictly concave in p. Solving the first-order condition in p, we obtain the optimal $\alpha = \frac{p}{\theta} = \frac{m+1}{m+2}$. The optimal use duration is $T_M^* = \frac{(\theta-p)^2[2p-m(\theta-p)]}{4k(1+r^E)}$, where T_M^* is also strictly concave in p. Solving the first-order condition in p, we obtain the optimal $\alpha = \frac{3m+2}{3m+6}$.

When the operator moves first, it is straightforward to show that both $\delta_O^* = \frac{9m\theta^2(1-\alpha)^2}{16k(1+r^E)}$ and $T_O^* = \frac{27m\theta^3(1-\alpha)^3}{32k(1+r^E)}$ decrease in α.

Proof of Lemma 2. When the manufacturer moves first, the optimal quality level and use duration are $\delta_M^* = \frac{(\theta-p)[2p-m(\theta-p)]}{4k(1+r^E)}$ and $T_M^* = \frac{(\theta-p)^2[2p-m(\theta-p)]}{4k(1+r^E)}$ respectively. Both δ_M^* and T_M^* decrease in m. When the operator moves first, the optimal quality level and use duration are $\delta_O^* = \frac{9m(\theta-p)^2}{16k(1+r^E)}$ and $T_O^* = \frac{27m(\theta-p)^3}{32k(1+r^E)}$. Both $\delta_O^*$and T_O^* increase in m.

Proof of Proposition 1. When the manufacturer moves first, $\delta_M^*, T_M^*, \Pi_{Mm}^{E^*}$, and $\Pi_{Mo}^{E^*}$ should be more than zero, so we obtain the allowable range of $\alpha : \frac{m}{m+2} < \alpha < 1$. Analogously, when the operator moves first, we obtain the allowable α range of $\frac{9m}{9m+8} < \alpha < 1$. Note that $\frac{m}{m+2}$ and $\frac{9m}{9m+8}$ both increase in m. Hence, a higher m incurs a higher lower limit for α. In order to examine the ability to resist the risk of price fluctuation in different leadership scenarios, we derive the differences of the allowable range of α for different leaders: $\vartriangle = 1-\frac{9m}{9m+8}-(1-\frac{m}{m+2}) = -\frac{m}{m+\frac{8}{9}}+\frac{m}{m+2}$. We obtain $\vartriangle < 0$ when $m > 0$. Thus, the range of allowed α is wider when the manufacturer moves first.

Proof of Proposition 2. When the manufacturer moves first, the maximum profit of the manufacturer is $\Pi_{Mm}^{E^*} = \frac{\theta^4(1-\alpha)^2[2\alpha-m(1-\alpha)]^2}{16k(1+r^E)}$, where $\Pi_{Mm}^{E^*}$ is strictly concave in α. Solving the first-order condition in α, we obtain $\alpha = \frac{m+1}{m+2}$. The maximum utility of the operator is $\Pi_{Mo}^{E^*} = \frac{\theta^4(1-\alpha)^3[2\alpha-m(1-\alpha)]}{8k(1+r^E)}$. $\Pi_{Mo}^{E^*}$ is also strictly concave in α. Solving the first-order condition in α, we obtain $\alpha = \frac{2m+1}{2m+4}$.

When the operator moves first, the optimal profit of the manufacturer is $\Pi_{Om}^{E^*} = \frac{\theta^4 27m(1-\alpha)^3[8\alpha-9m(1-\alpha)]}{256k(1+r^E)}$, where $\Pi_{Om}^{E^*}$ is strictly concave in α. Solving the first-order condition in α, we obtain $\alpha = \frac{9m+2}{9m+8}$. The maximum utility of the operator is $\Pi_{Oo}^{E^*} = \frac{27m\theta^4(1-\alpha)^4}{128k(1+r^E)}$. It is straightforward that $\Pi_{Oo}^{E^*}$ decreases in α.

Proof of Proposition 3. When the manufacturer moves first, the maximum profit and utility are $\Pi_{Mm}^{E^*} = \frac{(\theta-p)^2[2p-m(\theta-p)]^2}{16k(1+r^E)}$ and $\Pi_{Mo}^{E^*} = \frac{(\theta-p)^3[2p-m(\theta-p)]}{8k(1+r^E)}$, respectively. Both $\Pi_{Mm}^{E^*}$ and $\Pi_{Mo}^{E^*}$ obviously decrease in m. When the operator moves first, the maximum profit is $\Pi_{Om}^{E^*} = \frac{27m(\theta-p)^3[8p-9m(\theta-p)]}{256k(1+r^E)}$, where $\Pi_{Om}^{E^*}$ is strictly concave in m. Solving the first-order condition in m, we obtain $m = \frac{4\alpha}{9(1-\alpha)}$.

The maximum utility of the operator is $\Pi_{Oo}^{E^*} = \frac{27m\theta(1-\alpha)^4}{128k(1+r^E)}$. It is straightforward that $\Pi_{Oo}^{E^*}$ increases in m.

Proof of Corollary 1. In order to examine the impact of α on the manufacturer's maximum profit for different leaders, we first obtain $\alpha = \frac{259m^2\pm12\sqrt{21}m+140m}{259m^2+280m+64}$ by assuming $\Pi_{Mm}^{E^*} = \Pi_{Om}^{E^*}$. In addition, when $m > 0$, $\frac{259m^2-12\sqrt{21}m+140m}{259m^2+280m+64} > \frac{m}{m+2}$ and $\frac{259m^2+12\sqrt{21}m+140m}{259m^2+280m+64} < 1$. Thus, if $\frac{259m^2-12\sqrt{21}m+140m}{259m^2+280m+64} < \alpha < \frac{259m^2+12\sqrt{21}m+140m}{259m^2+280m+64}$, then $\Pi_{Mm}^{E^*} < \Pi_{Om}^{E^*}$. In order to examine the impact of α on the operator's utility for different leaders, we obtain $\alpha > \frac{43m}{32+43m}$ by assuming $\Pi_{Oo}^{E^*} > \Pi_{Mo}^{E^*}$.

Proof of Proposition 4. It is evident that external financing decreases the members' benefits because there is a denominator (i.e.,$1+r^E$) in their benefit functions so all decrease in the interest rate (i.e.,r^E).

Proof of Table 2. Under internal financing, the operator always moves first. Based on the proof of Table 1, we obtain the optimal quality level, $\delta^* = \left(\frac{mT^2}{4k(1+r^I)}\right)^{\frac{1}{3}}$. The utility function is $\Pi_o^I = \max_{T\geqslant0,r^I\geqslant-1} \int_0^T \left(\theta-\frac{t}{\delta}\right)dt - pT + k\delta^2(r^I-r_f)$, where Π_o^I is strictly concave in T. By substituting δ^* into the utility function and solving the first-order condition in T, we obtain the optimal use duration, $T^* = \frac{27m(1+r^I)^2(\theta-p)^3}{4k[2(1+r^I)-m(r^I-r_f)]^3}$. Then we have the other outcomes, $\delta^* = \frac{9m(1+r^I)(\theta-p)^2}{4k[2(1+r^I)-m(r^I-r_f)]^2}$, $\Pi_m^{I^*} = \frac{27m(1+r^I)^2(\theta-p)^3\{(1+r^I)[8p-9m(\theta-p)]-4pm(r^I-r_f)\}}{16k[2(1+r^I)-m(r^I-r_f)]^4}$ and $\Pi_o^{I^*} = \frac{27m(1+r^I)^2(\theta-p)^4}{16k[2(1+r^I)-m(r^I-r_f)]^3}$. For the optimal interest rate, please see the proof of Proposition 5.

Proof of Proposition 5. The maximum use utility is $\Pi_o^{I^*} = \frac{27m(1+r^I)^2(\theta-p)^4}{16k[2(1+r^I)-m(r^I-r_f)]^3}$, where $\frac{\partial\Pi_o^I}{\partial r^I} = \frac{27(\theta-p)^4 m(1+r^I)(m(2r_f+r^I+3)-2(1+r^I))}{16k(mr_f-(m-2)r^I+2)^4}$ is always positive when $m > 2$. That is to say, the interest rate is "the bigger the better" for the operator. To ensure the manufacturer's profit is not negative (i.e., $\Pi_m^I\geqslant0$), we have $r^{I^*} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}-1$ when $\Pi_m^I = 0$. If $m < 2$, the solution to the first order condition yields only one local optimum that can be a maximizer, given by $r^{I^*} = -1-\frac{2m+2mr_f}{m-2}$. In order to ensure the manufacturer's profit is not negative, the operating efficiency(i.e., m) should satisfy the condition that $m < \frac{4\alpha}{3-\alpha}$ (i.e., $m < m_2^I$). As a result, if $m\geqslant m_2^I, r^{I^*} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}-1$.

Proof of Corollary 2. When $m < m_2^I$, the optimal interest rate is $r^{I^*} = -1-\frac{2m+2mr_f}{m-2}$, where r^{I^*} strictly increases in m. When $m > m_2^I$, $r^{I^*} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}-1$, where r^{I^*} decreases in m. Besides, if $m = m_2^I$, $-\frac{2m+2mr_f}{2-m} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}$. Thus, we get the highest value of r^{I^*} when $m = m_2^I$.

Proof of Corollary 3. A subsidy offered by the operator means the optimal interest rate is less than zero. In the case that $m < m_2^I$, we have $r^{I^*} = -1-\frac{2m+2mr_f}{m-2}$. We obtain $m < \frac{2}{3+2r_f}$ by assuming $r^{I^*} < 0$. When $m > m_2^I, r^{I^*} = \frac{4m\alpha(1+r_f)}{9m-8\alpha-5m\alpha}-1$. We obtain $m > \frac{8\alpha}{9-5\alpha-4\alpha(1+r_f)}$ by assuming $r^{I^*} < 0$.

Proof of Proposition 6. Based on Proposition 5, regardless of m and α, we can always get a solution of an interest rate that ensures their benefits nonnegative.

Proof of Proposition 7. If $m < m_2^I$, the maximum utility of the operator is $\Pi_o^{I^*} = \frac{(\theta-p)^4}{4k(2-m)^2(1+r_f)}$, where $\Pi_o^{I^*}$ strictly increases in m. While if $m > m_2^I$, solving the first-order condition of $\Pi_o^{I^*} = \frac{27m\left(1+r^{I^*}\right)^2(\theta-p)^4}{16k\left[2(1+r^{I^*})-m\left(r^{I^*}-r_f\right)\right]^3}$ in m by introducing $r^{I^*} = \frac{4m\alpha\left(1+r_f\right)}{9m-8\alpha-5m\alpha}-1$, we obtain $m = \frac{12\alpha}{9-5\alpha}$. As $\frac{12\alpha}{9-5\alpha} > \frac{4\alpha}{3-\alpha}$, $\Pi_o^{I^*}$ still increases in m when $\frac{4\alpha}{3-\alpha} < m < \frac{12\alpha}{9-5\alpha}$ and then decreases in m when $m > \frac{12\alpha}{9-5\alpha}$. According to the above, the operator gets the highest utility when $m = \frac{12\alpha}{9-5\alpha}$ rather than m_2^I that leads to the highest value of interest rate.

Proof of Proposition 8. If $m \geqslant m_2^I$, we get the optimal interest rate by assuming the manufacturer's profit is always zero(i.e.,$\Pi_m^{E^*} = 0$). If $m < m_2^I$, $\Pi_m^{I^*} = \frac{\theta^4(1-\alpha)^3(4\alpha+m\alpha-3m)}{2k(2-m)^3(1+r_f)}$, where $\frac{\partial \Pi_m^{I^*}}{\partial m} < 0$, when $\alpha < \frac{3}{7}$. However, if $\alpha > \frac{3}{7}$, we obtain the optimal $m = \frac{3-7\alpha}{\alpha-3}$.

Proof of Proposition 9. If $\alpha < \frac{m}{m+2}$, internal financing will be chosen because the service is not available under external financing. If $\alpha > \frac{m}{m+2}$, the manufacturer's profit under external financing is positive but if $\alpha < \frac{3m}{4+m}$ (i.e., $m \geqslant m_2^I$) his profit is always zero under internal financing. Thus, external financing is preferred when $\frac{m}{m+2} < \alpha < \frac{3m}{4+m}$. When $\alpha > \frac{3m}{4+m}$ (i.e., $m < m_2^I$) and m approaches m_2^I, the manufacturer's profit under internal financing is also close to zero, and then external financing is still preferred. We know $\frac{3m}{4+m}$ and $\frac{m}{m+2}$ increase in m, which means the allowable α that leads external financing to be preferred changes along with m. Thus, a low m and a high α or a high m and a low α lead to internal financing being preferred.

Proof of Corollary 4. When there is a high α such that p is close to θ, the benefits of the manufacturer (i.e.,$\frac{(\theta-p)^2[2p-m(\theta-p)]^2}{16k(1+r^E)}$) and the operator (i.e., $\frac{(\theta-p)^3[2p-m(\theta-p)]}{8k(1+r^E)}$) are close to zero under external financing. However, under internal financing, the benefits of the manufacturer (i.e.,$\frac{(\theta-p)^3(4p+mp-3m\theta)}{2k(2-m)^3(1+r_f)}$) and the operator (i.e.,$\frac{(\theta-p)^4}{4k(2-m)^2\left(1+r_f\right)}$) could be greater than zero because $2-m$ is very small when m is close to 2.

Proof of Proposition 10. By assuming $\Pi_{Mo}^{E^*} > \Pi_o^{I^*}$, we obtain $\alpha > \frac{m^3-4m^2+4m+2}{m^3-2m^2-4m+10}\frac{1+r^E}{1+r_f}$, where the first derivative of $\frac{m^3-4m^2+4m+2}{m^3-2m^2-4m+10}$ is positive when $0 < m < 2$.

Proof of Proposition 11. Under external financing, if $\alpha < \frac{9m}{9m+8}$, $\Pi_{Om}^{E^*} < 0$ and internal financing will be the only choice. If $\frac{9m}{9m+8} \leqslant \alpha \leqslant \frac{3m}{4+m}$, all the manufacturer's profit is extracted by the operator(i.e., $\Pi_m^{I^*} = 0$). Then the manufacturer prefers external financing. In addition, when α approaches $\frac{3m}{4+m}$, the profit of the manufacturer is also close to zero, which means the manufacturer obtains more profit under external financing. Therefore, as Region E(a) of Fig. 13 shows, the manufacturer prefers external financing because otherwise too much of his profit is extracted by the operator.

Proof of Corollary 5. Letting $m = 0$, $\Pi_{Om}^{E^*} = \frac{27m(\theta-p)^3[8p-9m(\theta-p)]}{256k(1+r^E)}$ will be zero but $\Pi_m^{I^*} = \frac{(\theta-p)^3(4p+mp-3m\theta)}{2k(2-m)^3(1+r_f)}$ is greater than zero. Thus, if m is close to zero, we have $\Pi_m^{I^*} > \Pi_{Om}^{E^*}$. When α is high, $\theta - p$ is close to zero. The maximum profit under external financing (i.e., $\Pi_{Om}^{E^*}$) is also close to zero. However, if m is close to 2, $(2-m)^3$ is approximately zero. The maximum profit under internal financing (i.e.,$\Pi_m^{I^*}$) could be greater than $\Pi_{Om}^{E^*}$. Therefore, if when m is close to 2 and α is high, internal financing is preferred.

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