



Research article

Hybrid financing strategies for capital-constrained 3D printing technology vendors: a game-theoretic approach to supply chain coordination

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Abstract: Unlike ordinary small and medium-sized enterprises (SMEs), 3D printing technology vendors rely on intangible technological assets and face R&D costs, uncertainty in patent valuation, and unstable cash flows from commercialization. To address the financing constraints faced by high-risk, asset-light SMEs in the 3D printing technology sector, we constructed a three-tier supply chain model consisting of a capital-constrained 3D printing technology vendor, a well-funded manufacturer, and a retailer. By embedding financing decisions into a supply chain coordination framework, we examine three financing mechanisms: intellectual property rights (IPR) pledges, internal debt, and internal equity. Our analysis reveals an inherent conflict of interest between the manufacturer (the primary fund provider) and the technology vendor (the capital demander). To mitigate this conflict, we proposed a hybrid financing structure that integrated the three mechanisms, resulting in four distinct financing modes. The results show that financing preferences are jointly affected by customization characteristics, customization cost, and financing structure. Hybrid financing can mitigate financing-preference conflicts between the technology vendor and the manufacturer by generating mutually acceptable financing regions, but its coordinating effect depends on the operating and financing environment. Monte Carlo robustness analysis further demonstrated that the feasible proportion of IPR pledges varied substantially across customization scenarios. Under low-customization conditions, a relatively higher IPR proportion remained feasible, whereas increasing customization complexity, cost pressure, and uncertainty reduced the acceptable IPR share and increased the importance of internal debt and equity financing. These findings indicated that IPR pledge financing should not be restricted by a universal threshold; instead, the appropriate proportion should be determined by technological characteristics and financing conditions.

Keywords: supply chain; 3D printing technology; hybrid financing; intellectual property pledge rights financing; internal debt financing

1. Introduction

In recent years, 3D printing technology has attracted increasing attention and developed rapidly worldwide. In China, a series of policies have promoted the application and development of 3D printing technology, particularly in manufacturing and technology innovation. In 2014, the National Development and Reform Commission, the Ministry of Science and Technology, and other government departments released the Additive Manufacturing Industry Development Action Plan, aiming to promote the industrial application of 3D printing technology through policy guidance and financial support. China's 14th Five-Year Plan also emphasizes breakthroughs and applications in advanced manufacturing technologies. Internationally, since 3D printing technology was first proposed in the 1980s by Chuck Hull, it has gradually matured and made substantial progress in aerospace, automotive manufacturing, healthcare, construction, and other fields [1]. However, because 3D printing technology requires high R&D investment and substantial funding, and because most firms in this sector are small and medium-sized enterprises, financing constraints have become one of the major challenges faced by technology vendors [2].

Industry financing practices further indicate that 3D printing firms rely heavily on external capital and strategic partnerships. According to financing data for the 3D printing industry, 30 financing events occurred worldwide in the first half of 2024, totaling approximately RMB 2.592 billion in funding. The number of strategic financing events increased significantly, indicating that investors increasingly seek to promote firm growth through resource integration and strategic partnerships. During the same period, Quantica raised USD 74 million, while Restor3D raised USD 70 million. Both firms focus on application-oriented technologies, suggesting that technologies with clear commercialization scenarios are more likely to attract capital. However, compared with the same period of the previous year, the total financing amount declined. Some 3D printing firms have also encountered profitability and capital-market pressures. For example, Shapeways filed for bankruptcy and delisting, while Xometry faced a securities-law-related investigation. In the short term, capital may become more cautious about entering the 3D printing industry. Therefore, given the decline in financing amounts and the stricter selection of investment targets, identifying appropriate financing methods to support technology vendors is crucial [3].

Traditional financing channels, such as bank loans and venture capital, often fail to fully meet the funding needs of 3D printing technology firms, especially when the technology has not fully matured, or market applications remain at an early stage [4]. On the one hand, bank loans typically require tangible collateral and stable cash flows, whereas the core assets of 3D printing firms often include patents, technical know-how, and R&D capabilities. On the other hand, venture capital can provide financial support but may also lead to equity dilution, changes in control rights, and pressure on profit distribution. In this context, intellectual property rights (IPR) pledge financing has emerged as an important financing option for technology-intensive firms. By using patents, trademarks, and other intellectual properties as collateral, technology firms can obtain financial support even when traditional collateral is insufficient [5]. In addition, some firms have adopted internal supply chain financing methods, such as internal debt financing and internal equity financing, to ease financial pressure and support production expansion and technological innovation [6]. Although these financing methods can alleviate funding constraints to some extent, firms still face complex issues related to financing-mode

selection, risk sharing, and coordination among supply chain members. Therefore, effectively combining multiple financing instruments and coordinating the interests of technology vendors and manufacturers is key to the sustainable development of 3D printing technology firms [7].

The financing problem examined in this paper is not a generic small and medium-sized enterprise (SME) financing problem. Ordinary SMEs often face credit constraints because of small scale, limited credit history, insufficient collateral, or information opacity. In contrast, 3D printing technology vendors face financing frictions rooted in their industrial characteristics. Their core assets are mainly intangible technological assets, including patents, process know-how, material systems, software capability, and accumulated customization experience. These assets are difficult for external financiers to value and liquidate. Moreover, commercialization usually requires continuous R&D investment, material validation, process testing, and market adaptation, which create unstable cash flows and high technological uncertainty. Therefore, the financing problem for 3D printing technology vendors is not only about access to credit but also about how to allocate valuation and technology development resources among supply chain members. Based on this background, in this paper, we develop a three-tier supply chain game model consisting of a capital-constrained 3D printing technology vendor, a well-funded manufacturer, and a retailer. The technology vendor provides technical services to the manufacturer and charges a technology fee, while the manufacturer and the retailer sequentially determine the wholesale and retail prices. We first examine three benchmark financing schemes: IPR pledge financing, internal debt financing, and internal equity financing. We then propose a hybrid financing mechanism that integrates these three financing instruments. Using backward induction, we derive the equilibrium decisions under each financing mode and analyze how key parameters, including customization level, customization cost coefficient, and the proportion of IPR pledge financing in the hybrid scheme, affect profit distribution and financing preferences between the technology vendor and the manufacturer.

We address the following research questions:

(1) How do IPR pledge financing, internal debt financing, internal equity financing, and hybrid financing affect profit allocation and financing preferences between technology vendors and manufacturers in a 3D printing supply chain?

(2) How do customization level and customization cost influence financing-mode selection, and under what conditions do financing preference conflicts arise among supply chain members?

(3) Under what conditions can a hybrid financing mechanism coordinate the interests of technology vendors and manufacturers and lead to a mutually acceptable financing arrangement?

Compared with the literature, the marginal contributions of this paper are as follows: First, we shift the focal financing entity from capital-constrained manufacturers, retailers, or ordinary suppliers to a 3D printing technology vendor. The financing friction examined here is not a generic SME credit problem. Rather, it arises from the mismatch between intangible technological assets, such as patents, process know-how, software capability, and customization expertise, and conventional financing mechanisms that rely mainly on tangible collateral, receivables, orders, or buyer credit.

Second, we compare IPR pledge financing, internal debt financing, and internal equity financing within a unified supply chain game framework. Unlike researchers who examine a single financing instrument or conventional combinations such as bank credit, trade credit, and platform financing, we jointly model external IPR-based collateral financing and internal supply-chain-based debt and equity financing. This unified comparison enables us to identify not only the preferred financing mode of

each party, but also the conditions under which financing preferences between the technology vendor and the manufacturer conflict.

Third, we develop hybrid financing as a coordination mechanism rather than merely as a capital-raising tool. The hybrid mode is modeled as a financing-proportion arrangement among IPR pledge financing, internal debt financing, and internal equity financing. This enables the analysis to characterize mutually acceptable financing regions that balance the interests of the technology vendor and the manufacturer instead of simply selecting one universally optimal financing mode.

Fourth, we link financing-mode selection with 3D-printing-specific technological and cost characteristics. By incorporating customization level, customization cost coefficient, and the IPR financing proportion, the model explains how technological complexity and cost pressure affect profit allocation, financing preferences, and the feasibility of hybrid financing. The findings therefore provide a conditional financing framework for 3D printing technology vendors rather than a fixed threshold rule for ordinary SMEs.

2. Literature review

In this study, we draw on four related research streams: the financing constraints of technology-intensive SMEs and 3D printing vendors, intellectual property financing, supply chain finance, and hybrid financing. In this section, we review these streams and introduce relevant insights from portfolio optimization and resource allocation under uncertainty to clarify the theoretical foundation and research positioning of the study.

2.1. *Subheading financing constraints of technology-intensive SMEs and 3D printing vendors*

The financing constraints faced by technology-intensive SMEs have received considerable attention in the literature. Information asymmetry, high uncertainty surrounding innovation outcomes, and the limited collateral value of intangible assets are widely recognized as major barriers to external financing for these firms [8]. As a representative type of technology-intensive SME, 3D printing technology vendors exhibit many of these financing characteristics. Over the past decades, 3D printing has evolved from rapid prototyping to customized production, complex-structure fabrication, spare-parts supply, and distributed manufacturing. Compared with conventional manufacturing technologies, 3D printing directly converts digital designs into physical products and reduces reliance on molds and standardized large-scale production lines, thereby improving design flexibility, shortening product development cycles, and enhancing firms' responsiveness to heterogeneous market demand [9,10]. Therefore, 3D printing is not merely a production technology but also a technological setting that reshapes firms' cost structures, supply chain organization, and financing needs.

The commercialization of 3D printing technology typically requires continuous investment in specialized equipment, material qualification, process development, software systems, and skilled technical personnel, often before firms can generate stable revenues and cash flows [11,12]. For small and medium-sized technology vendors, high upfront investment, long R&D cycles, and uncertain market demand can therefore create substantial financing constraints. Moreover, unlike conventional manufacturing firms that possess machinery, inventories, and other tangible assets, the core resources of 3D printing technology vendors are largely embedded in intangible assets, including patents, technical know-how, software capabilities, and accumulated process knowledge. This asset structure

limits firms' ability to obtain conventional collateral-based loans and makes it more difficult for external financial institutions to assess their creditworthiness and technological value [13,14].

Given these financing challenges, different financing mechanisms have been explored to support technology-intensive firms. The patent-intensive nature of 3D printing vendors makes IPR pledge financing a potential external financing channel. Research in corporate finance indicates that, under certain conditions, knowledge assets such as patents can serve as collateral, improving innovative firms' access to external finance [14]. Nevertheless, IPR pledge financing remains subject to valuation uncertainty, technological obsolescence, and default risk. A parallel stream of research on supply chain finance shows that financially constrained firms may obtain funding through debt, equity, platform-based financing, and other arrangements embedded in supply chain relationships, which, in turn, can affect pricing decisions, profit allocation, and the stability of supply chain cooperation [15,16].

Despite the growing literature on additive manufacturing, researchers have primarily focused on technological applications, production organization, and supply chain restructuring, while the financing challenges faced by capital-constrained 3D printing technology vendors have received relatively limited attention. In particular, how their reliance on intangible technological assets and exposure to high R&D investment and commercialization uncertainty shape financing needs and financing decisions remains insufficiently explored.

2.2. *Intellectual property financing for technology-intensive firms*

Research on intellectual property (IP) financing mainly entails how intangible technological assets can be transformed into pledgeable financing resources. Unlike conventional tangible collateral, intellectual property assets such as patents embody technological knowledge and legally granted exclusion rights. Therefore, for technology-intensive firms that lack sufficient tangible assets, patents and other intangible assets can provide an important basis for obtaining debt financing. Empirical evidence supports this argument. Mann [14] found that patents are widely used as collateral in debt contracts and that stronger creditor rights over patent collateral can facilitate innovation financing. Patent collateral also plays an important role in venture lending markets by strengthening investor commitment and improving innovative firms' access to credit [17]. These studies suggest that IP financing can, to some extent, alleviate the financing constraints faced by technology-intensive firms whose value is primarily embedded in intangible assets.

Patent collateral financing may also generate broader economic consequences. Luo et al. [18] found that patent collateralization affects firms' innovation trajectories, indicating that its influence extends beyond immediate financing accessibility to subsequent technological development. More broadly, the financing role of patents is closely related to their economic value and market liquidity. Patents differ substantially in their contributions to firm value and resource allocation [19], while Serrano [20] emphasizes the importance of patent transferability and renewal decisions in the development of secondary markets for patent assets. These findings suggest that patents are not homogeneous financing instruments and that their collateral value depends on technological quality, legal protection, commercialization potential, and asset redeployability.

However, the effectiveness of IP financing remains conditional. Differences in the economic value, technological quality, and commercial applicability of patents make their collateral value difficult to assess and price [17,19]. Moreover, the financing value of patent collateral depends on its redeployability and recoverability following default, while liquidity in secondary patent markets remains limited and highly technology-specific [21]. Recent studies further show that patent collateral

financing may affect firms' subsequent innovation trajectories and investment behavior [18,22]. Therefore, although IP financing can mitigate the mismatch between intangible technology-based value creation and conventional collateral-based financial evaluation, reliance on a single IP-based financing channel may be insufficient for technology-intensive firms facing substantial R&D expenditures, high customization costs, and uncertain commercialization prospects.

Despite considerable progress, researchers have primarily examined the effects of IP financing on external financing accessibility, borrowing capacity, and innovation outcomes, while relatively limited attention has been given to financing-mode selection when IPR pledge financing coexists with financing mechanisms embedded in supply chain relationships.

2.3. *Supply chain finance and hybrid financing*

Research on supply chain finance has increasingly examined how financing arrangements embedded in interfirm relationships can alleviate financial constraints and affect firms' operational decisions. Unlike conventional external financing, supply chain finance facilitates firms' access to capital by leveraging transaction information, cooperative relationships, and the creditworthiness of supply chain members. Related studies show that core enterprises and financially stronger supply chain members can provide credit support to capital-constrained firms, thereby improving financing accessibility and capital utilization efficiency [23,24]. Internal debt financing further facilitates capital allocation through debt relationships among supply chain members, enabling capital-constrained firms to obtain financial support based on transaction information, established cooperative relationships, and the creditworthiness of core enterprises [25]. However, debt financing also imposes repayment obligations and financing costs on capital-constrained firms. Equity financing provides an alternative mechanism by enabling capital providers to share future returns and risks. Compared with debt financing, this risk-sharing feature may be particularly important for technology-intensive firms facing high R&D investment and commercialization uncertainty. Related studies have compared external and internal equity financing and examined financing structures combining bank loans with supplier equity investment [26], while other studies suggest that equity participation can provide firms with longer-term financial support and greater financing flexibility [27]. However, studies generally examine debt and equity financing separately, leaving limited understanding of how capital-constrained firms and capital providers choose among financing mechanisms when their financing preferences diverge.

The differences in the cost and risk characteristics of financing mechanisms have motivated increasing research attention to multi-source financing structures. Hybrid financing can reduce firms' dependence on a single financing source and allocate financing costs, returns, and risks across financing instruments [28,29]. Related studies show that combining debt, equity, and other financing instruments can enhance financing flexibility and facilitate risk sharing [26,27]. From this perspective, hybrid financing is not merely a means of improving access to capital but also involves the allocation of financing resources among heterogeneous instruments with different cost, return, and risk-sharing characteristics. This issue is particularly relevant to technology-intensive firms because IPR pledge financing, internal debt financing, and internal equity financing differ substantially in collateral requirements, repayment obligations, residual claims, and risk allocation. Therefore, the effectiveness of hybrid financing depends not only on the availability of multiple financing sources but also on how financing proportions are allocated under different technological characteristics, cost conditions, and levels of uncertainty.

From a broader mathematical perspective, hybrid financing involves not only the combination of multiple financing modes but also the allocation of limited resources among financing instruments under uncertainty. Research on portfolio optimization provides useful insights into such resource allocation problems. Early studies in this stream entailed how parameter uncertainty affects resource allocation and decision robustness. Kara et al. [30] examined robust portfolio optimization under parallelepiped uncertainty and show that the specification of uncertainty sets and parameter variations can affect portfolio allocation and decision stability. Building on this perspective, subsequent studies further incorporate uncertainty into dynamic investment decisions. Baltas [31] investigated optimal investment under model uncertainty and reveals the relationship between uncertainty and dynamic capital allocation. Savku and Weber (2018) [32] further incorporated complex factors, including regime switching, jumps, and delays, into stochastic financial decision-making and developed a corresponding stochastic maximum principle. Savku and Weber [33] subsequently employed stochastic differential games to investigate optimal investment in a Markov regime-switching jump-diffusion market, extending this research stream to strategic interactions among multiple decision makers. Yılmaz et al. [34] further contributed to this literature from a numerical perspective by developing computational methods for stochastic optimal control problems. Overall, this literature has gradually evolved from robust resource allocation under uncertainty to dynamic stochastic decision-making and strategic interactions among participants, providing a richer analytical perspective on resource allocation in complex environments. Although these studies differ from supply chain financing in terms of their research settings and specific decision objectives, their insights into uncertainty, resource allocation, and strategic interactions provide useful references for analyzing the proportional allocation of different financing instruments and the financing decisions of supply chain members.

Taken together, studies have provided important insights into supply chain debt financing, equity financing, hybrid financing, and resource allocation under uncertainty. However, these research streams have largely developed separately, leaving limited understanding of how heterogeneous financing instruments can be combined to address financing preference conflicts among supply chain members.

2.4. Literature review and research gaps

Although substantial research has entailed the financing of technology-intensive SMEs, IP financing, and supply chain finance, these research streams remain insufficiently integrated. Supply chain finance studies primarily entail capital-constrained manufacturers, retailers, and conventional suppliers, with limited attention given to technology vendors whose core value is embedded in intangible assets such as patents, technical know-how, and customization capabilities. IP financing researchers mainly examine the effects of patents on external financing accessibility and corporate innovation, while paying less attention to the interaction between IPR pledge financing and internal financing mechanisms embedded in supply chain relationships. Moreover, hybrid financing studies investigate combinations of bank credit, trade credit, and equity financing, but the integration of external IPR financing with internal debt and equity financing within a unified framework remains underexplored.

These gaps are particularly relevant to 3D printing technology vendors because their financing decisions are jointly shaped by intangible technological assets, supply chain relationships, and customization-related technological and cost characteristics. However, limited research has entailed how IPR pledge financing, internal debt financing, and internal equity financing affect the financing

preferences of technology vendors and manufacturers within a unified supply chain framework or how hybrid financing can mitigate financing preference conflicts between them. To address these gaps, we develops a three-tier supply chain game model comprising a capital-constrained 3D printing technology vendor, a well-funded manufacturer, and a retailer. The model integrates the three financing mechanisms within a unified analytical framework and further examines the coordinating role of hybrid financing. By incorporating customization level, customization cost, and financing proportions, we analyzes how technological and cost characteristics affect equilibrium decisions, profit allocation, and financing preferences, and identify the conditions under which hybrid financing can mitigate financing preference conflicts and generate mutually acceptable financing arrangements.

Table 1. Study comparison table.

Research dimension	Current research on hybrid financing/supply chain finance	This article's model
Entities with limited funds	There are quite a few manufacturers, retailers, and suppliers	3D printing technology supplier
core asset	Inventory, accounts receivable, orders, credit	Patents, technical skills, customization abilities
Financing methods	Bank loans, trade credit, platform financing, equity financing, etc	IPR pledges, internal debt, internal equity, and their hybrid mechanisms
Supply chain structure	Common second- or third-tier supply chains	Three-tier structure of tech suppliers, manufacturers, and retailers
Key parameters	Price, order quantity, loan interest rate, etc	Technology fees, wholesale price, retail price, level of customization, customization cost, IPR financing ratio
Research Focus	Choosing the best financing method or comparing financing costs	Conflict of Financing Preferences and the Coordinating Role of Hybrid Financing

Table 2 presents a thematic review of the literature conducted in this study. It summarizes prior research across three key dimensions: 3D printing financing, supply chain finance, and hybrid financing structures.

Table 2. A brief literature survey.

Author	Financing Constraints of Technology- Intensive Firms	IP Financing	Supply Chain Finance and Hybrid Financing
Hull C.W. (1986)	√		
Hall B.H. (2010)	√		
Serrano C.J. (2010)		√	
Xiao X. (2011)	√	√	
Mellor S. et al. (2014)	√		
B. H. Hall . (2015)	√		
C. S. Tang. et al. (2018)			√
Hochberg Y.V. et al. (2018)	√	√	
T. I. Tunca. et al. (2018)			√
Liang X. et al. (2018)			√
Mann W. (2018)	√	√	
Savku E. (2018)			√
Caniato F. et al. (2019)			√
Kara G. et al. (2019)			√
Serrano C.J. (2019)		√	
Westerweel B. et al. (2021)	√		
Qin J. et al. (2021)			√
Savku E. (2022)			√
Sun H. et al. (2022)	√		√
W. Zhang. et al. (2022)	√		
Zhuo W.Y. (2022)			√
Fu H. et al. (2023)			√
Tong M., Li W. (2023)	√		√
X.L. et al. (2023)		√	
Baltas I. (2024)			√
Luo Y. et al. (2024)	√	√	
Mandal P. et al. (2024)		√	√
Yılmaz F. et al. (2024)			√
Zhang B.F., Xiao S. (2024)			√
X. He. et al. (2024)			√
Liu Z., Zhu H. (2025)	√	√	
This paper	√	√	√

3. Results of the model

In this chapter, we first present the model assumptions and introduce the variables. We then develop four models: intellectual property rights pledge financing (IPR), internal debt financing (IDF), internal equity financing (IEF), and hybrid financing (MF). Using backward induction, we solve for the optimal solutions of these four models. Finally, we analyze the four models by focusing on three key parameters: product customization level, product customization cost coefficient, and the proportion of IPR in MF.

3.1. Notations and assumptions

We consider a supply chain consisting of a capital-constrained 3D printing technology vendor, along with a capital-rich manufacturer and retailer. The product customization level δ is treated as an exogenous product and technological characteristic determined by customer requirements, application scenarios, and production complexity. It is commonly observed by all supply chain members before the game begins. Conditional on the given customization level, the technology vendor acts as the Stackelberg leader and determines the unit technology fee. The manufacturer subsequently determines the wholesale price, and the retailer determines the retail price. Table 3 presents the key parameters and their definitions. We make the following assumptions:

(1) For 3D printing customized products, the market demand for these products is influenced by the price and the level of customization. According to the assumptions about market demand by Wan et al. [35] and the research on customized 3D printed products by Tong et al. [36].

H1: We assume that the market demand for 3D printing customization products is

$$q = a - \beta p + \tau \delta,$$

where a is the potential market size, β is the product price coefficient, τ is the customization sensitivity coefficient, and δ is the product customization level [36].

(2) Based on the early studies of Nair et al. and Zhou et al., in addition to the normal R&D costs, the technology vendor also incurs costs related to customization [37,38]. Furthermore, the relationship between the technology vendor's costs and its available capital determines whether the vendor's R&D and production capabilities can meet the market demand for the product [39].

H2: We assume that the cost structure of the technology vendor is $c_1 q + \frac{n\delta^2}{2}$, where c_1 represents the unit normal R&D cost for the technology vendor, n is the customization cost coefficient, and δ is the level of product customization.

(3) In the IPR pledge financing mode, the technology vendor obtains external financing by pledging intellectual property rights. The financing cost is reflected in the IPR-backed loan interest rate, patent appraisal cost, and repayment obligation [39]. Although a technology-fee discount could be introduced as a proportional adjustment to the unit technology fee, such a proportional discount is fully absorbed by the technology vendor's optimal choice of the technology fee and does not affect the equilibrium prices, quantities, or profits.

H3: We assume that the unit technology fee is μ^h in the IPR model.

(4) Since third-party institutions have a certain level of expertise, they can provide more objective and comprehensive assessment results. Therefore, the technology vendor commissions a third-party evaluation agency to assess the 3D printing technology patent. Furthermore, the technology vendor must pay a patent evaluation commission to the evaluation agency. Moreover, according to the "Measures for the Administration of Asset Appraisal Fees (NDRC Price [2009] No. 2914) [40]" issued by the National Development and Reform Commission (NDRC) and the Ministry of Finance (MOF), the appraisal fee rate must not exceed 16%.

H4: We assume that the technology vendor must pay a patent evaluation commission λV to the evaluation agency and the commission rate is constrained $0 < \lambda < 0.16$.

(5) The value of intangible assets depends on the expected market returns, but these expected returns are influenced by factors such as market demand fluctuations, continuous technological

innovation, and changes in regulations and policies. When financial institutions face this uncertainty, they tend to be more cautious and are often skeptical about the patent valuations of technology vendors. Additionally, a higher level of customization implies greater technological content and innovative value, which enhances the value of IPR and the credibility of loans, thereby reducing the interest rate. Based on the benchmark interest rate plus a spread pricing method, we can get the interest rate for IPR pledge financing in 3D printing technology [36].

H5 : We assume that the interest rate for IPR pledge financing in 3D printing technology is

$$r = r_0 (1 + k_1 \theta_1 - k_2 \theta_2),$$

where r_0 represents the benchmark interest rate of the financial institution, and k_1 and k_2 are the impact coefficients of θ_1 and θ_2 , respectively.

H6: Common monetary base of hybrid financing.

The technology vendor's total capital requirement consists of its regular R&D expenditure and customization investment: $K(q, \delta) = c_1 q + \frac{n\delta^2}{2}$. After using its internal capital m , the financing gap is $F(q, \delta) = \max \left\{ c_1 q + \frac{n\delta^2}{2} - m, 0 \right\}$. We focus on the capital-constrained region in which $F(q, \delta) > 0$. In the hybrid-financing model, ϕ , φ , and $1 - \phi - \varphi$ are defined relative to this common financing gap and represent the shares funded through IPR-backed bank lending, internal equity, and internal debt, respectively.

Table 3. Relevant parameters and descriptions.

Parameters	Definition
a	indicates potential market size
β	indicates product price factor
τ	indicates customized sensitivity factor
δ	indicates level of customization
n	indicates customized cost factor
c	indicates unit product production cost
c_1	indicates unit product production cost of the technology vendor
c_2	indicates unit product production cost of the manufacturer
ρ	indicates cost saving factor
μ	represents discount rate for technical fees
m	indicates technology vendor's own funds
r_0	indicates benchmark interest rates for financial institutions
r_1	indicates IPR pledge financing interest rate
r_2	denotes internal debt financing interest rate
θ_1	indicates skepticism factor of financial institutions on patent valuations by appraisal organizations

Continued on next page

Parameters	Definition
θ_2	indicates the extent to which the level of 3D printing customization affects interest rates
λ_1	indicates percentage of commission paid to appraisal organizations by technology vendors
V	denotes valuation of total IPR of technology vendors
k_1	indicates impact factor for θ_1
k_2	denotes impact factor for θ_2
η	denotes equity share obtained by the manufacturer in the internal financing model
ϕ	indicates proportion of IPR pledge financing in hybrid financing
φ	indicates proportion of internal equity financing in hybrid financing
π_t	indicates technology vendor's profit
π_m	indicates manufacturer's profit
π_r	represents retailer's profit
Decision variables	
q	indicates product's market demand
p	indicates retailer's product price
w	indicates manufacturer's product price
h	represents unit technical costs

3.2. Model building

The research and promotion of 3D printing technology are constrained by the technology vendor's own capital. To address the funding issue and consider the characteristics of 3D printing technology vendors, we have developed models for IPR Pledge Financing, Internal Debt Financing, and Internal Equity Financing. Building upon these models, and to better assist 3D printing technology vendors with financing, we propose a Hybrid Financing Model for analysis. In this paper, we establish a 3D printing technology supply chain consisting of technology providers, manufacturers, and retailers, and discuss four models: The Intellectual Property Rights Pledge Financing Model (IPR), Internal Debt Financing Model (IDF), Internal Equity Financing Model (IEF), and Hybrid Financing Model (MF).

The decision sequence within the supply chain is as follows: Before the game begins, the product customization level δ , which is determined by customer requirements, application scenarios, and technological complexity, is exogenously given and commonly observed by all supply chain members. (1) Conditional on δ , the technology vendor, as the Stackelberg leader, determines the unit technology fee h ; (2) after observing h , the manufacturer determines the wholesale price w ; (3) after observing h and w , the retailer determines the retail price p ; and (4) the manufacturer pays a unit technology fee to the technology vendor.

For these three models, the first four decisions are the same, with the distinction lying in the subsequent financing decisions made by the technology vendor. In the case of the IPR model, the sequence is as follows: (5-I) An evaluation agency provides intellectual property assessment services to the technology vendor; (6-I) the technology provider pays an assessment fee to the evaluation agency; (7-I) a financial institution determines the loan interest rate to be provided to the technology vendor; and (8-I) after selling the products, the technology vendor repays the loan and interest. For the IDF

model, the sequence is: (5-D) The manufacturer determines the loan interest rate and amount to be provided to the technology vendor; and (6-D) after selling the products, the technology provider repays the loan and interest. For the IEF model, the sequence is: (5-E) The technology vendor and manufacturer negotiate the equity transaction method, with the manufacturer purchasing equity; and (6-E) after selling the products, the technology vendor distributes profits to the manufacturer.

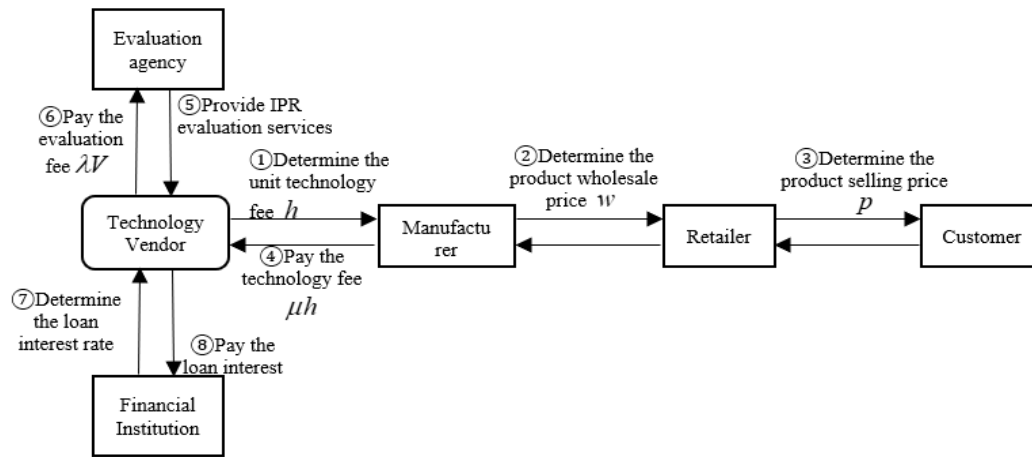


Figure 1. Decision flowchart of the IPR pledge financing model.

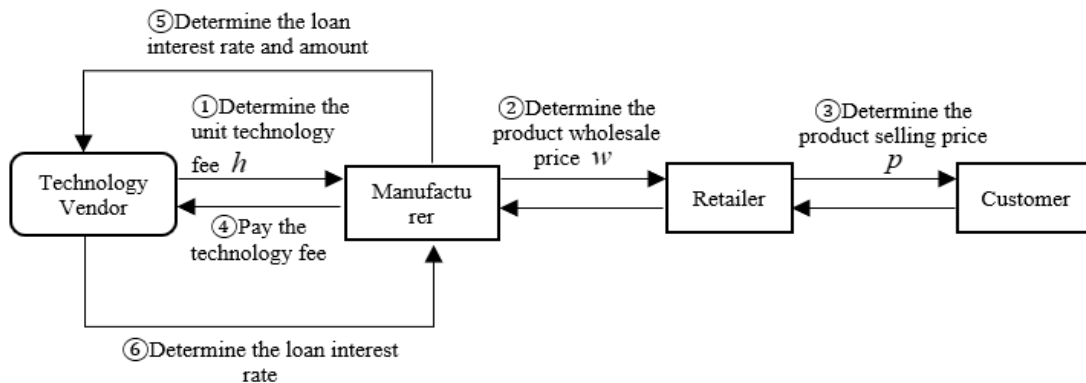


Figure 2. Decision flowchart of the internal debt financing model.

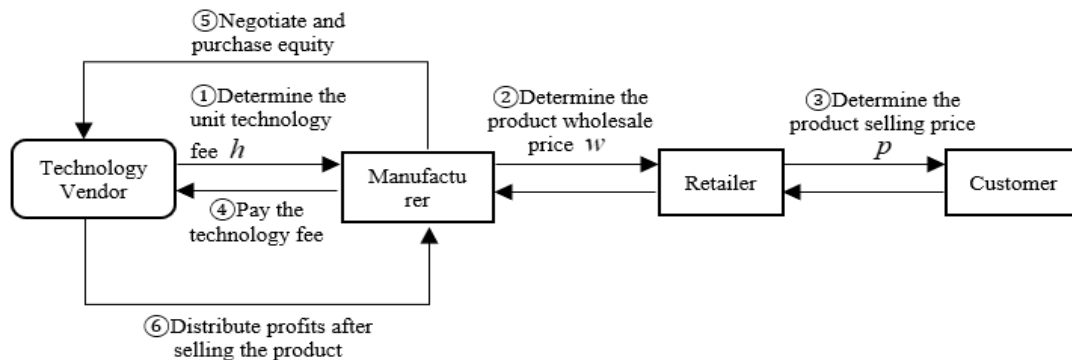


Figure 3. Decision flowchart of the internal equity financing model.

Table 4. Comparison table of the four models.

Aspect	Name	IPR	IDF	IEF	MF
Similarity	Financing goal	Assist technology vendors in financing to promote the research and development and application of 3D printing technology.			
	Capital structure	They will all have a certain impact on the capital structure of technology vendors, including changes to debt ratios, equity structure, and cost of liabilities.			
	Supply chain collaboration	There is a close collaborative relationship between technology vendors and manufacturers. Technology vendors may borrow money or transfer equity to manufacturers, while manufacturers also provide guarantees for technology vendors, thereby enhancing the flow of funds and collaboration within the supply chain			
Differences	Source of funds	External financing	Internal financing	Internal financing	Combination of external and internal financing
	Characteristic	The company does not need to give up equity or take on large amounts of debt	The manufacturer provides financial support, and there is no need for external financial institutions to be involved	The manufacturer provides financial support by acquiring equity and participating in the future profits of the technology vendor	By combining various financing methods, the company can flexibly address different aspects of its funding needs.
	Risk	The uncertainty in the valuation of IPR and the risk of loss of the reputation.	Failure to repay may affect the relationship with the manufacturer	The technology vendor must bear changes in the shareholder structure	It is necessary to manage multiple conflicts of interest and risk management

To better illustrate the relationships and differences between the four financing models, IPR, IDF, IEF, and MF, we present them in a table, as shown in Table 4. The similarities among the four financing methods lie in three aspects: financing goal, capital structure, and supply chain collaboration. The differences primarily stem from three aspects: source of funds, characteristic, and risk.

3.2.1. Model building intellectual property rights pledge financing model (IPR)

When the technology vendor has limited funds, it may have the intention to seek financing due to its research and development (R&D) needs. Compared to operating without financing, the technology vendor, by pledging IPR for financing, can access available funds that include its own capital m and the maximum loan amount V . After completing the R&D, the technology provider needs to repay the loan and interest to the bank based on the usage of the R&D funds and the interest rate r_1 . The total repayment amount is $(c_1q + \frac{n\delta^2}{2} - m)(1 + r_1)$, where $r_1 = r_0(1 + k_1\theta_1 - k_2\theta_2)$, θ_1 represents the skepticism coefficient of the financial institution regarding the patent valuation provided by the evaluation agency, and θ_2 is the impact of the 3D customization level on the interest rate. Additionally, the technology provider must pay an evaluation fee $\lambda_1 V$ to the evaluation agency.

Therefore, the profit functions of the technology vendor, manufacturer, and retailer are as follows:

$$\pi_{t,1} = (\mu h - c_1)q - \frac{n\delta^2}{2} - \left(c_1q + \frac{n\delta^2}{2} - m\right)[r_0(1 + k_1\theta_1 - k_2\theta_2)] - \lambda_1 V,$$

$$\pi_{m,1} = [w - (1 - \rho\delta)c_2 - \mu h]q,$$

$$\pi_{r,1} = (p - w)q.$$

The optimal pricing decisions for the supply chain are derived through backward induction as follows:

Proposition 1. In the IPR model, the optimal profit for the manufacturer, and optimal profit for the technology vendor are as follows:

$$\pi_{r,1}^* = \frac{\left\{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta[1 + r_0(1 + k_1\theta_1 - k_2\theta_2)]\right\}^2}{64\beta},$$

$$\pi_{m,1}^* = \frac{\left\{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta[1 + r_0(1 + k_1\theta_1 - k_2\theta_2)]\right\}^2}{32\beta},$$

$$\pi_{t,1}^* = \frac{\left\{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta[1 + r_0(1 + k_1\theta_1 - k_2\theta_2)]\right\}^2}{16\beta} + \left(m - \frac{n\delta^2}{2}\right) [r_0(1 + k_1\theta_1 - k_2\theta_2)] - \lambda_1 V - \frac{n\delta^2}{2}.$$

Proof. See Appendix A.

3.2.2. Internal debt financing model (IDF)

In the IDF model, it is assumed that the financing provider is the manufacturer. The total cost of the technology provider is $c_1q + \frac{n\delta^2}{2}$, and the technology vendor's own capital is m , so the required amount

of funding for the technology provider is $c_1q + \frac{n\delta^2}{2} - m$. The technology vendor needs to repay the loan and interest to the manufacturer based on the usage of the R&D funds and the interest rate r_2 .

Therefore, the profit functions of the technology vendor, manufacturer, and retailer are as follows:

$$\pi_{t,2} = (h - c_1)q - \frac{n\delta^2}{2} - \left(c_1q + \frac{n\delta^2}{2} - m\right)r_2,$$

$$\pi_{m,2} = [w - (1 - \rho\delta)c_2 - h]q + \left(c_1q + \frac{n\delta^2}{2} - m\right)r_2,$$

$$\pi_{r,2} = (p - w)q.$$

The optimal pricing decisions for the supply chain are derived through backward induction as follows:

Proposition 2. In the IDF model, the optimal profit for the manufacturer, and optimal profit for the technology vendor are as follows:

$$\pi_{r,2}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{64\beta},$$

$$\pi_{m,2}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{32\beta} + \left(\frac{n\delta^2}{2} - m\right)r_2,$$

$$\pi_{t,2}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{16\beta} + mr_2 - \frac{n\delta^2}{2}(1 + r_2).$$

Proof. See Appendix B.

3.2.3. Internal equity financing model (IEF)

In the IEF model, we assume that the financing provider is the manufacturer. Specifically, the manufacturer obtains a certain percentage of equity in the technology vendor by providing funds, with the equity stake denoted as η , serving as a guarantee for investment returns and promoting a win-win cooperation between the two parties.

Therefore, the profit functions of the technology vendor, manufacturer, and retailer are as follows:

$$\pi_{t,3} = (1 - \eta) \left[(h - c_1)q - \frac{n\delta^2}{2} \right],$$

$$\pi_{m,3} = [w - (1 - \rho\delta)c_2 - h]q + \eta \left[(h - c_1)q - \frac{n\delta^2}{2} \right],$$

$$\pi_{r,3} = (p - w)q.$$

The optimal pricing decisions for the supply chain are derived through backward induction as follows:

Proposition 3. In the IEF model, the optimal profit for the manufacturer, and optimal profit for the technology vendor are as follows:

$$\pi_{r,3}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{64\beta},$$

$$\pi_{m,3}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{32\beta} - \frac{\eta n\delta^2}{2},$$

$$\pi_{t,3}^* = \frac{(a + \tau\delta - c_1\beta - c_2\beta + c_2\beta\rho\delta)^2}{16\beta} - \frac{(1-\eta)n\delta^2}{2}.$$

Proof. See Appendix C.

3.2.4. Hybrid financing model (MF)

To better meet the financing needs of small and medium-sized enterprises such as technology vendors, we propose a hybrid financing model that combines IPR pledge financing, internal equity financing, and internal debt financing. In practice, the hybrid financing arrangement can be implemented through a simple sequential negotiation procedure. First, after assessing the customization level, customization cost, and financing gap, the technology vendor and the manufacturer calculate their profits using internal debt and equity financing as their respective reference points. Second, the technology vendor proposes a hybrid financing structure, including the proportions of IPR pledge financing, internal debt financing, and internal equity financing. The manufacturer evaluates whether the proposal falls within the mutually acceptable compromise set defined above. If it does not, the financing proportions are revised until a feasible combination acceptable to both parties is reached. Therefore, this model identifies the feasible negotiation range rather than endogenously determining bargaining power or a unique negotiated outcome. To combine the three structurally different financing instruments within a unified framework, we define their proportions relative to the technology vendor's financing gap $F(q, \delta)$, rather than relative to total investment, firm ownership, or total profit. The financing amounts provided through the three channels are: $L_I = \phi F(q, \delta)$, $L_E = \varphi F(q, \delta)$, $L_D = (1 - \phi - \varphi)F(q, \delta)$, subject to $\phi \geq 0$, $\varphi \geq 0$, $\phi + \varphi \leq 1$. Hence,

$L_I + L_E + L_D = F(q, \delta)$. Here, ϕ denotes the share of the financing gap funded by an external IPR-backed bank loan; φ denotes the share funded through the manufacturer's equity investment; and $1 - \phi - \varphi$ denotes the share funded through internal debt provided by the manufacturer. These parameters are financing-amount shares rather than ownership or profit-sharing ratios.

The equity-financing amount share φ is distinct from the contractual profit-sharing rate η . Parameter η denotes the manufacturer's profit claim when the entire financing gap is funded through internal equity. To preserve analytical tractability, we adopt a proportional-participation assumption: When internal equity accounts for a fraction φ of the financing gap, the manufacturer's effective profit claim is $\varphi\eta$. Let the technology vendor's operating profit before financing allocation be

$\pi_t^0 = (h - c_1)q - \frac{n\delta^2}{2}$. The manufacturer's equity return in the MF model is therefore

$$\pi_t^0 = \varphi\eta \left[(h - c_1)q - \frac{n\delta^2}{2} \right].$$

Therefore, the profit functions of the technology vendor, manufacturer, and retailer are as follows:

$$\begin{aligned} \pi_{t,4} = & (h - c_1)q - \frac{n\delta^2}{2} - \phi \left\{ (1 - \mu)hq + \left(c_1q + \frac{n\delta^2}{2} - m \right) [r_0(1 + k_1\theta_1 - k_2\theta_2)] + \lambda_1 V \right\} \\ & - \varphi\eta \left((h - c_1)q - \frac{n\delta^2}{2} \right) - (1 - \phi - \varphi) \left(c_1q + \frac{n\delta^2}{2} - m \right) r_2, \end{aligned}$$

$$\begin{aligned} \pi_{m,4} = & [w - (1 - \rho\delta)c_2 - h]q + (1 - \mu)\phi hq + \varphi\eta \left((h - c_1)q - \frac{n\delta^2}{2} \right) \\ & + (1 - \phi - \varphi) \left(c_1q + \frac{n\delta^2}{2} - m \right) r_2, \end{aligned}$$

$$\pi_{r,4} = (p - w)q.$$

In Equation (21), the principal amounts L_I , L_E , and L_D do not independently enter net profit because the financing inflows and principal repayments offset each other. The profit functions retain the net financing costs and returns, including loan interest, appraisal fees, technology-fee discounts, and equity profit sharing.

Remark 1 (Boundary consistency of the MF model). The MF model nests the three benchmark financing models as boundary cases:

$$(\phi, \varphi) = (1, 0) \Rightarrow MF = IPR,$$

$$(\phi, \varphi) = (0, 0) \Rightarrow MF = IDF,$$

$$(\phi, \varphi) = (0, 1) \Rightarrow MF = IEF.$$

Therefore, the MF model is a continuous extension of the three benchmark models based on the common financing gap $F(q, \delta)$.

The optimal pricing decisions for the supply chain are derived through backward induction as follows:

Proposition 4. In the MF model, the optimal profit for the manufacturer, and optimal profit for the technology vendor are as follows:

$$\begin{aligned} \pi_{r,4}^* = & \frac{1}{\beta} \left[\frac{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta(1 + \phi r_1)}{8} \right]^2, \\ \pi_{m,4}^* = & \frac{2}{\beta} \left[\frac{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta(1 + \phi r_1)}{8} \right]^2 - mr_2(1 - \phi - \varphi) \\ & + \frac{\delta^2 n [(1 - \phi - \varphi)r_2 - \eta\varphi]}{2}, \end{aligned}$$

$$\pi_{t,4}^* = \frac{4}{\beta} \left[\frac{a + \tau\delta - c_2\beta + c_2\beta\rho\delta - c_1\beta(1 + \phi r_1)}{8} \right]^2 + mr_2(1 - \phi - \varphi) + mr_1\phi - \frac{\delta^2 n [1 + \phi r_1 + (1 - \phi - \varphi)r_2 - \eta\varphi]}{2}.$$

Proof. See Appendix D.

3.3. Model analysis

To better study the impact of product customization level and product customization cost coefficient as important components of cost on supply chain profits, as well as the effect of the proportion of IPR pledge financing in MF on the negotiation role of MF, we select the three important parameters: customization level δ , customization cost coefficient n , and the proportion of IPR in MF ϕ for proposition analysis:

Proposition 5. In the IPR model, there exists the following relationship between customization level, customization cost coefficient, the proportion of IPR in MF, and the profits of the manufacturer, retailer, and technology vendor:

- (1) When $\Omega_1 > 0$, $\pi_{m,1}^*$ and $\pi_{r,1}^*$ increase as δ increases, and when $\Omega_2 > 0$, $\pi_{t,1}^*$ increases as δ increases.
- (2) $\pi_{m,1}^*$ and $\pi_{r,1}^*$ are independent of n . $\pi_{t,1}^*$ decreases as n increases.
- (3) $\pi_{m,1}^*$, $\pi_{r,1}^*$ and $\pi_{t,1}^*$ are independent of ϕ .

Proof. See Appendix E.

From Proposition 5, it can be seen that the profits of manufacturers, retailers, and technology vendors are influenced by the level of product customization. However, only when certain conditions are met will an increase in the customization level lead to higher profits. This is because achieving a high level of customization requires significant investment costs, and this condition is also affected by the product market demand and the interest rates on loans. Since technology providers are primarily responsible for product development and technological innovation, their profits are directly related to the technical complexity and costs of customization. As a result, only the profits of technology providers are influenced by the product customization cost coefficient, and their profits decrease as the product customization cost coefficient increases. Additionally, since the proportion of IPR in MF appears only in the profit function of the MF model, the profits of the manufacturer, retailer, and technology vendor in the IPR model are independent of this proportion.

Proposition 6. In the IDF model, the following relationships exist between the level of customization, the customization cost coefficient, the proportion of IPR in MF, and the profits of manufacturer, retailer, and technology vendor:

- (1) When $\Omega_3 > 0$, $\pi_{m,2}^*$ increases as δ increases. When $\Omega_4 > 0$, $\pi_{r,2}^*$ increases as δ increases. When $\Omega_5 > 0$, $\pi_{t,2}^*$ increases as δ increases.

(2) $\pi_{r,2}^*$ is independent of n . $\pi_{m,2}^*$ increases as n increases. $\pi_{t,2}^*$ decreases as n increases.

(3) $\pi_{m,2}^*$, $\pi_{r,2}^*$ and $\pi_{t,2}^*$ are independent of ϕ .

Proof. See Appendix F.

From Proposition 6, it can be seen that the profits of all supply chain entities are influenced by the level of product customization. To increase profits through higher levels of product customization, certain conditions must be met. These conditions are closely related to market demand, costs, and internal debt interest rates. In the IDF model, since the loan amount for the technology vendor is linked to costs, part of the manufacturer's profit is also related to the technology vendor's costs. As a result, only the profits of the technology vendor and the manufacturer are affected by the product customization cost coefficient. Moreover, a higher product customization cost coefficient is detrimental to the technology vendor's profit, while it may increase interest income, thereby benefiting the manufacturer's profit. Since the proportion of IPR in MF appears only in the profit function of the MF model, the profits of the manufacturer, retailer, and technology vendors in the IDF model are unaffected by this proportion.

Proposition 7. In the IEF model, the following relationships exist between the level of customization, the customization cost coefficient, the proportion of IPR in MF, and the profits of manufacturer, retailer, and technology vendor:

(1) When $\Omega_6 > 0$, $\pi_{m,3}^*$ increases as δ increases. When $\Omega_7 > 0$, $\pi_{r,3}^*$ increases as δ

increases. When $\Omega_8 > 0$, $\pi_{t,3}^*$ increases as δ increases.

(2) $\pi_{r,3}^*$ is independent of n . $\pi_{m,3}^*$ increases as n increases. $\pi_{t,3}^*$ decreases as n increases.

(3) $\pi_{m,3}^*$, $\pi_{r,3}^*$ and $\pi_{t,3}^*$ are independent of ϕ .

Proof. See Appendix G.

From Proposition 7, it can be seen that, regarding the impact of product customization level, the IEF model, like the previous two models, requires certain conditions to be met to increase profits by enhancing the product customization level. However, the effect of the customization cost coefficient differs from the IDF model. In the latter, an increase in the product customization cost coefficient is detrimental to the technology vendor's profit but benefits the manufacturer's profit. In contrast, in the IEF model, part of the manufacturer's profit comes from the dividends paid by the technology vendor at the end of the period. Therefore, when the product customization cost coefficient increases, it implies a rise in costs, which leads to a reduction in the technology vendor's profit and a decrease in the manufacturer's profit share. Since the proportion of IPR in MF appears only in the profit function of the MF model, the profits of the manufacturer, retailer, and technology vendor in the IEF model are unaffected by this proportion.

Proposition 8. In the MF model, the following relationships exist between the level of customization, the customization cost coefficient, the proportion of IPR in MF, and the profits of the manufacturer, retailer, and technology vendor:

- (1) When $\Omega_9 > 0$, $\pi_{m,4}^*$ increases as δ increases. When $\Omega_{10} > 0$, $\pi_{r,4}^*$ increases as δ increases. When $\Omega_{11} > 0$, $\pi_{t,4}^*$ increases as δ increases.
- (2) $\pi_{r,4}^*$ is independent of n . When $\Omega_{12} > 0$, $\pi_{m,4}^*$ increases as n increases. $\pi_{t,4}^*$ decreases as n increases.
- (3) When $\Omega_{13} > 0$, $\pi_{m,4}^*$ increases as ϕ increases. When $\Omega_{14} > 0$, $\pi_{r,4}^*$ increases as ϕ increases. When $\Omega_{15} > 0$, $\pi_{t,4}^*$ increases as ϕ increases.

Proof. See Appendix H.

From Proposition 8, it can be observed that in the MF model, the level of product customization will bring only higher profits to all parties in the supply chain when certain conditions are met. Unlike the previous three models, these conditions are more complex, involving the proportions of the first three models within the hybrid financing framework. Regarding the impact of the product customization cost coefficient, only the profits of the technology vendor and the manufacturer are affected. An increase in the customization cost coefficient implies higher costs, which negatively impacts the technology vendor's profit. However, for the manufacturer, who is the capital provider, it is beneficial. As for the influence of the proportion of IPR in MF, higher profits for all supply chain parties can be achieved only when certain complex conditions are met. This condition is related to the loan interest rate and equity ratio in the first three financing models, as well as the amount of own funds held by the technology vendor.

4. Numerical analysis

In the four financing models, IPR, IDF, IEF, and MF, the focus is on analyzing the impact of product customization level, product customization cost coefficient, and the proportion of IPR in MF on the profits of the three parties in the supply chain. Since the profit function of the retailer remains unchanged across all four financing models, the sensitivity analysis and decision domain analysis concentrate on the profits of the technology vendor and the manufacturer. To investigate the impact of key parameters such as product customization level, product customization cost coefficient, and the proportion of IPR in MF, we assign values to the following basic parameters based on the literature:

$a = 150$, $c_1 = 9$, $c_2 = 10$, $\tau = 12$, $\beta = 1$, $\rho = 0.3$, $r_0 = 0.1$, $k_1 = 0.1$, $k_2 = 0.2$, $\theta_1 = 0.5$, $\theta_2 = 0.6$,
 $\lambda_1 = 0.12$, $V = 100$, $\eta = 0.015$, $r_2 = 0.035$, $m = 300$. When examining the product customization level, it is assumed that $n = 700$ to eliminate the impact of the product customization cost coefficient. When analyzing the customization cost coefficient, it is assumed that $\delta = 1$ to eliminate the influence of the product customization level. Similarly, when the proportion of IPR in hybrid financing is considered as an influencing factor, it is assumed that $\delta = 1$ and $n = 700$.

4.1. The impact of product customization-related parameters on supply chain profit

In this section, we analyze the impact of product customization level, product customization cost coefficient, and the proportion of IPR in MF on the profits of the technology vendor and the manufacturer in the IPR, IDF, and IEF financing models. In cases where a conflict arises between the financing choices of the technology vendor and the manufacturer, MF is selected for further analysis.

4.1.1. The impact of product customization level on the profits of technology vendors and manufactures in each financing model

As a significant cost factor, the product customization level also affects the profits of the technology vendor and the manufacturer. Therefore, in this section, we analyze the impact of product customization level. To study its effect on the profits of both parties, we use the optimal solutions derived from the model and the reasonable range of product customization levels referenced from relevant literature. By combining these with the basic parameter settings, we obtain Figure 4:

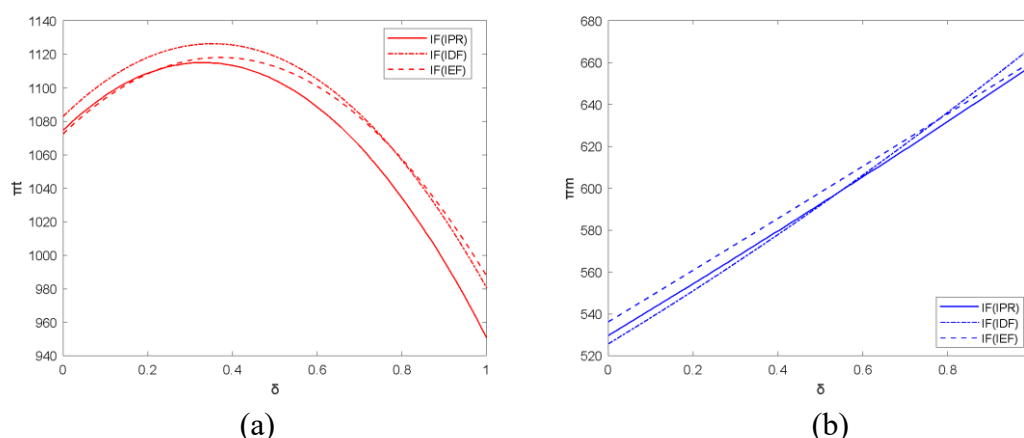


Figure 4. The impact of product customization level on the profits of technology vendors and manufacturers under three financing models. (a) About the technology vendor; and (b) about the manufacturer.

As shown in Figure 4, the profits of technology vendors and manufacturers are affected by the level of product customization, regardless of the financing model. For technology vendors, their profits initially increase with higher customization levels due to market demand and differentiated competition. However, after a certain point, the profits begin to decline as costs rise, competition intensifies, and the market becomes saturated. For manufacturers, as the level of customization increases, they can continue to boost profits by meeting personalized demands, establishing a competitive advantage through differentiation, reducing costs, and responding quickly to market changes. Therefore, as product customization levels rise, the profits of manufacturers also increase. Additionally, Figure 4 validates the parts of Propositions 5 to 8 regarding the impact of product customization level on the profits of technology providers and manufacturers.

When choosing among the three financing models, if the level of customization is relatively low, namely $0 < \delta \leq 0.77$, the profit for the technology vendor is optimal under the IDF model, while the profit for the manufacturer is optimal under the IEF model. This is because a lower level of customization implies lower costs. For the technology vendor, borrowing is reduced, leading to lower

interest expenses, which benefits their profit. Additionally, lower costs result in higher profits for the technology vendor, which in turn enables higher dividends to the manufacturer, thus benefiting the manufacturer's profit. Conversely, when the level of customization is relatively high, namely $0.77 < \delta \leq 1$, the profit for the technology vendor is optimal under the IEF model, while the profit for the manufacturer is optimal under the IDF model. This is because, when costs are higher, the dividends paid by the technology vendor to the manufacturer decrease, which favors the technology vendor's profit. Furthermore, a higher level of customization means higher costs. For the technology vendor, insufficient capital leads to increased borrowing, which raises the interest expenses paid to the manufacturer, benefiting the manufacturer's profit.

To address the conflict regarding the financing model choices for the technology vendor and manufacturer under different thresholds of customization levels, we employ a hybrid financing model. In this model, the profit functions of both the technology vendor and the manufacturer are fixed between IEF and IDF models. Both parties make appropriate concessions to reach a consensus. Specifically, as shown in Figure 4, in panel (a), when $0 < \delta \leq 0.22$, the technology vendor's profit function in the IPR model lies between the IDF and IEF. In panel (b), when $0 < \delta \leq 0.53$, the technology vendor's profit function in the IPR model also lies between the IEF and IDF. This illustrates that the IPR model can be a choice where the technology vendor and the manufacturer make concessions. Therefore, in the subsequent figures, we analyze and compare the profit functions of the IPR and MF models, both of which lie between the IDF and IEF, using the case where $\delta = 0.2$ to help the technology vendor and manufacturer make better financing model choices.

Since the proportions of IPR (represented by ϕ) and IEF (represented by φ) in the MF model are variables that need to be explored, we can derive the relationship between ϕ and φ when the MF is fixed between IDF and IEF. Additionally, since δ is an important variable in this section, to establish the relationship between ϕ and φ , we consider $\delta = 0.22$ and $\delta = 0.77$, where the IPR and IEF, as well as IDF and IEF, intersect. Therefore, we examine the points near the two intersections by setting $\delta = 0.2$, $\delta = 0.7$, and $\delta = 0.8$, and substituting these values into the profit functions of the technology vendor and manufacturer in the MF model. From this, we obtain the following: For the technology vendor, when $\delta = 0.2$, the solution gives the range $\varphi \in (\varphi_1, \varphi_2)$; when $\delta = 0.7$, the solution gives the range $\varphi \in (\varphi_3, \varphi_4)$; and when $\delta = 0.8$, the solution gives the range $\varphi \in (\varphi_5, \varphi_6)$. For the manufacturer, when $\delta = 0.2$, the solution gives the range $\varphi \in (\varphi_8, \varphi_7)$; when $\delta = 0.7$, the solution gives the range $\varphi \in (\varphi_9, \varphi_{10})$; and when $\delta = 0.8$, the solution gives the range $\varphi \in (\varphi_{12}, \varphi_{11})$. Detailed information can be found in Appendix I.

The twelve critical values are tested under the conditions $0 \leq \phi \leq 1$ and $0 \leq \varphi \leq 1$. Among them, six critical values satisfy these condition ranges, and they are displayed graphically. This leads to Figure 5:

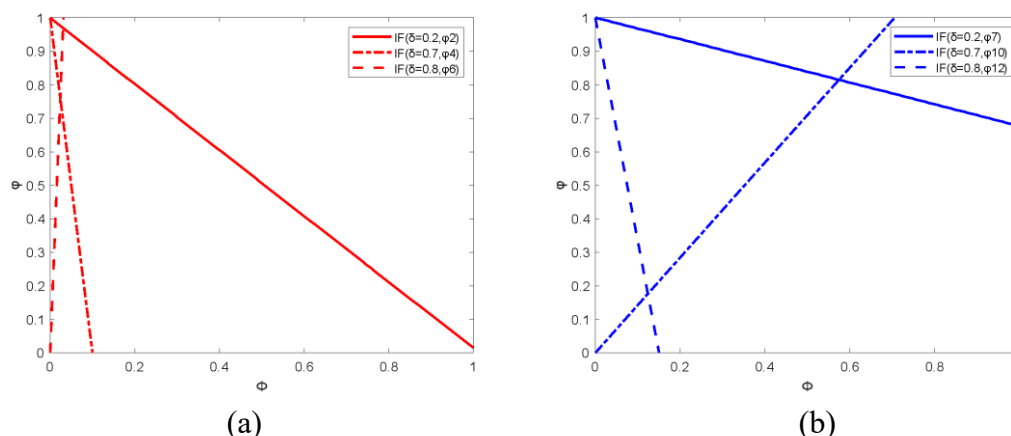


Figure 5. Relationship between ϕ and φ for the critical values that satisfy the conditions.

(a) About the technology vendor; and (b) about the manufacturer.

As shown in Figure 5, ϕ represents the proportion of IPR in the MF model, and φ represents the proportion of IEF. When the level of product customization is low, i.e., when $\delta = 0.2$, the two proportions exhibit an inverse relationship, meaning that as one proportion increases, the other must decrease. Specifically, for the technology vendor, IPR and IEF have a higher probability of being the dominant proportion. However, for the manufacturer, under the condition that the sum of the two proportions cannot exceed 1, IEF is more likely to dominate. This is because, for the technology vendor, their core value typically lies in technology and intellectual property. As a result, IPR and IEF are more likely, with the specific proportions depending on their technological accumulation and funding needs. In contrast, for manufacturers, whose core competitiveness generally lies in production capacity rather than intellectual property, tend to rely more on shareholder investments to support the expansion of production scale and market development when the level of customization is low.

When the level of product customization is high, i.e., when $\delta = 0.7$ and $\delta = 0.8$, the two proportions show opposite trends for both manufacturers and technology vendors. Although there are cases where IEF and IPR proportions either increase together or shift inversely, the proportion of IPR remains consistently small. This suggests that the proportion of intellectual property pledge financing should not be too high in hybrid financing. This is because high-customization products typically require more flexible financing solutions, and technology providers and manufacturers tend to rely more on equity and debt financing. The value of intellectual property as collateral may be difficult to fully leverage in such scenarios. Additionally, the longer research and development cycles and the complexity of the technologies involved in high-customization products lead to lower reliance on intellectual property pledge financing by technology vendors and manufacturers, thus affecting its proportion in the hybrid financing structure.

After testing and analyzing the critical values obtained, we substitute the appropriate solution into the profit functions of the technology vendor and the manufacturer in the MF model. After substitution, the only remaining unknown parameter to be discussed is the proportion of IPR, denoted as ϕ . This leads to the results shown in Figure 6:

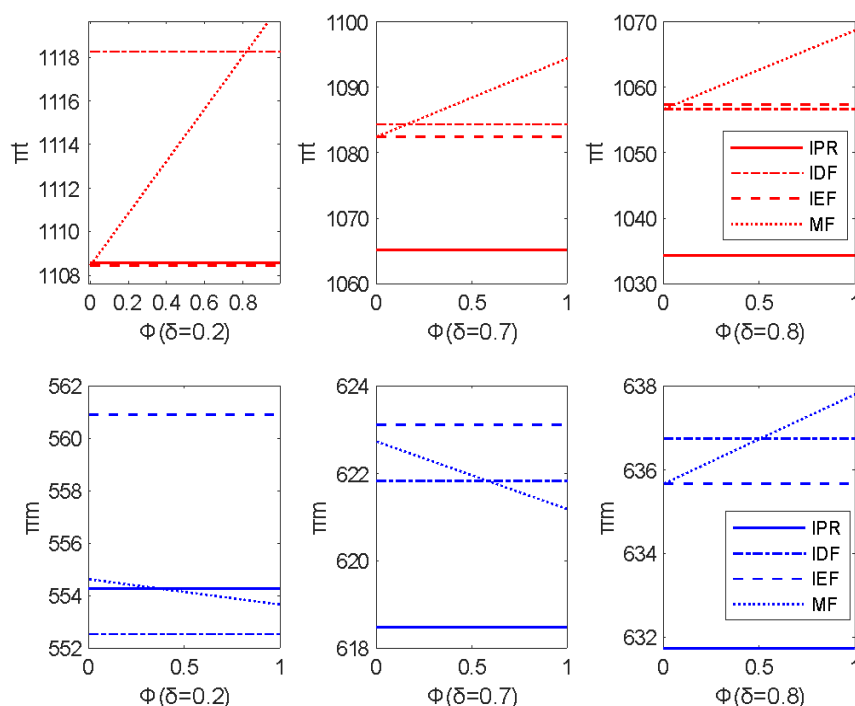


Figure 6. The impact of the proportion of IPR in hybrid financing on the profits of technology vendors and manufacturers under four financing models.

As shown in Figure 6, for the three levels of product customization, there always exists a proportion ϕ of IPR in MF that places the profit function of MF between those of IEF and IDF. To align the interests of both parties, the intersection of these proportions is considered. Overall, the proportion of IPR pledge financing in MF should remain relatively small. This can be explained by referencing Figure 4, where the profit functions in the three models change as product customization increases. In the IPR model, the profit function is consistently not the optimal choice, and at higher levels of product customization, its impact on profit growth is less significant compared to the other two financing models. Therefore, the proportion of IPR in MF should be kept as small as possible. However, this proportion should not be minimized indiscriminately. For instance, when the product customization level is low (with a value of 0.2), for the technology vendor, if the proportion of IPR in MF is below 0.01, the IPR model is more beneficial than the MF model. This is because when the proportion of IPR in MF is too low, its potential to enhance profits is not fully realized.

In addition, our study on the impact of the proportion of IPR on profits reveals that for technology vendors, an increase in the proportion of IPR under the three levels of product customization will promote their profit growth. This effect is particularly advantageous at lower levels of product customization. However, for manufacturers, an increase in the proportion of IPR will only enhance profits when the product customization level is high. This is because, at lower levels of product customization, technology vendors can gain more market benefits through IPR pledge financing, while at higher levels of product customization, manufacturers are better able to leverage the value of intellectual property to boost their profits.

4.1.2. The impact of the product customization cost coefficient on the profits of technology vendors and manufactures in each financing model

After analyzing the sensitivity of product customization levels, we found that the product customization cost coefficient is also an important variable affecting costs. Therefore, in this section, we focus on analyzing the impact of the product customization cost coefficient. To study its effect on the profits of technology vendors and manufacturers, we referenced relevant literature to determine the range of the product customization cost coefficient. This leads to the results shown in Figure 7:

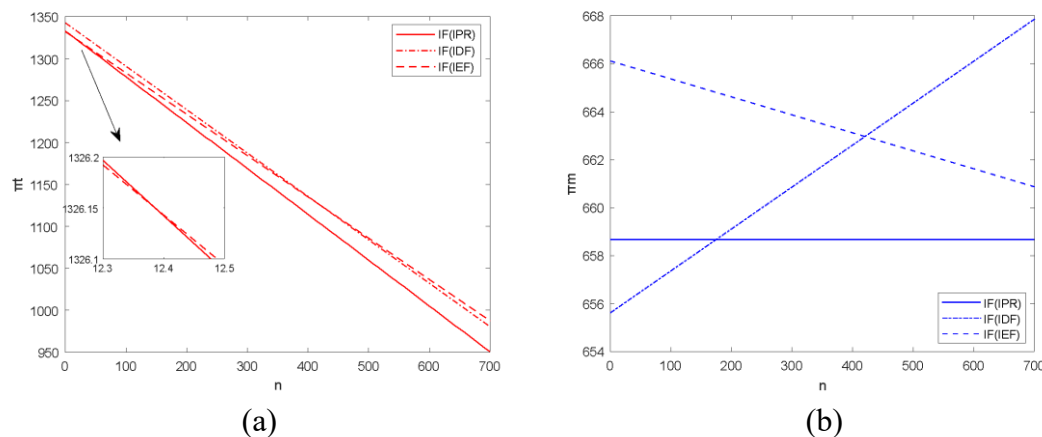


Figure 7. The impact of the product customization cost coefficient on the profits of technology vendors and manufactures under three financing models. (a) About the technology vendor; and (b) about the manufacturer.

As shown in Figure 7, the product customization cost coefficient has no impact on the manufacturer's profit under the IPR model. This is because, under the IPR model, the manufacturer's profit is primarily influenced by the technical fee discount and is not affected by the product customization cost. For technology vendors, regardless of the financing model, an increase in the product customization cost coefficient means higher production and R&D costs, which leads to a decrease in their profits. However, for manufacturers, an increase in the customization cost coefficient will result in higher profits under the IDF financing model, while it will lead to lower profits under the IEF financing model. This is because, in the internal debt financing model, the manufacturer's interest income remains relatively fixed and clear, but under the IEF model, an increase in customization costs reduces the technology vendor's profits, which in turn reduces the dividends paid to the manufacturer, thereby lowering the manufacturer's profit level. Additionally, Figure 7 validates the findings in Propositions 5 through 8 regarding the impact of the product customization cost coefficient on the profits of technology providers and manufacturers.

When selecting among the three financing models, if the customization cost coefficient is relatively low (i.e., $0 < n \leq 420$), the technology vendor's profit is maximized under the IDF model, while the manufacturer's profit is maximized under the IEF model. This is because lower costs reduce borrowing for the technology vendor, which in turn decreases interest expenses, benefiting the technology vendor's profit under the IDF model. Additionally, lower costs lead to more stable profits for the technology vendor and larger dividends for the manufacturer, thus benefiting the manufacturer's profit under the IEF model. However, when the customization cost coefficient is relatively high (i.e., $420 < n \leq 700$), the technology vendor's profit is maximized under the IEF model,

while the manufacturer's profit is maximized under the IDF model. This is because as customization costs rise, the technology vendor's profit decreases, and the dividends paid to the manufacturer also decrease. The relatively lower expenses benefit the technology vendor's profit. Furthermore, increased costs lead to higher borrowing by the technology vendor, which raises the manufacturer's interest expenses, thus benefiting the manufacturer's profit under the IDF model.

To resolve the conflict in financing model selection between the technology vendor and manufacturer under different thresholds of the customization cost coefficient, we still employ a hybrid financing model. In this model, the profit functions for the technology vendor and the manufacturer are fixed between the IEF and IDF models. Both parties make appropriate concessions to reach an agreement. Specifically, as shown in Figure 7, in panel (a), when $0 < n \leq 12.38$, the technology vendor's profit function under the IPR lies between the IDF and IEF models. In panel (b), when $0 < n \leq 177$, the technology vendor's profit function under the IPR model also lies between the IEF and IDF models. This suggests that the IPR model could be a viable compromise, with the technology vendor and manufacturer making concessions. Therefore, in subsequent graphs, we focus on the case where $n = 12$ to analyze and compare the profit functions of IPR and the MF model, both of which lie between the IDF and IEF models. This will help the technology vendor and manufacturer make a more informed financing model choice.

Since the proportions of IPR (represented by ϕ) and IEF (represented by φ) in the MF are variables that need to be explored, we can derive the relationship between ϕ and φ when the MF is fixed between IDF and IEF. Additionally, since n is an important variable in this section, to establish the relationship between ϕ and φ , we consider $n = 12.38$ and $n = 420$, where the IPR and IEF, as well as IDF and IEF, intersect. Therefore, we examine the points near the two intersections by setting $n = 12$, $n = 419$, and $n = 421$, and substituting these values into the profit functions of the technology vendor and manufacturer in the MF model. From this, we obtain the following: For the technology vendor, when $n = 12$, the solution gives the range $\varphi \in (\varphi_{13}, \varphi_{14})$; when $n = 419$, the solution gives the range $\varphi \in (\varphi_{15}, \varphi_{16})$; and when $n = 421$, the solution gives the range $\varphi \in (\varphi_{17}, \varphi_{18})$. For the manufacturer, when $n = 12$, the solution gives the range $\varphi \in (\varphi_{19}, \varphi_{20})$; when $n = 419$, the solution gives the range $\varphi \in (\varphi_{21}, \varphi_{22})$; and when $n = 421$, the solution gives the range $\varphi \in (\varphi_{23}, \varphi_{24})$. Detailed information can be found in Appendix J.

The twelve critical values are tested under the conditions $0 \leq \phi \leq 1$ and $0 \leq \varphi \leq 1$. Among them, six critical values satisfy these condition ranges, and they are displayed graphically. This leads to Figure 8:

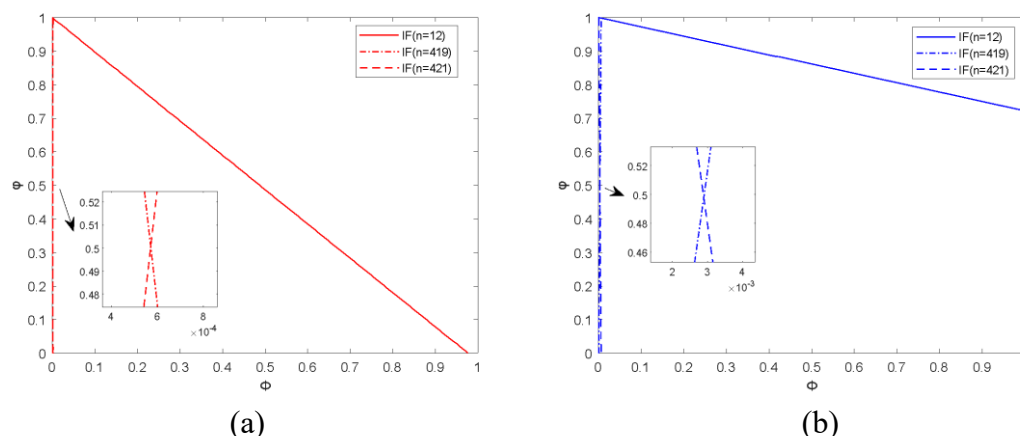


Figure 8. Relationship between ϕ and φ for the critical values that satisfy the conditions.

(a) For the technology vendor; and (b) for the manufacturer.

As shown in Figure 8, ϕ represents the proportion of IPR in MF, while φ represents the proportion of IEF in the mixed financing structure. When the product customization cost coefficient is relatively low, i.e., $n = 12$, both proportions show an inverse relationship. However, the situation differs for each party. For the technology vendor, there is a higher likelihood of a larger proportion for IPR, while for the manufacturer, the proportion of IPR is more likely to be smaller. This is because the core competitiveness of technology vendors often lies in their technology and intellectual property, making them more likely to secure funding through IPR pledges and internal equity financing. The specific financing proportions depend on the depth of their technological accumulation and the size of their funding needs. On the other hand, manufacturers' competitive advantage mainly comes from their production capacity rather than intellectual property. As a result, they rely more heavily on internal equity financing to support the expansion of their production capabilities and market reach.

When the product customization cost coefficient is high, specifically when $n = 419$ and $n = 421$, the two proportions show opposite trends for manufacturers and technology vendors. Although IEF and IPR proportions may either grow together or fluctuate in a complementary manner, the proportion of IPR remains consistently small. This indicates that the share of IPR in MF should not be too high. This finding is consistent with the results observed when studying the impact of product customization levels. The reason lies in the fact that high-cost-customization products typically require flexible and diverse financing solutions. The limited flexibility, valuation challenges, and lower risk coverage associated with IPR pledge financing result in its relatively small share in hybrid financing.

After testing and analyzing the critical values obtained from the solution, we will substitute the appropriate solution into the profit functions of the technology vendor and manufacturer in the MF model. After substitution, only the proportion of IPR, represented by the unknown parameter ϕ , remains to be discussed. This leads to the following figure, Figure 9:

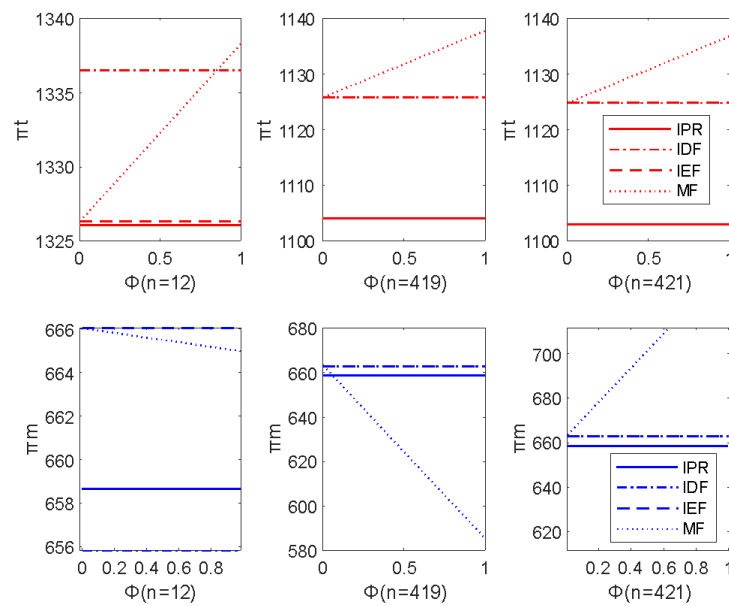


Figure 9. The impact of the IPR hybrid financing ratio on the profits of technology vendors and manufacturers under four financing models.

As shown in Figure 9, under the influence of three product customization levels, there always exists a proportion ϕ of IPR in MF that places the profit function of hybrid financing between IEF and IDF. Particularly when the customization cost coefficient is extremely low, regardless of the value of ϕ , the profit function of hybrid financing is always positioned between internal equity and internal debt financing for the manufacturer. To balance the interests of both parties, the proportion that satisfies this condition should be taken as the intersection. Overall, the proportion of IPR in MF should be relatively small. Analyzing Figure 7 explains this. In Figure 7, regardless of the customization cost coefficient, IPR is not the optimal financing choice. Moreover, as the customization cost coefficient increases, the gap between IPR and the other two financing methods widens. Therefore, when the customization cost coefficient is high, the proportion of IPR in MF should be minimized to ensure that the profit function of hybrid financing remains between internal debt and internal equity financing.

Specifically, when the customization cost coefficient is extremely small, such as a value of 12, for technology vendors, when the proportion of IPR in MF is less than 0.02, the IPR financing model outperforms the MF financing model. For manufacturers, when this proportion is less than 0.6, the IPR financing model also outperforms the MF financing model. Therefore, when both the customization cost coefficient and the proportion of IPR in hybrid financing are low, the technology vendor and the manufacturer can choose IPR as a mutually beneficial compromise. After analyzing the effects of different customization cost coefficients and the proportion of IPR in MF, it is found that when the customization cost coefficient is relatively high and the proportion of IPR in MF is low, hybrid financing can be used for negotiation. When the customization cost is also low, IPR pledge financing can be considered for negotiation.

4.2. Optimal financing model selection for 3D printing product supply chain

In this section, we first combine the product customization level with the proportion of IPR in MF to analyze their impact on the financing decisions of technology vendors and manufacturers. Then, we combine the product customization cost coefficient with the proportion of IPR in MF to examine how these factors affect financing decisions. Our goal is to understand how technology vendors and manufacturers make optimal financing decisions under varying levels of product customization, product customization cost coefficients, and the proportion of IPR in MF. Since, in the sensitivity analysis, we use three fixed values for product customization level and product customization cost coefficient to analyze the impact of the proportion of IPR in hybrid financing on profits, the decision domain section is also divided into three parts for analysis.

4.2.1. The impact of the product customization level and the proportion of IPR in MF on the decision domain of technology vendors and manufactures

After analyzing the individual impacts of product customization level and the proportion of IPR in MF on the profits of technology vendors and manufacturers in the sensitivity analysis section, we combine their effects to examine how they influence the financing decisions of technology vendors and manufacturers under the four models. This leads to Figure 10 and Figure 11:

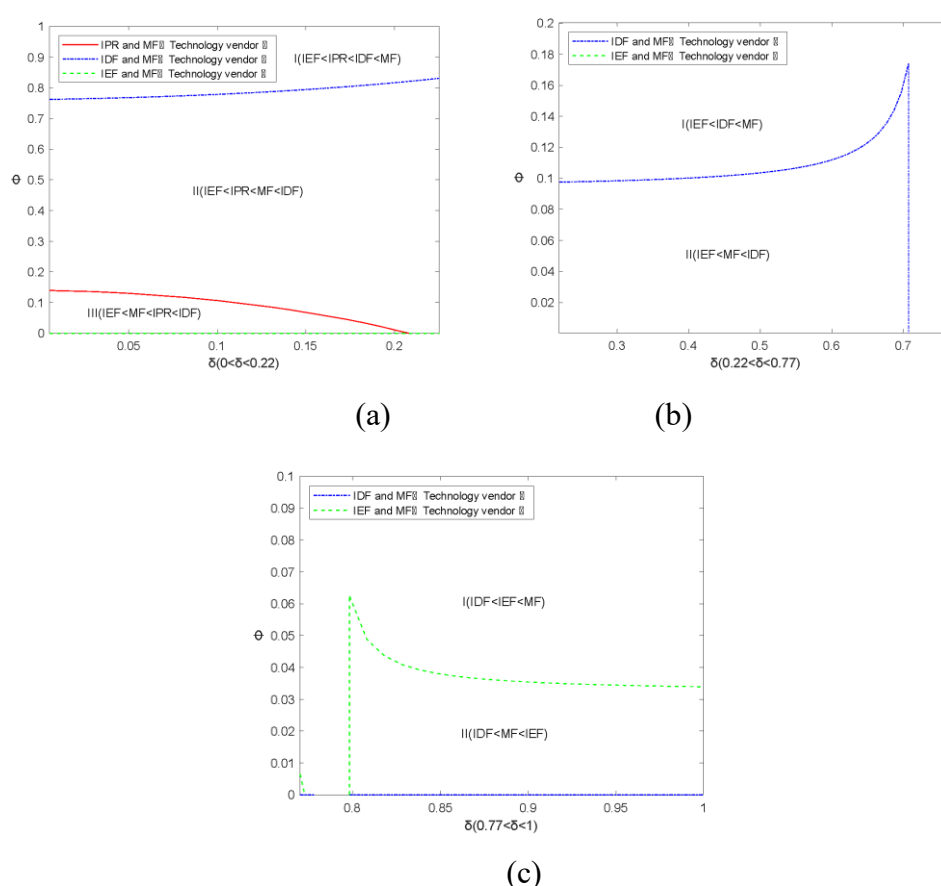


Figure 10. Decision domain of technology vendors under the combined influence of product customization level and the proportion of IPR in hybrid financing. (a) When $0 < \delta \leq 0.22$; (b) when $0.22 < \delta \leq 0.77$; and (c) when $0.77 < \delta \leq 1$.

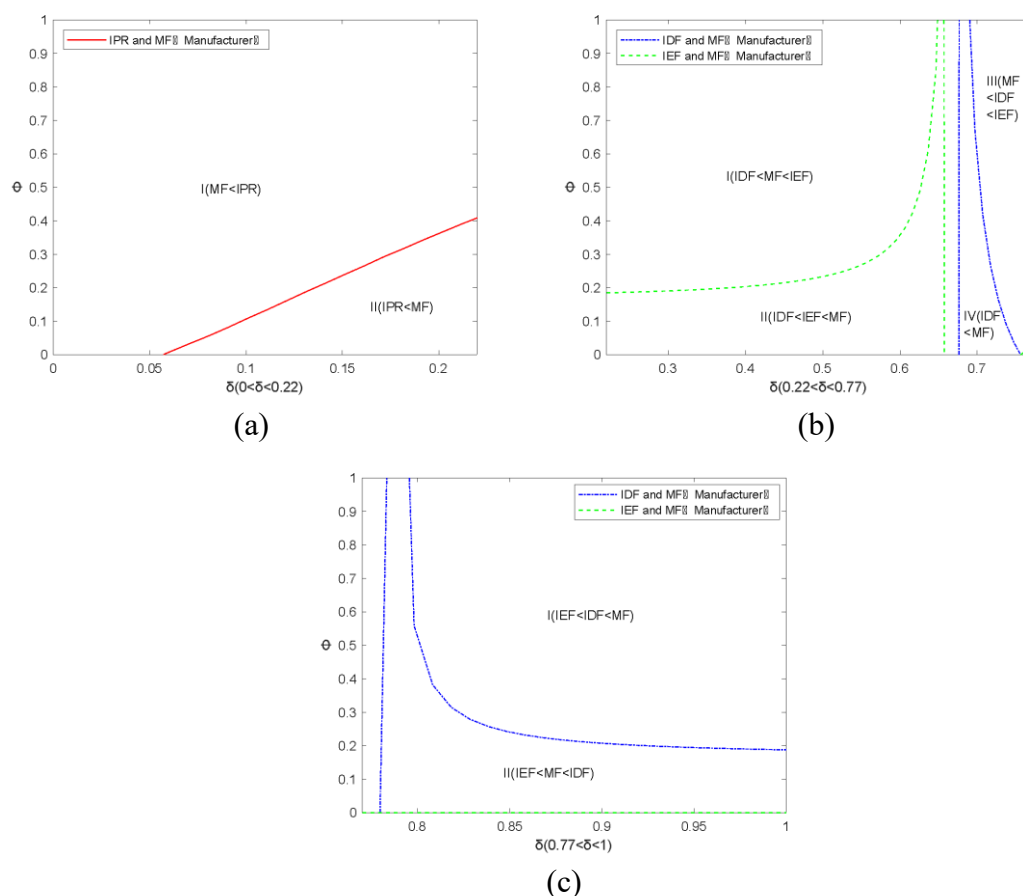


Figure 11. Manufacturer's decision domain under the joint influence of product customization level and the proportion of IPR in hybrid financing. (a) When $0 < \delta \leq 0.22$; (b) when $0.22 < \delta \leq 0.77$; and (c) when $0.77 < \delta \leq 1$.

As shown in Figure 10, in panel (a), when the product customization level is relatively low (i.e., $0 < \delta \leq 0.22$), the technology vendor can compare IPR pledge financing and hybrid financing to make better decisions in negotiations with the manufacturer. In Region I, hybrid financing is not positioned between internal debt financing and internal equity financing, making this region ineffective. In Region II, hybrid financing is preferable to IPR pledge financing. This region is characterized by a moderate proportion of IPR pledge financing in hybrid financing, which is neither too high nor too low. As the product customization level increases, this region expands. In Region III, IPR pledge financing is superior to hybrid financing. The defining feature of this region is that the proportion of IP pledge financing in hybrid financing is relatively low, and as the product customization level increases, this region shrinks.

As shown in Figure 10 (b), when the product customization level is moderate (i.e., $0.22 < \delta \leq 0.77$), the effectiveness of IPR pledge financing is influenced by the impact of product customization on costs. Compared to internal equity financing and internal debt financing, IPR pledge financing becomes less effective, and thus, it is not considered within this range. In Region I, hybrid financing is not positioned between internal debt financing and internal equity financing, making this region ineffective. In Region II, the internal debt financing model is the most optimal. Hybrid financing lies between internal debt financing and internal equity financing in this region, characterized by a lower proportion of IPR pledge financing in hybrid financing. As the product customization level increases, this region expands.

As shown in Figure 10 (c), when the product customization level is high (i.e., $0.77 < \delta \leq 1$), the situation contrasts with that of moderate customization. In this case, internal equity financing becomes the most optimal model, followed by hybrid financing. In Region I, since hybrid financing is not positioned between internal debt financing and internal equity financing, this region is ineffective. In Region II, hybrid financing lies between internal debt financing and internal equity financing. This region is characterized by a lower proportion of IPR pledge financing in hybrid financing, and as the product customization level increases, this region shrinks.

As shown in Figure 11 (a), when the level of product customization is relatively low (i.e., $0 < \delta \leq 0.22$), it is beneficial to compare IPR pledge financing and hybrid financing to facilitate negotiations with manufacturers. This enables technology vendors to make better decisions. In this scenario, regardless of the product customization level or the proportion of IPR pledge financing in hybrid financing, hybrid financing always lies between internal equity financing and internal debt financing, meaning there are no ineffective regions in this graph. In Region I, IPR pledge financing is preferred over hybrid financing, and this region is characterized by a higher proportion of IPR pledge financing in hybrid financing. In Region II, hybrid financing is superior to IPR pledge financing, and this region is defined by a lower proportion of IPR pledge financing in hybrid financing.

In Figure 11 (b), when the level of product customization is moderate (i.e., $0.22 < \delta \leq 0.77$), in Region I, hybrid financing lies between internal equity financing and internal debt financing. In this case, hybrid financing can be seen as a result of both manufacturers and technology vendors making concessions. This region is characterized by a proportion of IPR pledge financing in hybrid financing that will not be particularly low. In Region II, hybrid financing does not fall between internal equity financing and internal debt financing, making it an ineffective region. Similarly, Region III is also an ineffective region. In Region IV, hybrid financing again lies between internal equity financing and internal debt financing. This region is characterized by the potential for varying proportions of IPR pledge financing in hybrid financing, and as the level of product customization increases, this region expands.

In Figure 11 (c), when the level of product customization is high (i.e., $0.77 < \delta \leq 1$), in contrast to the previous two cases, internal equity financing becomes superior to internal debt financing. In Region I, hybrid financing does not fall between internal equity financing and internal debt financing, making it an ineffective region. In Region II, hybrid financing lies between internal equity financing and internal debt financing. This region is characterized by the potential for varying proportions of IPR pledge financing in hybrid financing, and as the level of product customization increases, this region shrinks.

4.2.2. The impact of the product customization cost coefficient and the proportion of IPR in MF on the technology vendor's decision domain

After analyzing the individual impacts of the product customization cost coefficient and the proportion of IPR in hybrid financing on the profits of technology providers and manufacturers in the sensitivity analysis section, we then combine their effects to examine how they influence the financing decisions of technology vendors and manufacturers under the four modes. This analysis leads to Figure 12 and Figure 13:

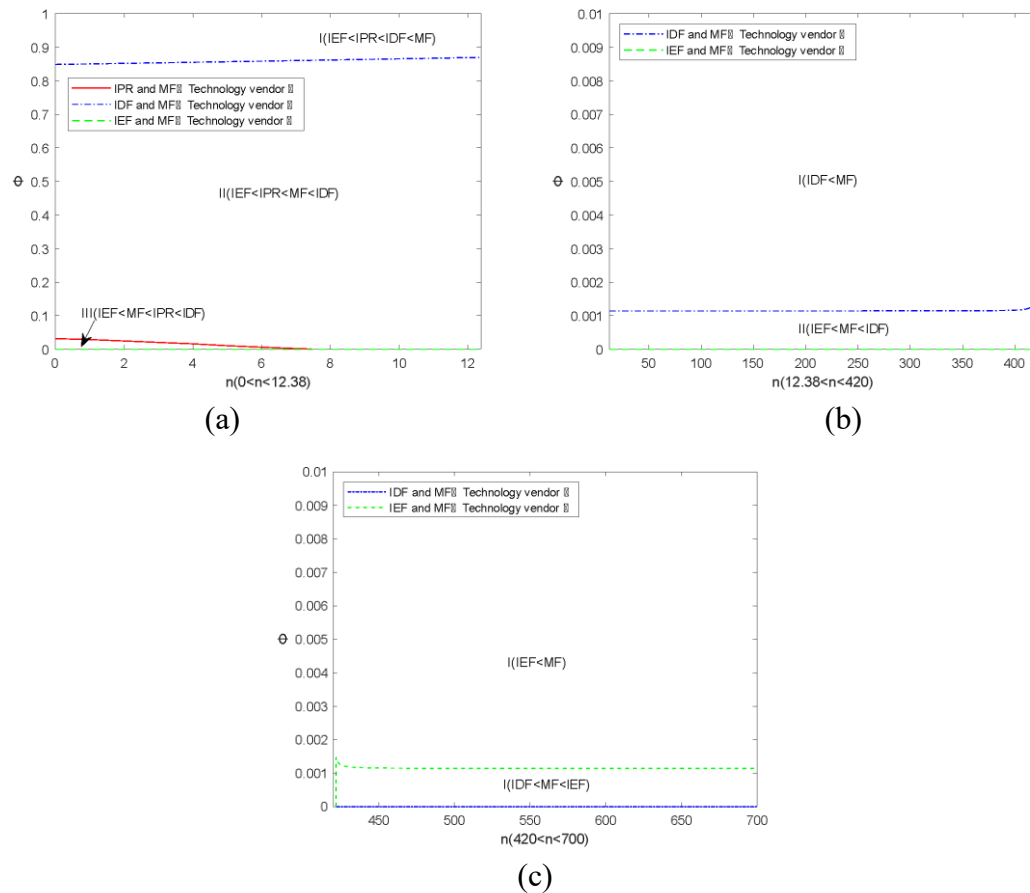


Figure 12. The decision domain of technology vendors under the combined influence of product customization cost coefficient and the proportion of IPR in hybrid financing. (a) When $0 < n \leq 12.38$; (b) when $12.38 < n \leq 420$; and (c) when $420 < n \leq 700$.

As shown in Figure 12, in panel (a), when the product customization cost coefficient is low, i.e., $0 < n \leq 12.38$, IPR pledge financing can emerge as a viable option alongside hybrid financing, offering a compromise choice for technology vendors and manufacturers. In Region I, hybrid financing is not positioned between internal equity financing and internal debt financing, making it an invalid area. In Region II, hybrid financing is preferred over IPR pledge financing. This region is characterized by a balanced proportion of IPR pledge financing within the hybrid financing, neither too low nor too high. As the product customization cost coefficient increases, this region expands. In Region III, IPR pledge financing is favored over hybrid financing. This region is characterized by a very low proportion of IPR pledge financing within the hybrid financing, and as the product customization cost coefficient increases, this region shrinks.

As shown in Figure 12 (b), when the product customization cost coefficient is moderate, i.e., $12.38 < n \leq 420$, IPR pledge financing is not considered within this range. In Region I, hybrid financing does not lie between internal equity financing and internal debt financing, making it an invalid area. In Region II, hybrid financing falls between internal equity financing and internal debt financing. This region is characterized by a very low proportion of IPR pledge financing within the hybrid financing, and as the product customization cost coefficient increases, this region expands.

As shown in panel (c), when the product customization cost coefficient is high, i.e., $420 < n \leq 700$, the situation reverses compared to the previous two cases, with internal equity financing outperforming

internal debt financing to become the optimal choice. In Region I, hybrid financing does not lie between internal equity financing and internal debt financing, making it an invalid area. In Region II, hybrid financing falls between internal equity financing and internal debt financing. This region is characterized by a very low proportion of IPR pledge financing within the hybrid financing, and as the product customization cost coefficient increases, this region shrinks.

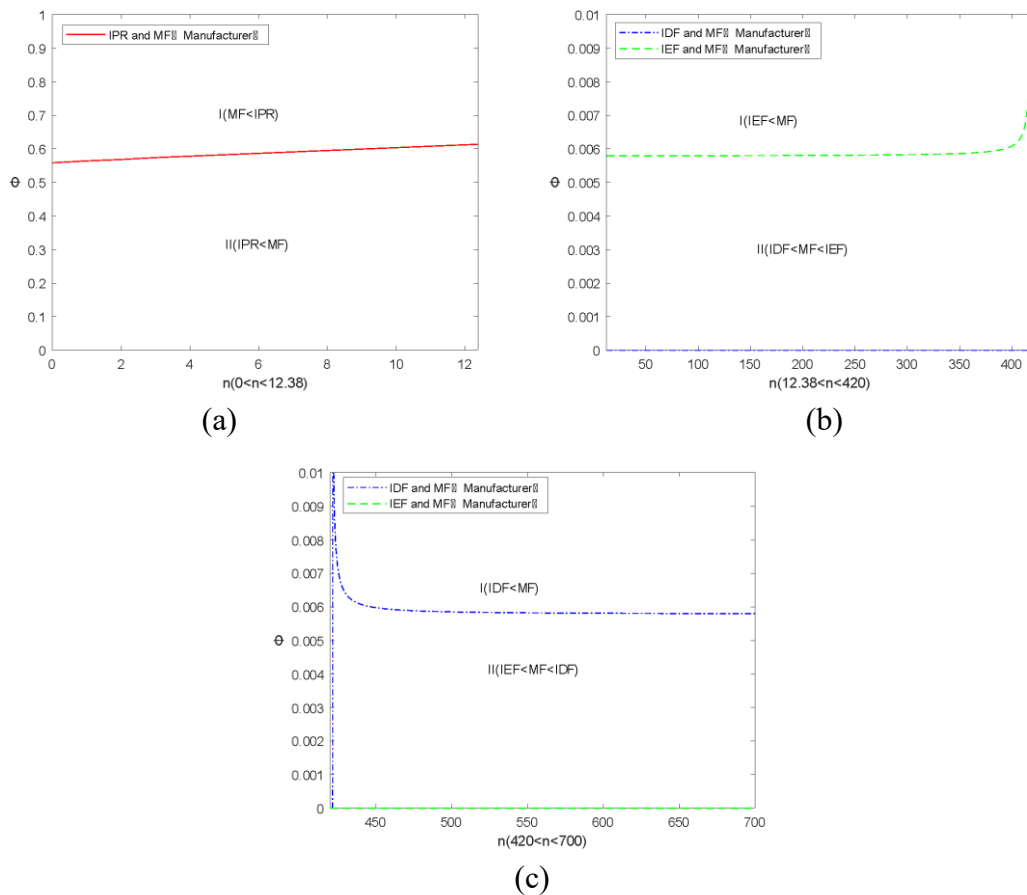


Figure 13. Manufacturer's decision domain under the joint influence of product customization cost coefficient and the proportion of IPR in hybrid financing. (a) When $0 < n \leq 12.38$; (b) when $12.38 < n \leq 420$; and (c) when $420 < n \leq 700$.

From Figure 13, it can be observed that in panel (a), when the product customization cost coefficient is relatively low (i.e., $0 < n \leq 12.38$), IPR pledge financing emerges as a viable option alongside hybrid financing, enabling the technology provider and manufacturer to make concessions. In this scenario, regardless of the values of product customization level and the proportion of IPR pledge financing in hybrid financing, hybrid financing always lies between internal equity financing and internal debt financing, so no invalid region exists in this chart. In Region I, IPR pledge financing outperforms hybrid financing. This region is characterized by a higher proportion of IP pledge financing within hybrid financing, and it shrinks as the product customization level increases. In Region II, hybrid financing is superior to IPR pledge financing. This region is characterized by a lower proportion of IPR pledge financing in hybrid financing, and it expands as the product customization level increases.

In Figure 13 (b), when the product customization cost coefficient is moderate (i.e., $12.38 < n \leq 420$), IPR pledge financing is not considered within this range. In Region I, hybrid financing does not lie

between internal equity financing and internal debt financing, making this an invalid region. In Region II, hybrid financing is positioned between internal equity financing and internal debt financing. This region is characterized by a low proportion of IPR pledge financing within hybrid financing, and it expands as the product customization cost coefficient increases.

In Figure 13 (c), when the product customization cost coefficient is high, the situation is reversed compared to the previous two cases, with internal equity financing becoming the preferred choice over internal debt financing. In Region I, hybrid financing does not lie between internal equity financing and internal debt financing, making this an invalid region. In Region II, hybrid financing falls between internal equity financing and internal debt financing. This region is characterized by a low proportion of IPR pledge financing within hybrid financing, and it shrinks as the product customization cost coefficient increases.

5. Extension study

5.1. Motivation and parameter sources

The benchmark model adopts the deterministic linear demand function:

$$q = a - \beta p + \tau \delta,$$

This specification preserves analytical tractability and isolates the effects of customization and financing structure. Actual demand for 3D-printed products is nevertheless affected by order fluctuations, changing application scenarios, technological substitution, and macroeconomic conditions. Moreover, the numerical switching values reported in the benchmark analysis, including $\delta = 0.77$, $n = 420$, $n = 12.38$, and the IPR-share values of 0.1, 0.2, and 0.5, are generated by a particular parameter configuration. They are not parameter-free theoretical constants.

We therefore extend the analysis in two directions. First, a stochastic demand shock is introduced. Second, one-at-a-time and global Monte Carlo sensitivity analyses are conducted for $a, n, V, m, \eta, \beta, c_1, c_2$. For the analysis, we evaluate the distributions of the customization-cost threshold, and feasible upper bound of the IPR share.

The cited literature supports the functional forms of demand, customization cost, and financing profits but does not directly estimate every numerical parameter for this setting. Parameters without transferable industry estimates are explicitly identified as normalized scenario values and examined over broad robustness ranges.

Table 5. Parameter sources, baseline values, and robustness ranges.

Parameter	Meaning	Baseline	Parameter type and source	Robustness range
a	Potential market size	150	Linear demand based on Tong and Li (2023) [36]; normalized value	[75, 225]
β	Price sensitivity	1	Demand-price effect based on Sun et al. (2022) [2]; normalized value	[0.5, 1.5]
τ	Customization-demand sensitivity	12	Customization effect based on Tong and Li (2023) [36].	[6, 18]
c_1	Unit R&D cost	9	Cost structure based on Nair and Narasimhan (2006) [37] and Zhou et al. (2016) [38]; normalized value	[4.5, 13.5]
c_2	Manufacturer's unit production cost	10	Production-cost structure based on Qin et al. (2021) [41]; normalized value	[5, 15]
n	Quadratic customization-cost coefficient	700	Quadratic cost based on Nair and Narasimhan (2006) [37] and Zhou et al. (2016) [38]; normalized value	[350, 1050]
V	Appraised patent value	100	IPR-value structure based on Wan et al. (2023) [35]; normalized value	[50, 150]
m	Initial capital	300	Capital constraint based on Qin et al. (2021) [41]; normalized value	[150, 450]
η	Manufacturer's equity share	0.015	Equity-sharing structure based on Fu et al. (2023) [6]; scenario value	[0.0075, 0.0225] extended test: [0.10, 0.30]
λ_1	Patent-appraisal fee rate	0.12	Scenario value satisfying the appraisal-fee restriction	[0.06, 0.16]
r_2	Internal debt rate	0.035	Internal debt structure based on Qin et al. (2021) [41]; scenario value	[0.0175, 0.0525]

5.2. Expanding demand uncertainty

Under a random market state s , the demand function is extended as follows:

$$q_s = \max \{0, a - \beta p + \tau \delta + \varepsilon_s\},$$

Where $\varepsilon_s \sim N(0, \sigma_\varepsilon^2)$. Here, ε_s denotes a random demand shock caused by changes in customer orders, market preferences, and the macroeconomic environment. The non-negativity constraint is imposed to avoid economically meaningless negative demand values. In the main Monte Carlo analysis, we set: $\sigma_\varepsilon = 0.1a_0$, where $a_0 = 150$ is the benchmark value of potential market size. In each simulation, $a_s = a + \varepsilon_s$ is substituted into the equilibrium profit functions under the four financing modes, and the conditional equilibrium is recalculated under a given exogenous customization level δ .

This extension is a market-state robustness analysis rather than a complete two-stage stochastic game in which firms maximize expected profits before demand shocks are realized. Its purpose is to examine whether the benchmark financing conclusions remain stable under different possible demand states.

Let the technology vendor's profits under the IDF and IEF modes be equal: $\pi_t^{IDF} = \pi_t^{IEF}$. Then the

switching boundary is given by: $\delta^* = \sqrt{\frac{2mr_2}{n(r_2 + \eta)}}$. Here, δ^* is not the optimal customization level chosen by the technology vendor. Instead, it is a parameter boundary at which the profit ranking between IDF and IEF changes as the exogenous customization environment varies.

The profit difference of the technology vendor can be written as: $\pi_t^{IDF} - \pi_t^{IEF} = mr_2 - \frac{n\delta^2}{2}(r_2 + \eta)$.

Therefore, when $\delta < \delta^*$, the technology vendor prefers IDF, while the manufacturer prefers IEF. When $\delta > \delta^*$, the financing preference ranking of the two parties reverse. Under the benchmark parameter setting: $\delta^* = 0.7746$. Given an exogenous customization level δ , the switching boundary of the

customization cost coefficient is: $n^*(\delta) = \frac{2mr_2}{\delta^2(r_2 + \eta)}$. Therefore, n^* must be reported jointly with the specific value of δ . For example, when the exogenous customization level is $\delta = 1$: $n^*(1) = 420$.

About the hybrid financing areas acceptable to both parties, let ϕ denote the proportion of IPR financing in hybrid financing, and let φ denote the proportion of internal equity financing. Then the proportion of internal debt financing is $1 - \phi - \varphi$, satisfying: $\phi \geq 0, \varphi \geq 0, \phi + \varphi \leq 1$. For participant $i \in \{t, m\}$, if $\min\{\pi_i^{IDF}, \pi_i^{IEF}\} \leq \pi_i^{MF}(\phi, \varphi | \delta) \leq \max\{\pi_i^{IDF}, \pi_i^{IEF}\}$, then the corresponding hybrid financing combination is defined as a mutually acceptable compromise between IDF and IEF. This definition is used to

characterize coordination of financing preferences and does not imply that the centralized supply chain optimum is achieved. The mutually acceptable set is defined as: $C(\delta) = \{(\phi, \varphi) : \dots\}$, and the above condition holds simultaneously for the technology vendor and the manufacturer. The feasible upper bound of the IPR financing proportion under a given exogenous customization level is defined as: $\bar{\phi}(\delta) = \sup\{\phi : (\phi, \varphi) \in C(\delta)\}$. This method searches for feasible financing combinations over the full financing-proportion simplex, without pre-fixing the proportions of equity financing or debt financing.

The additional test for demand volatility is provided in Appendix K.

5.3. Monte Carlo design

We conduct 5,000 Monte Carlo simulations using Latin hypercube sampling. The relevant parameters $a, n, V, m, \eta, \beta, c_1, c_2$ are assumed to follow triangular distributions, with the lower bound set at 50% of the benchmark value, the upper bound set at 150% of the benchmark value, and the mode equal to the benchmark value. The demand shock satisfies: $\varepsilon_s \sim N(0, (0.1a_0)^2)$.

The parameter vector in the s -th simulation is given by: $\Omega_s = (a_s, n_s, V_s, m_s, \eta_s, \beta_s, c_{1s}, c_{2s}, \varepsilon_s)$.

Each parameter set is used to calculate the following outcomes:

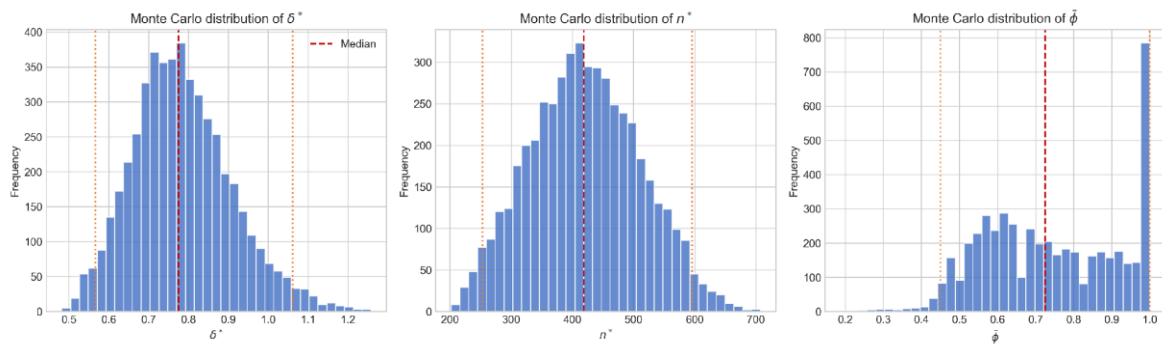
- (1) The financing preference switching boundary under an exogenous customization level δ_s^* .
- (2) The customization-cost $n_s^*(1)$ switching boundary when $\delta = 1$.
- (3) $\delta = 0.2, 0.7, 1.0$ under a given $\bar{\phi}_s(\delta)$.
- (4) The probability that a given exogenous δ lies on either side of the switching boundary.
- (5) Whether an intersection between the IPR and IEF profit functions exists, and the location of that intersection.

The financing-proportion space is searched using a grid with a step size of 0.0125. To ensure the reproducibility of the simulation results, the seed of the pseudo-random number generator is fixed at 20260619. The seed value has no economic meaning. The three exogenous customization scenarios use the same parameter samples and the same n_s , so that the differences across scenarios mainly arise from δ , rather than from simultaneous changes in the customization cost coefficient.

Monte Carlo simulations are conducted to examine the robustness of the financing preference switching boundary. The simulation results are presented in Table 6.

Table 6. Monte Carlo results for the financing preference switching boundary.

Indicator	Valid observations	Mean	Median	95% simulation interval
Exogenous customization boundary δ^*	5,000	0.7849	0.7747	[0.5661, 1.0610]
Cost boundary $n^{*(l)}$	5,000	421.56	418.98	[253.24, 595.78]
Technology vendor's IPR–IEF intersection	2,710	116.55	101.88	[5.98, 305.32]

**Figure. 14.** Monte Carlo distribution of the financing switching boundary under global parameter uncertainty.

As shown in Figure 14, the median of δ^* is 0.7747, which is almost identical to the benchmark value of 0.7746. This indicates that the mechanism through which financing preferences switch with changes in the exogenous customization environment is relatively stable. However, its 95% simulation interval is [0.5661, 1.0610]. Therefore, 0.77 should be interpreted only as a representative boundary under the benchmark parameter setting.

The median of $n^{*(l)}$ is 418.98, which is close to the benchmark value of 420, while its 95% simulation interval is [253.24, 595.78]. Therefore, the directional conclusion that rising customization cost changes financing preferences is robust, but 420 should not be interpreted as a universally applicable cost threshold.

The intersection of profitability functions for technology suppliers under the Intellectual Property and Industrialization Fund (IEF) existed only in 2,710 simulation samples, with a corresponding probability of 54.2%. The reference intersection is 12.38. The intersection of profitability functions for technology suppliers under the Intellectual Property and Industrialization Fund (IEF) existed only in 2,710 simulation samples, with a corresponding probability of 54.2%. The reference intersection is 12.38. Regarding the financing proportions under different exogenous customization scenarios, we set the following values to identify the impact of the exogenous customization environment on the hybrid financing structure: $\delta_L = 0.2, \delta_M = 0.7, \delta_H = 1.0$

The three scenarios use exactly the same parameter samples, with only δ being varied.

Table 7. Financing preferences and IPR proportions under different exogenous customization scenarios.

Scenario	δ	$P(\delta < \delta^*)$	Mean ($\bar{\phi}$)	Median ($\bar{\phi}$)	95% interval	$P(\bar{\phi} < 0.5)$
Low customization	0.2	100.00%	0.7410	0.7250	[0.4500, 1.0000]	6.76%
Medium customization	0.7	74.38%	0.3627	0.2000	[0.0000, 1.0000]	67.60%
High customization	1.0	5.56%	0.2493	0.2500	[0.0250, 0.4375]	98.88%

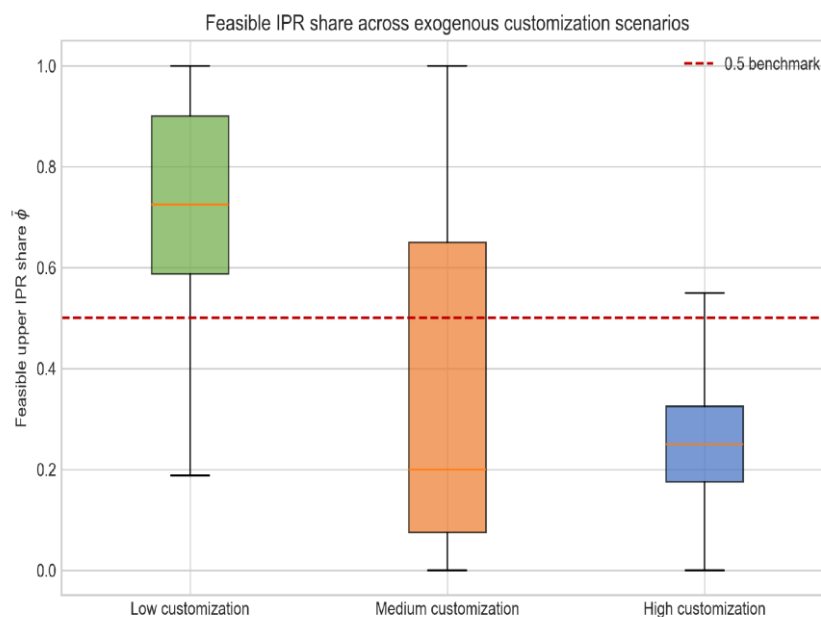


Figure 15. Feasible upper IPR share across exogenous customization scenarios.

As shown in Figure 15, under the low-customization scenario, all samples satisfy $\delta < \delta^*$. Therefore, the technology vendor generally prefers IDF, whereas the manufacturer prefers IEF. In this case, the median of $\bar{\phi}$ is 0.725, and only 6.76% of the simulations require the IPR proportion to be below 0.5. This indicates that the original upper bound of 0.5 is not robust in a low-customization environment. Under the medium-customization scenario, 74.38% of the samples satisfy $\delta < \delta^*$, suggesting that this scenario is close to the financing preference switching region. In this case, the median of $\bar{\phi}$ decreases to 0.20, and 67.60% of the samples require the IPR proportion to be below 0.5. Furthermore, the 95% simulation interval is relatively wide, indicating that the medium-customization environment is the most sensitive to changes in market, cost, and financing parameters. Under the high-customization

scenario, only 5.56% of the samples satisfy $\delta < \delta^*$, which means that most samples have already crossed the financing preference switching boundary. In this case, the median of $\bar{\phi}$ is 0.25, the upper bound of the 95% simulation interval is only 0.4375, and 98.88% of the samples require the IPR proportion to be below 0.5.

Therefore, the conclusion that the IPR proportion should remain relatively low mainly applies to high-customization environments, rather than to all customization levels. Compared with a fixed threshold of 0.5, a more accurate conditional conclusion is that, as the exogenous customization level increases, the acceptable IPR proportion in hybrid financing generally decreases, and firms should strengthen the risk-sharing role of internal debt financing and internal equity financing.

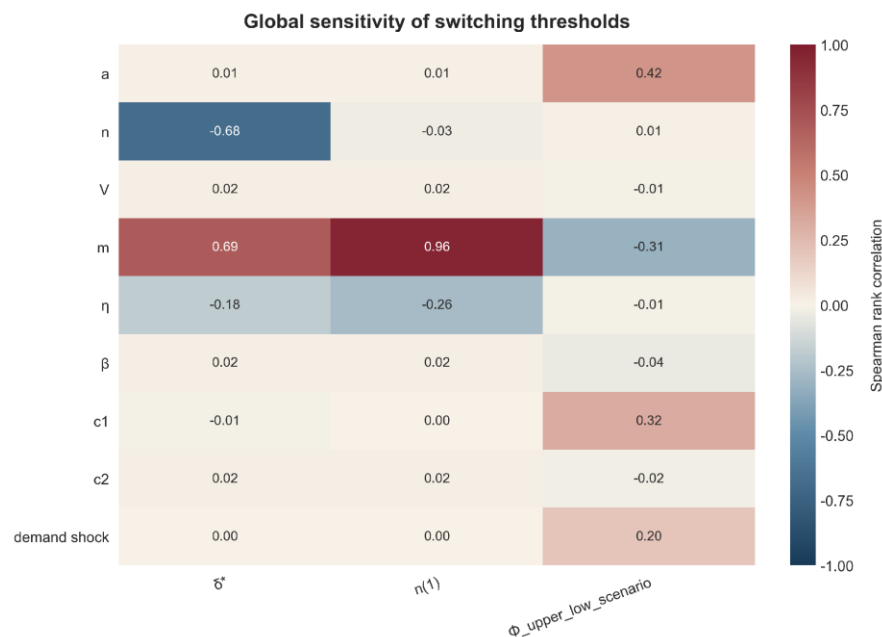


Figure 16. Correlation coefficients between key parameters and financing switching boundaries.

As shown in Figure 16, δ^* is strongly and positively correlated with the firm's internal funds m , with a correlation coefficient of 0.694. It is also strongly and negatively correlated with the customization cost coefficient n , with a correlation coefficient of -0.685. This indicates that firms with more sufficient internal funds can continue to rely on debt financing at higher levels of customization, whereas higher customization costs cause financing preferences to switch at an earlier stage.

The correlation coefficient between $n(1)$ and internal funds m is 0.958, while the correlation coefficient between $n(1)$ and the equity share η is -0.260. These results suggest that internal funds are the dominant driver of the customization-cost switching boundary.

In the low-customization scenario, $\bar{\phi}^{(0.2)}$ is positively correlated with market size a , positively correlated with the unit R&D cost c_1 , and negatively correlated with internal funds m . The correlation with patent value V is relatively weak. This is because the coordination region in this study is defined by whether the MF profit lies between the IDF and IEF profits, rather than by using the standalone IPR profit as the direct boundary. Therefore, this result should not be interpreted as evidence that patent value is unimportant for IPR pledge financing.

The convergence test of the Monte Carlo simulations is provided in Appendix L.

An additional robustness check for the manufacturer's equity share:

The benchmark value $\eta = 0.015$ represents a low-dilution internal equity scenario. Since η directly affects the comparison between internal equity financing (IEF) and internal debt financing (IDF), the local robustness range $[0.0075, 0.0225]$ may be too narrow to evaluate cases with substantial manufacturer equity participation. Therefore, we conduct an additional robustness test in which η is allowed to vary over a larger range: η in $[0.10, 0.30]$. This test does not replace the benchmark calibration. Rather, it examines whether the qualitative mechanism survives when the manufacturer obtains a more substantial equity claim in the technology vendor.

From the analytical switching boundary, $\delta^* = \sqrt{\frac{2mr_2}{n(r_2 + \eta)}}$ and $n^*(1) = \frac{2mr_2}{r_2 + \eta}$, a larger η lowers both the exogenous customization switching boundary δ^* and the cost switching boundary $n^*(1)$. Economically, when the manufacturer receives a larger equity share, the profit allocation under IEF changes more strongly, and the IDF-IEF preference ranking switches at a lower customization level or lower customization-cost threshold.

Table 8. Sensitivity of IDF-IEF switching boundaries to larger equity shares under benchmark parameters.

η	δ^*	$n^*(1)$
0.015	0.7746	420.00
0.100	0.4714	155.56
0.150	0.4027	113.51
0.200	0.3573	89.36
0.250	0.3244	73.68
0.300	0.2993	62.69

Table 8 shows that the IDF-IEF comparison is highly sensitive to η . When η increases from 0.015 to 0.10, δ^* decreases from 0.7746 to 0.4714, and $n^*(1)$ decreases from 420.00 to 155.56. When η reaches 0.30, δ^* further decreases to 0.2993 and $n^*(1)$ decreases to 62.69. Therefore, the benchmark values $\delta^* 0.7746$ and $n^*(1) = 420$ should be interpreted as low-dilution benchmark results rather than general empirical thresholds.

To examine this issue under global parameter uncertainty, we repeat the Monte Carlo analysis using the same design as above, except that η follows a triangular distribution on $[0.10, 0.30]$ with mode 0.20. The other parameters retain the robustness ranges in Table 5, and the demand shock remains $\varepsilon_s \sim N(0, (0.1a_0)^2)$. The Latin hypercube sample size is 5,000, and the random seed is again fixed at 20260619.

Table 9. Extended Monte Carlo results under η in $[0.10, 0.30]$.

Indicator	Valid observations	Mean	Median	95% simulation interval
Manufacturer's equity share η	5,000	0.2000	0.2000	[0.1224, 0.2776]
Exogenous customization boundary δ^*	5,000	0.3659	0.3596	[0.2540, 0.5145]
Cost boundary $n^*(l)$	5,000	92.26	89.35	[50.44, 152.91]
Technology vendor's IPR-IEF intersection	2,710	43.75	37.89	[2.32, 116.61]

The extended Monte Carlo results confirm the analytical pattern. Under η in $[0.10, 0.30]$, the median δ^* decreases to 0.3596, and the median $n^*(l)$ decreases to 89.35. Thus, the qualitative mechanism that η shifts the IDF-IEF preference boundary remains valid, but the numerical boundary changes substantially. This result confirms that the IEF-IDF comparison should not be based on a single small equity-share calibration.

Table 10. Financing preferences and feasible IPR shares under η in $[0.10, 0.30]$.

Scenario	δ	$P(\delta < \delta^*)$	Mean ($\bar{\phi}$)	Median ($\bar{\phi}$)	95% interval	$P(\bar{\phi} < 0.5)$
Low customization	0.2	100.00%	0.6752	0.6375	[0.3000, 1.0000]	21.60%
Medium customization	0.7	0.00%	0.7892	0.8000	[0.5500, 0.9625]	1.08%
High customization	1.0	0.00%	0.7914	0.8000	[0.6500, 0.9125]	0.00%

Table 10 further shows that the feasible IPR share is also affected by the equity-share environment. Under the extended η range, the low-customization scenario still satisfies $\delta < \delta^*$ in all simulations. However, the medium- and high-customization scenarios lie above the switching boundary in essentially all simulations. In this larger-equity-share environment, the feasible upper IPR share does not decline monotonically with customization. The median feasible upper IPR share is 0.6375 under low customization, 0.8000 under medium customization, and 0.8000 under high customization.

This result qualifies the benchmark interpretation. The conclusion that the feasible IPR share should decline sharply in high-customization scenarios is supported under the low-dilution benchmark $\eta=0.015$, but it is not invariant to substantially larger manufacturer equity participation. When η is

large, the equity component absorbs more risk and changes the IDF-IEF reference interval, so a higher IPR share can still fall within the mutually acceptable hybrid-financing region. Therefore, the robust conclusion is not a fixed IPR threshold. Rather, the robust conclusion is that the feasible financing mix depends jointly on customization, customization cost, internal funds, debt cost, and the manufacturer's equity share.

5.4. Robust conclusions

The robustness analysis supports the following mechanism-based conclusions: The exogenous customization environment, customization cost, and financing structure jointly affect the financing preferences of the technology vendor and the manufacturer. When the exogenous customization level crosses δ^* , the profit ranking between IDF and IEF reverses. Across a relatively broad parameter space, hybrid financing can form a mutually acceptable compromise region between IDF and IEF.

However, the specific critical values are parameter-dependent. The benchmark value of 0.77 and the value of 420 obtained under the scenario of $\delta = 1$ are close to the medians of the Monte Carlo distributions. Therefore, they can be interpreted as representative boundaries under the benchmark parameter setting, but they should not be treated as uniform industry standards applicable to all firms or all market environments.

The extended equity-share robustness test further shows that η is an important driver of the IEF–IDF comparison. The benchmark value $\eta = 0.015$ represents a low-dilution scenario. When η is increased to the range $[0.10, 0.30]$, the qualitative switching mechanism remains, but the numerical boundaries change substantially. The median δ^* falls to 0.3596, and the median $n^{*(1)}$ falls to 89.35. Therefore, the IDF–IEF ranking should be interpreted as parameter-dependent, and the benchmark values should not be treated as universal thresholds. Economically, a larger η means that the manufacturer obtains a stronger residual claim under IEF, while the technology vendor gives up a larger share of future returns. This changes the relative attractiveness of IEF and IDF for both parties and causes the preference-switching boundary to occur at lower customization levels and lower customization-cost thresholds. Thus, the robust implication is not that $\eta = 0.015$ is generally representative, but that equity sharing, internal funds, debt cost, and customization cost jointly determine the IEF–IDF comparison. In practical applications, η should be calibrated according to the proposed equity participation arrangement rather than fixed at the low-dilution benchmark value.

These results suggest that the IPR pledge proportion is not governed by a universal upper bound. Instead, feasible financing proportions depend on customization conditions, cost pressure, and technological uncertainty. In the low-customization scenario, the upper bound of 0.5 for the IPR proportion lacks robust support, as only a small fraction of simulations require the IPR proportion to be below this level. In contrast, under high-customization conditions, 98.88% of simulation results indicate that the IPR proportion should remain below 0.5. Therefore, the conclusion that “the IPR proportion should remain relatively low” is conditional and mainly applies to high-customization, high-cost, and high-uncertainty environments.

Based on the above robustness results, the managerial implications of this paper should be understood as conditional recommendations rather than fixed threshold rules. Product customization is usually exogenously determined by customer requirements and technological application scenarios. Firms should choose their financing structures after observing the specific customization environment,

rather than applying a fixed IPR proportion rule. In low-customization environments, the IPR financing proportion has greater room for adjustment. As customization increases, R&D cycles become longer, patent valuation becomes more difficult, and financing risk rises. Accordingly, the IPR proportion in hybrid financing should generally decline, while internal debt financing and internal equity financing should play a greater role in risk sharing. The specific financing proportions should still be recalibrated at the firm level according to market size, internal funds, cost structure, demand volatility and the proposed equity share.

6. Case study: Equity-based financing under high technological complexity-evidence from Markforged Holding Corporation

In this section, we use Markforged Holding Corporation as a case study to examine the financing choices of an additive manufacturing technology vendor amid high technological complexity and the directional consistency of these choices with the theoretical logic of this paper. It should be noted that this case is not intended to provide a causal test of the theoretical model. Moreover, Markforged's financing event does not directly correspond to the internal equity financing (IEF) mechanism modeled in this study, because the observed equity financing was conducted through a SPAC business combination and PIPE investment rather than a manufacturer acquiring an equity stake in the technology vendor. Therefore, this case is interpreted as an illustration of the risk-sharing advantage of equity financing rather than direct empirical evidence of the specific IEF mechanism. Rather, it provides a publicly verifiable, real-world reference showing how a firm can use a financing structure to alleviate liquidity constraints and absorb technology development risk under high R&D intensity, high technological complexity, and substantial commercialization uncertainty.

Markforged is selected as the case for three major reasons. First, Markforged is a representative industrial additive manufacturing technology vendor. The company integrates industrial 3D printers, proprietary metal and composite materials, and cloud-based software into the Digital Forge platform. Its products are used in industrial tooling, machinery manufacturing, regulated part production, spare-parts manufacturing, and mission-critical industrial applications in aerospace, defense, automotive, healthcare, and other sectors. These characteristics are highly relevant to the high technological complexity, product customization, and continuous R&D investment needs considered in the "technology vendor–manufacturer–retailer" framework of this paper. Second, Markforged's key financing event and financial data can be verified through filings submitted to the U.S. Securities and Exchange Commission (SEC), which improves the reliability of the case evidence. Third, the case illustrates the boundary of the theoretical implications: Financing can improve short-term liquidity and risk-bearing capacity, but it does not automatically generate sustained revenue growth or operating profitability.

6.1. Data sources and verification method

The transaction information and accounting data used in this case are obtained from Markforged's Form 8-K and Form 10-K filings submitted to the SEC. The observation period is 2020–2024. Revenue, R&D expenses, operating loss, and year-end cash and cash equivalents are taken from audited consolidated financial statements. We use operating loss rather than net income as the operating-performance indicator because Markforged's net income in some years was affected by non-operating and non-cash items, such as changes in the fair value of warrant liabilities and contingent earnout

liabilities. In comparison, operating loss more directly reflects the firm's core business pressure in R&D, sales, production, and commercialization. This case is mainly used to show that, under high cost, high technological complexity, and high uncertainty, firms may be more likely to rely on equity capital with stronger risk-absorption capacity rather than heavily depending on fixed-payment financing or high-proportion intellectual property pledge financing.

On July 14, 2021, Markforged completed its AONE, a special purpose acquisition company. The transaction included two major sources of equity capital. First, after redemptions by certain AONE shareholders, approximately USD 150.9 million remaining in AONE's trust account was released to Markforged Holding Corporation. Second, AONE completed a private investment in public equity (PIPE) transaction, in which investors subscribed for 21 million shares of common stock at USD 10 per share, for an aggregate amount of USD 210 million. Before the business combination, Markforged also repurchased approximately USD 45 million of securities from certain stockholders. This financing event had a feature of equity capital injection. Such a financing choice is directionally consistent with the theoretical prediction of this paper under high technological complexity and high-cost scenarios. When the level of product customization, R&D investment, and commercialization uncertainty is high, firms need financing instruments that can absorb risk. A high-proportion IPR pledge financing arrangement may be constrained by patent valuation uncertainty, technological obsolescence risk, collateral discount, and repayment pressure. By contrast, equity capital does not impose fixed interest payments or mandatory principal repayment obligations, and therefore can better absorb early-stage technology-development and commercialization risk.

Therefore, Markforged's financing choice provides an industry illustration consistent with the directional implication of the model: When customization cost and technology risk increase, firms may reduce their dependence on high-proportion IPR pledge financing and place greater emphasis on risk-absorbing capital instruments. This case is not a direct validation of the complete hybrid financing model. Rather, it provides a real-world reference for the mechanism that the dependence on IPR pledge financing should be reduced under high complexity and high-cost conditions.

6.2. *Financial changes after financing*

Figure 17 shows Markforged's revenue and R&D intensity from 2020 to 2024. Revenue increased from USD 71.851 million in 2020 to USD 85.090 million in 2024. R&D expenses increased from USD 17.176 million in 2020 to USD 32.444 million in 2024. R&D intensity, calculated as R&D expenses divided by revenue, increased from 23.9% to 38.1%.

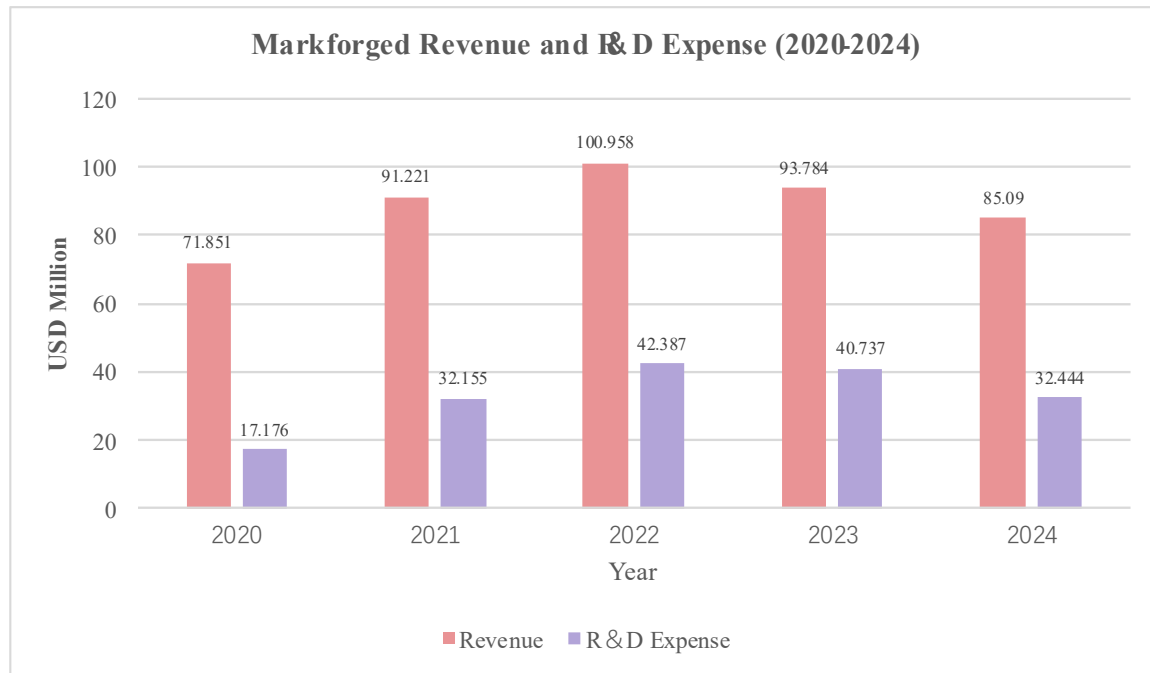


Figure 17. Markforged revenue and R&D intensity, 2020–2024. Note: Revenue is reported in USD million. R&D intensity is calculated as R&D expenses divided by revenue. Source: Markforged Form 10-K filings; R&D intensity calculated by the authors.

Figure 17 shows that, after the 2021 equity financing, Markforged's R&D investment capacity improved significantly, and its revenue also increased during 2021–2022. This is consistent with the basic logic of the model: When a technology vendor obtains capital support, its R&D and customization capabilities can be expanded, thereby supporting product development and market expansion. However, Figure 17 also shows that revenue growth was not monotonic. After 2022, revenue declined continuously. This suggests that financing can alleviate capital constraints, but it cannot replace market demand, commercialization efficiency, or cost control. Therefore, financing should not be interpreted as a one-way mechanism that necessarily increases revenue. Rather, it is a capital allocation mechanism that improves risk-bearing capacity and R&D investment capacity.

In addition, Figure 18 presents Markforged's year-end cash and cash equivalents and operating loss from 2020 to 2024. After the 2021 business combination and PIPE financing, the company's year-end cash and cash equivalents increased sharply from USD 58.715 million in 2020 to USD 288.603 million in 2021, and then declined to USD 53.629 million in 2024. Operating loss increased from USD 17.739 million in 2020 to USD 61.040 million in 2021, and narrowed to USD 86.679 million in 2024.

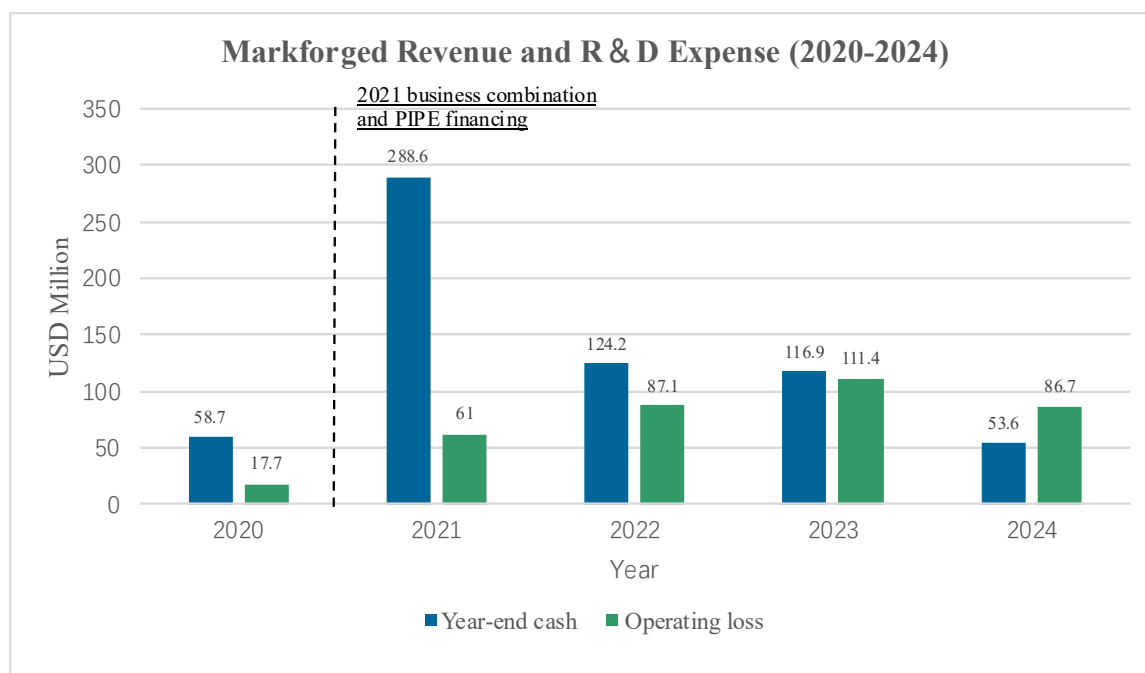


Figure 18. Markforged year-end cash and cash equivalents and operating loss, 2020–2024. Note: Cash refers to year-end cash and cash equivalents only and excludes short-term investments. Operating loss is reported as a positive loss amount for comparability. Source: Markforged Form 10-K filings.

Figure 18 further shows that equity financing significantly improved Markforged’s short-term liquidity, but did not eliminate operating losses. After 2021, the cash balance continued to decline, indicating that the firm still faced cash consumption caused by R&D investment, commercialization activities, and daily operations. Markforged’s 2024 Form 10-K also disclosed substantial going-concern uncertainty and the possible need for additional financing. This is consistent with the practical implication of the model: Financing structure can change risk sharing and capital availability, but it cannot substitute for final demand realization or operating efficiency improvement. Table 11 summarizes the key financial indicators used in this case.

Table 11. Key financial indicators of Markforged were verified through SEC filings (Unit: USD million).

Year	Revenue	R&D expenses	R&D intensity	Operating loss	Year-end cash and cash equivalents
2020	71.851	17.176	23.9%	17.739	58.715
2021	91.221	32.155	35.2%	61.040	288.603
2022	100.958	42.387	42.0%	87.084	124.242
2023	93.784	40.737	43.4%	111.381	116.854
2024	85.090	32.444	38.1%	86.679	53.629

*Note: R&D intensity is calculated by the authors as R&D expenses divided by revenue. Operating loss is reported as a positive loss amount for comparability. Year-end cash refers to cash and cash equivalents only and excludes short-term investments.

6.3. *Consistency between the case and the theoretical conclusions*

The Markforged case is directionally consistent with the theoretical model in three aspects. First, higher technological complexity and stronger product customization capability are accompanied by continuous R&D investment. Markforged's R&D intensity remained above 35% during 2021–2024 and exceeded 40% in 2022 and 2023. This supports the basic assumption of the model that the financing demand of a technology vendor increases as the product customization level and customization cost rise.

Second, Markforged's key verifiable financing event was equity-dominant. Public filings do not show that the company primarily relied on high-proportion IPR pledge financing in 2021. This is consistent with the model's prediction under high-cost and high-uncertainty scenarios: When technology-development and commercialization risks are high, firms should reduce their dependence on collateral-based IPR pledge financing and rely more on capital instruments that can absorb risk.

Third, the post-financing financial trajectory reveals the boundary of the financing mechanism. The 2021 equity financing significantly increased the company's cash holdings, but its cash balance declined afterward, and operating losses persisted. This indicates that a financing structure can improve financial resilience and risk sharing, but it cannot guarantee profitability or automatically create sustained demand.

This case shows directional consistency between real-world financing choices and the theoretical predictions, rather than providing causal validation of the model's equilibrium results. SEC filings can verify the changes in financing events, cash balances, R&D expenses, revenue, and operating losses, but they cannot identify the counterfactual outcomes that would have occurred if Markforged had adopted IPR pledge financing or internal debt financing. The causal mechanism of this paper still mostly comes from the theoretical model and numerical simulations.

6.4. *Case summary and boundary evidence from Velo3D's debt renegotiation*

In this paper, we use Velo3D only as an auxiliary illustration of fixed-payment financing risk. The event suggests that, under high cost and high uncertainty, the fixed repayment obligations of debt financing may create renegotiation pressure and may require additional equity-linked compensation. This is consistent with the model's conclusion that firms should avoid excessive reliance on fixed-payment financing during high-customization and high-cost stages. As a brief comparison, Velo3D's financing experience illustrates the renegotiation risk of fixed-payment debt under high uncertainty. According to Velo3D's Form 8-K filed on July 1, 2024, the company entered into a third amendment to its senior secured notes due 2026. The amendment deferred the USD 10.5 million partial redemption payment originally due on July 1, 2024, and revised the subsequent repayment arrangement. As consideration for the deferral, the company issued warrants to the noteholders to purchase 1.65 million shares of common stock at an exercise price of USD 3 per share.

Markforged provides a replicable and clearly bounded case for the theoretical framework of this paper. Its business characteristics reflect high technological complexity, platform integration capability, proprietary material systems, and continuous R&D needs. The verifiable equity financing in 2021 significantly improved short-term cash holdings. However, the post-financing financial trajectory also shows that the firm faced declining revenue, cash consumption, and operating losses. Overall, this case is consistent with the core implication of the model: As product customization, cost pressure, and uncertainty increase, technology vendors should reduce their dependence on high-proportion IPR pledge

financing and rely more on financing instruments with stronger risk-absorption capacity. Furthermore, the case also reminds us that a financing structure mostly improves risk allocation and financial resilience, but does not guarantee sustained revenue growth or operating profitability.

7. Conclusions, strategic recommendations, and future research directions

3D printing technology, with its vast and versatile applications across industries, has experienced rapid growth in recent years. However, as companies in the 3D printing sector push technological boundaries and work towards scaling their operations, they face considerable challenges, particularly in securing adequate financing. The high cost of financing is one of the key barriers to expansion, especially when companies are striving to develop more sophisticated and customized products.

Here, we explore three major financing options, IPR pledge financing, internal debt financing, and internal equity financing, to provide a comprehensive understanding of the financial tools available to 3D printing companies. Moreover, in situations where conflicts arise between technology providers and manufacturers, we examine the role of hybrid financing as a potential compromise that could balance the interests of both parties. By comparing and analyzing these financing models, key findings and recommendations have emerged, offering valuable insights into the most effective strategies for securing funding in this growing sector.

7.1. Conclusions

In this study, we develop a game-theoretic framework to examine financing mode selection in a three-tier supply chain comprising a capital-constrained 3D printing technology vendor, a manufacturer, and a retailer. Four financing modes are compared: IPR pledge financing, internal debt financing, internal equity financing, and hybrid financing. The results show that financing preferences are jointly affected by the exogenous customization environment, customization cost, and the financing structure.

When customization and its associated costs are relatively low, IPR pledge financing can remain an important component of the financing portfolio because technological assets are relatively easier to evaluate and financing risks are limited. However, as customization complexity, R&D expenditure, and commercialization uncertainty increase, excessive reliance on IPR pledge financing may increase valuation and repayment risks. Under these conditions, hybrid financing can distribute risks among IPR pledge, internal debt, and internal equity financing and may generate a financing arrangement acceptable to the technology vendor and the manufacturer.

However, hybrid financing should not be interpreted as universally optimal. Its effectiveness depends on firm-specific and market-specific conditions. Moreover, coordination in this study refers to the existence of a mutually acceptable financing arrangement that mitigates the preference conflict between the technology vendor and the manufacturer. It does not necessarily mean that the centralized supply chain optimum is achieved. The numerical thresholds reported in this paper are scenario-dependent reference values rather than universal industry standards. In particular, the feasible IPR pledge proportion should be determined according to customization conditions, cost pressure, and technological uncertainty rather than a fixed upper bound.

The robustness analyses further confirm that the main mechanism is relatively stable, while the feasible financing proportions vary across customization scenarios. When customization-related uncertainty and cost pressure are relatively low, higher IPR pledge proportions may remain feasible

because technology assets are easier to evaluate and financing risks are relatively limited. In contrast, as customization complexity and uncertainty increase, firms should reduce excessive reliance on IPR pledge financing and place greater emphasis on internal debt financing, internal equity financing, or other risk-sharing mechanisms. Therefore, the appropriate financing structure should be recalibrated according to the specific operating and financing environments.

7.2. *Strategic recommendations*

To improve the practical applicability of the results, managers may implement financing decisions through the following procedure. First, managers should assess the firm's financing environment before selecting a financing mode. This assessment should include the customization level, expected customization cost, financing gap, available internal capital, patent value and its valuation reliability, expected cash flow, and repayment capacity. Firms should not select a financing structure solely on the basis of technological value or the availability of patent collateral.

Second, managers can classify financing situations according to their technological complexity and risk exposure. In a relatively low-customization and low-cost environment, IPR pledge financing may be considered when patent valuation is sufficiently reliable and expected cash flows can cover repayment obligations. In a medium-customization or medium-cost environment, managers should compare the benefits of IPR pledge financing with its valuation and repayment risks and consider introducing internal debt or internal equity financing. In a high-customization, high-cost, or highly uncertain environment, firms should avoid excessive reliance on IPR pledge financing and place greater emphasis on equity participation and other risk-sharing instruments.

Third, the technology vendor and the manufacturer should identify a mutually acceptable financing range before determining the final financing proportions. They may use their expected profits under internal debt financing and internal equity financing as reference points. The technology vendor can then propose a combination of IPR pledge, internal debt, and internal equity financing. If the proposal does not satisfy the participation requirements of both parties, the financing proportions should be adjusted until they fall within the mutually acceptable set. Thus, the model provides a feasible negotiation range rather than a fixed financing formula.

Fourth, the financing arrangement should include periodic review and adjustment clauses. Managers should monitor changes in customization costs, order demand, patent valuation, R&D progress, cash flows, and repayment capacity. When these indicators deviate substantially from their initial values, the financing proportions, repayment schedule, or equity-sharing arrangement should be renegotiated. Such dynamic adjustment can prevent a financing structure that was initially feasible from becoming excessively risky as market or technological conditions change. Therefore, the managerial implications of this study should be understood as a conditional decision framework. Managers can use the model to identify relevant trade-offs and feasible financing ranges, but the final proportions must be determined according to firm-level data, bargaining power, risk tolerance, and prevailing financing conditions.

7.3. *Future research directions*

This study has several limitations that provide opportunities for future research. First, although the extended analysis introduces a stochastic demand shock and examines parameter uncertainty through Monte Carlo simulations, it does not construct a complete multi-stage stochastic game.

Researchers could consider nonlinear demand, demand learning, and decisions made before and after uncertainty is realized. Second, this model treats patent value and several financing parameters as observable or exogenously given. In practice, patent valuation is affected by technological obsolescence, commercialization prospects, legal enforceability, and differences in information between technology vendors, manufacturers, and financial institutions. Researchers could incorporate stochastic patent values, technology depreciation, and asymmetric information into the financing game. Third, bankruptcy and default risks are not explicitly modeled. Researchers may introduce limited liability, endogenous default decisions, collateral recovery rates, bankruptcy costs, and risk-sensitive interest rates. This would enable researchers to examine how default risk affects the optimal combination of IPR pledge, internal debt, and internal equity financing. Fourth, the model does not endogenously determine the bargaining power of the technology vendor and the manufacturer or select a unique financing combination from the mutually acceptable set. Researchers could introduce Nash bargaining, alternating-offer bargaining, or asymmetric bargaining power to investigate how the final financing proportions and profit allocation are negotiated. Fifth, actual financing conditions change over time because of interest-rate adjustments, government policies, investor risk preferences, and the availability of external capital. A dynamic model could examine how firms adjust their financing structures across stages of technology development and commercialization. External financing channels, including venture capital, government subsidies, and commercial bank lending, could also be incorporated.

Finally, researchers could examine the retailer's participation in financing and contract design and use firm-level or industry-level data to empirically test the model. These extensions would improve the external validity and practical applicability of the proposed financing framework.

Author contributions

Liurui Deng: Conceptualization, methodology, writing-review and editing, funding acquisition, supervision; Shaodan Li: Conceptualization, formal analysis, writing-original draft preparation, visualization; Lingling Jiang: Formal analysis and investigation, writing-original draft preparation, writing - review and editing, visualization.

Use of Generative-AI tools declaration

The authors declare that Artificial Intelligence (AI) tools were used only for language polishing and improving the clarity of expression in this manuscript. All research ideas, model development, methodological design, numerical experiments, and result analysis were independently completed by the authors. The authors take full responsibility for the content of this manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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