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Production and Operations Management

3D Printing-as-a-Service: An Economic Analysis of Pricing and Co-creation

Abstract: 3D printing technology has opened up possibilities of product design collaborations between device providers and customers. To enable an environment of co-creation, device providers are now renting 3D printers via the 3D-as-a-Service (3DaaS) model. Although prior research has examined pricing and quality issues in the traditional manufacturing setup, these studies have not analyzed such decisions in the 3D printing supply chain setting, where end users possess the ability to customize product designs. Therefore, several important questions remain unanswered from the perspective of the 3D printing device provider. For example, what is the appropriate pricing model for providing 3DaaS? How do factors like the extent of design customization and the complexity influence the pricing strategy of the 3DaaS firm? Our analysis shows that if the customers' impact on the product quality is relatively high or low, the pay-per-build pricing model generates a higher profit than the fixed-fee pricing model. Interestingly, we also find that if customers frequently print highly intricate product designs, the firm might choose the pay-per-build pricing model, only if the likelihood of design failure for these complex structures is low. Otherwise, the firm might opt for a fixed-fee pricing model.

Key words: Digital Operations; 3D Printing; Pricing; 3D-as-a-Service; Co-creation; Supply Chain

1 Introduction

3D printing or additive manufacturing is a technology through which a product or component is constructed layer by layer (PricewaterhouseCoopers 2023). During the onset of the COVID-19 pandemic, a hospital in Italy urgently required ventilator valves. A start-up, with the help of a 3D printer, produced 100 valves in a day and supplied it to the hospital. These valves were immediately used to treat 10 patients (Mullainathan 2020). The advantages of 3D printing are many: high design flexibility, no batch size requirements, lower cost per part, and lower material wastage (PricewaterhouseCoopers 2023, Arkema 2023). Moreover, as compared to conventional manufacturing, in 3D printing, the capital investments required to achieve scope are lower, production can be conducted at the point of use, the ability to customize a product is higher, and the lead time is lower (Deloitte 2022, DHL 2023). This paper analyzes a supply chain setting where a firm provides the 3D printing service that customers utilize to build products. We study the pricing strategies of the 3D printing service provider.

1.1 Problem and Motivation

Various startups and small businesses cannot own a 3D printer due to cash constraints. Therefore, they prefer to print the product and the prototypes via 3D printing services. An Ernst and Young study revealed that around one-third of the survey respondents were expected to print their requirements via 3D printers owned by service providers (Ernst and Young 2019). As a result, various device manufacturers such as

Hewlett-Packard and Carbon rent 3D printing devices to their customers as a service to help them integrate 3D printing into their digital manufacturing strategies. Such a *3D-as-a-Service* (3DaaS) model makes digital manufacturing of products more accessible, scalable, and affordable for customers (Allan 2019).

Typically, 3D printing device firms offer 3DaaS (or rent 3D printers) through two pricing models: Fixed-fee and pay-per-build pricing models. In the fixed-fee pricing model, customers need to commit to using the printer for a certain period and pay a certain amount for this long-term usage contract. For example, Hewlett-Packard provides the HP Jet Fusion 340 3D printer through a fixed-fee pricing mechanism. In this pricing strategy, the customer needs to sign up for a 1-year commitment and pay a $5,000 up-front fee and $3,500 monthly fee, which amounts to a fixed-fee of $47,000 for the year (Molitch-Hou 2023). Similarly, Carbon provides the Carbon M2 3D Printer though a fixed-fee pricing model. In this case, the customer needs to sign-up for a 3-year commitment and pay $50,000 per year, that is, the fixed-fee for the 3-year contract period is $150,000 (Carbon 2023a). Overall, pricing is not impacted by the number of objects the customer prints during the subscription period in this model.

In the pay-per-build pricing model, the pricing is based on the actual number of builds (or products, objects, or components) printed by the customers using the 3D printing service. For example, Hewlett-Packard offers the HP Jet Fusion 5200/4200 Series and HP Jet Fusion 500 Series 3D printers through the pay-per-build pricing model. In this 3DaaS model, the company tracks the usage of the printer and charges the customer based on the number of builds (Molitch-Hou 2023). In this paper, we study these 3DaaS pricing models as implemented by various 3D printing vendors.

In a traditional supply chain setting, customers source their requirements from a firm that designs and manufactures the final product. Unlike conventional manufacturing processes, in the 3D printing supply chain, the customer can customize product design and prepare digital models using 3D modeling software. Then, using the developed digital model and the feed material, the final product is printed on the 3D printing hardware (DHL 2023). For example, traditionally, customers used to purchase toys designed and manufactured by firms. In recent times, certain companies have started to provide 3D printers through which children can print out their toys. The 3D printer includes software allowing customers to customize existing design templates and add various features to create the final digital files. Finally, the prepared digital files can be exported to the 3D printer. Therefore, one of the important features of the 3D printing supply chain is that the customer also bears the cost of product quality customization. This is because customers first need to customize the final product by deciding various complex product design parameters. They also need to understand technical details such as product geometry, material guidelines, and printing technology while preparing the final design files.

One of the criteria for the selection of 3D printers by customers is the extent of customer engagement in the final design of the 3D printed object. For certain 3D printing applications, the customer efforts majorly determine the final utility of the object. These applications typically include sophisticated engineering requirements, complex dental designs, and designing and printing jewelry. There are some applications for which the customer's impact on the final product quality is low. For several end products, the 3DaaS firm provides customers with a large number of design templates. The customers simply select these templates and make some minor modifications to print the final object; that is, the quality of the end product is mostly due to the software templates provided by the device firm. Examples of such applications include designing standard geometrical designs and simple template selection-based applications such as candy printing. In this paper, we evaluate the impact of the customer's ability to contribute toward product design on the strategic pricing model adopted by 3DaaS firms.

1.2 Research Questions and Key Findings

Motivated by the discussion in Section 1.1, we study a stylized model with a 3DaaS provider and customers renting 3D printers. The customers are heterogeneous in the usage frequency of the 3D printer. First, the 3D printing service provider decides its pricing strategy and simultaneously determines its efforts to develop initial design file templates. Then, the customers decide the product design decision (product customization efforts). In this paper, we evaluate two pricing strategies of the 3DaaS provider: (1) Fixed-fee pricing, where the customer rents a 3D printer for a certain time period and pays a fixed-fee that is independent of the number of builds printed by the customer; and (2) Pay-per-build pricing, where the customer pays only for the number of builds they print using the 3D printer.

While prior studies have addressed vendor-client co-creation scenarios, their primary emphasis has been on investigating effort-dependent and output-dependent contract structures within B2B supply chain scenarios (Demirezen et al. 2016, 2020). Our contribution extends this body of work by shedding light on the effects of factors like the extent of product design customization and product complexity on the pricing strategies of 3DaaS firms under both fixed-fee and pay-per-build models. Additionally, existing research concerning pricing issues in supply chains considering quality co-creation has not factored in product design customization and product design failures due to increased design complexity (Avinadav et al. 2020, Basu and Bhaskaran 2018). We contribute to the above literature by providing new insights into how the degree of design customization and complexity influences the payoff of 3DaaS firm under differing pricing models.

In the 3D printing supply chain setting, there is a significant level of collaboration between the upstream firm and the customer while customizing the product design quality. Hence, it is important to understand how 3DaaS firms should set the price of each build or device in these pricing models. This important issue has not yet been addressed because the extant research has not considered such product design customization in 3D printing supply chains (Arbabian and Wagner 2020, Westerweel et al. 2018). Therefore, to gain a deeper understanding of the impact of customization on pricing strategies, we examine the following question: *How does the relative ability of supply chain players to customize the product influence the unit price* *of the product set by a 3DaaS firm?* One might expect that as the firm's relative impact on product quality increases, due to higher product quality investment, the firm should always increase the price. However, our analysis reveals that under certain conditions, an increase in the firm's impact on the product quality might also decrease the price. Our results suggest that 3DaaS firms should charge a high price if the relative ability of any of the players to customize the product is considerably high. However, if the players are equally responsible for the product customization, then 3DaaS firms should charge a relatively lower price.

In reality, customers tend to experience product design and printing-related failures while utilizing 3D printers to print complex designs. Therefore, we ask the following research question: *How does the complexity of product design impact the 3DaaS firm's pricing strategy?* Our findings indicate that for intricate designs, the optimal strategy for the firm involves setting a higher unit price (in both pricing models) when the likelihood of failure is low, and the expected use frequency of the customers is high. The above insight suggests that customers such as the design departments of large manufacturing companies, who have strong expertise in creating intricate tasks (so the probability of design failure is low) and frequently use 3DaaS for printing highly complex designs, should be offered 3DaaS at higher prices.

Since the selection of the pricing model has a significant impact on the profitability of 3DaaS firms such as HP and Carbon, we finally ask the following research question: *What is the appropriate pricing model for offering 3DaaS?* Our analysis reveals that if the extent of product design customization by users of 3DaaS is relatively high or low, the pay-per-build pricing model generates higher profits for the 3DaaS firm than the fixed-fee pricing model. If the extent of customization by users is in the moderate range, the fixed-fee pricing model generates higher profits for the firm. This suggests that when customers use 3D printing services for tasks such as standard product designs, where a 3DaaS firm provides ready-made design templates (so not much customization is needed), or highly sophisticated engineering jobs (requiring a high degree of customization by 3DaaS users), the pay-per-build pricing model might be implemented by firms.

Furthermore, the complexity of the product design plays an important role in how the 3DaaS firm decides on the pricing model. Specifically, if customers are really good at creating very complex product designs (so the chances of design failures are low), the 3DaaS firm may prefer implementing a pay-per-build pricing model. However, suppose customers print highly complex designs but face a high chance of failure, possibly because they are not as skilled or tend to experiment with new designs. In that case, the firm might prefer using a fixed-fee pricing model. Lastly, when the design complexity is low, the fixed-fee model generates higher profits for the firm. Overall, this insight suggests that as users become more skilled at handling highly intricate designs over time, the 3DaaS firm might lean toward using a pay-per-build model. However, for 3DaaS used in printing less complex structures, the fixed-fee model could be the preferred choice.

The structure of the paper is as follows. We review the extant literature in Section 2. In Section 3, we describe our analytical model. In Section 4, we present the analysis of the main model. Then, in Section 5, we consider the design complexity and product failures in the 3D printing supply chain setup. In Section 6, we present multiple model extensions. Finally, in Section 7, we conclude the paper. All proofs are included in the E-companion to this paper (see Section EC.1).

2 Literature Review

Our paper is mainly related to three streams of literature: (i) pricing issues of service, (ii) collaborations in supply chains, and (iii) operational issues in the 3D printing industry. To highlight our key contributions in these three streams, in Figure EC.1 (in the E-companion), we present the research context. Next, we discuss each of the above research streams and position our work.

2.1 Pricing Issues of Service

We refer interested readers to Kumar et al. (2018) for an excellent overview of models on pricing issues in operations management and information systems literature. Mantena and Saha (2022) study unit pricing and market share-dependent pricing in the context of healthcare procurements. Unlike them, we focus on pricing issues in 3D printing supply chains under product customization. The papers in the B2C context study pricing issues in software services. Feng et al. (2018) find that the initial quality gap between competitors in the software-as-a-service offering market impacts their subscription pricing strategy. We further contribute to the above literature by studying pay-per-build and fixed-fee pricing models in 3D printing supply chains. Chellappa and Mehra (2018) study optimal pricing under versioning of information goods. They find that marginal cost and customer's usage cost impact pricing and versioning strategy. Unlike us, they do not consider the fixed-fee pricing model. Our focus is to compare various pricing models in a 3D printing supply chain setting.

Recently, a set of papers studies pricing issues in cloud computing markets. Jain and Hazra (2019) and Saha et al. (2021) study pay-as-you-go pricing models under finite data center capacity. They provide insights into how available capacity, demand profile, and customer congestion sensitivity impact the pricing strategy. Chen et al. (2019) study a client's pricing model decision when one of the vendors offers utilization-based pricing (similar to pay-as-you-go) and another vendor offers a reservation-based pricing model. They find that under high demand volatility, the client prefers the vendor offering a utilization-based pricing model. In contrast, we study the vendor's choice of offering fixed-fee and pay-per-build pricing models.

Finally, we review a set of papers contrasting different pricing mechanisms that is closest to this work. Jain and Kannan (2002) compare subscription-based, connect-time, and search-based pricing mechanisms for databases on online servers. They show that under a high demand load, the firm may prefer a subscription-based pricing model. Cachon and Feldman (2011) study fixed-fee and pay-as-you-go pricing models under the congestion effect. They find that if customers' disutility due to congestion is high, the firm may prefer implementing a fixed-fee model. Balasubramanian et al. (2015) study usage-based and subscription-based pricing under the presence of clock-ticking effects. They show that hybrid pricing mechanism yields the highest payoff for the firm. Li et al. (2020) study selling, subscription, and mixed pricing models of digital music. They find that advertisement revenue rate impacts the music provider's selection of pricing models. On the other hand, we study fixed-fee and pay-per-build pricing models in the 3DaaS supply chain and find that the extent of product customization and degree of product design complexity impact the upstream firm's selection of pricing model. Specifically, our analysis uncovers that when customers are either highly engaged or minimally involved in customizing product design, the pay-per-build model generates higher payoffs for the 3DaaS firm. Furthermore, our results demonstrate that the adoption of a pay-per-build pricing model might be favorable for the firm only in cases of highly intricate job structures characterized by low customer failure probabilities. We provide a summary in Table EC.1 (in the E-companion) to contrast our work with the most related papers in this stream.

2.2 Collaborations in Supply Chains

We refer readers to Roels (2014) for a review of analytical models on collaboration between various supply chain players. In this stream, the papers investigating the dynamics of product design customization share relevance with our research. In an empirical study, Kumar and Telang (2011) delve into the influence of product customization on a firm's call center expenses. Their findings reveal that customers who choose a customization plan exhibit a 21 percent decrease in interactions with the call center, suggesting that customization could reduce call center costs. Lin et al. (2018) investigate the influence of online reputation mechanisms on client's vendor selection decisions for customized production in the context of online labor markets. Differing from their focus on vendor selection, our study centers on the implications of players' customization levels on the pricing of 3D printing services offered by the upstream firm. Esenduran et al. (2022) delve into the product return policy for customized products, highlighting the potential for higher payoffs if returns are allowed. In contrast, our contribution revolves around the role of customization within the 3DaaS supply chain involving the 3DaaS provider and customer. Specifically, we contribute to this stream by finding that relatively high or low user design customization might lead the 3DaaS firm to prefer a pay-per-build pricing model over a fixed-fee pricing model.

A related body of literature addresses co-creation in B2C supply chain contexts. For instance, Basu and Bhaskaran (2018) examine customer and upstream firm collaboration to enhance product quality, shedding light on its impact on product line pricing, targeting high-value and low-value customers. Avinadav et al. (2020) explore upstream co-creation between platforms and service providers, focusing on pay-as-you-go pricing for services provided to customers. Differing from them, our study centers on co-creation between downstream customers and upstream 3DaaS service providers under pay-per-build and fixed-fee pricing models. Yang et al. (2021) delve into customer-firm co-creation, aiding customers in evaluating product value precisely; however, co-creation in our model setup enhances product quality. Moreover, the above papers on B2C supply chain setup do not compare various pricing models, which we do in our paper.

Several papers study quality co-creation in B2B supply chains. Bhaskaran and Krishnan (2009) analyze different product co-development mechanisms, including cost sharing and innovation sharing, where one player invests effort while the other shares costs or both collaborate in co-creation within a vendor-client supply chain. They find that when players possess distinct capabilities, innovation sharing results in high-quality investment. In contrast, we provide implications of users' customization of product design in a 3D printing supply chain. Furthermore, our primary aim is to elucidate how product design customization influences the pricing dynamics of 3DaaS. Garg et al. (2023) explore the co-creation between an IoT platform and app developers, aiming to enhance app quality and security features under revenue-sharing contract structure. Their findings indicate that with the introduction of a new app over the platform, efforts to improve quality and security are escalated across both existing apps and the platform. Unlike us, they do not compare various pricing models between the upstream service provider and downstream customers, which is the crux of our paper.

Beer and Qi (2023) investigate the dynamics of quality co-creation in a two-stage collaboration between a focal firm and its partner. They observe that when product value is high, both entities exert high efforts, resulting in the most efficient outcome. In their setup, the firms' payoffs are linked to overall product output, mirroring scenarios where joint product development contracts tie revenue to final product sales. In contrast, in the 3D printing supply chain context, customer's payoff correlate with product quality, while the 3DaaS firm's earnings hinge on customer payments for utilizing the service. This leads us to offer new insights into the pricing dynamics of 3DaaS services and new perspectives on how product design customization and complexity impact the firm's pricing and quality investment strategies.

Rahmani et al. (2017) explore a scenario involving client-vendor co-creation under uncertain outcomes and flexible scope. They consider a time-based payment contract and find that intense collaboration tends to concentrate close to the project deadline, especially when efforts can be verified. In contrast, our focus within the 3D printing supply chain revolves around fixed-fee and pay-per-build pricing models. Gupta et al. (2023) study collaborative value co-creation between one client and two vendors under an effort-dependent payment structure. They contribute by finding conditions under which the client may prefer to add a secondary vendor along with a primary vendor (in value co-creation). Demirezen et al. (2016) study output co-creation between a client firm and a vendor firm in IT project setting. They find the conditions under which a client may prefer implementing an output-dependent contract over an effort-dependent contract (or vice versa). In another paper, Demirezen et al. (2020) consider a hybrid of effort-dependent and output-dependent contract structure. They find that the client may prefer a hybrid contract (over effort or output-dependent) if the output sensitivity to the vendor's effort is high. Differing from the aforementioned studies, our study centers on the collaborative enhancement of quality between the 3DaaS firm and customers within a B2C framework, marked by features such as product customization and design complexities. We delve into pricing structures like pay-per-build and fixed-fee, prevalent within the 3DaaS supply chain, offering insights into the circumstances favoring the adoption of each pricing model. We augment the existing literature by revealing that a relatively high or low degree of product design customization by the customer could propel the 3DaaS firm toward opting for a pay-per-build pricing model. Furthermore, increased product complexity might sway the 3DaaS firm toward embracing a pay-per-build pricing model contingent on customers facing lower design failure probability. We provide a summary in Table EC.2 (in the E-companion) to contrast our work with the papers on collaboration issues in supply chains.

2.3 Operational Issues in 3D Printing Industry

We refer readers to Olsen and Tomlin (2020) for a review of emerging issues in the area of digitization of manufacturing. We also refer readers to Guha and Kumar (2018) for a discussion of big data applications in the 3D printing industry. Song and Zhang (2020) study the design of a spare part logistics system where the spare part can be stocked or 3D printed. They find that as the cost of 3D printing reduces and the printing rate increases, the value of 3D printing increases. Further, they find that as the part variety increases, the value of 3D printing increases. Sethuraman et al. (2023) study product quality decisions in a 3D printing supply chain setting. Unlike us, they do not study fixed-fee and pay-per-build pricing models used by the upstream firm to offer 3DaaS, which is the crux of our paper. Moreover, we further contribute to the above stream by providing implications about the product design customization and complexity on the 3DaaS firm's pricing strategies and the payoff.

Westerweel et al. (2018) study a setting where a firm uses a hybrid of regular production and 3D printing technology. They find that if the 3D printing design cost is high, and if the install base (volume) is large, the customer might prefer 3D printing technology. Unlike us, they do not consider the pricing of 3D printing service. Arbabian and Wagner (2020) study the impact of 3D printing technology in a manufacturer-retailer supply chain. They find that if the 3D printing cost structure is low, then the upstream firm uses 3D printing technology. Unlike us, they do not incorporate the product quality (or design) decision by the upstream firm and downstream customers, which is one of the key features of additive manufacturing and is incorporated in our model. Further, we study the pricing of 3D printing services. Moreover, we provide interesting implications about the impact of product complexity (which may impact product failures) on the 3DaaS firm's pricing strategy. We provide a summary in Table EC.3 (in the E-companion) to contrast our work with the papers in this stream. Overall, this study contributes to the literature on additive manufacturing by focusing on the following aspects:

1. We study the pricing of 3D-as-a-service by the device provider and discuss which model is most preferred by the 3DaaS firm.
2. We characterize the quality decisions of 3DaaS firm and customers while they collaborate and decide the product quality.
3. We offer insights into how the extent of product design customization and the complexity of product design influence the pricing strategies of the 3DaaS provider.

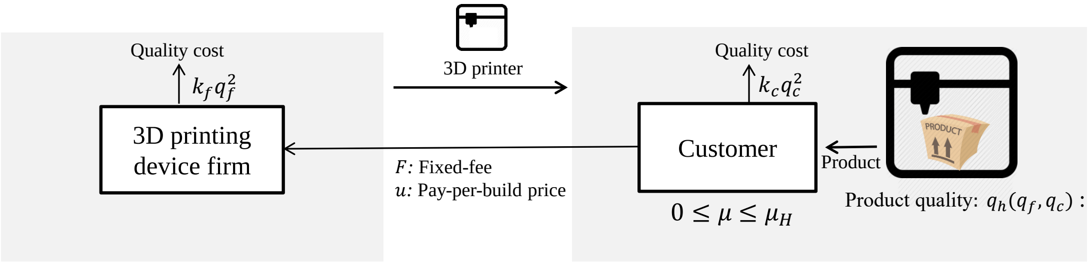


Figure 1 3D printing supply chain considered in the paper

3 Model Description

We consider a firm offering 3D printing devices to multiple customers through the 3DaaS model. The customer uses the 3D printing device to design and manufacture the product. As mentioned in Section 1.1, the supply chain setting consisting of a 3D printing service provider and the customer utilizing the printing services is realistic in practice (DHL 2023, Ben-Ner and Siemsen 2017). In real-life practice, there is a differentiation between the offerings of 3D printing service providers such as HP and Carbon. This differentiation is due to 3D printing technology, printing speed, material, and color offerings (McKenna 2016). Due to such differentiation in our model setup, we consider the monopolistic market structure where the customers prefer a specific 3DaaS vendor. However, later in Section 6.3, we relax this assumption and study a model setup considering the downstream market competition. In the following subsections, we describe the various features of the model setting that is considered in the paper. The 3D printing supply chain setting is presented in Figure 1.

3.1 Customers' Printer Usage Heterogeneity

In general, customers are heterogeneous in the usage frequency of the 3D printer to produce the final products. This is because in a particular time frame, some customers might print a large number of products using the printer, while others might print only a few products. This heterogeneity is also due to the differences in customers' business type and business requirements. The customer base showcases a wide range of clients, including an automobile manufacturer engaging in high-frequency usage by printing numerous vehicle parts, and a medical facility with low-frequency usage, occasionally printing specific devices (Carbon 2023b). Moreover, the customer usage heterogeneity is underscored by other examples in the design and engineering domain. This encompasses fields like fashion and jewelry design, where the utilization of 3D printing can differ based on design cycles and fashion collections. Similarly, within the aerospace industry, usage variation arises due to distinct use cases. Certain customers employ 3DaaS for research, while others incorporate it into regular production phases. Furthermore, the spectrum of customer usage heterogeneity is vividly illustrated in the use cases such as architectural design and cultural heritage preservation. Architectural entities' usage of 3DaaS firms varies based on the number of ongoing projects and client's demand. Please note that a single 3DaaS vendor may cater to various clients, consequently amplifying the usage heterogeneity. Therefore, in our model setting, for a particular period, we denote the usage frequency of customer *i* by μ. Customer *i*'s use frequency μ is uniformly distributed in the interval $\mu \in [0, \mu_H]$. This is consistent with previous literature (Balasubramanian et al. 2015, Bala and Carr 2010).

In general, while signing the contract with a 3D device provider, there is often a clause related to the commitment period for which the device needs to be utilized by the customer (Molitch-Hou 2023). In our paper, μ refers to the use frequency of customer *i* in this commitment period. For example, if the commitment period required by a 3DaaS firm is one year, then it is possible that a customer might print 20 objects during that year, i.e., $\mu = 20$. However, it is also possible that another customer might print 2000 objects in one year, i.e., $\mu = 2000$ for this customer.

3.2 Customers' Product Valuation

If the quality of the customized product consumed by the customer is denoted by x, then, the consumer's maximum valuation (or willingness to pay) for the product with quality level x is denoted by θx, where $\theta > 0$. The parameter θ can be interpreted as the marginal valuation of the customer for a unit increment in the product quality. In our modeling context, θx denotes the utility derived by the customer from the final printed product or the spare part. The assumption of linear utility (θx) from the product with quality x is widely utilized in literature (Moorthy 1988). We normalize the customer market size to 1. Later in Section EC.6.3, we also consider the case when the customers may be heterogeneous in valuation. We find our insights to be robust.

3.3 3D Printing-as-a-Service Pricing Models

As motivated in Section 1.1, we consider two pricing strategies used by the 3D printing device manufacturer: Fixed-fee pricing model and pay-per-build pricing model.

3.3.1 Fixed-fee Pricing Model

In the fixed-fee pricing model, the firm charges a fixed-fee, denoted by F, to the customer for renting a 3D printer. The customer uses the printer to print the product, and the net payment made by the customers to the device firm is independent of the utilization of the printer.

3.3.2 Pay-per-build Pricing Model

In the pay-per-build pricing model, the firm offering the 3D printer device charges the customers based on the number of products printed by them using the device. For each product printed by the customer, the 3D printer provider charges a unit price of u. Furthermore, the 3DaaS firm incurs the monitoring and tracking costs associated with printing-related transactions. Specifically, the firm incurs the monitoring cost denoted as τ for each printing transaction. In practice, such monitoring cost structure is necessary to uphold transparency and guarantee fair compensation for the 3DaaS service. Some examples of activities that may impact this cost structure include the maintenance of software or technology dedicated to real-time tracking of printing transactions, the necessity for travel and on-site visits to conduct thorough audits of the number of printing transactions, and the installation and maintenance of sensors within printing devices. This ensures that the reported transactions align with the actual transaction volume.

3.4 Product Quality Collaboration and Quality Cost Structure

As discussed in Subsection 1.1, in various industrial settings, the provider of the 3D printer and the customer collaborate to design the final product. In such collaboration relationships, the device firm exerts efforts toward providing 3D model design templates, designing software to transform 2D sketches into the 3D object, and providing printer-specific design software (Rayna et al. 2015, Xometry 2022). Further, the customer exerts customization efforts toward preparing the final digital models using templates, design software, and other assistance provided by the device firm (DHL 2023). This means that the design resources provided by the 3DaaS firm act as the starting point for customers to begin their design efforts and prepare the digital model. Therefore, we consider the product quality collaboration between the device provider firm and the customer.

We assume that the consumer's product quality is given by $q_h\left(q_c, q_f\right) = \alpha q_c + (1-\alpha) q_f$, where $0 \leq \alpha \leq 1$. Here, q_c and q_f are the quality investment decisions made by the customer and the firm, respectively. The parameter α can be interpreted as the relative weight of the customer's quality level of the product attained through its investment. Alternatively, α can also be construed as the proportion of overall quality ascribed specifically to the customization endeavors undertaken by the customers.

In this additive quality collaboration structure, the firm can substitute for the customer's efforts and vice versa. Such collaboration structure might make sense in 3D printing design modeling because, on one extreme, the firm may prepare and provide the 3D modeling files (i.e., $\alpha = 0$ and $q_h = q_f$), or on another extreme, the customer may prepare the entire 3D modeling file and print it (i.e., $\alpha = 1$ and $q_h = q_c$). If $0 < \alpha < 1$, both parties contribute to the final design (i.e., the firm may provide initial model files via accompanying software, subsequently enabling customers to undertake additional customization of these initial files and thereby finalize the design). The previous literature also considers similar quality collaboration structure (Roels 2014, Roels et al. 2023). Later, as a robustness check in a model extension (see Section 6.1), we also present the analysis of the output function where efforts by both players complement each other.

Further, the customer and firm incur the quality investment costs given by κq_c^2 and κq_f^2, respectively. The assumption of the quadratic quality cost makes sense in our problem context. While designing the product, during the initial phases, the quality cost is low. However, due to various hidden issues in product design, the quality improvement cost is considerably high during the later stages. This assumption is consistent with the previous literature (Sethuraman et al. 2023, Basu and Bhaskaran 2018). For example, in the context

Notation	Description	Section
μ	Usage frequency of customer i. Usage frequency μ follows Uniform$(0,\mu_H)$.	Main model
θ	Consumer's marginal valuation towards product quality	Main model
q_c	Product quality investments by the customer	Main model
κ	Quality cost investment parameter	Main model
F	Fixed-fee per printer charged by the 3DaaS firm	Main model
u	Unit pay-per-build price charged by the 3DaaS firm	Main model
q_h	Net product quality due to collaboration	Main model
α	Extent of product design customization by customers	Main model
q_f	Product quality investments made by the 3DaaS firm	Main model
U_c	Customer utility function	Main model
D_{3D}	Demand for 3D printing devices	Main model
Π_{3D}	3DaaS firm's payoff	Main model
CS	Customer surplus	Main model
β	Product complexity parameter	Section 5
λ	Product failure probability parameter	Section 5
q_{cL}	Quality investments by low-usage type customers	Section 6.2
q_{cH}	Quality investments by high-usage type customers	Section 6.2
A	Usage frequency of low-usage type customers	Section 6.2
$A+\mu$	Usage frequency of high-usage type customers	Section 6.2
R_0	Customer's outside option net value	Section 6.3

Table 1 Summary of key notations

of 3D printing design modeling, it is relatively easy to set up an initial work plan, adding basic shapes, merging different shapes, and adding colors. However, later, in the design phase, fine-tuning the design file is quite complex. Furthermore, allocating quality cost in a divided structure (where $\kappa q_c^2 + \kappa q_f^2$ constitutes the total quality cost) also aligns with business practice. This is because, after the firm exerts initial quality effort and provides preliminary design files, augmenting the overall product quality through the customer's customization endeavors may entail comparatively lower costs. This cost reduction is attributed to the customer's possession of specialized knowledge and enhanced comprehension of distinct business requisites (Thomke and Von Hippel 2002). With their profound understanding, customers are equipped to fine-tune the design files (Rayna and Striukova 2016). In contrast, generic 3DaaS providers may lack the industry-specific insights possessed by customers, which could result in excessively intricate designs if efforts are intensified, consequently contributing to elevated expenses.

3.5 Sequence of Events

In practice, the 3DaaS firm exerts efforts to prepare 3D modeling templates and announces its pricing strategy. For example, HP has invested upfront in 3D modeling utility software, known as HP Smart Stream 3D Build Manager (HP 2023a). Furthermore, before the customers make the purchase decision, HP upfront posts its pricing strategy (HP 2023a,b). In response, the customer utilizes the 3D modeling utility to prepare the final design and print it using HP's 3DaaS service. Therefore, the timeline of the game played by the 3DaaS firm, and customers is as follows:

- **Event 1 (3DaaS firm's pricing and quality investment):** The 3DaaS firm decides the prices and the product quality investment (q_f) in both pricing models.
- **Event 2 (Customer purchase and design investment):** The customer decides whether to opt for the firm's 3DaaS offering and the quality collaboration investment (q_c).

Please note, such a sequential quality investment game structure where the follower invests after observing the quality efforts of the leader, is commonly considered (Avinadav et al. 2020). A summary of notations is provided in Table 1. In Table 1, please note that we have also included additional notations used in various model extensions. However, a detailed discussion on each of these new notations is provided while explaining the setup of the particular extension later in the corresponding section. We now present the model analysis.

4 Main Model Analysis

In this section, we present the analysis of the fixed-fee pricing model and pay-per-build pricing model in Sections 4.1 and 4.2, respectively.

4.1 Fixed-fee Pricing Model

In this setting, the firm charges the customer a fixed-fee F and rents out the printer. The customer, with use frequency μ, designs and prints μ units using the printer. The customer derives utility $\mu\theta q_h(q_c, q_f)$ and incurs the total design cost of $\mu\kappa q_c^2$ toward designing μ items. The utility of the customer is given by $U_c = \mu\theta q_h(q_c, q_f) - \mu\kappa q_c^2 - F$, where $q_h(q_c, q_f) = \alpha q_c + (1-\alpha)q_f$. This utility function is concave in q_c. Therefore, after solving the first-order condition, we get equilibrium quality investment given by $q_c^* = \frac{\alpha\theta}{2\kappa}$. Thus, the utility derived by the customer with use frequency μ is given by $U_c^* = \frac{\alpha^2\theta^2\mu}{4\kappa} + (1-\alpha)\theta\mu q_f - F$. Now, the demand for 3D printing devices D_{3D} is given by:

$$D_{3D} = \Pr(U_c^* \geq 0) = 1 - \frac{4F\kappa}{\theta\mu_H(\alpha^2\theta + 4(1-\alpha)\kappa q_f)}.$$

From the above expression, we see that as the fixed-fee F increases, the demand for 3D printing devices decreases. The profit function of the 3D printing service provider firm is given by:

$$\Pi_{3D} = FD_{3D} - \kappa q_f^2 = F\left(1 - \frac{4F\kappa}{\theta\mu_H(\alpha^2\theta + 4(1-\alpha)\kappa q_f)}\right) - \kappa q_f^2.$$

In the above formulation, the first term denotes the revenue earned and the second term denotes the quality cost. In Lemma 1, we state the equilibrium fixed-fee and the quality efforts by the 3DaaS firm.

LEMMA 1. *The optimal fixed-fee F^*, and the efforts made by the firm q_f^* are given by:*

$$F^* = \frac{\theta^2\mu_H(2\alpha^2 + (1-\alpha)^2\mu_H)}{16\kappa}, \text{and } q_f^* = \frac{(1-\alpha)\theta\mu_H}{8\kappa}.$$

From Lemma 1, we find that as the expected usage frequency of the 3D printing device $\left(\frac{\mu_H}{2}\right)$ increases, the fixed-fee and the firm's efforts increase. Next, in Proposition 1, we study the impact of the collaboration parameter α on the equilibrium quality and pricing decision.

PROPOSITION 1. *The following are true about the impact of the collaboration parameter α on the fixed-fee (F^*), quality investment $\left(q_f^*\right)$, firm's payoff (Π_{3D}^*), and customer surplus (CS^*):*

(a) As the relative impact of the customer (α) *increases, the firm's quality investment decreases (i.e.,* $\frac{\partial q_f^*}{\partial \alpha} < 0$*).*

(b) As α *increases, the fixed-fee increases if and only if* α *is above a threshold; otherwise, the fixed-fee decreases (i.e.,* $\frac{\partial F^*}{\partial \alpha} \geq 0 \Leftrightarrow \alpha \geq \alpha_{th1}$*).*

(c) As α *increases, the firm's payoff and customer surplus decrease if and only if* α *is below a threshold value (i.e.,* $\frac{\partial \Pi_{3D}^*}{\partial \alpha} < 0 \Leftrightarrow \alpha < \alpha_{th2}$*, and* $\frac{\partial CS^*}{\partial \alpha} < 0 \Leftrightarrow \alpha < \alpha_{th1}$*).*

Since the impact of firm's efforts on overall product quality decreases with increase in α (i.e., $\frac{\partial^2 q_h}{\partial q_f \partial \alpha} < 0$), in Proposition 1(a), we observe that higher α motivates the firm to reduce its efforts (i.e., $\frac{\partial q_f^*}{\partial \alpha} < 0$). Interestingly in Proposition 1(b), we find that as the impact of the 3DaaS firm in enhancing the quality decreases (i.e., α increases), the fixed-fee decreases until a threshold value, after which it increases. As observed in Proposition 1(a), the 3DaaS firm tends to invest high in quality when α is low (i.e., $\frac{\partial q_f^*}{\partial \alpha} < 0$), therefore, due to high investment, it charges a higher fixed-fee if and only if α is low (i.e., $\alpha < \alpha_{th1} \Leftrightarrow \frac{\partial F^*}{\partial \alpha} < 0$). However, when α is high, due to higher relative impact, the customer tends to invest high in quality (i.e., $\frac{\partial q_c^*}{\partial \alpha} > 0$). Due to high investment, since the customer can extract high value from the 3D printer (due to the high quality of the designed product), the device provider strategically increases the fixed-fee in a high range of α (i.e., $\alpha \geq \alpha_{th1} \Leftrightarrow \frac{\partial F^*}{\partial \alpha} \geq 0$).

Since the fixed-fee charged by the firm is high if α is relatively high or low, therefore in Proposition 1(c), we find that the firm's payoff is also high (i.e., $\frac{\partial \Pi_{3D}^*}{\partial \alpha} \geq 0 \Leftrightarrow \alpha \geq \alpha_{th2}$). Moreover, when α is high, due to the high product quality investment made by the customer, the customer surplus is high (i.e., $\frac{\partial CS^*}{\partial \alpha} \geq 0 \Leftrightarrow \alpha \geq \alpha_{th1}$). However, when α is relatively low, the quality investment made by the firm is high (since $\frac{\partial q_f^*}{\partial \alpha} < 0$), which also leads to a high customer surplus.

Interestingly, we find that as the average use frequency $\left(\frac{\mu_H}{2}\right)$ increases, the threshold values (α_{th1} and α_{th2}) increase. Further, as μ_H tends to a relatively large value, the threshold value tends to 1. This implies that, if the expected use frequency is relatively high, then as α increases, the optimal fixed-fee always decreases. Since the customer incurs design costs for each printed product, it will incur a high design cost structure if the expected use frequency is high. In order to motivate customers to opt for the 3D printing service, the firm charges a low fixed-fee when μ_H is high.

Previous research in a vendor-client co-creation setup has analyzed the impact of collaboration dynamics on the effort/output-dependent payment structures (Demirezen et al. 2016, 2020). For example, Demirezen et al. (2016) find that optimal payment (dependent on overall output) is strictly decreasing in the client's relative impact on output. In contrast, in a fixed-fee-based pricing mechanism, we find that if the customer's relative impact is high or low, it may result in higher fixed-fee payments. Overall, we contribute to previous literature by adding new insights on firm-customer collaboration dynamics in a 3D printing supply chain under fixed-fee and pay-per build pricing structure.

Our results have some implications for business practice. Based on our insight, the 3DaaS providers need to understand the collaborative dynamics of product design and the customer use-frequency while pricing 3DaaS services. If the degree of customization by the users of 3DaaS is relatively low or high, the 3DaaS firm should charge a high price. However, based on the above discussion, they should not set high price, when the expected printing requirements are high, even if the relative impact of the customer on the product design is high.

4.2 Pay-per-build Pricing Model

The customer with use frequency μ derives $\theta q_h(q_c, q_f)$ utility, incurs $\mu\kappa q_c^2$ as product design cost, and pays μu as printing charges. The net utility of the customer is given by:

$$U_c = \mu\theta q_h(q_c, q_f) - \mu u - \mu\kappa q_c^2,$$

where $q_h(q_c, q_f) = \alpha q_c + (1-\alpha) q_f$. Since this utility function is concave in q_c, by solving the first-order condition, we get $q_c^* = \frac{\alpha\theta}{2\kappa}$. Therefore, the utility of customer is given by $U_c^* = \frac{\alpha^2\theta^2\mu}{4\kappa} + (1-\alpha)\theta\mu q_f - \mu u$. The customer opts for 3DaaS if and only if $U_c^* \geq 0 \Longrightarrow \frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}{4\kappa} \geq u$. Therefore, when $\frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}{4\kappa} \geq u$, the expected number of units printed by the customer is given by $E_\mu[\mu] = \frac{\mu_H}{2}$. However, if $\frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}{4\kappa} < u$, the number of units printed is 0. Hence, the firm must set the product price $u^* = \frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}{4\kappa}$ to extract the entire customer surplus. Now, given q_f, the expected payoff of the 3DaaS firm is given by:

$$\Pi_{3D} = u^*\left(E_\mu[\mu]\right) - \kappa q_f^2 - \tau\left(E_\mu[\mu]\right).$$

In the above formulation, the first term denotes the firm's expected revenue due to on-average $E_\mu[\mu]$ units designed and printed by customers. The second term denotes the fixed cost of product design. Finally, the last term denotes the expected cost of monitoring transactions. Next, in Lemma 2, we characterize the equilibrium quality efforts made by the firm and the unit pay-per-build price.

LEMMA 2. *The optimal pay-per-build price u^*, and the efforts made by the firm q_f^* are given by:*

$$u^* = \frac{\theta^2\left(\alpha^2 + (1-\alpha)^2\mu_H\right)}{4\kappa}, \textit{and } q_f^* = \frac{(1-\alpha)\theta\mu_H}{4\kappa}.$$

Similar to the fixed-fee pricing model, we find that as the expected number of units printed by the customer increases, both unit price and the firm's quality investment increase. Interestingly, we find that the firm's quality investment is higher in the pay-per-build model compared to the fixed-fee model.

Due to the higher impact of the customer on the overall product quality, as α increases, the quality investment made by the 3DaaS firm decreases. Further, we find that the impact of α on the pricing strategy is similar to that in the fixed-fee pricing model (as seen earlier in Proposition 1(b)). Moreover, similar to Proposition 1(c), we find a *u*-shaped relationship between the firm's payoff and the collaboration parameter α. The intuition is similar to our discussion in Proposition 1. Interestingly, unlike the fixed-fee pricing model, the consumer surplus is not impacted by α. The reason is, in the pay-per-build pricing model, the upstream firm completely extracts the customer surplus. This is because the pay-per-build pricing model perfectly discriminates customers based on use frequency.

As discussed in Section 1.1, it is important to understand which pricing model is appropriate for 3DaaS firms such as HP and Carbon. Therefore, in Proposition 2, we compare the firm's payoff in both pricing models.

PROPOSITION 2. *If the product customization parameter α is between two thresholds (i.e, $\dot{\alpha} \leq \alpha \leq \ddot{\alpha}$), the firm's payoff under fixed-fee model is higher compared to that under pay-per-build pricing model. Otherwise, if α is below a lower threshold (i.e., $\alpha < \dot{\alpha}$) or α is above a higher threshold (i.e., $\alpha > \ddot{\alpha}$), the firm's payoff under pay-per-build pricing model is higher compared to that under fixed-fee pricing model.*

One may expect that since the firm charges a fixed amount under the fixed-fee model (even if customer use frequency is low), the firm's payoff under the fixed-fee pricing model may always be higher as compared to the pay-per-build pricing model. Interestingly, this is not always the case. Specifically, we find that when the relative impact of either the customer or the firm on product quality is high (i.e., $\alpha > \ddot{\alpha}$ or $\alpha < \dot{\alpha}$), implementing a pay-per-build pricing model yields higher payoff for the firm. When α is high, the resultant product quality is high due to the high efforts exerted by the customer (since, $\frac{\partial q_c^*}{\partial \alpha} > 0$). Consequently, the firm sets a high unit price under the pay-per-build pricing model. The higher demand and high unit price under the pay-per-build model lead to higher profit (in contrast to the fixed-fee pricing model). Conversely, when α is low, the product quality is again high, primarily due to the high firm's effort leading to a higher price of 3DaaS. However, the firm's quality effort under the pay-per-build model is higher compared to fixed-fee (see the discussion of Lemma 2), leading to a high unit price under the pay-per-build model, overall leading to higher payoffs (compared to the fixed-fee pricing model).

Next, in the intermediate range of α (i.e., $\dot{\alpha} \leq \alpha \leq \ddot{\alpha}$), overall product quality is low due to relatively lower investments by players. Therefore, while offering 3DaaS via a pay-per-build pricing model, the firm needs to set a relatively low unit price due to the lower value gained by the customers. However, under the fixed-fee pricing model, the firm sets a relatively high fixed-fee (F^*) to screen high-use frequency customers (as they gain high value due to the consumption of multiple prints), leading to a relatively higher payoff compared to the pay-per-build pricing model.

Earlier literature on pricing issues in service supply chain find that factors like high customers' congestion disutility (which may be prominent in the industry, such as cloud computing), low ticking meter effects (which may be present for utilities), and high demand volume may motivate customers to prefer fixed-fee pricing model (Jain and Kannan 2002, Cachon and Feldman 2011, Balasubramanian et al. 2015). We further contribute to the above stream by finding out that the extent of players' customization while designing the product quality impacts the 3DaaS firm's decision regarding the pricing model. Specifically, we find that when both the customer and the firm have a relatively similar impact on product quality, the fixed-fee model results in a higher profit for the 3DaaS firm.

5 Impact of Design Complexity and Failure Rate on 3DaaS Pricing

One of the primary challenges encountered by customers utilizing 3D printing services is the elevated failure rate of jobs with a higher degree of complexity. The intricacy of these jobs significantly heightens the likelihood of failures, prompting customers to engage in multiple attempts at designing and printing until a viable, usable version is ultimately achieved. Therefore, we modify the main model of our paper and consider a setup where customers may experience product design failures while designing complex jobs. In this setup, the customer designing a job with level of complexity denoted by β may experience product failure with probability $\lambda\beta$ (and $(1-\lambda\beta)$ denotes the probability of the customer being successfully able to print a complex product design). In other words, the job with higher degree of complexity has higher probability of product failure.

Typically, highly complex designs tend to have sophisticated geometry, sometimes making it extremely difficult to print fully functional designs. Such complex architectures are typically printed for application areas like automobile engineering, construction design, and biomedical engineering. A few examples of such complex designs are brake calipers, hip implants, and turbine components (AMFG 2023). Even though highly complex jobs may have a higher probability of failure, a successful print of complex design generates higher value to customers due to better functionality and higher benefits. Therefore, to incorporate such benefits, we denote the final product quality of design with complexity β by $\beta q_h(q_c, q_f)$, where $\beta \geq 1$, i.e., successfully printed complex designs also generate higher value for customers. Furthermore, in our setup, the customers incur liability costs in the event of product failure. We denote l as unit liability cost in case a product failure is experienced by the customer. This cost reflects the potential harm caused by a defective printed product to the user (Iliff 2017). The customer with a usage frequency denoted by μ, is required to print μ functional jobs. In the event of job failure, which is more likely for jobs with higher complexity, the customer must reattempt the printing process. As a result, the expected total number of jobs printed by this customer, with use frequency μ, can be expressed as $\frac{\mu}{1-\lambda\beta}$ (ensuring the final acquisition of μ fully functional jobs). Similar to our analysis in Section 4, next, we try to understand the implications of product complexity on pricing strategy under both mechanisms.

5.1 Fixed-fee Pricing Model

The customer's utility derived from consuming a job with complexity level β, given their use frequency μ, is given by $\theta\beta q_h(q_c, q_f)\mu$. Nevertheless, to achieve the desired μ jobs, the customer is expected to design and print a total of $\frac{\mu}{1-\beta\lambda}$ units, leading to an expected design cost of $\left(\frac{\mu}{1-\beta\lambda}\right)\kappa q_c^2$. Since the expected number of failed units is $\frac{\mu}{1-\beta\lambda} - \mu$, the net liability incurred by the customer can be expressed as $l\left(\frac{\mu}{1-\beta\lambda} - \mu\right)$. Overall, the utility of customers under the fixed-fee model is as follows: $U_c = \theta\beta q_h(q_c, q_f)\mu - \left(\frac{\mu}{1-\beta\lambda}\right)\kappa q_c^2 - l\left(\frac{\mu}{1-\beta\lambda} - \mu\right) - F$. Similar to our previous analysis, we could show that the equilibrium quality investment by the customer is given by $q_c^* = \frac{\alpha\beta\theta(1-\beta\lambda)}{2\kappa}$. It is easy to see that if the product complexity (β) is low (i.e., $\beta < \frac{1}{2\lambda}$), then further increase in complexity leads to higher quality investment (i.e., $\frac{\partial q_c^*}{\partial \beta} > 0$). Next, we maximize 3DaaS firm's profit function and characterize the equilibrium fixed-fee and quality investment in Lemma 3.

LEMMA 3. *The equilibrium fixed-fee F^* and quality investment q_f^* by the firm when faced with customers printing jobs with complexity β, are given by:*

$$F^* = \frac{\beta\mu_H\left(2\alpha^2\beta\theta^2(1-\beta\lambda)^2 + (1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H - 8\kappa\lambda l\right)}{16\kappa(1-\beta\lambda)}, \text{and } q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{8\kappa}.$$

Similar to the main model, we find that a higher relative impact of customers (α) on product quality leads to lower quality investment by the firm (i.e., $\frac{\partial q_f^*}{\partial \alpha} < 0$). Moreover, as α increases, the fixed-fee increases if and only if α is above a threshold, which is consistent with our analysis in Section 4.1. Furthermore, it is observed that with an increase in β, the threshold value of α also rises, indicating that when customers are dealing with highly complex products (where β is high), the 3DaaS firm opts to decrease the fixed-fee within a high range of α. As the likelihood of product failure λ increases, the quality investment by the customer decreases (i.e., $\frac{\partial q_c^*}{\partial \lambda} < 0$). Therefore, due to lower value gained by customers (due to lower product quality), the fixed-fee charged by the firm decreases (i.e., $\frac{\partial F^*}{\partial \lambda} < 0$). Next, in Proposition 3, we study the impact of product complexity parameter β.

PROPOSITION 3. *The following are true about the impact of product complexity parameter β under fixed-fee pricing model:*

(a) As the product complexity increases, the firm's quality investment increases (i.e., $\frac{\partial q_f^*}{\partial \beta} > 0$). Furthermore, an increase in product complexity leads to an increase in fixed-fee if and only if the expected use frequency is above a threshold value (i.e., $\mu_H \geq \ddot{\mu}_H \Leftrightarrow \frac{\partial F^*}{\partial \beta} \geq 0$).

(b) As the product complexity parameter increases, the firm's payoff and customer surplus increase if and only if the expected use frequency is above a threshold (i.e., $\mu_H \geq \widehat{\mu_H} \Leftrightarrow \frac{\partial \Pi_{3D}^*}{\partial \beta} \geq 0$, and $\mu_H \geq \ddot{\mu}_H \Leftrightarrow \frac{\partial CS^*}{\partial \beta} \geq 0$).

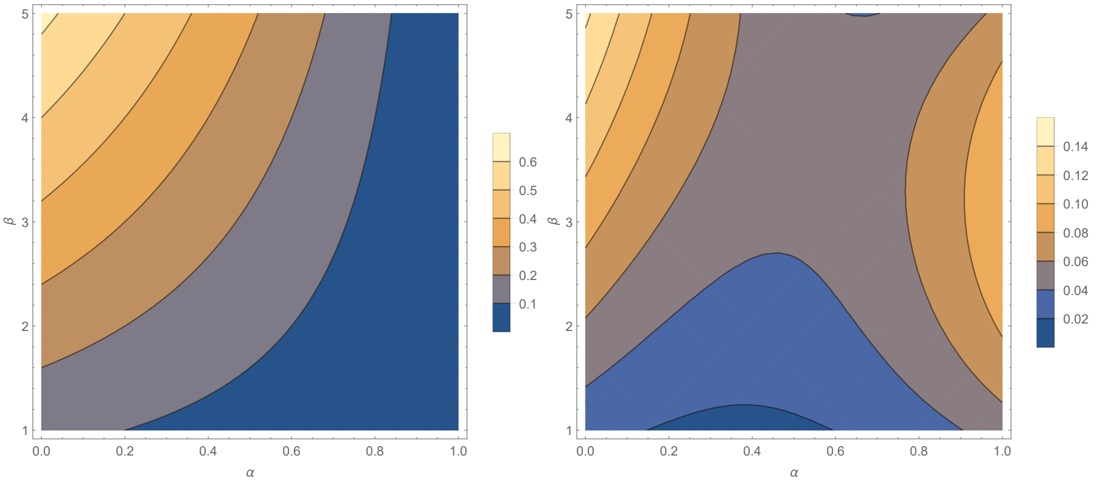
Proposition 3 provides some insights into how a 3DaaS firm should tailor its pricing and quality investment strategy depending on the complexity of jobs printed by customers. According to Proposition 3(a), the 3DaaS firm always benefits by increasing the fixed-fee with an increase in product complexity. By making high quality investment for highly complex jobs, the 3DaaS firm strategically stimulates customers toward purchasing its services, thereby seeking to boost market demand. On the contrary, should it opt to reduce quality investment for such intricate jobs, customers may be deterred from selecting 3DaaS due to apprehensions regarding elevated design costs and increased liability expenses associated with handling highly complex job structures.

Interestingly, the 3DaaS firm benefits by increasing the fixed-fee with an increase in product complexity as long as the customer's expected use frequency is above a threshold (i.e., $\mu_H \geq \ddot{\mu}_H$). The intuition is, only if the expected use frequency is high, the customer derives high utility from all successfully printed jobs (given by $\mu\theta\beta q_h$); therefore, the firm charges a high fixed-fee from the customer printing highly complex design (which also has high quality due to high firm's investment). Moreover, in Proposition 3(b), we observe that when μ_H exceeds a certain threshold (i.e, $\mu_H \geq \widehat{\mu_H}$), and β is high, due to higher fixed-cost charged by firm (i.e, $\frac{\partial F^*}{\partial \beta} \geq 0$), the payoff of the firm is high (i.e, $\frac{\partial \Pi^*_{3D}}{\partial \beta} \geq 0$). Furthermore, due to high quality investment made by the firm toward highly intricate designs (i.e., $\frac{\partial q^*_f}{\partial \beta} > 0$), and higher value derived from the extensive utilization of 3DaaS for printing intricate job structures (since $\frac{\partial \theta\beta q_h\left(q_c, q_f\right)\mu}{\partial \mu} > 0$), the overall surplus of customers engaging in the printing of highly complex tasks is high only if the customers' expected use frequency is high (i.e., $\mu_H \geq \ddot{\mu}_H \Leftrightarrow \frac{\partial CS^*}{\partial \beta} \geq 0$).

We could show that the threshold of expected use frequency is increasing in λ (i.e., $\frac{\partial \ddot{\mu}_H}{\partial \lambda} > 0$), consequently, implying that if λ is below a threshold, then the firm increases fixed-fee with an increase in complexity (i.e., $\frac{\partial F^*}{\partial \beta} \geq 0$). Conversely, if λ is high (above a threshold), the fixed-fee decreases with an increase in product complexity (i.e., $\frac{\partial F^*}{\partial \beta} < 0$). Please note when λ is low, the product failure probability is low. Since the highly complex job generates higher value for the firm, when λ is low, the number of repetitions required to print a fully functional high-complexity job would be low, motivating the firm to increase fixed-fee with an increase in job complexity. Based on above discussion, the 3DaaS firm may consider charging a higher fixed-fee to customers who print exceedingly intricate job structures. However, this approach is reasonable only if these customers exhibit a high frequency of use and encounter minimal product failure probabilities. Notably, this category of clients often includes the Research and Development (R&D) divisions of automotive or biomedical enterprises. Such divisions frequently explore numerous intricate designs, therefore, possessing a high level of expertise that mitigates the likelihood of design failures. Given that a subset of these complex designs may yield substantial value for these customers, the 3DaaS firm could impose a high fixed-fee.

Next, we provide a visual representation of the impact of parameters α and β on both fixed-fee pricing and the firm's quality investment in Figure 2. When α is low and β is high, we observe high quality investment by the firm (see Figure 2(a)). Further, in Figure 2(b), we observe that as α increases, fixed-fee decreases until a threshold post which it increases (consistent with discussion of Lemma 3) . When α is high, as β increases, the fixed-fee increases until a threshold post which it deceases. This is because, as discussed earlier, the customer increases quality investment with an increase in β only when β is below a threshold (i.e, $\beta < \frac{1}{2\lambda} \Leftrightarrow \frac{\partial q^*_c}{\partial \beta} > 0$), implying that at a relatively low or high range of β, the customer invests low in quality, motivating the firm to set a low fixed-fee. However, when α is low, due to an increase in the firm's quality investment (i.e., $\frac{\partial q^*_f}{\partial \alpha} < 0$), an increase in β leads to an increase in the fixed-fee.

The past literature dealing with product complexity-related issues has mainly focused on identifying potential reasons for product failure and evaluating the impact of such failures on supply chains (Marucheck et al. 2011). For example, Mackelprang et al. (2015) empirically examine the effects of product innovativeness on product failure. Kirshner et al. (2017) study the implications of product failure on product upgrades.



(a) Firm's product quality investment (b) Firm's fixed-fee

Figure 2 Impact of collaboration parameter α and product complexity parameter β on fixed-fee and 3DaaS firm's product quality investment. Please note that different color shades in the above figure represent the magnitude of equilibrium strategies. Specifically, the darker shades in Figures 2(a) and 2(b) represent lower magnitudes of the firm's quality investments and fixed-fee, respectively. Base parameter values: $\lambda = 0.1$, $l = 0.25$, $\theta = 1$, $\kappa = 1$, and $\mu_H = 1$.

However, unlike us, none of the prior studies have discussed the implications of product complexity and product failure on pricing in the 3D printing supply chain.

5.2 Pay-per-build Pricing Model

Similar to the fixed-fee pricing model, the customer with use frequency μ, derives value from μ successful prints and incurs design cost given by $\left(\frac{\mu}{1-\beta\lambda}\right)\kappa q_c^2$. Furthermore, the customer also incurs expected liability costs given by $l\left(\frac{\mu}{1-\beta\lambda}-\mu\right)$ due to $\left(\frac{\mu}{1-\beta\lambda}-\mu\right)$ expected number of failures. Therefore, the utility of the customers with use frequency μ under the pay-per-build pricing model is given by: $U_c = \theta\beta q_h(q_c,q_f)\mu - \left(\frac{\mu}{1-\beta\lambda}\right)\kappa q_c^2 - l\left(\frac{\mu}{1-\beta\lambda}-\mu\right) - \left(\frac{\mu}{1-\beta\lambda}\right)u$. We find that the equilibrium quality efforts by the customer are given by $q_c^* = \frac{\alpha\beta\theta(1-\beta\lambda)}{2\kappa}$. In Lemma 4, we state the firm's equilibrium pay-per-build price and quality investment.

LEMMA 4. *The equilibrium pay-per-build price u^*, and quality investment q_f^* by the firm when faced with customers printing jobs with complexity β, are given by:*

$$u^* = \frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2 + (1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H - 4\kappa\lambda l\right)}{4\kappa}, \textit{and } q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{4\kappa}.$$

We find that the impact of the customization parameter α is similar to that observed in the main model. Moreover, similar to our discussion in the main model, the firm invests high in quality under the pay-per-build pricing model (compared to the fixed-fee pricing model). Next in Proposition 4, we study the impact of product complexity parameter β.

PROPOSITION 4. *The following are true about the impact of product complexity parameter β under pay-per-build pricing model:*

(a) As the product complexity increases, firm's quality investment increases (i.e., $\frac{\partial q_f^*}{\partial \beta} > 0$*). Furthermore, if the product failure probability parameter is above a threshold (i.e.,* $\lambda > \frac{2}{3\beta}$*), higher product complexity leads to lower unit pay-per-build price (i.e.,* $\frac{\partial u^*}{\partial \beta} < 0$*). Otherwise, if the product failure probability parameter is below a threshold (i.e.,* $\lambda \leq \frac{2}{3\beta}$*), then an increase in product complexity leads to an increase in unit pay-per-build price if and only if the expected use frequency of the customer is high (i.e.,* $\mu_H \geq \ddddot{\mu}_H \Leftrightarrow \frac{\partial u^*}{\partial \beta} \geq 0$*).*

(b) As the product complexity increases, the firm's payoff increases if and only if μ_H *is above a threshold (i.e.,* $\mu_H \geq \acute{\mu}_H \Leftrightarrow \frac{\partial \Pi_{3D}^*}{\partial \beta} \geq 0$*).*

Similar to our observation from Proposition 3, we find that under the pay-per-build pricing model, high complexity faced by customers leads to an increase in the firm's quality investment. Moreover, similar to our discussion in Proposition 3(a), we find that high product complexity β may result in an increase or decrease in unit pay-per-build price. Specifically, we find that when λ is above a threshold (i.e., $\lambda > \frac{2}{3\beta}$), due to customers' reduced inclination to invest in highly complex jobs (i.e., $\frac{\partial q_c^*}{\partial \beta} < 0$), the 3DaaS firm decreases unit pay-per-build price to motivate customers to opt for 3DaaS. However, when the product failure rate is relatively low (λ is below a threshold, i.e., $\lambda \leq \frac{2}{3\beta}$), the firm increases the unit pay-per-build price charged for highly complex jobs, when the customers' expected use frequency falls above a specific threshold (i.e., $\mu_H \geq \ddddot{\mu}_H$).

This is because, when λ is below a threshold, higher complexity motivates both firm and customer to invest high. Moreover, only when the expected usage by the customer is high, due to the high value gained by customers from multiple highly-complex high-quality prints, the firm increases the unit price. Next, similar to Proposition 3(b), we could show that higher complexity leads to a higher firm's payoff if and only if the expected use frequency is above a threshold. The intuition is similar to our discussion of Proposition 3(b). Overall, the 3DaaS firm must consider failure probability, expected customers' usage, and the magnitude of product complexity while designing the pay-per-build pricing strategy. Next, in Proposition 5, we compare the firm's payoff under both pricing models.

PROPOSITION 5. *If the product customization parameter* α *is between two thresholds (i.e.,* $\ddot{\alpha}(\beta) \leq \alpha \leq \ddddot{\alpha}(\beta)$*), the firm's payoff under the fixed-fee model is higher compared to that in the pay-per-build pricing model. Otherwise, if* α *is below a lower threshold (i.e.,* $\alpha < \ddddot{\alpha}(\beta)$*) or* α *is above a higher threshold (i.e.,* $\alpha > \ddot{\alpha}(\beta)$*), the firm's payoff under pay-per-build pricing model is higher compared to that in the fixed-fee pricing model.*

Similar to the main model in Proposition 5, we find that if the extent of the product design customization by 3DaaS users is relatively high or low (i.e., α is relatively high or low), the firm's payoff under pay-per-build pricing model is higher as compared to that in the fixed-fee pricing model. However, if the extent of customization is in the moderate range (i.e., α is in the medium range), the fixed-fee model generates a higher firm's payoff. The intuition is similar to our discussion of Proposition 2.

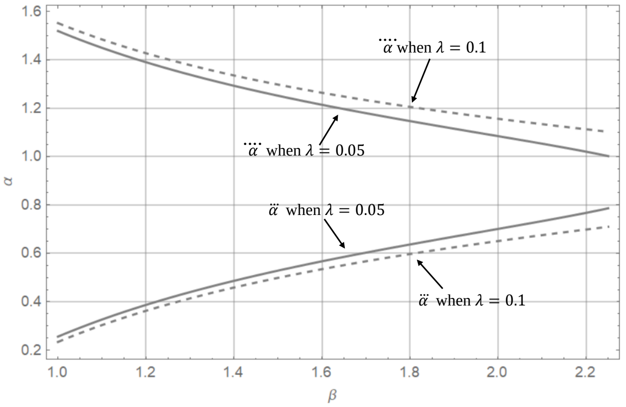


Figure 3 Impact of β and λ on thresholds obtained in Proposition 5

Base parameter values: $\alpha = 1/2$, $\tau = 1/2$, $l = 0.01$, $\theta = 1$, $\kappa = 1$, and $\mu_H = 10$.

In Figure 3, we illustrate the impact of product complexity and failure rate parameters (β and λ) on the threshold characterized in Proposition 5. Please note that when $\beta = 1$ and $\lambda = 0$, the threshold reduces to that characterized in Proposition 2. We observe that as β increases, the higher threshold reduces, but the lower threshold increases, signaling a decrease in the difference between the thresholds (with an increase in β). As a result, with an increase in product complexity, the firm leans towards implementing a pay-per-build pricing model for a larger range of α ($\alpha > \ddot{\alpha}(\beta)$ and $\alpha < \ddddot{\alpha}(\beta)$). This choice stems from the firm's strategy of setting a higher pay-per-build price for customers deriving substantial value from printing products with a high degree of complexity. Additionally, as the design failure rate (λ) increases, the higher threshold rises, whereas the lower threshold falls (indicating an increase in the difference between thresholds with an increase in λ). Consequently, in situations where the product failure probability is high, the firm tends to prefer fixed-fee model for a broader range of α ($\ddot{\alpha}(\beta) \leq \alpha \leq \ddddot{\alpha}(\beta)$). The rationale behind this preference is the firm's inclination to set a higher fixed-fee, aiming to capture high-usage frequency customers who still perceive significant value despite the elevated failure risks.

Next, we try to understand the role of product complexity parameter on the 3DaaS firm's choice of pricing model. We also present a visual representation of the payoff comparison across different ranges of λ and β, depicted in Figure EC.2 in the E-companion. We observe that when λ is low, the 3DaaS firm prefers pay-per-build pricing model if and only if the product complexity parameter (β) is above a threshold. However, when λ is in the high range, the 3DaaS firm prefers the pay-per-build pricing model if and only if the product complexity parameter β is between two threshold values.

The reason is when the product has a low failure probability (λ is low), higher complexity leads to higher quality investments by the firm and customer, overall making the printed product highly valuable for the customers. Therefore, when β is high, the firm charges a high unit pay-per-build price to all customers in the market, leading to higher profit (as compared to the fixed-fee pricing model). However, when λ and β are in a lower range, even though a relatively lower value per unit is generated for customers (due to the low quality investments), the firm sets high price under fixed-fee pricing model, just to attract customers with high use frequency (as they have relatively high valuation due to consumption of multiple 3D printed units), leading to higher firm's payoffs (as compared to the pay-per-build pricing model).

Interestingly, we observe that when λ is in a higher range, a higher threshold on β appears, where beyond this threshold, the firm prefers the fixed-fee pricing model. Please note that when the probability of failure is high, and product design is highly complex, the expected number of failed prints is high. Therefore, to attract customers to opt for 3DaaS, the firm sets a lower unit price under the pay-per-build model (leading to lower payoffs). In contrast, while implementing a fixed-fee pricing model, the firm charges a bit higher as customers can print multiple iterations without paying for each failed attempt, generating high value from all successfully printed jobs.

As mentioned in the discussion of Proposition 3, the previous research has mainly focused on understanding the implications of product failure and product complexity on various issues in product design (Mackelprang et al. 2015, Kirshner et al. 2017). However, these papers do not provide insights into the implication of product complexity on payoffs of 3DaaS firms under different pricing models, which is one of the key focus of our work. We suggest that implementing a pay-per-build pricing model would generate relatively higher benefits for 3DaaS firms when faced with customers printing highly complex designs with a relatively low probability of failure. As the 3DaaS sector matures over time, the evolution is anticipated to lead to greater proficiency through enhanced learning-by-doing and accumulated experience in managing intricate designs. This progressive refinement may consequently contribute to a reduction in the probability of product design failures. In the broader temporal context, we could reasonably anticipate witnessing an upswing in the prevalence of firms embracing the pay-per-build model when catering to customers seeking to create highly complex products.

Our analysis further uncovers that when customers employ 3D printing devices to produce highly complex jobs accompanied by a substantial probability of failure, the fixed-fee model yields a higher payoff for the 3D printing service provider. This scenario often encompasses 3D printing services tailored to prepare intricate jobs designed for Research and Development (R&D) purposes. Given the inherently frequent occurrence of design failures in this context, setting a high fixed-fee emerges as a strategic approach, potentially targeting customers with a high frequency of usage within this category. In contrast, for scenarios characterized by a moderate level of complexity, our recommendation continues to lean toward implementing a pay-per-build pricing model. Due to the relatively high likelihood of successful prints (attributed to the comparatively lower complexity of these jobs), 3DaaS firms are apt to set a premium unit pay-per-build price aligned with the heightened value bestowed upon customers.

Lastly, we demonstrate that 3D printing services used for tasks involving exceedingly low complexity are best suited for a fixed-fee pricing structure. Instances of such tasks encompass 3D printing services adopted by hobbyists for endeavors like creating toys (since these applications have straightforward instructions, the designs aren't intricate). In general, customers in this category acquire limited value from these tasks (owing to the reduced usefulness of less intricate work). Consequently, the firm sets a substantial fixed-fee for extending these services to customers who engage in frequent usage (since these customers attain a relatively high value).

5.3 What Happens When the Firm Incurs Liability Cost?

We further extended our setup with product design complexity by considering a scenario where the firm incurs liability cost structure. In this setup, the customer is only charged for successful prints under pay-per-build pricing scenario. Due to space constraints, we provide the full detailed analysis in Section EC.5 of E-companion of the paper. We find all our insight on the impact of product co-creation parameter α to be robust in this setup. Further, all insights on the impact of product failure rate and product complexity parameters characterized in Propositions 3, 4, and 5 are also robust.

Additionally, we find that under the pay-per-build pricing model, the profit of the 3DaaS firm is the same irrespective of whether the customer or firm shares the product failure liability. This is because this mechanism can extract the entire customer surplus. Therefore, when the firm incurs liability costs, this additional cost burden gets offset by the higher surplus extracted from customers (as customers do not face any liability cost structure). Interestingly, under the fixed-fee pricing model, we observe that the firm's profit and customer surplus are higher when the customers bear the liability cost (as compared to when the firm pays for the liability losses). The reason is, when the firm bears the liability losses, it tends to charge a high fixed-fee and invests low in quality (compared to when customers bear liability losses). The higher fixed-fee and lower quality investment reduce customer surplus, as well as, reduce the demand faced by the firm. Therefore, this leads to lower payoffs for the 3DaaS firm when it bears the liability losses. This observation may provide a possible explanation for real-life practice in the 3D printing industry where customers typically incur such liability losses.

6 Model Extensions

We now extend the main model to verify the robustness of our results. First, we present the analysis of the output function where efforts by both players have a synergistic influence on the overall product quality. In the second extension, we consider a different customer utility model considering uncertainty about customer use frequency. In the third extension, we consider a market structure under competition. In the fourth extension, we also consider the case when the customer is a mass manufacturer and prints multiple copies of a single design using the 3D printing service. In our paper, apart from the above robustness checks, we also consider several other model extensions. Due to space constraints, we summarize them in this section. However, we provide a more detailed discussion in Section EC.6 in the E-companion file.

6.1 Alternate Quality Collaboration Function

In practice, there exists the possibility of quality efforts by both the 3DaaS firm and customers complementing each other, wherein a low magnitude of efforts by either player might negatively impact the overall output. Illustrations of such job structures within the context of the 3D printing industry might involve designing 3D-printed electronic circuit items, complex car engine assemblies, and biomedical implants. The reason behind such dynamics is that the availability of high-quality design template files (due to the firm's high q_f) can further enhance the customer's quality efforts (q_c in our setup). To model such dynamics, we extend our existing model by considering the Cobb-Douglas quality collaboration function. In this collaboration structure, the efforts by the 3DaaS firm and the customer have a synergistic influence on the overall product quality. Hence, we assume the quality collaboration function is given by $q_h = q_c^{\alpha} q_f^{1-\alpha}$; where $0 \leq \alpha \leq 1$. If one of the players does not exert any quality efforts, the other player's efforts have no impact on overall quality. Moreover, a 1% increase in investment by the customer and the 3DaaS firm increases product quality by $\alpha\%$ and $(1-\alpha)\,\%$, respectively. Therefore, similar to the main model, α can be interpreted as a relative impact of the customer on the product quality. By substituting the above quality function, we find the equilibrium quality investment by the customer given by $q_c = 2^{\frac{1}{\alpha-2}} \left(\frac{\alpha\theta q_f^{1-\alpha}}{\kappa} \right)^{\frac{1}{2-\alpha}}$. Under both pricing models, we find that the characterization of the firm's quality and optimal pricing strategy is quite complicated. Due to high complexity, we could only study the behavior of the equilibrium strategy with the help of computational studies. Figure EC.5 in the E-companion illustrates the impact of parameter α on payoffs and decisions. We observe that all our key insights from the main model are robust in this model extension.

6.2 Comprehensive Customer Utility Model

As discussed in Section 3.1, the variations in customers' business requirements lead to heterogeneity in the usage frequency of 3D printing services (Carbon 2023b). In this extension, we consider a more comprehensive model to capture the uncertainty associated with customer usage frequency. Specifically, we analyze a setup where a customer can be of the low-usage type (with use frequency equal to A) with a probability of ρ. Additionally, with a probability of $1-\rho$, the customer may belong to the high-usage type, with a use frequency of $A+\mu$ (where μ is uniformly distributed between 0 and μ_H). We denote quality investments by high-usage type customers and low-usage type customers by q_{cH} and q_{cL}, respectively. It is evident that under fixed-fee pricing model, the utility of high-usage type customers is $\theta(A+\mu)\left(\alpha q_{\text{cH}} + (1-\alpha) q_f\right) - \kappa(A+\mu) q_{\text{cH}}^2 - F$, while $A\theta\left(\alpha q_{\text{cL}} + (1-\alpha) q_f\right) - A\kappa q_{\text{cL}}^2 - F$ represents the utility of low-usage type customers. Similar to our analysis in the main model, we find that the customer's equilibrium quality investment is given by $q_{\text{cL}}^* = q_{\text{cH}}^* = \frac{\alpha\theta}{2\kappa}$. Now, under the fixed-fee pricing model, the demand for 3D printing devices is as follows:

$$D_{3D} = \Pr\left(U_c^* \geq 0\right) = \begin{cases} \dfrac{(1-\rho)\left(A+\mu_H-\frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}\right)}{\mu_H} & \text{when } A < \frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}, \\ 1 & \text{when } A \geq \frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}. \end{cases}$$

The above expression reveals that when A is significantly high, implying both high-type and low-type customers exhibit high expected usage, the entire market is covered due to the high derived utility. However, when A falls below a threshold, the market is only partially covered, serving a fraction of high-type customers (specifically those with higher μ). Under fixed-fee pricing model, the profit function of the 3DaaS firm can be expressed as follows:

$$\Pi_{3D} = \begin{cases} F.\left((1-\rho)\left(A+\mu_H-\frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}\right)\right)-\kappa q_f^2 & \text{when } A < \frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}, \\ F.1-\kappa q_f^2 & \text{when } A \geq \frac{4F\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}. \end{cases}$$

Similar to the main model, we could show that the equilibrium fixed-fee and firm's quality investment are given by:

$$F^* = \begin{cases} \frac{\theta^2(A+\mu_H)\left((1-\alpha)^2A^2(1-\rho)+2\mu_H\left((1-\alpha)^2A(1-\rho)+\alpha^2\right)+(1-\alpha)^2(1-\rho)\mu_H^2\right)}{16\kappa\mu_H} & \text{when } A < \mu_H \\ \frac{A\theta^2\left(\alpha^2+2(1-\alpha)^2A\right)}{4\kappa} & \text{when } A \geq \mu_H \end{cases}, \text{and}$$

$$q_f^* = \begin{cases} \frac{(1-\alpha)\theta(1-\rho)(A+\mu_H)^2}{8\kappa\mu_H} & \text{when } A < \mu_H \\ \frac{(1-\alpha)A\theta}{2\kappa} & \text{when } A \geq \mu_H \end{cases}.$$

We find that in scenarios where both high-type and low-type customers exhibit high usage (i.e., A is high), the firm invests high in quality and sets a high fixed-fee (i.e., $\frac{\partial q_f^*}{\partial A} > 0$ and $\frac{\partial F^*}{\partial A} > 0$). Furthermore, as the probability of a customer being of the low-type increases (owing to low expected printer usage by customers), both the fixed-fee and the firm's quality investment decrease. Moreover, we observe that all our insights regarding the collaboration parameter α, derived from Proposition 1 (in the main model), remain robust in this setup. Specifically, as α increases, the fixed-fee and firm's payoff increase if and only if α surpasses a certain threshold. Additionally, we find that this threshold value increases with A and decreases with ρ.

Under the pay-per-build pricing model, we find that the customer's quality investment is given by $\frac{\alpha\theta}{2\kappa}$. Similar to the main model, we can show that if unit price u falls below a threshold, both high-type and low-type customers choose 3DaaS; otherwise, none of them opt for it. Consequently, the firm sets the price at $u^* = \frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)}{4\kappa}$ to extract the entire surplus. With all customers opting for 3DaaS, the expected number of transactions per customer is $(1-\rho)\left(A+\frac{\mu_H}{2}\right)+A\rho$. Hence, the firm's expected payoff is given by:

$$\Pi_{3D} = u^*\left((1-\rho)\left(A+\frac{\mu_H}{2}\right)+A\rho\right)-\kappa q_f^2-\tau\left((1-\rho)\left(A+\frac{\mu_H}{2}\right)+A\rho\right).$$

Next, we could show that the optimal pay-per-build price and firm's quality investment strategy are given by:

$$u^* = \frac{\theta^2\left(\alpha^2+(1-\alpha)^2\left(2A+(1-\rho)\mu_H\right)\right)}{4\kappa}, \text{and } q_f^* = \frac{(1-\alpha)\theta\left(2A+(1-\rho)\mu_H\right)}{4\kappa}.$$

Similar to the fixed-fee model, we observe that as parameter A increases (or ρ decreases), both the unit pay-per-build price and the firm's quality investment increase. Finally, we could also prove the robustness of all our insights from the main model.

6.3 Competition Faced by 3DaaS Provider

In real-life scenarios, it is plausible that customers have the option to utilize 3D printing services from other competing providers. For instance, in business practice, 3DaaS providers like HP may face competition from companies like Carbon. Thus, in this section, we investigate the consequences of a customer's outside option. We assume that each unit's net value gained by the customer from the outside option (obtained by subtracting the unit price from the consumption utility) is denoted by R_0. In our scenario, the competitor assumes a non-reactive and passive role. This situation may accurately reflect the dynamics when dealing with a smaller player or one with significantly distinct offerings. Similar to the main model, under a fixed-fee pricing strategy, we could show that the customer demand is given by $1 - \frac{4F\kappa}{\mu_H\left(\alpha^2\theta^2+4(1-\alpha)\theta\kappa q_f-4\kappa R_0\right)}$. As R_0 increases, customers tend to switch to the outside option due to the higher value derived from it, consequently leading to a reduction in market demand. We could show that the equilibrium fixed-fee and firm's quality investment are given by:

$$F^* = \frac{\mu_H\left(\theta^2\left(2\alpha^2+(1-\alpha)^2\mu_H\right)-8\kappa R_0\right)}{16\kappa}, \text{and } q_f^* = \frac{(1-\alpha)\theta\mu_H}{8\kappa}.$$

We find that the presence of an outside option does not influence the firm's quality investment but leads to a reduction in the fixed-fee charged by it (i.e., $\frac{\partial F^*}{\partial R_0} < 0$). Consequently, due to the lower fixed-fee, we also observe a reduction in the firm's payoff with an increase in R_0. In the pay-per-build pricing model, we find that if unit price u is below a threshold, all customers opt for 3DaaS. In comparison to the main model, the 3DaaS firm reduces its unit price to prevent customers from switching to rival offerings. In equilibrium, we could show that unit pay-per-build price and firm's quality investment are given by:

$$u^* = \frac{\theta^2\left(\alpha^2+(1-\alpha)^2\mu_H\right)-4\kappa R_0}{4\kappa}, \text{and } q_f^* = \frac{(1-\alpha)\theta\mu_H}{4\kappa}.$$

We find that as R_0 increases, the firm decreases u^* to deter customers from switching to an outside option. Similar to the main model, we observe that our insights regarding the comparison of payoff functions remain robust in this extension. Furthermore, as R_0 increases, the payoff difference between pricing models reduces. This reduction is attributed to the decreased magnitude of payoffs when R_0 is high.

6.4 Repetitive Manufacturing Scenario

In real life, the customers are heterogeneous in their design requirements while using 3D printing services. Some customers might like to design multiple products and print them (design customers). However, some customers might design one product and print multiple replicas of the design file (repetitive manufacturers). Therefore, we extended the main model to consider the scenario where the customers prepare a unique design file to print multiple product replicas. We present the detailed analysis of this extension in Section EC.7.2 of E-companion. All our insights from the main model setup are robust in this extension. Additionally, we compare the firm's pricing strategy toward design and repetitive manufacturing customers. We find that if the relative impact of the customer on the product quality is high and the expected number of units printed is low, then 3DaaS firms should charge a higher price from the design customer as compared to the repetitive manufacturing customer (in all pricing models). Therefore, 3DaaS providers need to understand customer usage and collaboration dynamics while deciding the pricing strategy.

7 Conclusion

Companies like HP and Carbon utilize diverse pricing models to offer 3D-as-a-service (3DaaS). In this paper, we analyze a supply chain setting with 3D printing device providers and downstream customers who use the 3D printer to customize and print a final object. We examine the different pricing strategies used by 3DaaS firms, namely, fixed-fee and pay-per-build pricing models. We characterize the equilibrium product quality customization efforts and the optimal pricing strategy for both pricing models. To find the best pricing model from the perspective of the 3D printing device provider, we compare the payoff under different settings. Our analysis reveals that the 3DaaS firm's choice of pricing model is primarily driven by factors such as (i) the extent of product design customization and (ii) product design complexity.

We find that an increase in the extent of customization by the 3DaaS users might not always lead to a lower price charged by the firm. Specifically, if the degree of customization by users is relatively high or low, then the fixed-fee or pay-per-build price should be high. But in the moderate range of the extent of customization, the prices should be low. Additionally, we find that if either the 3DaaS firm or the customers significantly impact the quality of product, the 3DaaS firm earns a higher profit when it implements a pay-per-build pricing model. On the other hand, if both players have a similar effect on product quality, the 3DaaS firm finds it more advantageous to implement a fixed-fee pricing model.

The above finding indicates that 3D printing services utilized for products such as standard smartphone cases, cable holders, educational puzzles, hobbyist kits, and basic decorative items (where the 3DaaS firm provides standard design files, so the customer doesn't exert much product design customization efforts), can be offered using a pay-per-build pricing model. Furthermore, when customers need something unique, such as designing premium jewelry, distinctive architectural models, medical implants, or engineering designs, the firm might still choose the pay-per-build pricing model since the customers will be exerting most of the product design customization efforts.

The 3DaaS firms must be also careful about the complexity of 3D design models printed by customers. This is because highly complex designs may face a high failure rate (which may discourage customers from opting for 3DaaS); on the flip side, if printed successfully, it may generate a higher utility for the customers. Our analysis reveals that high design complexity may increase or decrease the 3DaaS firm's unit prices (under both pricing models). Specifically, if the product design complexity is high, but the product failure rate is low, and printing use frequency is high, then the prices of 3DaaS should be high. Typically, such a customer profile may include engineering divisions of businesses, who might be printing multiple

Optimal pricing strategy (→) **Product design characteristics** (↓)	**Pay-per-build pricing model**	**Fixed-fee pricing model**
Extent of customization	Suitable when either 3DaaS users primarily customize product design or when 3DaaS providers handle most design work with minimal user customization.	Suitable when both customers and the firm invest significant effort in preparing the design file.
Extent of complexity (under low design failure probability)	Suitable when design complexity is high	Suitable when design complexity is low
Extent of complexity (under high design failure probability)	Suitable when design complexity is moderate	Suitable when design complexity is relatively high or low

Table 2 Optimal 3D printing pricing strategies

designs but have a certain level of 3D printing design experience, ensuring that the product failure rate is not drastically high.

Furthermore, when the product design is quite complex, and the chances of design failures for such complicated structures are minimal, the firm might opt for the pay-per-build pricing model for its 3DaaS services. Yet, in situations where the customers frequently engage in designing and printing tasks that involve either less complex or highly intricate designs (with a high likelihood of design failures), the firm could choose to utilize the fixed-fee pricing model. In practice, if a particular kind of 3D printing service is used for complex new R&D designs that carry a high chance of failure, according to our findings, these specific 3DaaS services may be provided using a fixed-fee pricing approach. Moreover, fixed-fee pricing might be also more appropriate when 3DaaS is used for tasks like printing well-defined geometric shapes, functional components such as brackets and clips, simple fixtures, or less intricate jewelry items. It's only when serving customers who are adept at handling complex designs (and thus encounter lower chances of failure) that the firm might go with the pay-per-build pricing model. We present the summary of key insights in Table 2.

Our study contributes to emerging research on operational issues in 3D printing supply chains, which has mainly focused on inventory-related issues in 3D printing supply (Westerweel et al. 2018, Song and Zhang 2020, Arbabian and Wagner 2020). We also contribute by providing insights or the implications of pricing model selection by the firm offering 3DaaS. The previous literature on collaboration issues in service supply chains has mainly focused on B2B setups with vendor-client quality collaborations under output/effort-based pricing structures (Demirezen et al. 2016, 2020). Unlike them, we focus on studying product quality collaboration between customers and 3DaaS firms under pay-per-build and fixed-fee structures. Ultimately, our contribution extends to the existing literature on pricing dynamics in service supply chains as we elucidate how elements like the degree of product design customization and the level of product design complexity influence the decision-making process of 3DaaS firms regarding their chosen pricing model within the realm of a 3D printing supply chain.

All URLs below were last accessed on December 7, 2023.

References

Allan, D. (2019). HP adopts mobile phone-style contracts for 3D printing service. Tech Radar, url: `https://www.techradar.com/in/news/hp-adopts-mobile-phone-style-contracts-for-3d-printing-service`

AMFG (2023). 7 complex designs achieved with 3D printing. AMFG Blog, url: `https://amfg.ai/2019/07/24/7-complex-designs-achieved-with-3d-printing/`

Arbabian, M. E., & Wagner, M. R. (2020). The impact of 3D printing on manufacturer–retailer supply chains. European Journal of Operational Research, 285(2), 538-552.

Arkema (2023). How to scale up 3D printing with data sharing and collaboration? Arkema, url: `https://www.arkema.com/global/en/resources/post/how-to-scale-up-3D-printing-with-data-sharing-and-collaboration/`

Avinadav, T., Chernonog, T., Fruchter, G. E., & Prasad, A. (2020). Contract design when quality is co-created in a supply chain. European Journal of Operational Research, 286(3), 908-918.

Bala, R., & Carr, S. (2010). Usage-based pricing of software services under competition. Journal of Revenue and Pricing Management, 9(3), 204-216.

Balasubramanian, S., Bhattacharya, S., & Krishnan, V.V. (2015). Pricing information goods: A strategic analysis of the selling and pay-per-use mechanisms. Marketing Science, 34(2), 218-234.

Basu, A., & Bhaskaran, S. (2018). An economic analysis of customer co-design. Information Systems Research, 29(4), 787-786.

Beer, R., & Qi, A. (2023). To communicate or not? Interfirm communication in collaborative projects. Management Science, (forthcoming).

Ben-Ner, A., & Siemsen, E. (2017). Decentralization and localization of production: The organizational and economic consequences of additive manufacturing (3D printing). California Management Review, 59(2), 5-23.

Bhaskaran, S. R., & Krishnan, V. (2009). Effort, revenue, and cost sharing mechanisms for collaborative new product development. Management Science, 55(7), 1152-1169.

Cachon, G. P., & Feldman, P. (2011). Pricing services subject to congestion: Charge per-use fees or sell subscriptions? Manufacturing & Service Operations Management, 13(2), 244-260.

Carbon (2023a). Standard pricing. Carbon Official Website, url: `https://s3.amazonaws.com/carbon-static-assets/downloads/pricing/Carbon_Pricing_.pdf`

Carbon (2023b). Carbon 3D case studies. Carbon Official Website, url: `https://www.carbon3d.com/case-studies/`

Chellappa, R. K., & Mehra, A. (2018). Cost drivers of versioning: Pricing and product line strategies for information goods. Management Science, 64(5), 2164-2180.

Chen, S., Lee, H., & Moinzadeh, K. (2019). Pricing schemes in cloud computing: Utilization-based vs. reservation-based. Production and Operations Management, 28(1), 82-102.

Deloitte (2022). 3D opportunity in aerospace and defense. Deloitte White Paper, url: `https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-3d-opportunity-in-aerospace/DUP_706-3D-Opportunity-Aerospace-Defense_MASTER2.pdf`

Demirezen, E. M., Kumar, S., & Shetty, B. (2016). Managing co-creation in information technology projects: A differential games approach. Information Systems Research, 27(3), 517-537.

Demirezen, E. M., Kumar, S., & Shetty, B. (2020). Two is better than one: A dynamic analysis of value co-creation. Production and Operations Management, 29(9), 2057-2076.

DHL (2023). 3D printing and the future of supply chains - A DHL perspective on the state of 3D printing and implications for logistics. DHL Customer Solutions & Innovation, url: `https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/dhl-trendreport-3dprinting.pdf`

Ernst and Young (2019). 3D Printing: Hype or game changer? A global EY report 2019, Ernst & Young Report, url: `https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/advisory/ey-3d-printing-game-changer.pdf`

Esenduran, G., Letizia, P., & Ovchinnikov, A. (2022). Customization and returns. Management Science, 68(6), 4517-4526.

Feng, H., Jiang, Z., & Liu, D. (2018). Quality, pricing, and release time: Optimal market entry strategy for new software-as-a-service vendors. MIS Quarterly, 42(1), 333-353.

Garg, A., Demirezen, E. M., Dogan, K., & Cheng, H. K. (2023). Financial sustainability of IoT platforms: The role of quality and security. Production and Operations Management (forthcoming).

Guha, S., & Kumar, S. (2018). Emergence of big data research in operations management, information systems, and healthcare: Past contributions and future roadmap. Production and Operations Management, 27(9), 1724-1735.

Gupta, S., Roy, A., Kumar, S., & Mudambi, R. (2023). When worse is better: Strategic choice of vendors with differentiated capabilities in a complex co-creation environment. Management Science, 69(5), 2833-2851.

HP (2023a). HP 3D software solutions. HP Official Website, url: `https://www.hp.com/us-en/printers/3d-printers/software.html`

HP (2023b). HP 3DaaS: The Hardware-as-a-Service model. 3Dprint.com, url: `https://3dprint.com/261016/hp-3daas-the-hardware-as-a-service-model/`

Iliff, C., (2017). Printing in 3D: Who's liable for product failures? ALM Global Blog, url: `https://www.propertycasualty360.com/2017/10/19/printing-in-3d-whos-liable-for-product-failures/`

Jain, S., & Kannan, P. K. (2002). Pricing of information products on online servers: Issues, models, and analysis. Management Science, 48(9), 1123-1142.

Jain, T., & Hazra, J. (2019). Hybrid cloud computing investment strategies. Production and Operations Management, 28(5), 1272-1284.

Kim, S. H., & Netessine, S. (2013). Collaborative cost reduction and component procurement under information asymmetry. Management Science, 59(1), 189-206.

Kirshner, S. N., Levin, Y., & Nediak, M. (2017). Product upgrades with stochastic technology advancement, product failure, and brand commitment. Production and Operations Management, 26(4), 742-756.

Kumar, A., & Telang, R. (2011). Product customization and customer service costs: An empirical analysis. Manufacturing & Service Operations Management, 13(3), 347-360.

Kumar, S., Mookerjee, V., & Shubham, A. (2018). Research in operations management and information systems interface. Production and Operations Management, 27(11), 1893-1905.

Li, S., Luo, Q., Qiu, L., & Bandyopadhyay, S. (2020). Optimal pricing model of digital music: Subscription, ownership or mixed? Production and Operations Management, 29(3), 688-704.

Lin, M., Liu, Y., & Viswanathan, S. (2018). Effectiveness of reputation in contracting for customized production: Evidence from online labor markets. Management Science, 64(1), 345-359.

Mackelprang, A. W., Habermann, M., & Swink, M. (2015). How firm innovativeness and unexpected product reliability failures affect profitability. Journal of Operations Management, 38, 71-86.

Mantena, R., & Saha, R. L. (2022). Market share contracts in B2B procurement settings with heterogeneous user preferences. Production and Operations Management, 31(3), 1290-1308.

Marucheck, A., Greis, N., Mena, C., & Cai, L. (2011). Product safety and security in the global supply chain: Issues, challenges and research opportunities. Journal of Operations Management, 29(7-8), 707-720.

McKenna, B. (2016). HP Inc. vs. Carbon: How do these compelling new 3D printing entrants stack up? The Motley Fool Official Website, url: `https://www.fool.com/investing/2016/06/04/hp-inc-vs-carbon-how-do-these-compelling-new-3d-pr.aspx`

Molitch-Hou, M. (2023). HP 3DaaS: The hardware-as-a-service model. 3dprint.com, url: `https://3dprint.com/261016/hp-3daas-the-hardware-as-a-service-model/`

Moorthy, K. S. (1988). Product and price competition in a duopoly. Marketing science, 7(2), 141-168.

Mullainathan, S. (2020). To fight the coronavirus, cut the red tape. New York Times, url: `https://www.nytimes.com/2020/03/24/business/coronavirus-medical-supplies-regulations.html`

Olsen, T. L., & Tomlin, B. (2020). Industry 4.0: Opportunities and challenges for operations management. Manufacturing & Service Operations Management, 22(1), 113-122.

PricewaterhouseCoopers, (2023). Turning additive manufacturing into business. PricewaterhouseCoopers Report, url: `https://www.pwc.nl/en/assets/documents/pwc-turning-additive-manufacturing-into-business.pdf`

Rahmani, M., Roels, G., & Karmarkar, U. S. (2017). Collaborative work dynamics in projects with co-production. Production and Operations Management, 26(4), 686-703.

Rayna, T., Striukova, L., & Darlington, J. (2015). Co-creation and user innovation: The role of online 3D printing platforms. Journal of Engineering and Technology Management, 37, 90-102.

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. Technological Forecasting and Social Change, 102, 214-224.

Roels, G. (2014). Optimal design of coproductive services: Interaction and work allocation. Manufacturing & Service Operations Management, 16(4), 578-594.

Roels, G., Smirnov, V., Tsetlin, I., & Wait, A. (2023). Why Do Managers Under-Delegate? A Co-Productive Principal-Agent Model. SSRN Working Paper, url: `https://papers.ssrn.com/sol3/papers.cfm?abstractid=3892218`

Saha, R. L., Singha, S., & Kumar, S. (2021). Does congestion always hurt? Managing discount under congestion in a game-theoretic setting. Information Systems Research, 32(4), 1347-1367.

Sethuraman, N., Parlakturk, A. K., & Swaminathan, J. M. (2023). Personal fabrication as an operational strategy: Value of delegating production to customer using 3D printing. Production and Operations Management., 32(7), 2362-2375.

Song, J. S., & Zhang, Y. (2020). Stock or print? Impact of 3D printing on spare parts logistics. Management Science, 66(9), 3860-3878.

Thomke, S., & Von Hippel, E. (2002). Customers as innovators: A new way to create value. Harvard Business Review, 80(4), 74–81.

Westerweel, B., Basten, R. J., & van Houtum, G. J. (2018). Traditional or additive manufacturing? Assessing component design options through lifecycle cost analysis. European Journal of Operational Research, 270(2), 570-585.

Xometry (2022). 3D printing consumer vs professional. Xometry White paper, url: `https://cdn2.hubspot.net/hubfs/340051/Design_Guides/Xometry__Consumer_vs_Professional_3D_Printing.pdf`

Yang, R., Tang, W., Dou, M., & Zhang, J. (2021). Pricing and investing in co-creation with customers for a duopoly. International Journal of Production Economics, 237, 108145.

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EC.1 Proofs of Results

Proof of Lemma 1

As discussed in Section 4.1, the objective function of the 3DaaS firm is given by:

$$\Pi_{3D} = FD_{3D} - \kappa q_f^2 = F\left(1 - \frac{4F\kappa}{\theta\mu_H\left(\alpha^2\theta + 4(1-\alpha)\kappa q_f\right)}\right) - \kappa q_f^2.$$

Solving the first-order conditions $\frac{\partial\Pi_{3D}}{\partial q_f} = 0$ and $\frac{\partial\Pi_{3D}}{\partial F} = 0$, we get the equilibrium $q_f^* = \frac{(1-\alpha)\theta\mu_H}{8\kappa}$, and $F^* = \frac{\theta^2\mu_H\left(2\alpha^2+(\alpha-1)^2\mu_H\right)}{16\kappa}$. Next, we evaluate the Hessian matrix for Π_{3D}:

$$\begin{bmatrix} \frac{\partial^2\Pi_{3D}}{\partial F^2} & \frac{\partial^2\Pi_{3D}}{\partial F\partial q_f} \\ \frac{\partial^2\Pi_{3D}}{\partial q_f\partial F} & \frac{\partial^2\Pi_{3D}}{\partial q_f^2} \end{bmatrix} \Rightarrow \begin{bmatrix} -\frac{8\kappa}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)} & \frac{32(1-\alpha)F\kappa^2}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)^2} \\ \frac{32(1-\alpha)F\kappa^2}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)^2} & -\frac{128(1-\alpha)^2F^2\kappa^3}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)^3} - 2\kappa \end{bmatrix}.$$

Further, we evaluate the first minor and the determinant of the Hessian matrix. The first order leading principal minor is $\frac{\partial^2\Pi_{3D}}{\partial F^2} = -\frac{8\kappa}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)} < 0$. The determinant of the Hessian matrix is given by $\left(\frac{\partial^2\Pi_{3D}}{\partial F^2}\right)\left(\frac{\partial^2\Pi_{3D}}{\partial q_f^2}\right) - \left(\frac{\partial^2\Pi_{3D}}{\partial q_f\partial F}\right)^2 = \frac{16\kappa^2}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa q_f\right)} > 0$. Therefore, the function Π_{3D} is maximized when $q_f^* = \frac{(1-\alpha)\theta\mu_H}{8\kappa}$, and $F^* = \frac{\theta^2\mu_H\left(2\alpha^2+(1-\alpha)^2\mu_H\right)}{16}$. This establishes Lemma 1.

Proof of Proposition 1

(a) From the expression stated in Lemma 1, we have $\frac{\partial q_f^*}{\partial\alpha} = -\frac{\theta\mu_H}{8\kappa} < 0$. (b) Next, we have $\frac{\partial F^*}{\partial\alpha} = \frac{\theta^2\mu_H(4\alpha\kappa-2(1-\alpha)\kappa\mu_H)}{16\kappa^2}$. Therefore, when $\alpha \geq \alpha_{th1} \overset{def}{=} \frac{\mu_H}{\mu_H+2}$, then $\frac{\partial F^*}{\partial\alpha} \geq 0$; otherwise, when $\alpha < \alpha_{th1}$, then $\frac{\partial F^*}{\partial\alpha} < 0$. (c) We have $\Pi_{3D}^* = (F^*)D_{3D} - \kappa\left(q_f^*\right)^2 = \frac{\theta^2\mu_H\left(4\alpha^2+(1-\alpha)^2\mu_H\right)}{64\kappa}$. Next, we have $\frac{\partial\Pi_{3D}^*}{\partial\alpha} = \frac{\theta^2\mu_H(8\alpha+2(\alpha-1)\mu_H)}{64\kappa}$. Therefore, when $\alpha > \alpha_{th2} \overset{def}{=} \frac{\mu_H}{\mu_H+4}$, then $\frac{\partial\Pi_{3D}^*}{\partial\alpha} > 0$; otherwise, when $\alpha \leq \alpha_{th2}$, we have $\frac{\partial\Pi_{3D}^*}{\partial\alpha} \leq 0$. Further, the customer surplus is given by $CS^* = \int_{\frac{4F^*\kappa}{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f^*\right)}}^{\mu_H}\left(\frac{\alpha^2\theta^2 x}{4\kappa} + (1-\alpha)\theta x q_f^* - F^*\right)\left(\frac{1}{\mu_H}\right)dx = \frac{\theta^2\mu_H\left(2\alpha^2+(1-\alpha)^2\mu_H\right)}{64\kappa}$. Next, we get $\frac{\partial CS^*}{\partial\alpha} = \frac{\theta^2\mu_H^2\left(2\alpha^2+(1-\alpha)^2\mu_H\right)}{64\kappa}$. Now, when $\alpha > \alpha_{th1} \overset{def}{=} \frac{\mu_H}{\mu_H+2}$, then $\frac{\partial CS^*}{\partial\alpha} > 0$. Otherwise, when $\alpha \leq \alpha_{th1}$, we have $\frac{\partial CS^*}{\partial\alpha} \leq 0$. This establishes Proposition 1.

Proof of Lemma 2

From our discussion in Section 4.2, the firm's objective function under the pay-per-build pricing model is given by:

$$\Pi_{3D} = u^*\left(\frac{\mu_H}{2}\right) - \kappa q_f^2 - \tau\left(\frac{\mu_H}{2}\right) = \left(\frac{\theta\left(\alpha^2\theta + 4(1-\alpha)\kappa q_f\right)}{4\kappa}\right)\left(\frac{\mu_H}{2}\right) - \kappa q_f^2 - \tau\left(\frac{\mu_H}{2}\right).$$

Now, we have the first-order condition given by $\frac{\partial\Pi_{3D}}{\partial q_f}|_{q_f=q_f^*} = \frac{1}{2}(1-\alpha)\theta\mu_H - 2\kappa\left(q_f^*\right) = 0$. Hence, we have $q_f^* = \frac{(1-\alpha)\theta\mu_H}{4\kappa}$. The second-order condition is given by $\frac{\partial^2\Pi_{3D}}{\partial q_f^2} = -2\kappa < 0$. Further, we have $u^* = \frac{\theta\left(\alpha^2\theta+4(1-\alpha)\kappa q_f^*\right)}{4\kappa} = \frac{\theta^2\left(\alpha^2+(1-\alpha)^2\mu_H\right)}{4\kappa}$. This establishes Lemma 2.

Proof of Proposition 2

As discussed in proof of Proposition 1, the payoff of 3DaaS firm in the fixed-fee pricing model is given by $\frac{\theta^2\mu_H\left(4\alpha^2+(1-\alpha)^2\mu_H\right)}{64\kappa}$. Further, it is easy to show that the payoff of the firm in the pay-per-build pricing model is given by $\frac{\mu_H\left(2\alpha^2\theta^2+(1-\alpha)^2\theta^2\mu_H-8\kappa\tau\right)}{16\kappa}$. Next, we have the difference in the firm's payoff under pay-per-build and fixed-fee pricing model is given by $\frac{\mu_H\left(4\left(\alpha^2\theta^2-8\kappa\tau\right)+3(1-\alpha)^2\theta^2\mu_H\right)}{64\kappa}$. Now, $\frac{\mu_H\left(4\left(\alpha^2\theta^2-8\kappa\tau\right)+3(1-\alpha)^2\theta^2\mu_H\right)}{64\kappa} \leq 0 \Longrightarrow \dot{\alpha} \leq \alpha \leq \ddot{\alpha}$, where $\dot{\alpha} \overset{\text{def}}{=} \frac{3\theta^2\mu_H-2\sqrt{\theta^2\left(32\kappa\tau-3\mu_H\left(\theta^2-8\kappa\tau\right)\right)}}{\theta^2(3\mu_H+4)}$ and $\ddot{\alpha} \overset{\text{def}}{=} \frac{3\theta^2\mu_H+2\sqrt{\theta^2\left(32\kappa\tau-3\mu_H\left(\theta^2-8\kappa\tau\right)\right)}}{\theta^2(3\mu_H+4)}$. Therefore, when $\dot{\alpha} \leq \alpha \leq \ddot{\alpha}$, the firm's payoff under fixed-fee pricing model is higher compared to that under pay-per-build pricing model. Otherwise, when $\alpha < \dot{\alpha}$ or $\ddot{\alpha} < \alpha$, the firm's payoff under pay-per-build pricing model is higher compared to that under fixed-fee pricing model. This establishes Proposition 2.

Proof of Lemma 3

The objective function of the 3DaaS firm is given by:

$$\Pi_{3D} = FD_{3D} - \kappa q_f^2 = F\left(1 - \frac{4F\kappa(1-\beta\lambda)}{\mu_H\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2 + 4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f - 4\kappa\lambda l\right)}\right) - \kappa q_f^2.$$

Solving the first-order conditions $\frac{\partial\Pi_{3D}}{\partial q_f} = 0$ and $\frac{\partial\Pi_{3D}}{\partial F} = 0$, we get the equilibrium $q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{8\kappa}$, and $F^* = \frac{\beta\mu_H\left(2\alpha^2\beta\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H-8\kappa\lambda l\right)}{16\kappa(1-\beta\lambda)}$. Next, we evaluate the Hessian matrix for Π_{3D}:

$$\begin{bmatrix} \frac{\partial^2\Pi_{3D}}{\partial F^2} & \frac{\partial^2\Pi_{3D}}{\partial F\partial q_f} \\ \frac{\partial^2\Pi_{3D}}{\partial q_f\partial F} & \frac{\partial^2\Pi_{3D}}{\partial q_f^2} \end{bmatrix} \Rightarrow \begin{bmatrix} -\frac{8\kappa(1-\beta\lambda)}{\beta\mu_H\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)} & \frac{32(1-\alpha)F\theta\kappa^2(1-\beta\lambda)^2}{\beta\mu_H\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)^2} \\ \frac{32(1-\alpha)F\theta\kappa^2(1-\beta\lambda)^2}{\beta\mu_H\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)^2} & -2\kappa - \frac{128(1-\alpha)^2F^2\theta^2\kappa^3(1-\beta\lambda)^3}{\beta\mu_H\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)^3} \end{bmatrix}.$$

Further, we evaluate the first minor and the determinant of the Hessian matrix. The first order leading principal minor is $\frac{\partial^2\Pi_{3D}}{\partial F^2} = -\frac{8\kappa(1-\beta\lambda)}{\beta\mu_H\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)} < 0$. The determinant of the Hessian matrix evaluated at $q_f = q_f^*$ and $F = F^*$ is given by $\left(\frac{\partial^2\Pi_{3D}}{\partial F^2}\right)\left(\frac{\partial^2\Pi_{3D}}{\partial q_f^2}\right) - \left(\frac{\partial^2\Pi_{3D}}{\partial q_f\partial F}\right)^2|_{q_f=q_f^*,F=F^*} = \frac{32\kappa^2(1-\beta\lambda)}{\mu_H\beta\left((1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H+2\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2-4\kappa\lambda l\right)\right)} > 0$. Therefore, the function Π_{3D} is maximized when $q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{8\kappa}$, and $F^* = \frac{\beta\mu_H\left(2\alpha^2\beta\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H-8\kappa\lambda l\right)}{16\kappa(1-\beta\lambda)}$. This establishes Lemma 3.

Proof of Proposition 3

(a) From the expressions obtained in Lemma 3, we have $\frac{\partial q_f^*}{\partial\beta} = \frac{(1-\alpha)\theta\mu_H}{8\kappa} > 0$. Furthermore, from Lemma 3, we have $\frac{\partial F^*}{\partial\beta} = \frac{\mu_H\left((1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2\mu_H+\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2-4\kappa\lambda l\right)}{8\kappa(1-\beta\lambda)^2}$. It is easy to see that when $\mu_H \geq \ddot{\mu}_H \overset{\text{def}}{=} \frac{4\kappa\lambda l-\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2}{(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2}$, we have $\frac{\partial F^*}{\partial\beta} \geq 0$. Otherwise, when $\mu_H < \ddot{\mu}_H$, we have $\frac{\partial F^*}{\partial\beta} < 0$. (b) From the expressions obtained in Lemma 3, the equilibrium payoff of 3DaaS firm is given by $\Pi_{3D}^* = \frac{\beta\mu_H\left((1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H+4\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2-4\kappa\lambda l\right)\right)}{64\kappa(1-\beta\lambda)}$. Next, we have:

$$\frac{\partial\Pi_{3D}^*}{\partial\beta} = \frac{\mu_H\left((1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2\mu_H - 2\left(\alpha^2\beta\theta^2(3\beta\lambda-2)(1-\beta\lambda)^2 + 4\kappa\lambda l\right)\right)}{32\kappa(1-\beta\lambda)^2}.$$

It is easy to see that when $\mu_H \geq \widehat{\mu_H} \overset{\text{def}}{=} \frac{2\left(4\kappa\lambda l-\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2\right)}{(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2}$, we have $\frac{\partial \Pi_{3D}^*}{\partial \beta} \geq 0$. Otherwise, when $\mu_H < \widehat{\mu_H}$, we have $\frac{\partial \Pi_{3D}^*}{\partial \beta} < 0$. Furthermore, we have $CS^* = \int_{\frac{4F^*\kappa(1-\beta\lambda)}{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f^*-4\kappa\lambda l\right)}}^{\mu_H} \left(\frac{x\left(4(1-\alpha)\beta\theta\kappa(1-\beta\lambda)q_f^*+\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2-4\kappa\lambda l\right)\right)}{4\kappa(1-\beta\lambda)} - F^*\right)\left(\frac{1}{\mu_H}\right) dx = \frac{\beta\mu_H\left(2\alpha^2\beta\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H-8\kappa\lambda l\right)}{64\kappa(1-\beta\lambda)}$. Therefore, we have:

$$\frac{\partial CS^*}{\partial \beta} = \frac{\mu_H\left(\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2\mu_H-4\kappa\lambda l\right)}{32\kappa(1-\beta\lambda)^2}.$$

Next, when $\mu_H \geq \ddot{\mu}_H \overset{\text{def}}{=} \frac{4\kappa\lambda l-\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2}{(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2}$, we have $\frac{\partial CS^*}{\partial \beta} \geq 0$. Otherwise, when $\mu_H < \ddot{\mu}_H$, we have $\frac{\partial CS^*}{\partial \beta} < 0$. This establishes Proposition 3.

Proof of Lemma 4

From our discussion in Section 5.2, we have $U_c^* = \frac{\mu\left(\alpha^2\beta^2\theta^2(1-\beta\lambda)^2+4(1-\alpha)\beta\theta\kappa(1-\beta\lambda)q_f-4\kappa(\beta\lambda l+u)\right)}{4\kappa(1-\beta\lambda)}$. The customer opts for 3DaaS if and only if $U_c^* \geq 0 \implies \frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)}{4\kappa} \geq u$. Therefore, when $\frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)}{4\kappa} \geq u$, the expected number of units printed by the customer is given by $E_\mu[\mu] = \int_0^{\mu_H} \frac{x}{(1-\beta\lambda)}\left(\frac{1}{\mu_H}\right)dx = \frac{\mu_H}{2-2\beta\lambda}$. However, if $\frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)}{4\kappa} < u$, the number of units printed is 0. Hence, the firm must set the product price $u^* = \frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)}{4\kappa}$ to extract the entire customer surplus. Now, given q_f, the expected payoff of the 3DaaS firm is given by:

$$\begin{aligned}\Pi_{3D} &= u^* E_\mu[\mu] - \kappa q_f^2 - \tau E_\mu[\mu], \\ &= \left(\frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+4(1-\alpha)\theta\kappa(1-\beta\lambda)q_f-4\kappa\lambda l\right)}{4\kappa}\right)\left(\frac{\mu_H}{2-2\beta\lambda}\right) - \kappa q_f^2 - \tau\left(\frac{\mu_H}{2-2\beta\lambda}\right).\end{aligned}$$

Solving the first-order condition given by $\frac{\partial \Pi_{3D}}{\partial q_f}|_{q_f=q_f^*} = 0$, we have $q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{4\kappa}$. The second-order condition is given by $\frac{\partial^2 \Pi_{3D}}{\partial q_f^2} = -2\kappa < 0$. Further, we have $u^* = \frac{\beta\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H-4\kappa\lambda l\right)}{4\kappa}$. This establishes Lemma 4.

Proof of Proposition 4

(a) From the expressions obtained in Lemma 4, we have $\frac{\partial q_f^*}{\partial \beta} = \frac{(1-\alpha)\theta\mu_H}{4\kappa} > 0$. Furthermore, from Lemma 4, we have $\frac{\partial u^*}{\partial \beta} = \frac{2\alpha^2\beta\theta^2(1-\beta\lambda)(1-2\beta\lambda)+(1-\alpha)^2\beta\theta^2(2-3\beta\lambda)\mu_H-4\kappa\lambda l}{4\kappa}$. It is easy to see that when $\frac{2}{3\beta} < \lambda$, we have $\frac{\partial u^*}{\partial \beta} < 0$. However, when $\frac{2}{3\beta} \geq \lambda$, only if $\mu_H \geq \dddot{\mu}_H \overset{\text{def}}{=} \frac{4\kappa\lambda l-2\alpha^2\beta\theta^2(1-\beta\lambda)(1-2\beta\lambda)}{(1-\alpha)^2\beta\theta^2(2-3\beta\lambda)}$, we have $\frac{\partial u^*}{\partial \beta} \geq 0$. Otherwise, when $\frac{2}{3\beta} \geq \lambda$ and if $\mu_H < \dddot{\mu}_H$, we have $\frac{\partial u^*}{\partial \beta} < 0$. (b) From the expressions obtained in Lemma 4, the equilibrium payoff of 3DaaS firm is given by $\Pi_{3D}^* = \frac{\mu_H\left(2\alpha^2\beta^2\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta^2\theta^2(1-\beta\lambda)\mu_H-8\kappa(\beta\lambda l+\tau)\right)}{16\kappa(1-\beta\lambda)}$. Next, we have:

$$\frac{\partial \Pi_{3D}^*}{\partial \beta} = \frac{\mu_H\left(\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2+(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2\mu_H-4\kappa\lambda(l+\tau)\right)}{8\kappa(1-\beta\lambda)^2}.$$

It is easy to see that when $\mu_H \geq \acute{\mu}_H \overset{\text{def}}{=} \frac{4\kappa\lambda(l+\tau)-\alpha^2\beta\theta^2(2-3\beta\lambda)(1-\beta\lambda)^2}{(1-\alpha)^2\beta\theta^2(1-\beta\lambda)^2}$, we have $\frac{\partial \Pi_{3D}^*}{\partial \beta} \geq 0$. Otherwise, when $\mu_H < \acute{\mu}_H$, we have $\frac{\partial \Pi_{3D}^*}{\partial \beta} < 0$. This establishes Proposition 4.

Proof of Proposition 5

As discussed in proof of Proposition 3, the payoff of 3DaaS firm in the fixed-fee pricing model is given by $\frac{\beta\mu_H\left((1-\alpha)^2\beta\theta^2(1-\beta\lambda)\mu_H+4\left(\alpha^2\beta\theta^2(1-\beta\lambda)^2-4\kappa\lambda l\right)\right)}{64\kappa(1-\beta\lambda)}$. Further, the payoff of the firm in the pay-per-build pricing model (as shown in the proof of Proposition 4) is given by $\frac{\mu_H\left(2\alpha^2\beta^2\theta^2(1-\beta\lambda)^2+(1-\alpha)^2\beta^2\theta^2(1-\beta\lambda)\mu_H-8\kappa(\beta\lambda l+\tau)\right)}{16\kappa(1-\beta\lambda)}$. Next, it is easy to show that the difference in the firm's payoff under pay-per-build and fixed-fee pricing models is given by $\frac{\mu_H\left(4\alpha^2\beta^2\theta^2(1-\beta\lambda)^2+3(1-\alpha)^2\beta^2\theta^2(1-\beta\lambda)\mu_H-16\kappa(\beta\lambda l+2\tau)\right)}{64\kappa(1-\beta\lambda)}$. Now, $\frac{\mu_H\left(4\alpha^2\beta^2\theta^2(1-\beta\lambda)^2+3(1-\alpha)^2\beta^2\theta^2(1-\beta\lambda)\mu_H-16\kappa(\beta\lambda l+2\tau)\right)}{64\kappa(1-\beta\lambda)} \leq 0 \implies \ddot{\alpha}(\beta) \leq \alpha \leq \ddddot{\alpha}(\beta)$, where $\ddot{\alpha}(\beta) \stackrel{\text{def}}{=} \frac{3\beta^2\theta^2(1-\beta\lambda)\mu_H}{\beta^2\theta^2(1-\beta\lambda)(4-4\beta\lambda+3\mu_H)} - \frac{2\sqrt{\beta^2\theta^2(1-\beta\lambda)\left(3\mu_H\left(8\kappa\tau+4\beta\kappa\lambda l+2\beta^3\theta^2\lambda-\beta^4\theta^2\lambda^2-\beta^2\theta^2\right)+16\kappa(1-\beta\lambda)(\beta\lambda l+2\tau)\right)}}{\beta^2\theta^2(1-\beta\lambda)(4-4\beta\lambda+3\mu_H)}$ and $\ddddot{\alpha}(\beta) \stackrel{\text{def}}{=} \frac{3\beta^2\theta^2(1-\beta\lambda)\mu_H}{\beta^2\theta^2(1-\beta\lambda)(4-4\beta\lambda+3\mu_H)} + \frac{2\sqrt{\beta^2\theta^2(1-\beta\lambda)\left(3\mu_H\left(8\kappa\tau+4\beta\kappa\lambda l+2\beta^3\theta^2\lambda-\beta^4\theta^2\lambda^2-\beta^2\theta^2\right)+16\kappa(1-\beta\lambda)(\beta\lambda l+2\tau)\right)}}{\beta^2\theta^2(1-\beta\lambda)(4-4\beta\lambda+3\mu_H)}$. Therefore, we have when $\ddot{\alpha}(\beta) \leq \alpha \leq \ddddot{\alpha}(\beta)$, the firm's payoff under fixed-fee model is higher compared to that under pay-per-build pricing model. Otherwise, when $\alpha < \ddot{\alpha}(\beta)$ or $\ddddot{\alpha}(\beta) < \alpha$, the firm's payoff under pay-per-build pricing model is higher compared to that under fixed-fee pricing model. This establishes Proposition 5.

EC.2 Research Context

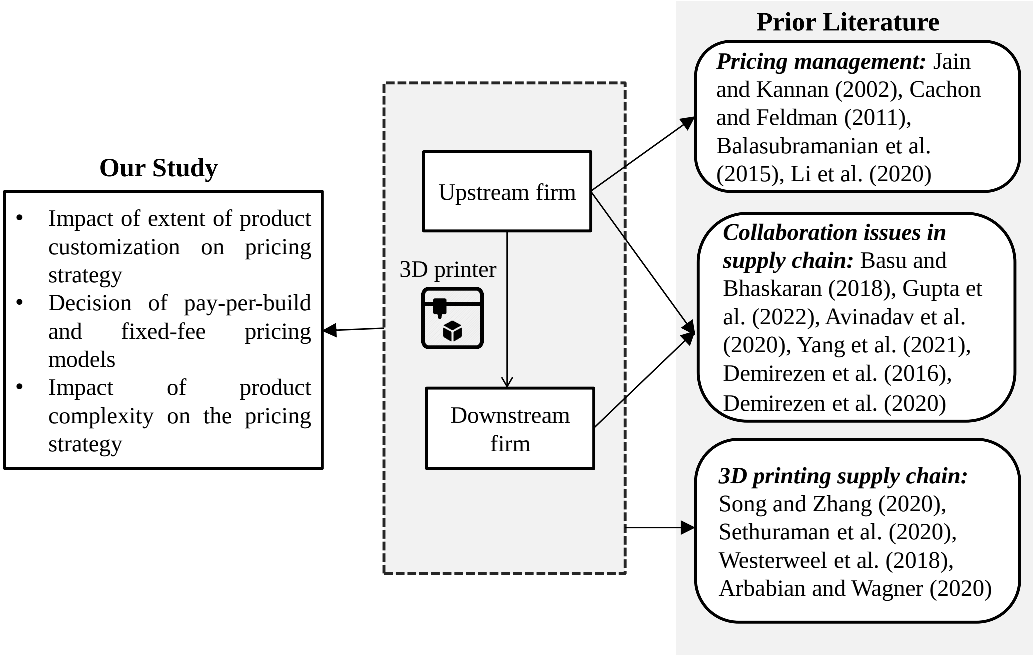


Figure EC.1 Research context

EC.3 Literature Review Summary

EC.3.1 Pricing Issues of Service

Paper	Model Setup	Context	Pricing model	Quality	Co-creation	Customer use hetero-geneity	Key Insights
Feng et al. (2018)	Two vendors - multiple customers	B2C	Subscription pricing	Software release time impacts quality	×	×	They find that the initial quality gap between competing players impacts pricing and release time strategy.
Li et al. (2020)	One music provider - multiple customers	B2C	Ownership, subscription, and mixed pricing	Endogenous	×	×	They find that factors such as advertising revenue rates and the customer's derived value impact the music provider's pricing model selection decisions.
Jain and Hazra (2019)	One client - one vendor	B2C	On-demand (pay-as-you-go) pricing	×	×	×	They find that higher available capacity lowers the unit price of cloud services.
Chen et al. (2019)	Two vendors - one client	B2C	On-demand and reservation-based pricing	×	×	×	They find that client may prefer sourcing capacity from the vendor providing on-demand instances if demand volatility is high.
Cachon and Feldman (2011)	One firm - multiple customers	B2C	Pay-as-you-go and fixed-fee pricing	×	×	✓	They find that the firm prefers fixed-fee pricing (over pay-as-you-go) when customers' dis-utility due to congestion is high.
Chellappa and Mehra (2018)	One firm - multiple customers	B2C	Pay-per-unit pricing (with versioning)	Decided by the upstream firm	×	×	They find that the in the presence of the customer resource usage cost, the versioning strategy is equally impacted by the firm's and customer's marginal cost.
Mantena and Saha (2022)	Two vendors - one buyer	B2B	Per-unit pricing and market share dependent pricing	×	×	×	They find that a market share contract may increase or decrease the buyer's unit price.
Balasubramanian et al. (2015)	One firm - multiple customers	B2C	Subscription, pay-as-you-go, and hybrid	×	×	✓	They find hybrid pricing mechanisms lead to higher payoffs. Further, the firm's profit from the pay-per-build mechanism is higher than subscription if and only if clock-ticking effects are low.
Jain and Kannan (2002)	One firm - multiple customers	B2C	Subscription, connect-time, and search-based pricing	×	×	×	They find that factors such as customer valuation and expertise variation impact a firm's optimal pricing strategy.
Saha et al. (2021)	Two vendors - one client	B2C	Pay-as-you-go pricing	×	×	×	They find that the vendor may decrease discounts toward congestion-sensitive customers under certain conditions.
Our paper	1 firm - multiple customers	B2B	Fixed-fee and pay-per-build pricing	✓	✓	✓	We observe that the firm's payoff is higher under the pay-per-build pricing model compared to the fixed-fee pricing model when customer product design customization is relatively high or low.

Table EC.1 Summary of Key Papers on Pricing Issues of Service

EC.3.2 Collaborations in Supply Chains

Paper	Model Setup	Context	Pricing model	Quality	Co-creation	Key Insights
Avinadav et al. (2020)	Platform, service provider, and customer	B2C	Pay-per-unit price	Impacted by platform's and service providers' efforts	Collaboration leads to higher quality	They find that if the platform is highly cost-efficient, it should bypass the service provider and produce the service independently.
Bhaskaran and Krishnan (2009)	1 client - 1 vendor	B2B	Cost and innovation sharing contracts	Innovation sharing: Quality is impacted by both players' efforts, and Cost sharing: Quality is impacted by one player's efforts	Co-creation efforts lead to higher quality	They find that cost sharing is particularly beneficial when development capability is concentrated in one of the firms, as it mitigates quality distortion effects and leads to optimal investments.
Garg et al. (2023)	1 IoT platform and multiple app developers	B2B	Revenue sharing contract	Impacted by efforts by all the players	Co-creation efforts lead to higher app quality and app security	They find that the entry of a new app doesn't lead to reduced profits for existing apps. Instead, profits for existing apps and the platform provider can increase as the number of participating apps grows.
Beer and Qi (2023)	2 firms	B2B	-	Impacted by efforts by both firms	Co-creation efforts lead to higher quality	They find that if the product value is high, it is beneficial for the firm to report (regardless of the magnitude) its initial quality investment to the collaborating firm.
Rahmani et al. (2017)	1 client - 1 vendor	B2B	Time-based contract	Impacted by both vendor's and client's efforts	Co-creation efforts lead to higher quality	They find that when efforts are verifiable, high-intensity collaboration occurs near the project deadline.
Gupta et al. (2023)	1 client - 2 vendors	B2B	Effort-dependent payment structure	Impacted by both vendors' and client's efforts	Co-creation efforts lead to higher output	They find that under certain conditions, the client may prefer to add a secondary vendor along with a primary vendor (in co-creation setups).
Demirezen et al. (2016)	1 client - 1 vendor	B2B	Effort and output-dependent payment structures	Impacted by both vendor's and client's efforts	Co-creation efforts lead to higher output	They find output-dependent contract is better for the client when output is relatively more sensitive to the vendor's efforts (compared to the client's efforts).
Demirezen et al. (2020)	1 client - 1 vendor	B2B	Effort-dependent, output-dependent, and hybrid contract	Impacted by both vendor's and client's efforts	Co-creation efforts lead to higher output	They find that when the output-effort sensitivity parameter of one of the players is high, the other player prefers a hybrid payment structure.
Our paper	1 firm - multiple customers	B2B	Fixed-fee and pay-per-build pricing	Impacted by both firm's and customer's efforts	Collaboration leads to higher quality	We observe that the firm's payoff is higher under the pay-per-build pricing model compared to the fixed-fee pricing model when customer product design customization is relatively high or low.

Table EC.2 Summary of Key Papers on Collaborations in Supply Chains

EC.3.3 Operational Issues in 3D Printing Industry

Paper	**Model Setup**	**Context**	**Pricing model**	**Quality**	**Co-creation**	**Product complexity**	**Product failure**	**Customer use heterogeneity**	**Key Insights**
Song and Zhang (2020)	1 firm	B2C	Exogenous	Not considered	×	×	Product failure leads to 3D printing demand creation	×	The spare part printing demand rate (or part failure rate), printing cost, and printing speed impact optimal printer utilization.
Sethuraman et al. (2023)	1 firm - multiple customers	B2C	Posted pricing	Impacted by customers' efforts	×	×	×	×	They find that value of 3D printing (or personalization) is high under markets with high horizontal dispersion and high vertical concentration.
Westerweel et al. (2018)	1 firm	B2B	Not considered	×	×	×	✓	×	They find that component reliability and product cost impact the firm's decision to adopt 3D printing manufacturing.
Arbabian and Wagner (2020)	1 manufacturer - 1 retailer	B2B	Lumpsum pricing under 3D printing/ wholesale pricing under traditional supply chain	×		×	×	×	They show that when 3D printing costs are low, then, in equilibrium, all the products will be 3D printed.
Our paper	1 firm - multiple customers	B2B	Fixed-fee and pay-per-build pricing	✓	✓	✓	✓	✓	We find that high product complexity may increase or decrease 3DaaS pricing.

Table EC.3 Summary of Key Papers on Operational Issues in 3D Printing Industry

EC.4 Impact of Design Complexity and Failure Rate on 3DaaS Pricing

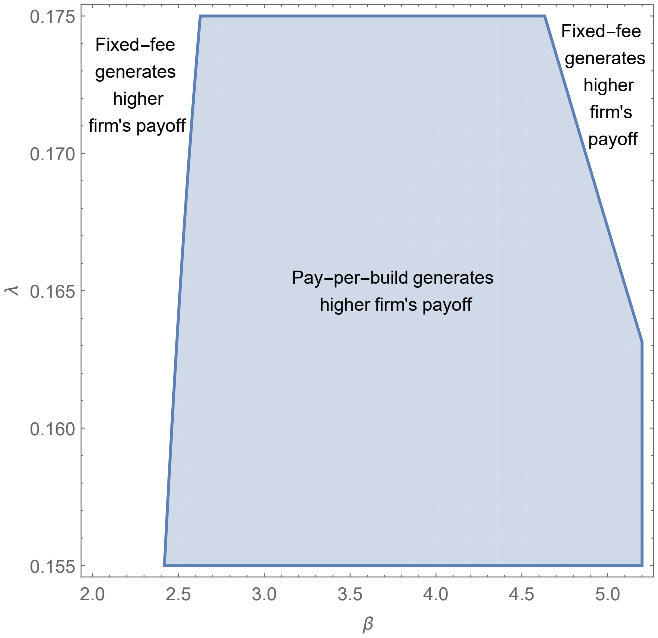


Figure EC.2 Payoff comparison under pay-per-build and fixed-fee models while considering product complexity

Base parameter values: $\alpha = 1/2$, $\tau = 1/2$, $l = 0$, $\theta = 1$, $\kappa = 1$, and $\mu_H = 1$.

EC.5 Details About Scenario Where Firm Incurs Liability Cost

In this section, we provide the details on the formulation of customer utility and 3DaaS firm's payoff, and characterization of equilibrium under scenario where the firm incurs the liability cost. Next, we elaborate on each of the pricing models.

EC.5.1 Fixed-fee Pricing Model

The customer with use frequency μ gains value given by $\theta\beta q_h\left(q_c, q_f\right)\mu$; however, it incurs the cost of exerting efforts toward designing units given by $\frac{\kappa\mu q_c^2}{1-\beta\lambda}$. Therefore, the utility of the customers under the fixed-fee model is as follows: $U_c = \theta\beta q_h\left(q_c, q_f\right)\mu - \frac{\kappa\mu q_c^2}{1-\beta\lambda} - F$. Similar to our previous analysis, we could show that the equilibrium quality investment by the customer is given by $q_c^* = \frac{\alpha\beta\theta(1-\beta\lambda)}{2\kappa}$. By solving $\text{Prob}\left(U_c \geq 0\right)$, we were able to characterize the 3DaaS firm's demand denoted by $D_{3D} = 1 - \frac{4F\kappa}{\beta\theta\mu_H\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f\right)}$. In this case, the firm pays the liability cost incurred by customers, and the total liability cost incurred by the firm is given by $\ell = l\int_{U_c(\mu)\geq 0}\frac{1}{\mu_H}\left(\frac{x}{1-\beta\lambda} - x\right)dx$. Therefore, the objective function of the 3DaaS firm is given by $\Pi_{3D} = FD_{3D} - \kappa q_f^2 - \ell$. Next, we find that the equilibrium fixed-fee pricing and quality strategy denoted by q_f^* and F^* are such that:

$$l = \frac{\beta\theta^2(1-\beta\lambda)\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f^*\right)^3\left(\frac{8(1-\alpha)\left(F^*\right)^2\kappa}{\beta\theta\mu_H\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f^*\right)^2} - q_f^*\right)}{32(1-\alpha)\left(F^*\right)^2\kappa^2\lambda}, \text{and}$$

$$F^* = \frac{\beta\theta^2(1-\beta\lambda)\mu_H\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f^*\right)^2}{8\kappa\left(\theta(1-\beta\lambda)\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f^*\right)-2\kappa\lambda l\mu_H\right)}.$$

Due to high complexity of the characterized equilibrium, we could only analyze this setup numerically. We provide the details about the key insights in the main manuscript.

EC.5.2 Pay-per-build Pricing Model

Similar to the fixed-fee pricing model, the customer with use frequency μ derives value from μ successful prints and incurs design cost given by $\frac{\kappa\mu q_c^2}{1-\beta\lambda}$. Moreover, the customer is only charged for a number of successful prints (i.e., it pays $u\mu$ to 3DaaS firm). Therefore, the utility of the customers with use frequency μ under the pay-per-build pricing model is given by: $U_c = \theta\beta q_h\left(q_c, q_f\right)\mu - \frac{\kappa\mu q_c^2}{1-\beta\lambda} - u\mu$. We find that the equilibrium quality efforts by the customer are given by $q_c^* = \frac{\alpha\beta\theta(1-\beta\lambda)}{2\kappa}$. Therefore, we have $U_c^* = \frac{\mu\left(\alpha^2\beta^2\theta^2(1-\beta\lambda)+4(1-\alpha)\beta\theta\kappa q_f-4\kappa u\right)}{4\kappa}$. The customer opts for 3DaaS if and only if $U_c^* \geq 0 \Longrightarrow \frac{\beta\theta\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f\right)}{4\kappa} \geq u$. Therefore, when $\frac{\beta\theta\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f\right)}{4\kappa} \geq u$, the expected number of units printed by the customer is given by $E_\mu\left[\mu\right] = \frac{\mu_H}{2}$. Hence, the firm must set the product price $u^* = \frac{\beta\theta\left(\alpha^2\beta\theta(1-\beta\lambda)+4(1-\alpha)\kappa q_f\right)}{4\kappa}$ to extract the entire customer surplus. Furthermore, the payment by the customer is only toward the successful prints, therefore, the expected number of successful prints is given by $\frac{\mu_H}{2}$. In this case, the firm pays the liability cost incurred by customers, and the total liability cost incurred by the firm is given by $\ell = l \int_0^{\mu_H} \frac{1}{\mu_H} \left(\frac{x}{1-\beta\lambda} - x \right) dx = \frac{\beta\lambda l \mu_H}{2-2\beta\lambda}$. The expected payoff of the 3DaaS firm is given by:

$$\begin{aligned}
\Pi_{3D} &= u^* \left(\frac{\mu_H}{2} \right) - \kappa q_f^2 - \ell - \tau \left(\frac{1}{1-\beta\lambda} \right) \left(\frac{\mu_H}{2} \right) \\
&= \left(\frac{\beta\theta \left(\alpha^2 \beta\theta (1-\beta\lambda) + 4(1-\alpha)\kappa q_f \right)}{4\kappa} \right) \left(\frac{\mu_H}{2} \right) - \kappa q_f^2 - \ell - \tau \left(\frac{1}{1-\beta\lambda} \right) \left(\frac{\mu_H}{2} \right).
\end{aligned}$$

Solving the first-order condition given by $\frac{\partial \Pi_{3D}}{\partial q_f} |_{q_f = q_f^*} = 0$, we have $q_f^* = \frac{(1-\alpha)\beta\theta\mu_H}{4\kappa}$. The second-order condition is given by $\frac{\partial^2 \Pi_{3D}}{\partial q_f^2} = -2\kappa < 0$. Further, we have $u^* = \frac{\beta^2\theta^2 \left(\alpha^2 (1-\beta\lambda) + (\alpha-1)^2 \mu_H \right)}{4\kappa}$. Therefore, we get the 3DaaS firm's equilibrium payoff as $\Pi_{3D}^* = \frac{\mu_H \left(2\alpha^2\beta^2\theta^2 (1-\beta\lambda)^2 + (1-\alpha)^2 \beta^2\theta^2 (1-\beta\lambda) \mu_H - 8\kappa(\beta\lambda l + \tau) \right)}{16\kappa(1-\beta\lambda)}$. We provide the details about the key insights in the main manuscript.

EC.6 Additional Robustness Studies

In this section, we provide the details of some additional robustness checks performed in the manuscript.

EC.6.1 Hybrid Pricing Model

In the main model, we examine situations where the firm provides 3DaaS through either a pay-per-build or fixed-fee pricing model. Next, we explore a scenario where the firm offers customers the flexibility to select either of these two pricing models. Specifically, in this context, we aim to ascertain whether providing such a hybrid of both pricing models results in greater profitability when compared to situations where each pricing model is presented individually. Therefore, in this scenario, we consider the case where the firm offers 3DaaS through both the pay-per-build and fixed-fee pricing models. In this setup, the utility of the customer is given by:

$$U_c = \begin{cases} \mu\left(\theta q_h\left(q_c, q_f\right) - \kappa q_c^2\right) - F & \text{if customer opts for fixed-fee pricing model,} \\ \mu\left(\theta q_h\left(q_c, q_f\right) - u - \kappa q_c^2\right) & \text{if customer opts for pay-per-build pricing model,} \\ 0 & \text{if customer does not opt for 3DaaS.} \end{cases}$$

Similar to the main model, the customer's optimal quality efforts are given by $q_c^* = \frac{\alpha\theta}{2\kappa}$. It is easy to show that, under the condition $\frac{\alpha^2\theta^2}{4\kappa} + (1-\alpha)\theta q_f > u$, the demand for both fixed-fee pricing (D_F) and pay-per-build pricing (D_P) models exists and is given by $D_F = 1 - \frac{F}{u\mu_H}$, and $D_P = \frac{F}{u\mu_H}$. In Figure EC.3, we pictorially represent market segmentation demonstrating the takers of pay-per-build and fixed-fee models.

As the fixed-fee increases, the demand for the fixed-fee model reduces, while the demand for the pay-per-build model increases. Further, if the pay-per-build price increases, the demand for the pay-per-build model decreases, and the demand for the fixed-fee model increases. Similar to the analysis in Section 4.2, given the quality q_f, the firm must set the product price $u^* = \frac{\theta\left(\alpha^2\theta + 4(1-\alpha)\kappa q_f\right)}{4\kappa}$ to extract the entire customer surplus. The objective function of the 3DaaS firm is as follows:

$$\Pi_{3D} = FD_F + uE_\mu\left[\mu\right]D_P - \kappa q_f^2 - \tau E_\mu\left[\mu\right]D_P.$$

In the above objective function, FD_F is the firm's payoff from offering 3D printers on a fixed-fee pricing model. Further, $uE_\mu\left[\mu\right]D_P$ is the firm's payoff from offering 3D printers as a pay-per-build service. The third term denoted by κq_f^2 is the total quality cost incurred by the 3DaaS firm. Finally, the last term given by $\tau E_\mu\left[\mu\right]D_P$ denotes the transactions monitoring cost incurred by firm. Next, similar to the main model, we find that the equilibrium pay-per-build price, fixed-fee, and quality investment are denoted by u^*, F^*, and q_f^*, such that:

$$\begin{aligned} u^* &= \frac{\alpha^2\theta^2}{4\kappa} + (1-\alpha)\theta q_f^*, \\ F^* &= \frac{\theta^2\mu_H\left(\alpha^2\theta + 4(1-\alpha)\kappa q_f^*\right)^2}{4\kappa\left(\alpha^2\theta^2 + 4(1-\alpha)\theta\kappa q_f^* + 4\kappa\tau\right)}, \text{and} \\ \mu_H &= \frac{4\kappa q_f^*\left(\alpha^2\theta^2 + 4(1-\alpha)\theta\kappa q_f^* + 4\kappa\tau\right)^2}{(1-\alpha)\theta^2\left(\alpha^2\theta + 4(1-\alpha)\kappa q_f^*\right)\left(\alpha^2\theta^2 + 4(1-\alpha)\theta\kappa q_f^* + 8\kappa\tau\right)}. \end{aligned}$$

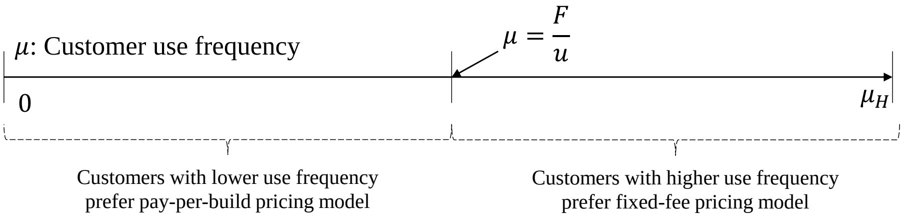


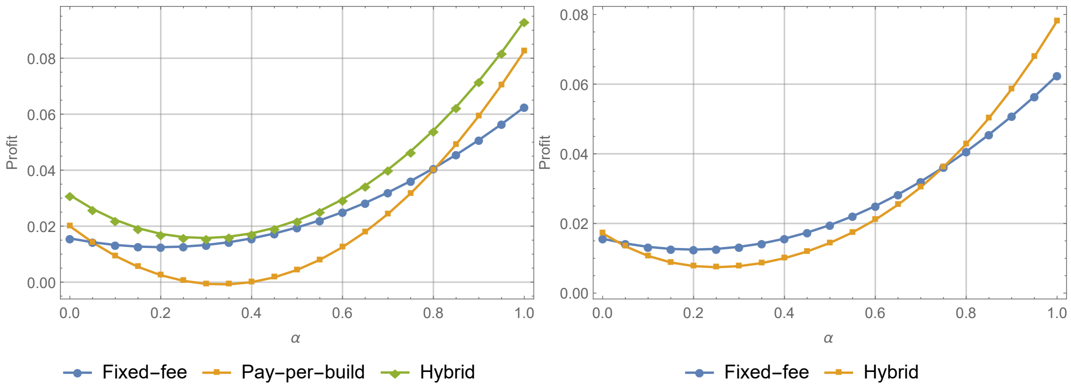
Figure EC.3 Market segmentation under hybrid pricing model

Subsequently, due to the high complexity of this setup, we next discuss various insights with the help of computational studies. Similar to discussions in Proposition 1 and Lemma 2, we find that the product quality is high due to high investment by the firm (or customer) when α is relatively low (or high) (i.e., $\frac{\partial q_f^*}{\partial \alpha} < 0$ and $\frac{\partial q_c^*}{\partial \alpha} > 0$). Therefore, we find that, as α increases, the pay-per-build price and the fixed-fee decrease until a threshold value, after which they increase. That is, the firm charges higher prices at a relatively high or low range of α.

Our analysis reveals that the firm's payoff under the hybrid pricing model is always higher as compared to the pay-per-build pricing model (see Figure EC.4(a)). This is because the hybrid model provides flexibility to the 3DaaS firm to screen high-usage customers via the fixed-fee pricing model and low-usage customers via the pay-per-build pricing model. Now, the effective number of the pay-per-build transaction are lower under the hybrid model (as high-usage customers opt for the fixed-fee pricing model). Therefore, due to savings from lower monitoring costs, the 3DaaS firm's payoff is higher under the hybrid model.

Interestingly, we find that the 3DaaS firm's payoff may be higher or lower under the hybrid model as compared to the fixed-fee model. Specifically, we find that the hybrid pricing model generates a higher payoff for the 3DaaS firm as compared to the fixed-fee model when the transactions monitoring cost is low (see Figure EC.4(a)). The hybrid pricing model provides flexibility to 3DaaS to design F and u, such that, it motivates the high-usage customers to opt for the fixed-fee model and low-usage customers to opt for the pay-per-build pricing model. Overall, due to high market coverage (and hence, high market demand) and lower monitoring cost of pay-per-build transactions, the hybrid model generates high profit when τ is low (compared to the fixed-fee model).

Interestingly, if the transaction monitoring cost is high, we find that the hybrid model generates a higher payoff as compared to the fixed-fee model if α is relatively high or α is relatively low (see Figure EC.4(b)). The reason is when α is relatively high (or α is relatively low) due to high-quality investment by the customer (or firm), the customer's net utility is high, motivating the firm to set high F and high u to extract high customer surplus. However, if α is in the intermediate range, relatively low efforts by the firm/customer may lead to lower value generation for the customer (due to lower product quality). Therefore, under the fixed-fee model, the firm strategically sets a higher fixed-fee to offer its services to high-use frequency customers



(a) Scenario when τ is low $(\tau = 0.085)$ (b) Scenario when τ is high $(\tau = 0.15)$

Figure EC.4 Comparison of payoffs under different pricing models

Base parameter values: $\theta = 1; \kappa = 1$ and $\mu_H = 1$

(who also have a relatively high willingness to pay). Under this case, suppose the firm would have offered a hybrid model; it would have set a lower u to attract low-usage customers (as they gain low consumption value). However, lower unit price (u) may also force some moderately high-use frequency customers to opt for a pay-per-build pricing model. Therefore, this might lead to lower fixed-fee F decided by the 3DaaS firm to make the fixed-fee model a bit more attractive to high-usage customers. Overall, lower u and F lead to a bit of dilution of revenue, reducing the 3DaaS firm's payoff as compared to the fixed-fee model.

EC.6.2 Scenario when Firm and Customer are Asymmetric in Design Cost Structure

In the main model, we considered the case where the firm and the customer have a similar quality cost structure. In this extension, we consider the case where the firm and the customer are asymmetric in quality cost. In business practice, such cost asymmetry arises due to differentiation in design capabilities, inherent domain knowledge, prior design experience, etc (Thomke and Von Hippel 2002). In this scenario, the firm's and the customer's quality investment costs are given by $\kappa_f q_f^2$ and $\kappa_c q_c^2$, respectively. As in the main model, we find that the equilibrium quality investment and fixed-fee decided by the 3DaaS firm are given by:

$$q_f^* = \frac{(1-\alpha)\theta\mu_H}{8\kappa_f}, \text{ and } F^* = \frac{\theta^2\mu_H\left((1-\alpha)^2\kappa_c\mu_H + 2\alpha^2\kappa_f\right)}{16\kappa_c\kappa_f}.$$

We find that as the quality cost parameter (of the firm or the customer) increases, the fixed-fee decreases. The equilibrium quality and the unit price of the firm, in pay-per-build pricing model, are given by:

$$q_f^* = \frac{(1-\alpha)\theta\mu_H}{4\kappa_f}, \text{ and } u^* = \frac{1}{4}\theta^2\left(\frac{\alpha^2}{\kappa_c} + \frac{(1-\alpha)^2\mu_H}{\kappa_f}\right).$$

We find that higher quality cost leads to lower price and quality. Similar to the main model, we could show that the firm's payoff in the fixed-fee model is higher than that in the pay-per-build pricing model if α is between two threshold values. Interestingly, the difference in the 3DaaS firm's profit under two pricing models decreases as the quality cost structure of either player increases. We also find that the impact of the customization parameter α is robust in this extension. Finally, our analysis reveals that the firm is better off when customers bear the entire product design responsibility if and only if the expected use frequency is below a threshold value.

EC.6.3 Scenario with Heterogeneity in Customer's Quality Valuation

In real-life practice, there exists heterogeneity in consumption utility among customers toward a product design of similar quality due to various factors such as differences in the perceived value and preferences (Shi et al. 2013). Therefore, in this extension, we consider heterogeneity in the customer's value gained from the product consumption. We consider the case where the customer's quality valuation is $\theta_H q$ with probability λ (high type customer), and valuation is $\theta_L q$ with probability $1-\lambda$ (low type customer), where $\theta_H > \theta_L$. Similar to the main model, in the fixed-fee pricing strategy, we could show that the demand of 3D printing devices for the customer with valuation θ_i, $i = L, H$ is given by $D_i = 1 - \frac{4F\kappa}{\theta_i \mu_H \left(\alpha^2\theta_i + 4(1-\alpha)\kappa q_f\right)}, i = L, H$. Therefore, the expected payoff of the 3DaaS firm under fixed-fee pricing model is given by:

$$\Pi_{3D} = \lambda F D_H + (1-\lambda)\, F D_L - \kappa q_f^2.$$

The equilibrium fixed-fee and the quality investment strategy of the 3DaaS firm are given by F^* and q_f^*, such that:

$$F^* = \frac{\left(\alpha^2\theta_H + 4(1-\alpha)\kappa q_f^*\right)\left(\alpha^2\theta_L + 4(1-\alpha)\kappa q_f^*\right)}{8\kappa(1-\lambda)\theta_H\mu_H\left(\alpha^2\theta_H + 4(1-\alpha)\kappa q_f^*\right) + 8\kappa\lambda\theta_H\mu_H\left(\alpha^2\theta_L + 4(1-\alpha)\kappa q_f^*\right)}, \text{ and}$$

$$\kappa = \frac{(1-\alpha)\theta_H\mu_H\theta_L\left(8(1-\alpha)\alpha^2\kappa q_f^*\left((1-\lambda)\theta_H^2 + \lambda\theta_L^2\right) + 16(1-\alpha)^2\kappa^2\left(q_f^*\right)^2\left((1-\lambda)\theta_H + \lambda\theta_L\right) + \alpha^4\left((1-\lambda)\theta_H^3 + \lambda\theta_L^3\right)\right)}{8q_f^*\left(4(1-\alpha)\kappa q_f^*\left((1-\lambda)\theta_H + \lambda\theta_L\right) + \alpha^2\left(\lambda\theta_L^2 + (1-\lambda)\theta_H^2\right)\right)^2}.$$

We find that as the probability of the customer being high type increases, the fixed-fee charged by the 3DaaS firm increases. Further, we find that the quality investment made by the firm also increases. The impact of α on the firm's strategy is the same as that observed in the main model. In the pay-per-build pricing model, we find that if $u \leq \frac{\theta_L\left(\alpha^2\theta_L + 4(1-\alpha)\kappa q_f\right)}{4\kappa}$, then both high type and low type customers opt for the printing service. However, if $\frac{\theta_L\left(\alpha^2\theta_L + 4(1-\alpha)\kappa q_f\right)}{4\kappa} \leq u \leq \frac{\theta_H\left(\alpha^2\theta_H + 4(1-\alpha)\kappa q_f\right)}{4\kappa}$, then only the high type customer opts for the printing service. We could show that if λ is above a given threshold value, then the optimal price and quality investment are given by:

$$q_f^* = \frac{(1-\alpha)\lambda\theta_H\mu_H}{4\kappa}, \text{and}\, u^* = \frac{\theta_H\left(\alpha^2\theta_H + (1-\alpha)^2\lambda\theta_H\mu_H\right)}{4\kappa}.$$

Otherwise,

$$q_f^* = \frac{(1-\alpha)\mu_H\theta_L}{4\kappa}, \text{and}\, u^* = \frac{\theta_L^2\left(\alpha^2 + (1-\alpha)^2\mu_H\right)}{4\kappa}.$$

If there is a high probability that the customer is of high type (λ), then the 3DaaS firm sets high prices to target just the high type customer. However, if λ is low, then it sets a lower price to target both high type and low type customers. Further, when λ is above the threshold, we find that as λ increases, the unit pay-per-build price and the quality investment increase. In our computational study, we observe that our insights about payoff comparisons under fixed-fee and pay-per-build models are robust in this extension. Finally, we find that our key insights on the impact of the product collaboration parameter α are robust.

EC.6.4 Scenario with Heterogeneity in Customer's Quality Cost

We modify the main model setup to consider heterogeneity in the customer's quality investment cost structure. This is because, in real life, customers' productivity in design customization may differ due to previous design experience and design capabilities (Ozer and Raz 2011). Therefore, we analyze the case where the quality cost is $\kappa_H q_c^2$ with probability λ (high type customer), and quality cost is $\kappa_L q_c^2$ with probability $1-\lambda$ (low type customer) where $\kappa_H > \kappa_L$. We find that the demand of the customer with quality cost κ_i, $i = L, H$ is given by $D_i = 1 - \frac{4F\kappa_i}{\theta\mu_H\left(\alpha^2\theta+4(1-\alpha)\kappa_i q_f\right)}, i = L, H$. Therefore, the expected payoff of the 3DaaS firm is given by:

$$\Pi_{3D} = \lambda F D_H + (1-\lambda)\, F D_L - \kappa q_f^2.$$

We obtain the equilibrium fixed-fee price and the firm's quality investment decision, F^* and q_f^* respectively, such that:

$$F^* = \frac{\theta\mu_H\left(\alpha^2\theta + 4(1-\alpha)\kappa_H q_f^*\right)\left(\alpha^2\theta + 4(1-\alpha)\kappa_L q_f^*\right)}{8\kappa_H\left(\alpha^2\theta\lambda + 4(1-\alpha)\kappa_L q_f^*\right) + 8\alpha^2\theta(1-\lambda)\kappa_L},$$

$$\kappa = 8(1-\alpha)\,(F^*)^2\left(\frac{(1-\lambda)\kappa_L^2\left(\alpha^2\theta + 4(1-\alpha)\kappa_H q_f^*\right)^2 + \lambda\kappa_H^2\left(\alpha^2\theta + 4(1-\alpha)\kappa_L q_f^*\right)^2}{\theta q_f^*\mu_H\left(\alpha^2\theta + 4(1-\alpha)\kappa_L q_f^*\right)^2\left(\alpha^2\theta + 4(1-\alpha)\kappa_H q_f^*\right)^2}\right).$$

We find that as the probability of the customer being high type increases, the equilibrium fixed-fee decreases, and the firm's optimal quality investment decreases. We also find the impact of α to be robust. In the pay-per-build pricing model, we find that if $\frac{\theta}{4}\left(\frac{\alpha^2\theta}{\kappa_H} + 4(1-\alpha)q_f\right) \geq u$, then the 3DaaS firm targets both high type and low type customers. However, if $\frac{\theta}{4}\left(\frac{\alpha^2\theta}{\kappa_L} + 4(1-\alpha)q_f\right) \geq u \geq \frac{\theta}{4}\left(\frac{\alpha^2\theta}{\kappa_H} + 4(1-\alpha)q_f\right)$, then the 3DaaS firm will ensure that only the low type customer opts for the 3D printing service. Next, our analysis reveals that if λ is below a given threshold value, then the pricing and quality decisions are as follows:

$$q_f^* = \frac{(1-\alpha)\theta(1-\lambda)\mu_H}{4\kappa}, \text{and}\, u^* = \frac{1}{4}\theta^2\left(\frac{\alpha^2}{\kappa_L} + \frac{(1-\alpha)^2(1-\lambda)\mu_H}{\kappa}\right).$$

Otherwise,

$$q_f^* = \frac{(1-\alpha)\theta\mu_H}{4\kappa}, \text{and}\, u^* = \frac{1}{4}\theta^2\left(\frac{\alpha^2}{\kappa_H} + \frac{(1-\alpha)^2\mu_H}{\kappa}\right).$$

Our analysis reveals that if λ is low, then the 3DaaS firm prices the service such that it only motivates low type customers to opt for the 3D printing service. Otherwise, at the higher range of λ, it motivates both high and low type customers to opt for the service. We find that when λ is below the threshold, as λ increases, unit price and quality investment decrease. We find that all our key insights are robust in this extension.

EC.6.5 Scenario with Feed Material Cost Structure

3D printers use various feed materials, such as plastics, metals, resins, or powders. Therefore, in the final set of robustness studies, we consider the presence of feed material cost structure. We analyzed this extension using two cases, (i) when the feed material cost is incurred by the firm, and (ii) when the customer incurs the feed material cost. Similar to the analysis of the main model, we were able to characterize the equilibrium strategies and payoff in all the pricing models. Our analysis reveals that when the customer bears the feed material cost, the firm reduces its prices (compared to the base case) under both the pricing models. Further, the payoff of the firm reduces due to reduced margins. Further, when the 3DaaS firm incurs the feed material cost, it reduces its fixed-fee (as compared to the fixed-fee charged in the main model). However, the unit pay-per-build price is not impacted. Finally, we find that all our insights from the main model are robust in this extension.

References

Shi, H., Liu, Y., & Petruzzi, N. C. (2013). Consumer heterogeneity, product quality, and distribution channels. Management Science, 59(5), 1162-1176.

Ozer, O., & Raz, G. (2011). Supply chain sourcing under asymmetric information. Production and Operations Management, 20(1), 92-115.

EC.7 Detailed Discussions of Some Model Extensions

In this section, we present the details of the characterization of bidding strategy and formulation of payoff functions in some model extensions discussed in Section 6 of the main paper. Along with discussion of insights, we also provide the visualization of key numerical studies conducted for each of the robustness check.

EC.7.1 Alternate Quality Collaboration Function

This section extends our primary model by considering the Cobb-Douglas quality collaboration function. In this collaboration structure, the efforts by the 3DaaS firm and the customer have a synergistic influence on the overall product quality. Hence, we assume that the quality collaboration function is given by $q_h = q_c^{\alpha} q_f^{1-\alpha}$, where $0 \leq \alpha \leq 1$. By substituting the above quality function, we find the equilibrium quality investment by the customer given by $q_c = 2^{\frac{1}{\alpha-2}} \left(\frac{\alpha\theta q_f^{1-\alpha}}{\kappa} \right)^{\frac{1}{2-\alpha}}$. Under all pricing models, we find that the characterization of the firm's quality and optimal pricing strategy is quite complicated. Due to high complexity, we could only study the behavior of the equilibrium strategy with the help of computational studies. Figure EC.5 illustrates the impact of parameter α on payoffs and decisions. We observed that all our insights on the effects of α from the main model are robust in this extension.

EC.7.2 Repetitive Manufacturing Scenario

As discussed in Section 1.2, the customer may also utilize 3DaaS for mass production purposes. Such customers tend to prepare the design file only once and utilize the same design file to print multiple replicas of the product. Similar to the analysis of the main model, we consider all three pricing scenarios for such a customer profile.

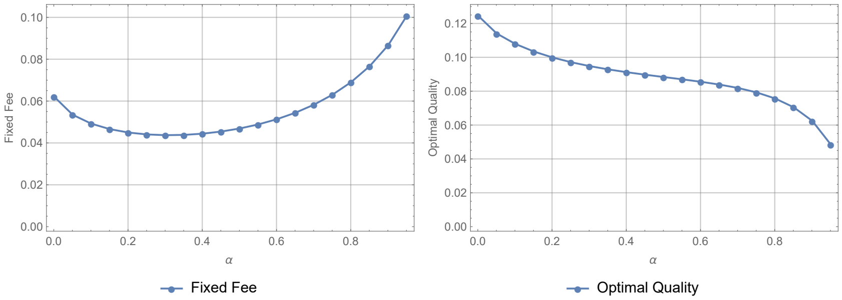
EC.7.2.1 Fixed-fee Pricing Model

The customer pays the fixed-fee F, and decides the product quality level q_c, and finally, prints μ copies of the product. The utility function of the customer is given by:

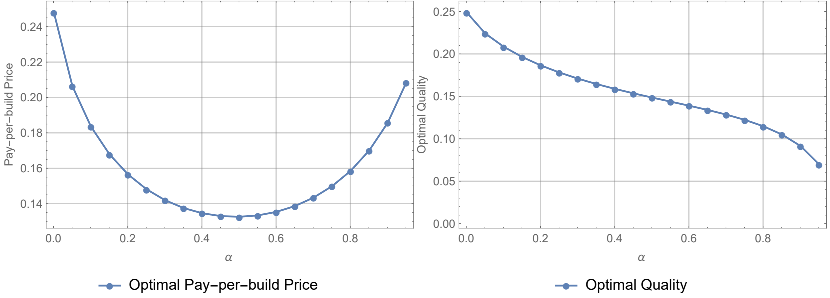
$$U_c = \mu\theta q_h \left(q_c, q_f\right) - F - \kappa q_c^2,$$

where $q_h \left(q_c, q_f\right) = \alpha q_c + (1-\alpha) q_f$. Further, we find the firm's optimal quality decision is given by $q_c^* = \frac{\alpha\theta\mu}{2\kappa}$. Therefore, given the quality efforts decision of the firm q_f, the customer with the use frequency μ obtains the utility $U_c^* = \frac{\alpha^2\theta^2\mu^2}{4\kappa} + (1-\alpha)\theta\mu q_f - F$. The 3D printing device demand faced by the firm D_{3D} is given by:

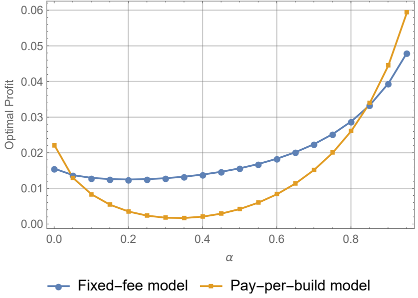
$$D_{3D} = \Pr\left(U_c^* \geq 0\right) = \frac{\mu_H - \frac{2\left(\sqrt{\theta^2\kappa\left((1-\alpha)^2\kappa q_f^2 + \alpha^2 F\right)} - (1-\alpha)\theta\kappa q_f\right)}{\alpha^2\theta^2}}{\mu_H}.$$



(a) F^* under fixed-fee model (b) q_f^* under fixed-fee model



(c) u^* under pay-per-build model (d) q_f^* under pay-per-build model



(e) Payoff comparison under
fixed-fee and pay-per-build models

Figure EC.5 Impact of α on equilibrium payoffs and decisions when $q_h = q_c^{\alpha} q_f^{1-\alpha}$

Base parameter values: $\theta = 1$, $\kappa = 1$, $\tau = 0.08$, and $\mu_H = 1$.

The 3DaaS firm decides the fixed-fee F to maximize the following payoff function:

$$\Pi_{3D} = FD_{3D} - \kappa q_f^2 = F\left(\frac{\mu_H - \frac{2\left(\sqrt{\theta^2\kappa\left((1-\alpha)^2\kappa q_f^2+\alpha^2 F\right)}-(1-\alpha)\theta\kappa q_f\right)}{\alpha^2\theta^2}}{\mu_H}\right) - \kappa q_f^2.$$

Similar to that main model, we find that the optimal fixed-fee F^* and quality investment q_f^* are such that:

$$\sqrt{\theta^2\kappa\left((1-\alpha)^2\kappa\left(q_f^*\right)^2+\alpha^2 F^*\right)} = \frac{(1-\alpha)^2 F^*\theta\kappa q_f^*}{F^*(1-\alpha)-\alpha^2\theta q_f^*\mu_H}, \text{ and}$$

$$F^* = \frac{\sqrt{\theta^2\kappa\left((1-\alpha)^2\kappa\left(q_f^*\right)^2+\alpha^2 F^*\right)}\left(2(1-\alpha)\theta\kappa q_f^* + \alpha^2\theta^2\mu_H - 2\sqrt{\theta^2\kappa\left((1-\alpha)^2\kappa\left(q_f^*\right)^2+\alpha^2 F^*\right)}\right)}{\alpha^2\theta^2\kappa}$$

We observe that as α increases, the fixed-fee decreases, and after a threshold, it increases. Further, similar to our observations from Section 4, as α increases, the firm's payoff and customer surplus decrease if and only if α is below a threshold value. Next, we compare the fixed-fee in the scenario where the customer is a design studio (main model setup considered in Section 4) with the case of the customer using 3DaaS for repetitive manufacturing.

We find that when the customer has no impact on product design, that is, $\alpha = 0$, then the fixed-fee charged from either a design customer or a repetitive manufacturing customer is the same. This is because the customer does not incur any design cost and simply prints unique or duplicate copies of the design supplied by the 3DaaS firm. Interestingly, if the impact of the customer on the product design is high (i.e., $\alpha \to 1$), under certain conditions, the 3DaaS firm may charge a higher or lower fixed-fee from the design firm. Specifically, we find that if the expected use frequency of the customer is above a threshold value, then fixed-fee charged from the design customer is lower. The reason is that when α is high, the customer tends to invest more and incurs a high design investment cost structure (as every print is a unique design). Therefore, the 3DaaS firm charges a lower fixed-fee to motivate the design customer to opt for 3DaaS.

EC.7.2.2 Pay-per-build Pricing Model

Similar to the analysis in Section EC.7.2.1, we first solve the customer's problem. The utility of the customer is given by:

$$U_c = \mu\theta q_h\left(q_c, q_f\right) - \mu u - \kappa q_c^2,$$

where $q_h\left(q_c, q_f\right) = \alpha q_c + (1-\alpha) q_f$. Since the customer designs the product once and prints it μ times, the pay-per-build cost paid to the firm and the quality cost are given by μu and κq_c^2, respectively. Similar to the previous analysis, the customer's quality investment decision is given by $q_c^* = \frac{\alpha\theta\mu}{2\kappa}$. It can be shown that the device demand faced by the 3DaaS firm is given by:

$$D_{3D} = \begin{cases} \frac{\mu_H - \frac{4\kappa\left(u-(1-\alpha)\theta q_f\right)}{\alpha^2\theta^2}}{\mu_H} & \text{if } u > (1-\alpha)\theta q_f, \\ 1 & \text{if } u \leq (1-\alpha)\theta q_f. \end{cases}$$

When the price is low, the market is fully covered. However, there is partial market coverage at a higher range of price. Further, the average number of units printed by the customer using the 3D printing device is given by:

$$E_\mu\left[\mu\right] = \begin{cases} \frac{\mu_H + \frac{4\kappa\left(u-(1-\alpha)\theta q_f\right)}{\alpha^2\theta^2}}{2} & \text{if } u > (1-\alpha)\theta q_f, \\ \frac{\mu_H}{2} & \text{if } u \leq (1-\alpha)\theta q_f. \end{cases}$$

Therefore, the payoff function of the 3DaaS firm is given by:

$$\Pi_{3D} = uE_\mu\left[\mu\right] D_{3D} - \kappa q_f^2 - \tau E_\mu\left[\mu\right] D_{3D}.$$

The first term $uE_\mu\left[\mu\right] D_{3D}$ denotes the total earning by the firm from the customers' payment toward each printed object. The second term κq_f^2 denotes the total quality cost incurred by the firm. Finally, the third term $\tau E_{\mu}[\mu] D_{3D}$ denotes the transactions monitoring cost incurred by the firm. Similar to the main model, we find that the optimal pay-per-build price u^* and quality investment q_f^* are such that:

$$\frac{\mu_H}{2} = \frac{8\kappa^2 \left(u^* - (1-\alpha)\theta q_f^*\right)\left(3u^* - (1-\alpha)\theta q_f^* - 2\tau\right)}{\alpha^4\theta^4\mu_H}, \text{ and}$$

$$q_f^* = \frac{8(1-\alpha)\kappa u^*(u^* - \tau)}{\alpha^4\theta^3\mu_H + 8(1-\alpha)^2\theta\kappa(u^* - \tau)}.$$

Similar to the scenario where the firm deals with design customers, we find that the firm's quality investment is higher under the pay-per-build pricing scenario (as compared to the fixed-fee model). Further, we find that as the impact of the customer on product quality (α) increases, the unit price decreases until a threshold value, after which it increases. Next, we numerically observe that in a relatively low range of α or a relatively high range of α, the firm's profit in the pay-per-build pricing model is higher than that in the fixed-fee pricing model. This indicates that all our insights from the main model are robust in this extension.