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Purchase or rent? Optimal pricing for 3D printing capacity sharing platforms ☆

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ABSTRACT

Online sharing platforms have attracted considerable research and management attention across a number of industries, including travel, real estate, and cloud computing. They also have great potential for the 3D printing (3DP) industry, offering users the choice between owning or renting 3DP capacity. For matching supply and demand, capacity pricing is crucial. In this paper we consider two fundamental questions concerning pricing: (i) What is the optimal pricing strategy for a 3DP capacity sharing platform? (ii) How do usage level and printer heterogeneity affect consumers' choice between in-house printing (owning) and outsourcing (renting)? Using queuing analysis, we derive the structural properties of the solutions to the problems. Furthermore, we conduct numerical studies using real-world data to generate managerial insights from the analytical findings. A key finding is that governments should focus on encouraging technological progress to lower the printers' prices in order to improve the well-being of the industry. When considering two types of printers, we find that it is more beneficial for the platform if the high capacity printer dominates the market, as the platform then retains the prominent role in "redistributing" the 3DP capacity.

1. Introduction

Three-dimensional printing (3DP), also known as additive manufacturing, has been around for decades and has become more widespread lately due to recent advances in the associated technologies. The rapid development of 3DP has transformed the conventional manufacturing process and thereby operational decision making, as many industries have undergone major changes after adopting 3DP for volume production. It has increased manufacturing flexibility (Chan, Ngai, & Moon, 2017; Chen, Cui, & Lee, 2021; Dilberoglu, Gharehpapagh, Yaman, & Dolen, 2017; Durão, Christ, Anderl, Schützer, & Zancul, 2016). In particular, 3DP can deal with special manufacturing requirements arising from intricate designs and provides production flexibility, especially for the aerospace, railway, automobile, medical services, power plant industries etc. It is used for prototyping to accelerate product development, and for low-volume production or even one-off custom parts (3D Hubs, 2020). It also enables the transition from traditional to information-driven personalized manufacturing (Dalenogare, Benitez, Ayala, & Frank, 2018; Madsen, Bilberg, & Hansen, 2016), transcending to Industry 4.0 (Olsen & Tomlin, 2020).

In tandem with the great advances in 3DP technology and information technologies, 3DP platforms have developed rapidly in the past decade (Dilberoglu et al., 2017), making 3DP services available to anyone with printing requests. The 3DP platform, which combines the benefits of information processing, digital technology, and additive manufacturing capability, provides rapid and accurate data transmission for high-quality component manufacturing, enabling flexibility in product design and production. More importantly, the platform carries all the information and data exchanged between the customer and the platform, including information on orders, products, transactions, deliveries etc. (Dilberoglu et al., 2017), which allows the platform to make real-time, efficient operations decisions. From the perspective of a supply chain, such a platform re-shapes the supply chain structure of the 3DP industry by separating the ownership and use right of the 3D printer. By gathering spare production capacity in the 3DP industry, the platform can efficiently match the spare capacity with real-time

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requirements (Li, Ding, Cui, Lei, & Mou, 2019), thereby promoting the flexibility and efficiency of the entire manufacturing industry.

Production capacity has been extensively considered in the literature, but for the traditional chain with clear lines of demarcation between supply and demand, and a known investment cost function for suppliers (Dobson & Yano, 2009; Golmohammadi & Hassini, 2019; Lee & Ward, 2019). Platforms create a more hybrid system, allowing small firms/individuals the option to not invest but still have access to printing capacity via the platform (Hopkinson, Hague, & Dickens, 2006; Gibson et al., 2015; Hedenstierna et al., 2019; Rogers, Baricz, & Pawar, 2016); while heavy users can purchase their own equipment and share access capacity.

There are essentially two types of 3DP platforms: (1) The capacity sharing platform, such as 3D hubs, acts as a matching center only, while the suppliers, i.e., owners of 3D printers, share their spare capacity with customers who do not own 3D printers. (2) The printing platform, such as Shapeways, has its own 3D printers and provides printing services and 3D design models to customers. Focusing on the former type of platform in this study, we explore the optimal pricing of the 3DP capacity sharing platform and its effects on the supply chain members. In what follows, we refer to this type of platform simply as a 3DP platform.

We conduct this study with a view to exploring the consumer purchasing versus renting decisions in the context of the sharing economy, and providing operations and pricing guidance for the 3DP platform. Indeed, usage level, which could be interpreted as consumer demand for printing capacity, is obviously a key factor in deciding whether to own or rent 3DP capacity, and so it is essential to take usage level heterogeneity into account when considering 3DP platforms. Moreover, we consider the heterogeneity of shared printer types, which plays an important role in platform operating decisions.

Specifically, we develop an analytical modelling framework for a 3DP platform, deriving the optimal price by using a queueing system to match supply and demand, where consumers choose between renting or owning 3D printers. The model provides general insights into decision-making for a platform and its users. Note that as a starting point for this exploratory study, we consider the platform that is the price setter, i.e., it has a dominant position in the industry. Furthermore, using data from real-world cases, we show numerically that a platform should set a higher capacity price when the fixed cost of owning plus using a 3D printer increases.

We organize the rest of the paper as follows. In Section 2 we review the related literature to identify the research gap and position our work. In Section 3 we introduce the problem and formulate the model to address the research issues. In Section 4 we present the analysis and discuss the findings. Moreover, we conduct numerical studies to generate practical insights from the analytical findings. In Section 5 we consider the effect of heterogeneity of shared products by extending the basic model to include two printer types. In Section 6 we consider several extensions of the basic model. Finally, we conclude the paper and suggest topics for future research in Section 7.

2. Literature Review

We discuss the benefits for firms/individuals of using 3DP (via a platform) versus traditional manufacturing in Section 2.1, before taking the peer-to-peer capacity sharing market perspective in Section 2.2, followed by discussion of our key contributions in Section 2.3.

2.1. Impact of 3DP on manufacturing firms

Whether or not to source printing capacity from 3DP platforms relates to the more general choice between in-house/decentralized or outsourced/centralized manufacturing (Chen & Bell, 2011; Sethuraman, Parlakturk, & Swaminathan, 2018). Compared with conventional manufacturing, the major benefit of outsourced printing comes from reducing the fixed and variable costs for small, complex, and customized production. In addition, firms can reduce their inventory and transport costs as new products and replacement parts can be printed on demand (Hopkinson and Dickens, 2003; Atzeni & Salmi, 2012; Baumers, Dickens, Tuck, & Hague, 2016; Chen, Fang, & Wen, 2013; Chen, Liang, Yao, & Sun, 2017; Gebler, Schoot Uiterkamp, & Visser, 2014; Sasson & Johnson, 2016; Thomas, 2016; Westerweel, Basten, & Houtum, 2018). Furthermore, customers gain more security as the additional costs and corresponding risks caused by unreliability, from, e.g., production failures or delayed deliveries, are transferred to the service provider (Rogers et al., 2016).

Compared with in-house printing, outsourcing avoids the need to invest in equipment acquisition and staff training, but leads to a higher distribution cost (Holmström, Partanen, Tuomi, & Walter, 2010; Huang, Liu, Mokasdar, & Hou, 2013; Khan & Mohr, 2015). If the customer's demand for a single type of product is relatively small, purchasing an expensive printer is obviously not worthwhile (Conner et al., 2014; Holmström et al., 2010; Rogers et al., 2016). It is also acknowledged that not all manufacturing firms or individuals that pursue small-volume, personalized customization are qualified to use 3DP (Rogers et al., 2016; Schniederjans, 2017; Weller, Kleer, & Piller, 2015). However, if an OEM sells licences or designs to firms for in-house printing, then decentralized printing can lead to more flexibility and higher profits (Westerweel, Song, & Basten, 2019).

2.2. Matching and pricing issues of peer-to-peer sharing platforms

We next review the literature on peer-to-peer sharing platforms/economies, of which the 3DP capacity sharing platform is a typical example. Most of the studies in this field either focus on the peer-to-peer market in general or the peer-to-peer market in specific industries. For the former, the effects of peer-to-peer product sharing on welfare improvement have been a key issue for researchers, and the conclusions are mixed. For example, Benjaafar, Kong, Li, and Courcoubetis (2018) analytically examined the efficiency of peer-to-peer product sharing, considering different factors such as ownership, profit, surplus, and welfare. They found that collaborative consumption always benefits the consumers. However, by applying an analytical model to study the consumer's purchasing and sharing decisions in collaborative consumption, Jiang and Tian (2018) found that the platform's pricing strategy helps improve the platform's profit, but damages consumer surplus. Other studies derive further insights by considering heterogenous consumers. Fraiberger and Sundararajan (2015) found, using US car rental data, that low-income consumers can profit most from the sharing economy. Studying the optimal on-demand service pricing considering the risk attitudes of customers in decision-making, Choi, Guo, Liu, and Shi (2020) found that the presence of risk seeking customers improves both the platform's profit and consumer surplus. However, they ignored the endogenous supply of shared products.

Few analytical results on the pricing and matching issues of 3DP capacity sharing platforms have been presented to date, and we next review them in detail. Hedenstierna et al. (2019) developed a "bidirectional partial outsourcing" (BPO) scheme considering the capacity sharing between the outsourcer and subcontractor. Through a case study of Shapeways and by adopting an analytical model, they found that BPO helps improve the cost efficiency and delivery performance of a 3DP service. Sun, Hua, Cheng, and Wang (2020a) studied the optimal pricing strategy for 3DP platforms considering a supply chain consisting of a platform, customers, and registered designers. They found that, for the platform, charging a fixed commission fee is more profitable than leaving it to the designers to add a mark-up dependent on product quality. By considering the recycling process in the 3DP industry, Sun, Wang, Hua, Cheng, and Dong (2020b) derived the optimal pricing strategy for 3DP platforms in a closed-loop circular supply chain. They found that while the platform could benefit from recycling, suppliers avoid producing high-quality products made from recycled material.

The fractional jet market can be seen as one of the earliest types of peer-to-peer sharing platforms. However, most studies on this market do not focus on pricing but take the transport perspective, e.g., considering the routing and maintenance problems (Yao, Ergun, & Johnson, 2007; Yao et al. 2008; Munari and Alvarez, 2019). For example, by adopting the scheduling approach, Yao et al. (2008) proposed flexible planning strategies in terms of aircraft maintenance, crew swapping, and customer demand to increase the plane utilization rate. For the ride-hailing market, the optimal pricing strategy has been a popular research topic, especially regarding the customer waiting time (Bai, So, Tang, Chen, & Wang, 2018; Benjaafar et al., 2018; Nourinejad & Ramezani, 2019; Sun, Teunter, Babai, & Hua, 2019; Sun, Teunter, Hua, & Wu, 2020c; Taylor, 2018; Wang, Liu, Yang, Wang, & Ye, 2020; Xu et al., 2020; Yang, Qin, Ke, & Ye, 2020). However, these studies typically do not consider matching; instead, they treat renting and purchasing decisions as exogenous.

2.3. Contributions

Many studies to date have considered either product/capacity sharing or pricing for the peer-to-peer market, especially in the context of transport (ride-hailing). However, the endogenous decisions of (becoming) renters and owners are typically ignored. Moreover, heterogeneity among shared capacity types has been ignored. Indeed, such heterogeneity plays less a role in the ride-sharing market that many researchers have considered, as the customers ultimately need to get from one location to another. However, in the 3DP industry, production speed and product quality may depend on the types of printers used.

Our research focuses on the operations of the 3DP platform, analyzing its ability to match supply and demand for 3DP services, and ascertaining its impacts on consumers' decision-making on renting and purchasing printers in the peer-to-peer market. Our study is the first to analytically examine matching supply and demand through pricing while considering the endogenous renting and buying options, system waiting time, and heterogeneity in the types of available 3D printers.

3. Basic model

We consider a 3DP platform, where users can either supply spare printing capacity or demand capacity. The platform sets a price per unit of capacity and charges a commission fee, with the objective to maximize profit from matching supply and demand. Note that we assume that the platform is a price setter, not a taker of the competitive market price, i.e., it has a dominant position in the industry. Although this is a natural starting point for our exploratory study, there may be situations in practice where platforms compete in the market. While more competitors can be considered, this would complicate the analysis. Indeed, that is why we assume a single platform in our analysis, which allows us to conduct insightful analysis and produce meaningful results.

Table 1
Notation used in the paper.

p	price for renting a unit of spare capacity
b	per unit net usage benefit
$\theta \in (0,1)$	usage level
$\rho(p) \in (0,1)$	utilization rate for excess capacity
τ	per unit waiting cost
$w(p)$	waiting time before a match is made
k	fixed cost for owning a 3D printer
$\varphi \in (0,1)$	fraction of the price that the platform earns
$\lambda(p)$	aggregate demand by the renters
$\mu(p)$	aggregate supply from the owners

Following Benjaafar et al. (2018), we assume that the users are heterogeneous in their 3DP requirements, modelled as a user's usage level θ being uniformly distributed between 0 and 1. Note that, in real life, the maximum utilization of 3D printer might be significantly lower than 100%; without loss of generality, we normalize the capacity (per time unit) of one 3D printer to 1. Also note that we do not directly consider the users with a usage level of more than 1 because such users would purchase the number of 3D printers that they need full-time, and only consider owning or renting for the remaining usage requirement. So, we only consider the remaining demand of such "large" users. Accordingly, if such users decide to rent capacity for their remaining demand, we regard them as renters because they act as renters for the platform considered, although they also own one or more 3D printers. In real life, dependent on the status of technology adoption and customers' request rate, new consumers may join the system and the platform may change its price from one period to the next. Analyzing such dynamic behaviour over time is of interest, however, we remark that though user's capacity sharing is a short-term event, e.g., on a daily / an hourly basis, on-demand platforms do not dynamically change their prices so frequently (Jiang & Tian, 2018). In this sense, we start our study by considering a single period, i.e., a snapshot of the system, which is exploratory in nature. For the single-period game, we assume that users are fully informed on the platform price at the start of the period, and the users make their decisions based on the price announced by the platform. Nevertheless, we extend our model to the multi-period setting in Section 6.1.

Each user can decide to purchase a 3D printer (so becoming an owner) and sell any excess capacity via a 3DP platform, or rent the required capacity from the platform, taking the option that maximizes utility. Gaining revenue from taking a fraction φ $(0 < \varphi < 1)$ of the rent, the platform aims to maximize its revenue and, therefore, its profit.

In Section 3.1, we present the user utility functions, formalize the objective of the platform, and derive the welfare function of the entire supply chain. We summarize in Table 1 the notation used in the paper.

3.1. Owning versus renting

For an owner, purchasing a 3D printer incurs a fixed cost, which is amortized to a cost per unit time denoted by k. Taking self-requirements as priority, an owner only offers its spare printing capacity for renting. The owner derives benefits from two sources: (i) using the printer and (ii) receiving rent on the shared spare capacity. Denoting by b the unit net usage benefit, i.e., the benefit minus material costs per unit, and recalling that θ is the owner's usage level, the usage benefit that the owner gains from satisfying its own need is $b\theta$. Besides the usage benefit gained from self-requirements, the owner receives a fraction $1 - \varphi$ $(0 < \varphi < 1)$ of the renter's payment for each transaction. Given the price for renting a unit of spare capacity p and the utilization rate $\rho(p)$, which is equal to the fraction of supply used to meet the demand, the owner's unit income from the shared capacity is $\rho(p)p(1-\varphi)$. Obviously, by scaling $1-\theta$, the total revenue that the owner can receive from selling its spare capacity is $\rho(p)p(1-\varphi)(1-\theta)$. Therefore, the utility/profit function for the owner with usage level θ is

$$U_O(\theta) = b\theta + \rho(p)p(1-\varphi)(1-\theta) - k. \tag{1}$$

The renter pays a price p for each unit of the spare capacity. Compared with in-house printing using a private printer, the renter needs to wait for its order to be successfully matched to an available owner, and we denote the average waiting time by $w(p)$. Note that we assume a constant own usage rate ignoring the waiting time for self-use. Let τ $(\tau \geq 0)$ be the unit waiting cost, then the expected waiting cost for the renter is $\tau w(p)$. Thus, the utility/profit function of the renter with usage level θ is

$$U_R(\theta) = [b - p - \tau w(p)]\theta. \tag{2}$$

Note from (2) that we assume that the waiting cost increases linearly with the waiting time. While this is a natural starting point for our exploratory analysis, there may also be situations in practice where customers become increasingly impatient as they wait for an available supplier, which would imply that the waiting cost is strictly convex rather than linear in the waiting time. In Section 6.3 we consider such situations by assuming a quadratic relation and further compare the results with those of the basic model. We remark that more general relations between the waiting cost and waiting time can also be considered, but this would further complicate the analysis. That is why we assume a linear relation in our main analysis, which allows us to conduct insightful analysis and generate meaningful results.

3.2. Matching supply and demand

The matching process follows a common procedure in the sharing economy, which begins with a service request from a customer. After specifying the order requirements online, including material, technology, design details, etc., the customer correspondingly receive an instant quote. As long as the customer agrees with the quote, the platform checks the availability with printer owners, and matches the customer with an available printer owner. Otherwise, the customer waits until the next owner becomes available. Once a match between a customer and an owner is made, the owner is committed to serving that customer next.

We propose an approximation scheme for the matching system. To establish the approximation scheme, we note that the matching process shares some similarities with a queueing system. In particular, the owners can be viewed as servers, while customers waiting for printing capacity can be viewed as customers waiting for service, which is a common method used when examining the matching for on-demand service platforms (Bai et al., 2018; Feng, Kong, & Wang, 2020).

Following Benjaafar et al. (2018), we assume that matching friction may arise because of short-term fluctuations in supply and demand, even though the overall supply and demand are constant in the long run. Such short-term fluctuations come from the latent variability in the arrivals of rental requests, which can lead to a long waiting time for the renters due to a lack of available capacity. Specifically, we assume that the customers do not arrive all at once, but the requests arise stochastically with random interval times. In this sense, even though the supply meets the demand in the long run, a short term, high intensity of arrivals may result in long customer waiting times. To capture this short-term matching friction, and make the model tractable, we model the renter waiting for spare capacity as an $M/M/1$ queue following Sun et al. (2020c). We note that this type of queue does not correspond exactly to the considered situation. On the capacity demand side, assuming a Poisson demand process is natural. On the supply side, while the uncertainty in the processing time is partly caused by not knowing when owners make capacity available, the queuing model converts the uncertainty to variations in the processing time. However, the $M/M/1$ queue seems a natural starting point to address the supply and demand matching issue, so we adopt it in this exploratory research.

A difficulty in analyzing the above queuing model is that the supply and demand (rates) of the printing capacity evidently depend on the price set by the platform, which affects the comparative attractiveness of owning and renting. In addition, as modelled in detail in Section 4.1, the waiting time also affects the user's decision as to whether to own or rent. We denote the supply and demand for a given price p as $\mu(p)$ and $\lambda(p)$, respectively, for which we derive the expressions in Section 4.1. The corresponding utilization of the system is $\rho(p) = \lambda(p)/\mu(p)$, for which the condition for the existence of a steady-state solution is $\rho(p) < 1$. Therefore, we only consider the prices under such a condition. This implies that all the demand is satisfied (after some waiting time), but not all the supply is rented. We remark that we also test our model under the condition of a lower system utilization (e.g., $\rho(p) < 0.8$), and the findings are consistent (as discussed later). Under such a condition, using standard queuing results, we obtain the waiting time of the renter as

$$w(p) = \frac{\rho(p)}{\mu(p) - \lambda(p)}. \tag{3}$$

3.3. The objective of the platform

The platform gains revenue from taking a fraction φ of the rent paid by the customer for each transaction. The objective of the platform is to maximize its profit gained from all the renters, subject to the system utilization constraint and the conditions that both options are selected by some of the consumers (as discussed later in Section 4.1), as follows:

$$\max_p \pi = \lambda(p)\varphi p. \tag{4}$$

s.t. $0 < \rho(p) < 1$;
$U_O(0) < U_R(0) = 0$;
$U_R(1) < U_O(1)$.

Note that in real life, dependent on customers' printing preferences and competition from other platforms, the customer may abort the order and leave the system. Exploring such customer behaviour is of interest, but is beyond the scope of this research.

3.4. Welfare of the supply chain

We next study the welfare/profit of the supply chain from a government perspective, which provides a social responsibility lens through which to consider the performance of industry and the effects of 3DP capacity sharing on supply chain members. Letting $\bar{\theta}$ denote the consumer who is indifferent to becoming a renter and an owner (to be determined in Section 4), we can derive the welfare/profit of the renter and the owner in the supply chain, respectively, as follows:

$$sw_R = \int_0^{\bar{\theta}} U_R(\theta)d\theta, \tag{5}$$

$$sw_O = \int_{\bar{\theta}}^1 U_O(\theta)d\theta. \tag{6}$$

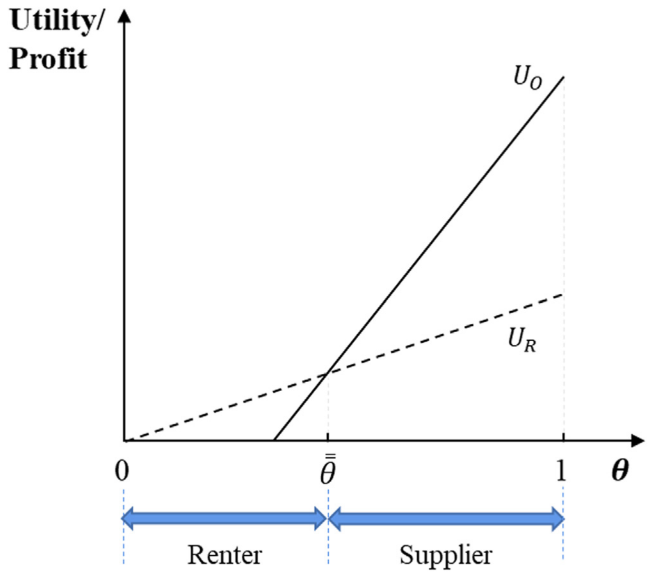

Fig. 1. Consumer catchment areas of owners and renters.

Combining (1), (2), and (4)-(6), we obtain the welfare function sw_{sc} of the supply chain, defined as the combination of user welfare/profit and platform profit, as

$$sw_{sc} = \pi + sw_O + sw_R = \lambda(p)\varphi p + \int_0^{\bar{\theta}} U_R(\theta)d\theta + \int_{\bar{\theta}}^1 U_O(\theta)d\theta. \tag{7}$$

In Section 4.2, we further explore into the measures which can promote the development of 3DP capacity sharing by analyzing the welfare of the supply chain.

4. Price optimization analysis

We first derive the renter's waiting time and analyze the fractions of consumers that opt for becoming a renter or owner in Section 4.1. Then, we propose the platform's maximization problem and derive the platform's optimal price by conducting numerical studies in Section 4.2.

4.1. Consumers' purchase decisions and platform's optimal price

Using (1) and (2), we can find the value of the preference $\bar{\theta}$ at which the users are indifferent between becoming a renter or an owner, i.e., where $U_O(\bar{\theta}) = U_R(\bar{\theta})$.

We remark that there are conditions under which either $U_O(\theta) < U_R(\theta)$ or $U_O(\theta) > U_R(\theta)$ for all the values of θ, implying that all the consumers opt for the same option. But these cases are of limited practical and theoretical interest. Therefore, rather than also considering these extreme cases, we provide the conditions under which both options are selected by some of the consumers. Obviously, the consumers with a low usage level should opt for becoming a renter, implying that $U_O(\theta) \le U_R(\theta)$ for $\theta = 0$. Besides, the consumers with a high usage level should opt for becoming an owner, implying that $U_O(\theta) \ge U_R(\theta)$ for $\theta = 1$. Depicting this situation in Fig. 1, we re-write the two conditions as $p \le \frac{k}{\rho(p)(1-\varphi)}$ and $p \ge k - \tau w(p)$. So, the relevant price range to be considered is from $k - \tau w(p)$ to $\frac{k}{\rho(p)(1-\varphi)}$. Within this price range, we equate (1) and (2) to yield

$$b\bar{\theta} + \left(1-\bar{\theta}\right)\rho(p)(1-\varphi)p - k = [b - p - \tau w(p)]\bar{\theta}, \tag{8}$$

which gives

$$\bar{\theta}(p) = \frac{k - (1-\varphi)p\rho(p)}{p[1-(1-\varphi)\rho(p)] + \tau w(p)}. \tag{9}$$

Letting $f(\theta) = 1$ denote the uniform density function of the usage distribution, the associated aggregate demand and supply generated from the renters and owners are, respectively, as follows:

$$\bar{\lambda}(p) = \int_0^{\bar{\theta}(p)} \theta f(\theta)d\theta = \frac{\bar{\theta}(p)^2}{2} \ge 0 \tag{10}$$

$$\bar{\mu}(p) = \int_{\bar{\theta}(p)}^1 (1-\theta)f(\theta)d\theta = \frac{\bar{\theta}(p)^2}{2} - \bar{\theta}(p) + \frac{1}{2} \ge 0. \tag{11}$$

The corresponding utilization rate and the customer waiting time are

$$\bar{\rho}(p) = \frac{\bar{\lambda}(p)}{\bar{\mu}(p)} = \frac{\bar{\theta}(p)^2}{\left(\bar{\theta}(p)-1\right)^2} \tag{12}$$

where $\bar{\rho}(p) \in (0, 1)$ and

$$\bar{w}(p) = \frac{\bar{\theta}(p)^2}{\left(\frac{1}{2} - \bar{\theta}(p)\right)\left(\bar{\theta}(p)-1\right)^2}. \tag{13}$$

According to the above results, we obtain an analytical validation of the fraction of consumers that opt for becoming an owner (ownership). We formalize the result in Proposition 1 (we give the detailed analysis in Appendix A1).

Proposition 1. *The fraction of consumers that opt for becoming an owner (ownership) is higher than 50%,* i.e., $\bar{\theta}(p) < 0.5$.

Proposition 1 implies that the availability of the sharing option will lead less than half of the users to forego printer ownership in favour of on-demand access. A possible explanation for this might be that the printing capacity sharing platform allows individuals to offset the high fixed cost of owning a 3D printer, even though the additional profit of acting as an owner also pulls in a fraction of the population that may not otherwise choose to own.

To further derive the closed-form indifference point $\bar{\bar{\theta}}\,(p)$ in equilibrium, we combine (9)-(13) to yield

$$\bar{\bar{\theta}}(p) = \tfrac{1}{8\varphi p}(\alpha + \sqrt{\alpha^2 - 16\varphi p\beta/3 - 4\gamma/3}$$
$$-\sqrt{2}\sqrt{\alpha^2 - \tfrac{16\varphi p\beta}{3} + \tfrac{4\gamma}{3\varphi p} + \tfrac{\sqrt{3}(\alpha^3 - 8a\beta\varphi p + 32\varphi^2 p^2(p+4k))}{\sqrt{3\alpha^2 - 4(4\varphi p\beta + \gamma)}}}),$$

where $\alpha = 3\varphi p + 2(p + \tau + k)$, $\beta = (3+\varphi)p + 5k$, $\gamma = \frac{2\cdot 2^{1/3}x}{[y^2 + \sqrt{y^2 - 4x^3} - 2\beta^3]^{1/3}} + 2^{2/3}(y^2 + \sqrt{y^2 - 4x^3} - 2\beta^3)^{1/3}$, $x = p[(\varphi^2 - 3\varphi + 3)p - 6\tau] - 2(\varphi p + 12\tau)k + k^2$, and $y = p^2[9\varphi^2 p - 2\varphi^3 p - 9\varphi(p - 2\tau) + 54\tau] - 3[(6 - 15\varphi + 7\varphi^2)p^2 + 6(14\varphi - 5)p\tau + 36\tau^2]k - 6(\varphi p - 24\tau)k^2 + 2k^3$.

Thus, the fractions of consumers renting and owning are $\bar{\bar{\theta}}(p)$ and 1-$\bar{\bar{\theta}}(p)$, respectively.

Thus, under the equilibrium condition mentioned above, the associated aggregate demand and supply generated from the renters and owners are expressed as $\bar{\bar{\lambda}}(p) = \int_0^{\bar{\bar{\theta}}(p)} \theta f(\theta)d\theta = \frac{\bar{\bar{\theta}}(p)^2}{2}$ and $\bar{\bar{\mu}}(p) = \int_{\bar{\bar{\theta}}(p)}^1 (1-\theta)f(\theta)d\theta = \frac{\bar{\bar{\theta}}(p)^2}{2} - \bar{\bar{\theta}}(p) + \frac{1}{2}$, respectively. Moreover, the corresponding utilization rate and the customer waiting time are $\bar{\bar{\rho}}(p) = \frac{\bar{\bar{\theta}}(p)^2}{(\bar{\bar{\theta}}(p)-1)^2}$ and $\bar{\bar{w}}(p) = \frac{\bar{\bar{\theta}}(p)^2}{(\frac{1}{2}-\bar{\bar{\theta}}(p))(\bar{\bar{\theta}}(p)-1)^2}$, respectively.

We re-write the platform profit (4) as

$$\max_p \bar{\bar{\pi}} = \bar{\bar{\lambda}}(p)\varphi p = \frac{\left(\bar{\bar{\theta}}(p)\right)^2 \varphi p}{2}. \tag{14}$$

s.t. $0 < \bar{\bar{\rho}}(p) < 1$;
$U_O(0) < U_R(0) = 0$;
$U_R(1) < U_O(1)$.

By solving the above maximisation problem, the optimal price per unit printing capacity can be determined. Due to the complexity, we numerically explore how the optimal price, the corresponding profit and welfare, depend on the model parameters in the next section.

4.2. Numerical studies

As discussed, the decision problem is to find the optimal p that maximizes the profit function $\bar{\bar{\pi}}\ (p)$ in (14), subject to (i) the utilization constraint $\bar{\bar{\rho}}\ (p) < 1$ and (ii) the conditions that both options are selected by some of the consumers $U_O(0) < U_R(0) = 0$ and $U_R(1) < U_O(1)$. Although we have obtained a closed-form solution for the indifference point $\bar{\bar{\theta}}\ (p)$ in equilibrium, its complexity prevents us from deriving the closed-form optimal price or conducting tractable analysis. However, we can solve the problem numerically. Specifically, under the above constraints, we perform an exhaustive numerical search for the optimal p^* that maximizes (14) for any feasible p. Then we compare the profit for each value of p. Hence, the optimal solution p^* is given by the largest value of $\bar{\bar{\pi}}\ (p)$ accordingly. We use the user-friendly software Mathematica to perform the calculations. Therefore, we perform numerical results in this subsection. In order to derive meaningful results, we first present a real-life inspired case and set the base values for the model parameters accordingly.

The printer type that we consider is Markforged Mark II, which is a professional 3DP printer with a relatively high printing capacity per time unit. We next discuss how we set the base case model parameter values for this printer based on public data.

- **Cost of owning plus using a 3D printer:** We include three cost components, namely hardware cost, power consumption, and consumables cost.

(i) Hardware cost: According to the real-time online quote from a retailer, the cost of purchasing Markforged Mark II is around 20,000 Euros (ANIWAA, 2021a). For an estimated lifetime of five years, the annual hardware cost is 4000 Euros, or 0.46 Euros per hour.

(ii) Power consumption: The power consumption of Markforged Mark II is 150 W. Comparing this with that of 500 W for Ultimaker S5 printer, which has a power consumption cost per hour of 0.076 Euros (Ultimaker, 2019), we estimate that the power consumption of Markforged Mark II is $0.076/500 \times 150 \approx 0.02$ Euros per hour.

(iii) Consumables cost: Unfortunately, we do not have a direct estimate of the consumables cost for the printer type that we consider. However, using the same consumables to hardware cost ratio as for the Ultimaker S5 printer, namely 173/1099 (Ultimaker, 2019) for an annual 1500-hour utilization, and recalling that the annual hardware cost of Markforged Mark II is 4000 Euros, we obtain an indirect estimate of $173/1099 \times 4000/1500 \approx 0.42$ Euros per hour.

Thus, we estimate the total cost of owning plus using a Markforged Mark II at 0.46+0.02+0.42=0.9 Euros per hour.

- **Unit net usage benefit:** According to the Royal Netherlands Army's assessment of the performance of Markforged Mark II, 14 types of top-ranked spare parts are suitable for printing with Markforged Mark II. The average benefit is around 94.6 Euros per item (based on the average part price). The average printing time for the 14 types of spare parts is 11.13 hours per item at the printing speed of 50 cubic centimeters per hour (Westerweel, Basten, Boer, & Houtum, 2020). Thus, we estimate the unit net usage benefit at $94.6/11.13 \approx 8.5$ Euros per hour.

Table 2
Base case parameter values.

Parameter	Value
Fixed cost for owning plus using a 3D printer (in Euros/hour)	$k = 0.9$
Unit waiting cost (in Euros/hour)	$\tau = 1.75$
Fraction of the price that the platform earns	$\varphi = 0.3$
Unit net usage benefit (in Euros/hour)	$b = 8.5$

- **Unit waiting cost:** We assume the unit waiting cost is 50% of the unit net usage benefit, i.e., 1.75 per hour.
- **Platform commission:** Following Benjaafar et al. (2018), given that many worldwide peer-to-peer sharing platforms charge a commission rate within a relatively narrow range, from 30% to 40%, we set the commission fee at φ=0.3.

Table 2 lists all the base case parameter values.

Fig. 2 shows how the price of the shared capacity affects the consumers' options (left) and the platform's profit (right) for the base case. From Fig. 2(a), we see that the proportion of owners increases with the price as the owners can gain more profits while the renters have to pay more for using the printers. From Fig. 2(b), the optimal price is around 3, and the fractions of consumers renting and owning are around 23% and 77%, respectively. Note that the results obtained under the condition of a lower system utilization (e.g., $\rho(p) < 0.8$) are similar to those shown in Fig. 2.

Next, we perform a sensitivity analysis, where we vary one parameter at a time from its base case value, while keeping the other parameters fixed. Fig. 3(a)-(b) illustrate how the optimal price p^* that maximizes the profit depends on the fixed cost of owning plus using a 3D printer $k(k > 0)$ and on the unit waiting cost $\tau(\tau > 0)$. As for the parameters' ranges, an upper bound on k, subject to the condition $U_O(\bar{\bar{\theta}}) = U_R(\bar{\bar{\theta}}) > 0$, is $k < 2.99$. Combining this with the assumption of a positive fixed cost $k > 0$, we obtain $k\epsilon(0,\ 2.99)$. For τ, we derive its upper bound by solving the boundary condition $p^* = 0$, which yields $\tau = 238.6$. In fact, no feasible p^* can be found within the range $\tau < 0.2$, and putting the upper and lower bounds together gives $\tau\epsilon(0.2,\ 238.6)$.

As shown in Fig. 3(a), the optimal price increases with the cost of owning plus using a 3D printer, as expected. Regarding Fig. 3(b), it is evident that a relatively high unit waiting cost, ceteris paribus, leads to a decrease in the renter's profit from printing via the platform, resulting in reduced capacity demand, reducing the platform's profit. Unless the waiting cost is small, the platform should set a lower capacity price to restore the balance. The effect of the unit waiting cost shown in Fig. 3(b) is less intuitive when the unit waiting cost is less than a certain value, since a higher price on top of a higher waiting cost are a double whammy for the renters. The reason is as follows: For such a case, it is essential to keep the waiting time short by ensuring that a larger fraction of the users decides to become an owner, and a higher price encourages more users to do so. Furthermore, it appears from Fig. 3 that, compared with the unit waiting cost, the platform is much more sensitive to the fixed cost of owning plus using a 3D printer when determining the optimal price. This result may be explained by the fact that, in real life, consumers are more sensitive to the fixed cost when making purchase decisions. Thus, the fixed cost is more vital to the platform's decision-making process. We thereby conduct a more detailed analysis of the fixed cost of owning plus using a 3D printer, as illustrated in Fig. 4.

From Fig. 4(a), the observed increase in the customer waiting time with the fixed cost could be attributed to a raised bar of becoming an owner, which generates more renters and thereby printing needs. Though a higher waiting time implies a lower system efficiency, it is beneficial for the platform, as Fig. 4(b) indicates. Indeed, if the fixed cost of owning plus using a 3D printer is high,

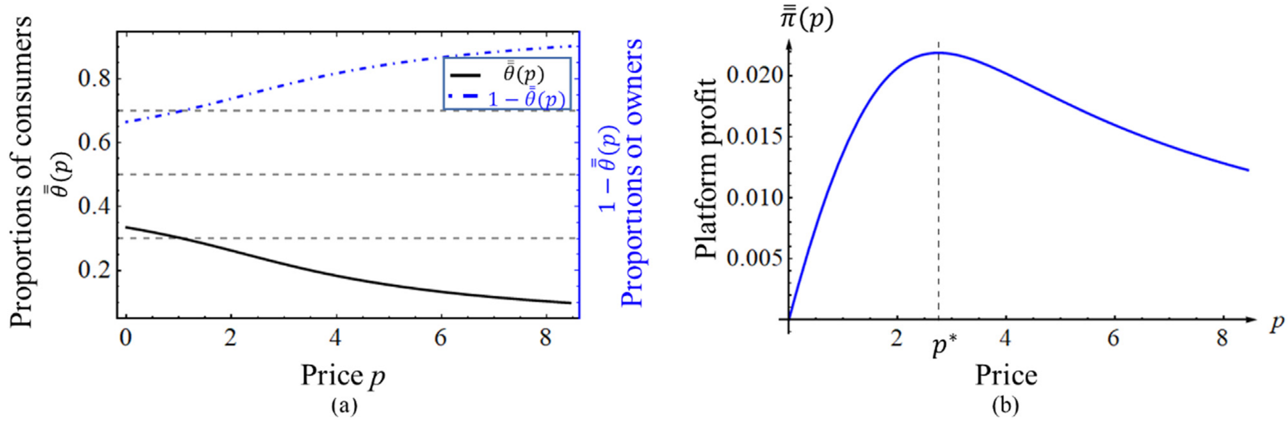

Fig. 2. Numerical results: (a) consumer catchments $\bar{\bar{\theta}}$ and $1-\bar{\bar{\theta}}$, and (b) platform's profit.

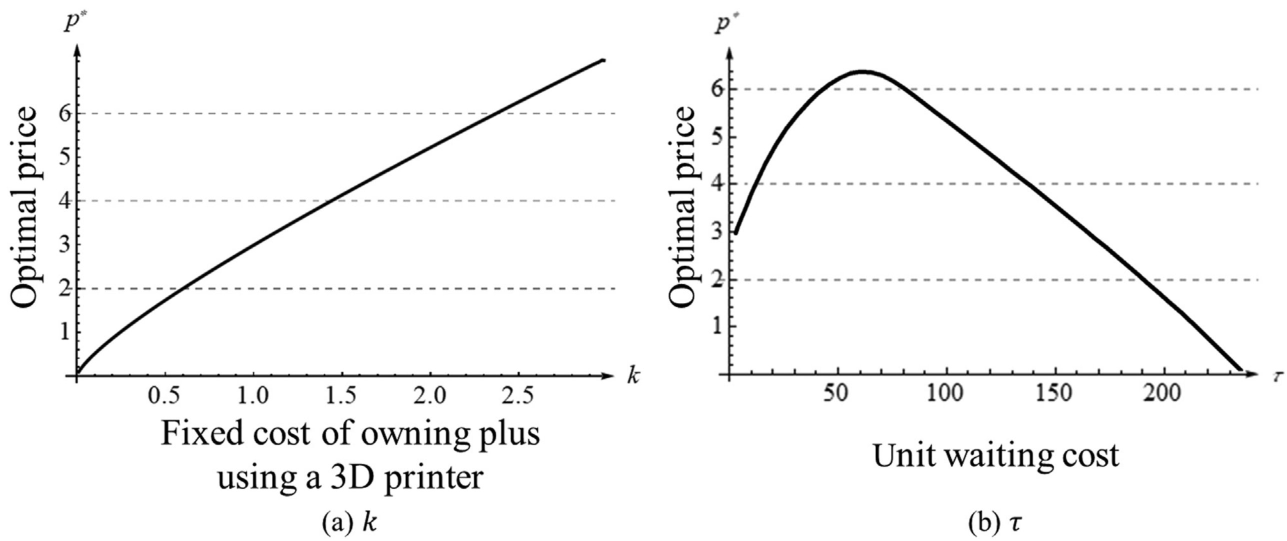

Fig. 3. Effects of the fraction of the fixed cost of owning plus using a 3D printer (k) and of the unit waiting cost (τ) on the optimal price.

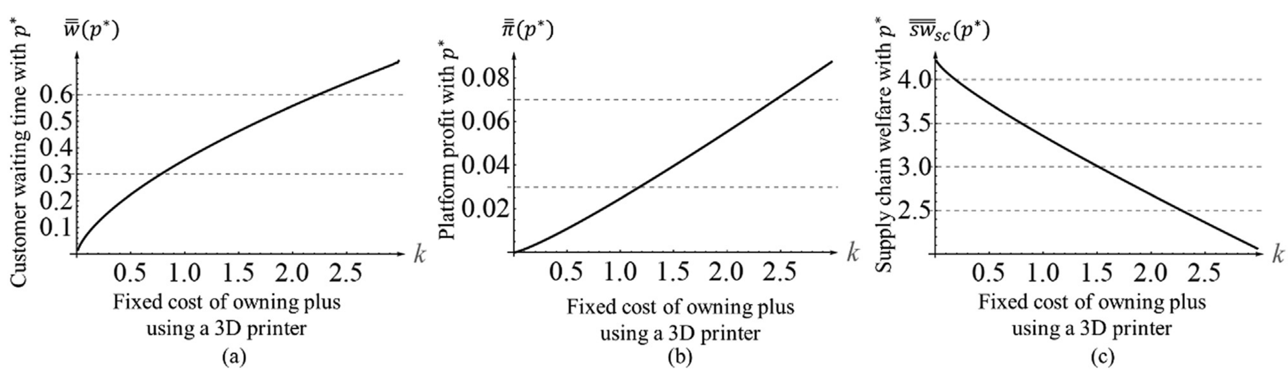

Fig. 4. Effects of the fraction of the fixed cost of owning plus using a 3D printer (k) on the customer waiting time ($\bar{\bar{w}}$), platform profit ($\bar{\bar{\pi}}$), and supply chain welfare ($\bar{\bar{SW}}_{sc}$).

users need to rent vast amounts of printing capacity due to the high entry bar, which leads to more capacity being traded and a high platform profit. Fig. 4(c) shows that the total welfare $\bar{\bar{sw}}_{sc}$ (p^*) does strictly decrease with the owning plus using cost, as to be expected. We remark that, in real life, the 3DP industry is still in a preliminary stage due to the immature technology, and the most critical limitation to adopt 3DP is the cost of entry (Sculpteo, 2020). This implies that governments should focus on encouraging technological progress to lower the printers' prices in order to improve the well-being of the industry.

5. Two types of 3D printers

In this section we explore the effects of the availability of more than one printer type on consumers' behaviour and the platform's decision. For tractability and clarity, we consider two types of 3D printers that differ in their maximum printing capacity per time unit and their owning plus using costs. We use L and H to represent the printer type with low and high printing capacity, respectively. We also let δ denote the maximum printing capacity of printer L relative to printer H, of which the capacity is normalized to 1. Obviously, for users who decide to own a printer, the choice

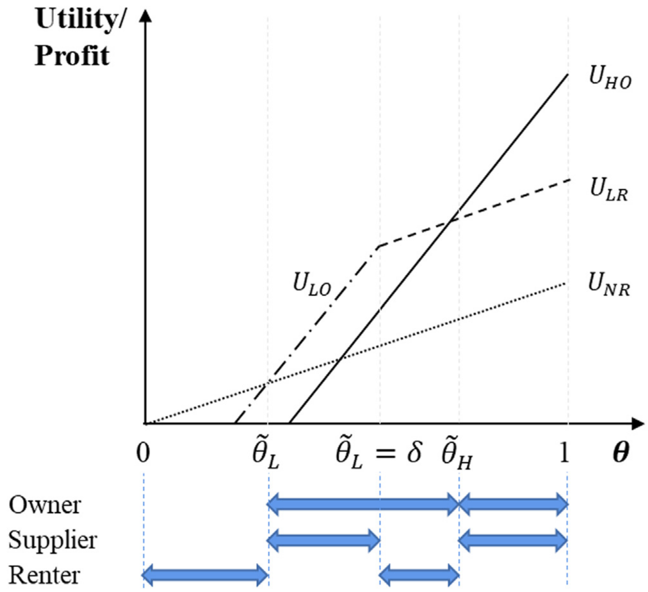

Fig. 5. Consumer catchment areas of owners and renters.

between the two types may allow them to better match capacity to their demand. We assume that the price $\tilde{p}$ per unit of capacity is the same for both printer types (as there is no difference in printing quality), and accordingly the renters are indifferent between them for satisfying their demand. Furthermore, the platform does not give priority to either type, implying that the utilization rate (for excess capacity) $\rho(\tilde{p})$ is the same for both printer types.

5.1. Consumers' purchase decisions and platform's optimal price

The utility/profit of Not purchasing a printer and therefore Renting (NR) is

$U_{NR}(\theta) = [b - \tilde{p} - \tau w(\tilde{p})]\theta.$

For users that purchase a printer, there are three options: purchase a low capacity printer and own excess capacity (LO), purchase a low capacity printer and rent additional capacity (LR), or purchase a high capacity printer and own excess capacity (HO). Here, we stick to the assumption made in our base case that "large" users with a usage level of more than 1 would purchase the number of 3D printers that they need full-time, so only the remaining demand of such as demand would be considered. Thus, the high capacity printer always offers more capacity than the maximum demand. Similar to the analysis in Section 3.1, we obtain the respective utility functions as

$U_{LO}(\theta) = b\theta + (\delta - \theta)\rho(\tilde{p})(1 - \varphi)\tilde{p} - k_L,$
$U_{LR}(\theta) = b\theta - [\tilde{p} + \tau w(\tilde{p})](\theta - \delta) - k_L,$ and
$U_{HO}(\theta) = b\theta + (1 - \theta)\rho(\tilde{p})(1 - \varphi)\tilde{p} - k_H.$

It is then straightforward to find the values of preference $\tilde{\theta}_L$, $\tilde{\theta}_M$, and $\tilde{\theta}_H$ at which the consumers are indifferent between becoming NR and LO, LO and LR, and LR and HO, respectively, i.e. where $U_{NR}(\theta) = U_{LO}(\theta)$, $U_{LO}(\theta) = U_{LR}(\theta)$, and $U_{LR}(\theta) = U_{HO}(\theta)$, with the "catchment areas" being depicted in Fig. 5. Those indifferent points are obtained, respectively, as

$$\tilde{\theta}_L(\tilde{p}) = \frac{k_L - \tilde{p}\delta\rho(\tilde{p}) + \varphi\tilde{p}\delta\rho(\tilde{p})}{\tilde{p}[1 - \rho(\tilde{p}) + \varphi\rho(\tilde{p})] + \tau w(\tilde{p})} \tag{15}$$

$\tilde{\theta}_M = \delta$, and

$$\tilde{\theta}_H(\tilde{p}) = \frac{\tilde{p}\delta + k_H - k_L - \tilde{p}\rho(\tilde{p}) + \varphi\tilde{p}\rho(\tilde{p})}{\tilde{p}(1 - \rho(\tilde{p}) + \varphi\rho(\tilde{p})) - \tau w(\tilde{p})}, \tag{16}$$

where we have $\tilde{\theta}_L(\tilde{p}) < \tilde{\theta}_M < \tilde{\theta}_H(\tilde{p})$ to keep all the options to be selected by part of the users with different utilisation level.

Furthermore, denoting the indifferent point between becoming NR and HO by $\hat{\theta}$, we quickly obtain the following observation from Fig. 5.

Observation 1. *For the case of two types of printers, we have $\hat{\theta} > \tilde{\theta}_L$.*

This observation indicates that the ownership for the case of two types of printers is higher compared with that for the case with only high capacity printers, which can be explained by the fact that both types of printers partly capture a portion of the market, leading to increased ownership. Thus, with the availability of the sharing option, the development of low capacity printers might improve the market penetration of 3DP technology.

Thus, letting $f(\theta) = 1$ denote the uniform density function of the usage distribution, we find that the fractions of consumers opting for renting and sharing capacity are, respectively, as follows:

$\int_0^{\tilde{\theta}_L} f(\theta)d\theta + \int_{\tilde{\theta}_M}^{\tilde{\theta}_H} f(\theta)d\theta = \tilde{\theta}_L + (\tilde{\theta}_H - \tilde{\theta}_M)$ and

$\int_{\tilde{\theta}_L}^{\tilde{\theta}_M} f(\theta)d\theta + \int_{\tilde{\theta}_H}^{1} f(\theta)d\theta = (\tilde{\theta}_M - \tilde{\theta}_L) + (1 - \tilde{\theta}_H).$

Similar to the argument in Section 4.1, the associated aggregate demand and supply generated from the renters and owners are, respectively, as follows:

$\tilde{\lambda}(\tilde{p}) = \int_0^{\tilde{\theta}_L} \theta f(\theta)d\omega + \int_{\tilde{\theta}_M}^{\tilde{\theta}_H} (\theta - \delta) f(\theta)d\omega = \frac{\tilde{\theta}_L^2}{2} + \frac{\tilde{\theta}_H^2}{2} - \tilde{\theta}_M\tilde{\theta}_H + \frac{\tilde{\theta}_M^2}{2}$ and

$\tilde{\mu}(\tilde{p}) = \int_{\tilde{\theta}_L}^{\tilde{\theta}_M} (\tilde{\theta}_M - \theta) f(\theta)d\theta + \int_{\tilde{\theta}_H}^{1} (1 - \theta) f(\theta)d\theta$
$= \frac{\tilde{\theta}_M^2}{2} - \tilde{\theta}_M\tilde{\theta}_L + \frac{\tilde{\theta}_L^2}{2} + \frac{1}{2} - \tilde{\theta}_H + \frac{\tilde{\theta}_H^2}{2}.$

Furthermore, we derive the corresponding utilization rate and customer waiting time are as follows:

$$\tilde{\rho}(\tilde{p}) = \frac{\tilde{\lambda}(\tilde{p})}{\tilde{\mu}(\tilde{p})} = \frac{\left(\tilde{\theta}_M - \tilde{\theta}_H\right)^2 + \tilde{\theta}_L^2}{1 + \tilde{\theta}_M^2 + \left(-2 + \tilde{\theta}_H\right)\tilde{\theta}_H - 2\tilde{\theta}_M\tilde{\theta}_L + \tilde{\theta}_L^2}. \tag{17}$$

and

$$\tilde{w}(\tilde{p}) = \frac{\tilde{\rho}(\tilde{p})}{\tilde{\mu}(\tilde{p}) - \tilde{\lambda}(\tilde{p})} = \frac{\left(\tilde{\theta}_M - \tilde{\theta}_H\right)^2 + \tilde{\theta}_L^2}{\left(1 + \tilde{\theta}_M^2 + \left(\tilde{\theta}_H - 2\right)\tilde{\theta}_H - 2\tilde{\theta}_M\tilde{\theta}_L + \tilde{\theta}_L^2\right)\left(\frac{1}{2} - \tilde{\theta}_H - \tilde{\theta}_M\tilde{\theta}_L + \tilde{\theta}_M\tilde{\theta}_H\right)}. \tag{18}$$

Based on the above results, we obtain an analytical validation of the fraction of consumers that opt to become an owner (ownership). Similar to Proposition 1, Proposition 2 implies that less than half of the consumers forego printer ownership. We formalize the result is in Proposition 2 (of which a detailed analysis can be found in Appendix A2).

Proposition 2. *For the case of two types of printers, the fraction of consumers that opt for becoming an owner (ownership) is higher than 50%, i.e., $\tilde{\theta}_L(\tilde{p}) < 0.5$,.*

By inserting (17)-(18) into (15)-(16), we derive $\tilde{\tilde{\theta}}_L$ and $\tilde{\tilde{\theta}}_H$ in equilibrium in the closed-form.

Furthermore, under this equilibrium condition, the associated aggregate demand and supply generated from the renters and owners are $\tilde{\tilde{\lambda}}(\tilde{p}) = \frac{\tilde{\tilde{\theta}}_L^2}{2} + \frac{\tilde{\tilde{\theta}}_H^2}{2} - \delta\tilde{\tilde{\theta}}_H + \frac{\delta^2}{2}$ and $\tilde{\tilde{\mu}}(\tilde{p}) = \frac{\delta^2}{2} - \delta\tilde{\tilde{\theta}}_L + \frac{\tilde{\tilde{\theta}}_L^2}{2} + \frac{1}{2} - \tilde{\tilde{\theta}}_H + \frac{\tilde{\tilde{\theta}}_H^2}{2}$, respectively. Moreover, the corresponding utilization rate and the customer waiting time are $\tilde{\tilde{\rho}}(\tilde{p}) = \frac{(\delta - \tilde{\tilde{\theta}}_H)^2 + \tilde{\tilde{\theta}}_L^2}{1 + \delta^2 + (-2 + \tilde{\tilde{\theta}}_H)\tilde{\tilde{\theta}}_H - 2\delta\tilde{\tilde{\theta}}_L + \tilde{\tilde{\theta}}_L^2}$ and $\tilde{\tilde{w}}(\tilde{p}) = \frac{(\delta - \tilde{\tilde{\theta}}_H)^2 + \tilde{\tilde{\theta}}_L^2}{(1 + \delta^2 + (\tilde{\tilde{\theta}}_H - 2)\tilde{\tilde{\theta}}_H - 2\delta\tilde{\tilde{\theta}}_L + \tilde{\tilde{\theta}}_L^2)(\frac{1}{2} - \tilde{\tilde{\theta}}_H - \delta\tilde{\tilde{\theta}}_L + \delta\tilde{\tilde{\theta}}_H)}$, respectively.

The platform gains revenue from taking a fraction $\tilde{\varphi}$ of the rent paid by the customer for each transaction. The objective of the platform is to maximize its profit gained from all the renters as follows:

$$\max_{\tilde{p}} \tilde{\tilde{\pi}} = \tilde{\tilde{\lambda}}(\tilde{p})\tilde{\varphi}\tilde{p}. \tag{19}$$

s.t. $0 < \tilde{\tilde{\rho}}(\tilde{p}) < 1$;
$U_{LO}(0) < U_{NR}(0) = 0$;
$0 < U_{LO}(\delta) = U_{LR}(\delta) < 1$;
$U_{HO}(1) > U_{LR}(1)$.

Similar to the argument in the basic model, this maximization is subject to the system utilization constraint and the conditions under which all four options are selected by some of the consumers, i.e., $U_{LO}(0) < U_{NR}(0) = 0$, $0 < U_{LO}(\delta) = U_{LR}(\delta) < 1$, $U_{HO}(1) > U_{LR}(1)$.

Due to the complexity of $\tilde{\tilde{\lambda}}(\tilde{p})$ and, in particular, $\tilde{\tilde{\rho}}(\tilde{p})$, we perform numerical studies to examine the platform's optimal pricing decision in Section 5.2.

Similar to the argument in Section 3.4, using the respective utility functions, we derive the welfare/profits of the renter and supplier in the supply chain, respectively, as follows:

$$\widetilde{\widetilde{sw}}_R = \int_0^{\tilde{\tilde{\theta}}_L} U_{NR}(\theta)d\theta + \int_{\tilde{\theta}_M}^{\tilde{\tilde{\theta}}_H} U_{LR}(\theta)d\theta, \tag{19}$$

$$\widetilde{\widetilde{sw}}_S = \int_{\tilde{\tilde{\theta}}_L}^{\tilde{\theta}_M} U_{LO}(\theta)d\theta + \int_{\tilde{\tilde{\theta}}_H}^{1} U_{HO}(\theta)d\theta. \tag{20}$$

Combining (18)-(20), we obtain the welfare function $\widetilde{\widetilde{sw}}_{sc}$ of the supply chain, defined as the combination of user welfare/profit and platform profit, as

$$\widetilde{\widetilde{sw}}_{sc} = \tilde{\tilde{\pi}} + \widetilde{\widetilde{sw}}_S + \widetilde{\widetilde{sw}}_R = \tilde{\tilde{\lambda}}(\tilde{p})\tilde{\varphi}\tilde{p} + \int_0^{\tilde{\tilde{\theta}}_L} U_{NR}(\theta)d\theta + \int_{\tilde{\theta}_M}^{\tilde{\tilde{\theta}}_H} U_{LR}(\theta)d\theta + \int_{\tilde{\tilde{\theta}}_L}^{\tilde{\theta}_M} U_{LO}(\theta)d\theta + \int_{\tilde{\tilde{\theta}}_H}^{1} U_{HO}(\theta)d\theta.$$

5.2. Numerical studies

We continue our previous real-life example, but consider a second 3D printer, namely Markforged Onyx Pro. It uses the same continuous fibre reinforcement (CFR) technology as Markforged Mark II, but has a smaller printing capacity. We list the related estimated parameter values below (see Table 2 for other model parameter estimates).

- **Owning plus using cost of Markforged Onyx Pro:** Using similar arguments as for Markforged Mark II, the owning plus using cost of a Markforged Onyx Pro contains the hardware cost (0.23 Euro/hour) (ANIWAA, 2021b), power consumption cost (0.02 Euro/hour), and consumables cost (0.21 Euro/hour). So the owning plus using cost of Markforged Onyx Pro is 0.23+0.02+0.21=0.46 Euros per hour.
- **Printing capacity:** Recall the cost of owning plus using a Markforged Mark II is 0.9 Euros per hour, we use the owning plus using cost ratio 0.46/0.9≈51.11% to estimate the printing capacity of L relative to H.

Fig. 6 shows how the platform's profit depends on the platform price in the base case settings, which shows that the optimal price $\tilde{p}^*$ is around 3.2.

Fig. 7 shows how the owning plus using cost of printer L affects the proportion of consumers opting for printer $i (i = L, H)$, demand rate, platform profit, and supply chain welfare.

From Fig. 7(a), we see that for a very low cost of owning plus using a low capacity printer, few users own a high capacity printer; also, for a very high cost, few users own a low capacity printer. In both situations, one of the two printer types dominates the market. As Figures 7(b) and 7(c) indicate, this is beneficial for the platform as it implies that many users need to rent or can supply a lot of printing capacity, leading to much capacity being traded and a high platform profit. Moreover, the platform earns more if the high capacity printer dominates the market. For moderate fixed costs of owning plus using a low capacity printer, both printer types capture a significant portion of the market, so the owners are better able to match supply with demand without the platform, leading to less trading and a lower platform profit. So the relation between the platform's profit and the owning plus using cost is not monotone. Fig. 7(d) shows that the total welfare $\widetilde{\widetilde{SW}}_{SC}$ strictly decreases with the owning plus using cost, as one would expect. This implies that governments should focus on encouraging technological progress to lower the printers' prices in order to improve the outcome for the industry. Note that the upper and lower bounds for the owning plus using cost of the low capacity printer considered are subject to the conditions $\tilde{\theta}_H > \tilde{\theta}_L > 0$ and $k_H > k_L$, respectively.

We also tested our model for the case at a lower system utilization rate (e.g., $\tilde{\tilde{\rho}}(\tilde{p}) < 0.8$), and the results are similar to those reported in Fig. 7 as the trends remain the same.

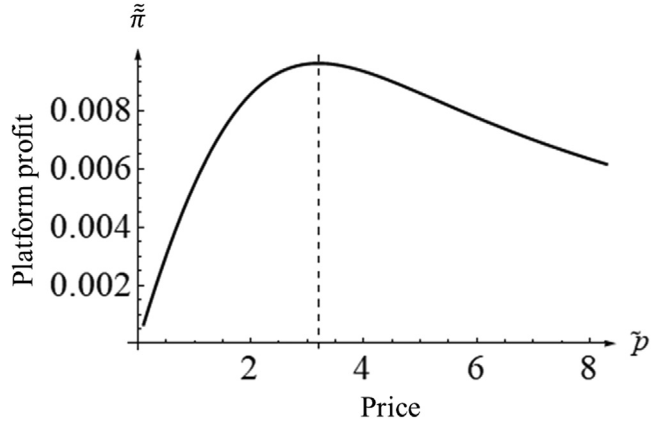

Fig. 6. Effect of price ($\tilde{p}$) on platform profit ($\tilde{\tilde{\pi}}$).

5.3. A special case: only high capacity printer owners are allowed to offer their spare capacity

In the above analysis, we consider that the shared capacity may come from the owner that purchases either a low or high capacity printer with excess capacity. However, in real life, the platform may try to increase its service level by only allowing the owner of a high capacity printer to provide its spare capacity for renting. In this subsection we consider such a case where the user that purchases a printer has two options: purchase a low capacity printer and rent additional capacity (LR) or purchase a high capacity printer and own excess capacity (HO). Thus, we assume that no owner of a low capacity printer can be a supplier, i.e., $\tilde{\theta}_L^* - \delta = 0$.

We obtain two analytical findings regarding the ownership level under this scenario, summarized in Proposition 3–4 (we give the detailed analyses in Appendices A3-A4, respectively).

Proposition 3. *Given the assumption* $\tilde{\theta}_L^* - \delta = 0$, *we have* $\tilde{\theta}_L^* - 1/2 < 0$.

Similar to the results obtained in Sections 4.1 and 5.1, the fraction of consumers that opt to become an owner (ownership) is higher than 50%.

Proposition 4. *Given the assumption* $\tilde{\theta}_L^* - \delta = 0$, *we have* $\tilde{\theta}_H^* - \delta < 1 - \tilde{\theta}_H^*$.

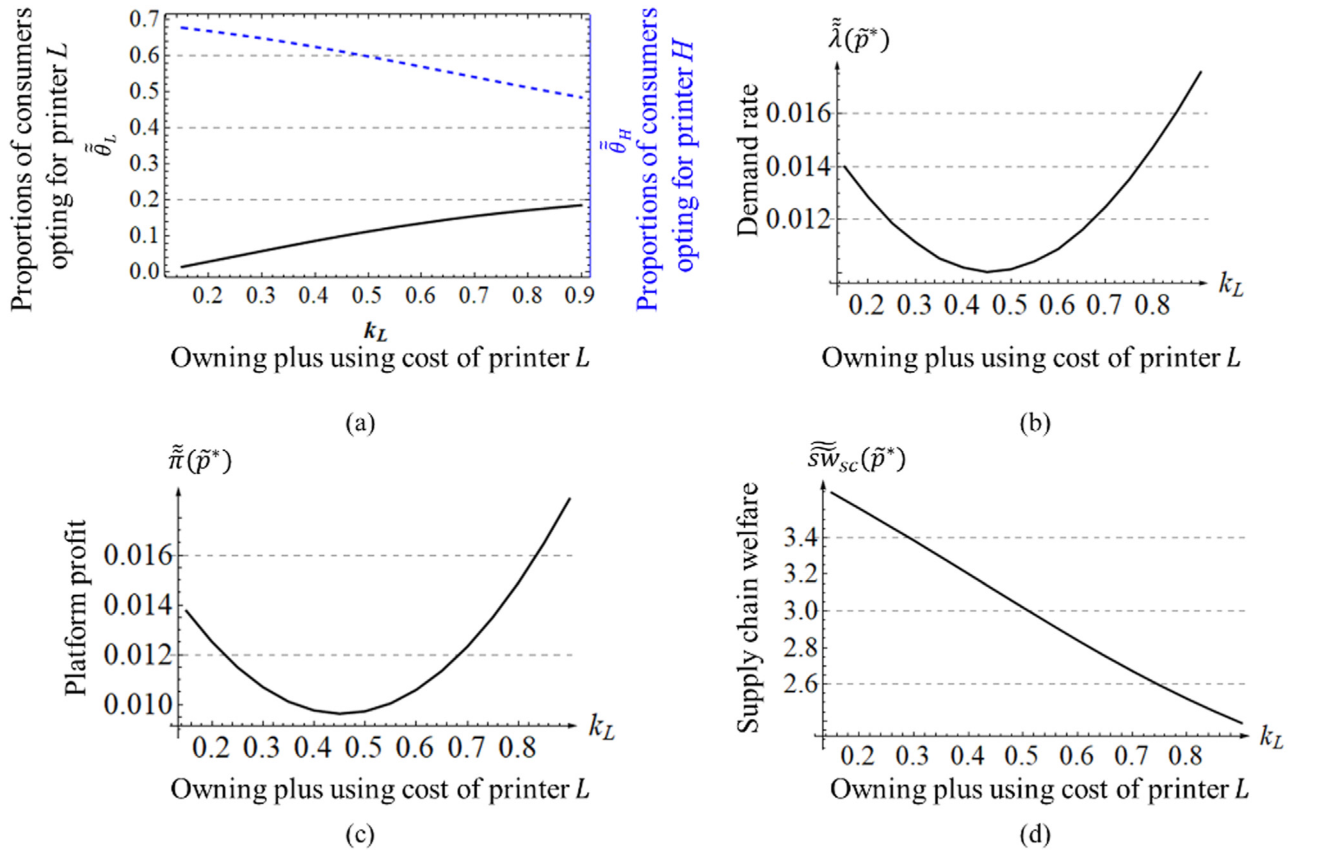

Fig. 7. Effects of the owning plus using cost of printer L (k_L) on proportions of consumers opting for printer i ($i = L, H$), demand rate ($\tilde{\tilde{\lambda}}$), platform profit ($\tilde{\tilde{\pi}}$), and supply chain welfare ($\widetilde{\widetilde{SW}}_{sc}$).

Proposition 4 indicates that the fraction of owners that opt for purchasing a high capacity printer is higher than that opt for purchasing a low capacity printer. This implies that if only the owner of a high capacity printer can act as an applier, then peer-to-peer sharing leads to a higher adoption level of the high capacity printer.

6. Alternative scenarios

In this section we analyze and discuss several alternative modelling assumptions. In Section 6.1, we extend the basic model to a multi-period setting. After that, in Section 6.2, we explore the effect of the maximum printer capacity of printer L. Finally, in Section 6.3, we explore the effect of impatient customers.

6.1. Multi-period users and platform decisions

In the base case, we consider a single-period model. In this section, we extend the model to a multi-period setting where the specific market characteristics are time-based and so affect the matching of demand and supply. Users and platform make their decisions at the beginning of each period to maximize their own profit for that period.

We assume that the market characteristics keep the same during period i, $i = 1, 2, \ldots n$, and define the set of market characteristics for its next period $i+1$ as $\Omega_{i+1} = \{b_{i+1},\ \tau_{i+1},\ \varphi_{i+1},\ k_{i+1}\}$. By applying the basic model using the updated values of these parameters, it is straightforward to obtain an adjusted equilibrium of the system for period $i+1$, i.e., $\Phi^* = \{\bar{\theta}_{i+1},\ p^*_{i+1}\}$, and the corresponding waiting time $w_{i+1}(p^*_{i+1})$. Recall that in the basic model the users renting and owning decision in equilibrium is $\bar{\theta}$ and we define $\bar{\theta}_i = \bar{\theta}$ as the equilibrium for period i, then we have:

(i) if $\bar{\theta}_{i+1} \le \bar{\theta}_i$, which implies that more users opt for becoming an owner compared with that of period i, then the previous renters with usage level of $\theta \in (\bar{\theta}_{i+1},\ \bar{\theta}_i)$ would switch to become an owner and purchase a printer at the beginning of period $i+1$.

(ii) if $\bar{\theta}_{i+1} > \bar{\theta}_i$, which implies the previous owners with usage level of $\theta \in (\bar{\theta}_i,\ \bar{\theta}_{i+1})$ would sell their printer and switch to become a renter. At the beginning of period $i+1$, the printer can be sold in a secondary used goods market and therefore the owner can receive some salvage value and switch to become a renter. We assume that the platform has complete information towards the printers ownership since period 0. Thus, in period $i+1$, for the renters (who used to be owner) $\theta \in (\bar{\theta}_i,\ \bar{\theta}_{i+1})$, let k_j the owning plus using cost for the printers purchased in period j, j =1, 2, … i, η_j the portion of the printers with cost of k_j, $t_j = i+1-j$ the periods that has been used for the printers with the cost of k_j. Under such case, the utility/profit for the renters of $\theta \in (\bar{\theta}_i,\ \bar{\theta}_{i+1})$ subject to $\vec{U}_R(\theta) = [b_{i+1} - p_{i+1} - \tau_{i+1} w_{i+1}(p_{i+1})]\theta + E(r_j)$, where $E(r_j)$ refers to the expected salvage value gained for the renters, and $r_j = k_j \varepsilon(t_j)$ refers to the salvage value of the printer k_j. Denoting the salvage value in period $i+1$ of the printer purchased in period j by $\varepsilon(t_j)$, where $0 < \varepsilon(t_j) < 1$, decreases with t_j, the expected salvage value gained for the owners who switch to renters in period $i+1$ can be expressed as $E(r_i) = \sum_{j=1}^{i} k_j \eta_j \varepsilon(t_j)$.

6.2. Effect of the maximum printer capacity of printer L

In the above analysis, we assume that the owning plus using cost of printer L (with lower printing capacity), k_L, is exogenously

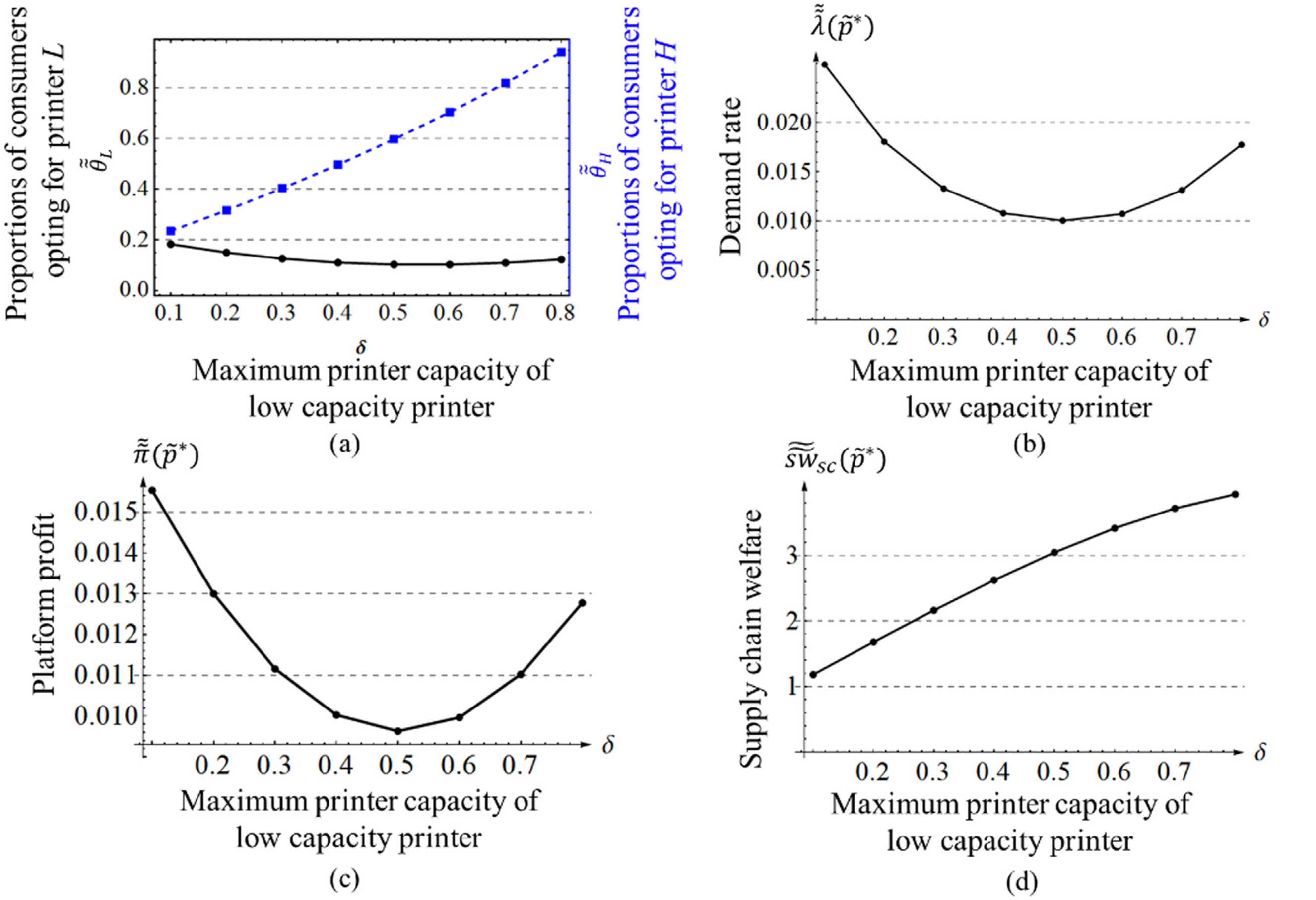

Fig. 8. Effects of the maximum printer capacity of low capacity printer δ on the proportions of consumers opting for printer $i(i = L, H)$, demand rate $\tilde{\tilde{\lambda}}$, platform profit $\tilde{\tilde{\pi}}$, and supply chain welfare $\widetilde{\widetilde{SW}}_{sc}$.

given. In this section, we consider an endogenously determined owning plus using cost of printer L by considering such cost increases linearly with its maximum capacity. Recall that the maximum printing capacity of printer L is δ, and denoting the expected owning plus using cost per unit capacity as x, so the total expected owning plus using cost for printer L is $k_L = \delta x$. Similar to the analysis for an exogenously owning plus using cost in Section 5.1, we obtain the respective utility/profit functions as

$\tilde{U}_{NR} = (b - \tilde{p} - \tau w(\tilde{p}))\theta$,
$\tilde{U}_{LO} = b\theta + (\delta - \theta)\rho(\tilde{p})(1 - \varphi)\tilde{p} - \delta x$,
$\tilde{U}_{LR} = b\theta - (\tilde{p} + \tau w(\tilde{p}))(\theta - \delta) - \delta x$, and
$\tilde{U}_{HO} = b\theta + (1 - \theta)\rho(\tilde{p})(1 - \varphi)\tilde{p} - k_H$.

The optimization process is similar to that solving the maximization problem of (17) in Section 5.1, and so we directly present the sensitivity result respect to δ, as shown in Fig. 8. Note that since $\delta \approx 0.51$, $k_L = 0.46$(as discussed in Section 5.2), we estimate the expected owning plus using cost per unit capacity as $x = 0.46/0.51 \approx 0.9$.

From Fig. 8(a), we observe that the ownership of the high capacity 3D printer $\tilde{\tilde{\theta}}_H$ rapidly decreases with the maximum printer capacity of the low capacity printer, so more users opt for renting capacity from the platform, especially for the heavy users $\tilde{\tilde{\theta}}_L$. Figures 8(b)-(c) are in line with the results given in Section 5.2 that it is beneficial for the platform if the high capacity printer dominates the market, where we treat the owning plus using cost of the low capacity printer as given. Moreover, Fig. 8(d) shows that the supply chain welfare increases with the maximum printer capacity of the low capacity printer through the increased competition between two types of printers, which appears as a win-win solution for the platform profit and supply chain outputs.

6.3. Effect of impatient customers

In the basic model we assume that the customer waiting cost increases linearly with the waiting time. Alternatively, reflecting that customers may grow increasingly impatient as they wait longer, it is interesting to consider another relation, e.g., a quadratic relation between the waiting for cost and waiting time. We do so in this extension where we assume that the cost of waiting time is quadratic, so the renter's utility/profit function is

$$\left[b - p + (\tau \cdot w(p))^2\right]\theta. \tag{21}$$

The analysis is similar to that of the linear cost case in the main text, so we present it as concisely as possible.

Using (1) and (21), we derive the value of the preference $\dot{\theta}(p)$ at which the users are indifferent between becoming a renter and an owner as

$\dot{\theta}(p) = \frac{k-(1-\varphi)p\rho(p)}{p[1-(1-\varphi)\rho(p)]+(\tau \cdot w(p))^2}$.

Although the analysis is not tractable, we numerically explore the effects of changing from a linear to a quadratic waiting cost on the optimal price. Tables 3-4 show the (numerical) results for the settings used in the main text and listed in Table 2. Table 3 shows the effects of different fixed costs on the optimal prices, from which we find that a higher optimal price should be set for the considered setting of a quadratic waiting cost. This is related to the increased customer impatience under a quadratic waiting cost. In terms of the effects of different unit waiting costs, we find a

Table 3
Optimal prices for different fixed costs per time unit.

Fixed cost for owning plus using a 3D printer	Linear waiting cost	Quadratic waiting cost
0.5	1.73	1.8
1	2.99	3.21
1.5	4.14	4.58
2	5.23	5.89

Table 4
Optimal prices for different unit waiting costs per time unit.

Unit waiting cost	Linear waiting cost	Quadratic waiting cost
12.5	4.33	5.15
25	5.18	6.43
37.5	5.77	7.20
50	6.24	6.08

similar result from Table 4, namely that a quadratic waiting cost leads to a higher optimal price, except for the setting of a very high unit waiting cost. Indeed, a very high unit waiting cost leads to very few renters on the platform, and so a lower price to keep enough renters interested. Moreover, the effects of the unit waiting cost are much more pronounced than those for the fixed cost of owning plus using a 3D printer.

7. Conclusions

Motivated by the taking off and increasing popularity of 3DP technology, we conduct this study to explore how the 3DP platform should determine the optimal price of per unit printing capacity, which plays the role of re-allocating printing capacity in the market. Note that the platform is considered as a price setter with a dominant position in the industry, as this study mainly focuses on the relationship between users and platform, rather than the relationship between platforms. Our study provides general insights into the decision-making of the platform and its users in the peer-to-peer market. The model can be re-applied over time to capture dynamics of the decision-making situation. By adopting real-world data, we numerically explore the effects of pricing on matching supply with demand, and derive the optimal price of the spare capacity to maximize the platform's profit. We also study the welfare of the entire 3DP supply chain comprising the platform and users.

We first consider a 3DP platform that provides printing services with one type of printer. The key findings are as follows. For platform managers, neglecting the pricing decision for the shared capacity can result in inferior matching, resulting in a considerable loss of profit. Specifically, setting too high a price for the shared capacity leads to very few renters on the platform, while setting too low a price of the shared capacity leads to a lack of owners. The platform's optimal price increases both in the owning cost and in the unit customer waiting cost unless the unit waiting cost is higher than a certain value. Moreover, the platform is more profitable if the fixed cost of owning plus using a 3D printer is high. From the social welfare perspective, governments should exercise interventions to encourage technological progress to lower the printers' prices to improve the well-being of the industry.

We also consider heterogeneity of the available printers by considering two printer types that differ in cost and capacity. A key finding is that it is better if the high capacity printer dominates the market from the platform's perspective. In such a situation, there is a considerable mismatch between owned and required capacity for many users, which leads to more trading and a higher platform profit. On the contrary, if both printer types occupy a considerable market share, the owned and required capacity are better matched, which leads to less platform trading and a lower platform profit. Moreover, a higher cost of owning a low capacity printer does always increase the total supply chain welfare.

There are several limitations of our research and findings, which offer opportunities for further research. First, we only focus on the waiting cost caused by matching friction between the supply and demand for 3DP services on the platform, whereas the 3D printer owners may not meet all the customers' printing requirements because of the risks of equipment damage, time conflicts etc. Besides, we assume that no waiting is needed for the owners as we ignore the uncertainty of internal demand. Future research could explore the stochasticity issue on other aspects, e.g., printing cost, in-house waiting cost, effect of seasonal demand on usage level etc. In addition, we consider a uniform density function of the usage distribution. Future research may consider the effect of different demand distributions on the optimal price.

Second, we ignore competition while focusing on consumers' purchasing and renting decision-making on a single platform. If more platforms or conventional manufacturing compete in the market, then the platforms' decision-making would certainly be affected. Future research could take competition into account.

Third, we assume that the customer waiting cost is constant, whereas it could vary in real life as customers may become increasingly impatient as waiting times get longer. Moreover, customers may be risk seeking or risk averse towards waiting time uncertainty. So, future research could explore the effects of impatient customers and customer risk preferences on the platform's pricing and fee decisions.

Fourth, our analysis in the basic model is static, e.g., we consider an exogenous number of consumers in each period, but in real life the number of consumers assigned to a 3DP platform may depend on the price of the hardware, government subsidies, technology development, and promotional activities from other competing platforms. One could perform a dynamic analysis incorporates more 3DP characteristics over multiple periods to study the adoption trajectories of 3DP technology.

Fifth, we assume a constant price per unit of capacity, but in real life other factors may affect the price, e.g., platform's incentives like quantity discounts. One could consider a broader picture to study the effects of different pricing strategies.

Finally, we focused on addressing the pricing issue of the 3DP capacity sharing platform in this study. However, there are other types of 3DP platform that adopt different modes of operation, e.g., some platforms have their own production systems supported by their own printers and factories. Future research may consider such platforms.

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Appendix

A1. Proof of Proposition 1

Substituting (10)-(11) into $\bar{\rho}(p) = \lambda(p)/\mu(p)$ and, given $\bar{\rho}(p) < 1$ or, equivalently, $\lambda(p) - \mu(p) < 0$, we obtain

$\lambda(p) - \mu(p) = \frac{\bar{\theta}(p)^2}{2} - (\frac{\bar{\theta}(p)^2}{2} - \bar{\theta}(p) + \frac{1}{2}) = \bar{\theta}(p) - \frac{1}{2} < 0$,

which yields $\bar{\theta}(p) < 0.5$. Moreover, combining this with the assumption that a user's usage level θ is uniformly distributed between 0 and 1, which is equivalent to $\bar{\theta}(p) \in (0, 1)$, we obtain that the fraction of consumers that opt for becoming a renter is $\bar{\theta}(p) \in (0,\ 0.5)$. Given that the other consumers opt for becoming an owner, we find that the ownership of the sharing system is higher than 0.5.

A2. Proof of Proposition 2

Using (16) and given that $\rho(\tilde{p}) < 1$ or, equivalently, $\lambda(\tilde{p}) - \mu(\tilde{p}) < 0$, we obtain

$\lambda(\tilde{p}) - \mu(\tilde{p}) = \frac{\tilde{\theta}_L^2}{2} + \frac{\tilde{\theta}_H^2}{2} - \tilde{\theta}_M\tilde{\theta}_H + \frac{\tilde{\theta}_M^2}{2} - (\frac{\tilde{\theta}_M^2}{2} - \tilde{\theta}_M\tilde{\theta}_L + \frac{\tilde{\theta}_L^2}{2} + \frac{1}{2} - \tilde{\theta}_H + \frac{\tilde{\theta}_H^2}{2}) = \tilde{\theta}_L\tilde{\theta}_M + \tilde{\theta}_H(1 - \tilde{\theta}_M) - \frac{1}{2} < 0$,

which yields $\tilde{\theta}_L\tilde{\theta}_M + \tilde{\theta}_H(1 - \tilde{\theta}_M) < 0.5$. Moreover, since $\tilde{\theta}_H > \tilde{\theta}_L > 0$, we have $\tilde{\theta}_L < \tilde{\theta}_L\tilde{\theta}_M + \tilde{\theta}_H(1 - \tilde{\theta}_M) < 0.5$. Moreover, combining this with the assumption that a user's usage level θ is uniformly distributed between 0 and 1, which is equivalent to $\tilde{\theta}_L \in (0, 1)$, we obtain that the fraction of consumers that opt for becoming a renter is $\tilde{\theta}_L \in (0,\ 0.5)$. Given that the other consumers opt for becoming an owner, we find that the ownership of the sharing system is higher than 0.5.

A3. Proof of Proposition 3

Using the result in Proposition 2, we have $\tilde{\theta}_L\tilde{\theta}_M + \tilde{\theta}_H(1 - \tilde{\theta}_M) < 0.5$. When $\tilde{\theta}_M = \delta = \tilde{\theta}_L$, the result $\tilde{\theta}_L\tilde{\theta}_M + \tilde{\theta}_H(1 - \tilde{\theta}_M) < 0.5$ still holds, yielding $\tilde{\theta}_L < 0.5$.

A4. Proof of Proposition 4

Recalling that $\lambda(\tilde{p}) = \frac{\tilde{\theta}_L^2}{2} + \frac{\tilde{\theta}_H^2}{2} - \tilde{\theta}_M\tilde{\theta}_H + \frac{\tilde{\theta}_M^2}{2}$ and $\mu(\tilde{p}) = \frac{\tilde{\theta}_M^2}{2} - \tilde{\theta}_M\tilde{\theta}_L + \frac{\tilde{\theta}_L^2}{2} + \frac{1}{2} - \tilde{\theta}_H + \frac{\tilde{\theta}_H^2}{2}$, letting $\tilde{\theta}_L = \mathbb{a}$, $\delta - \tilde{\theta}_L = \mathbb{b}$, $\tilde{\theta}_H - \delta = \mathbb{c}$, and $1 - \tilde{\theta}_H = \mathbb{d}$, and using (16)-(17), we have $\lambda(\tilde{p}) = \frac{\mathbb{a}^2 + \mathbb{c}^2}{2}$, $\mu(\tilde{p}) = \frac{\mathbb{b}^2 + \mathbb{d}^2}{2}$, and $\rho = \frac{\lambda(\tilde{p})}{\mu(\tilde{p})} = \frac{\mathbb{a}^2 + \mathbb{c}^2}{\mathbb{b}^2 + \mathbb{d}^2}$. Since $\tilde{\rho}(p) < 1$, we have $\mathbb{b}^2 + \mathbb{d}^2 > \mathbb{a}^2 + \mathbb{c}^2$, which gives $\mathbb{d} + (\mathbb{b} - \mathbb{a})\frac{\mathbb{b} + \mathbb{a}}{\mathbb{c} + \mathbb{d}} > \mathbb{c}$. Furthermore, since $\mathbb{b} + \mathbb{a} = \delta$, $\mathbb{c} + \mathbb{d} = 1 - \delta$, and $\delta < 1$, we have $(\mathbb{b} - \mathbb{a})\delta > (\mathbb{c} - \mathbb{d})(1 - \delta)$. Moreover, since $\tilde{\theta}_L^* - \delta = 0$, we have $\mathbb{b} = 0$, which gives $0 > -\mathbb{a}\delta > (\mathbb{c} - \mathbb{d})(1 - \delta)$, so $\mathbb{c} < \mathbb{d}$. Thus, we have $\tilde{\theta}_H - \delta < 1 - \tilde{\theta}_H$.

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