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Strategic Pricing, Lifespan Choices and Environmental Implications of Peer-to-Peer Sharing

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Abstract

Peer-to-peer sharing has become increasingly popular in recent years. Many digital platforms exist that allow individuals to use others' belongings part-time. These platforms explicitly mention their green credentials, as the environmental benefits of such sharing initiatives are often taken for granted. However, several recent empirical studies show evidence of the contrary. For the first time in the literature, we provide a theoretical framework to analyze the economic and environmental implications of peer-to-peer sharing. We present a stylized model where a monopolist supplies a product that is suitable for rent on a sharing platform. Counterintuitively, we find that the existence of such a platform is typically beneficial for the monopolist, especially if it can strategically choose the price and lifespan of the product to affect the use price in the sharing market. Such a scenario is not at all beneficial for consumers, especially for those who rent the good rather than buy it. Moreover, the existence of the sharing platform induces higher use and (under some likely conditions) larger production levels and shorter lifespans of the products. The combination of these three aspects contributes to a worse environmental impact with sharing, which provides a theoretical rationale for the aforementioned empirical studies.

Keywords: peer-to-peer sharing; environmental externalities; strategic pricing; strategic lifespan.

JEL codes: D16, D21, D62, L12, Q56.

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Introduction

In this paper, we propose an analytical framework to understand the environmental and economic implications of peer-to-peer sharing platforms. These business models have become increasingly popular in recent years, as they allow individuals to use others' belongings part-time. Some platforms focus on matching buyers and sellers of second-hand goods (e.g. Vinted or Gadget Salvation) or facilitate swaps of products (e.g. Swancy or Gumtree Swap Shop). Other platforms allow consumers access to products and services without transfer of ownership, ranging from platforms with a specific focus such as car-sharing (e.g. Cambio), ride-sharing (e.g. BlaBlaCar), or sharing of equipment (e.g. myTurn) to general platforms that allow access to a wide variety of goods and services (e.g. the Neighbor-Goods or Peerby platforms for 'renting with the neighbors').[1]

The growing availability of these sharing initiatives is related to a general trend toward the circular economy, which is increasingly felt to be critical as societies strive to satisfy societal needs without exceeding planetary boundaries (Ellen MacArthur Foundation, 2013; European Commission, 2015). In essence, the circular economy is about maintaining products and materials at their highest value level while minimizing their environmental impact (European Commission, 2015). In its broadest sense, the circular economy can be seen as a societal transition, in which the circulation of materials eventually contributes to economic, environmental, and societal benefits (Reichel et al., 2016; Alaerts et al., 2019). The transition towards the circular economy obviously requires a broader set of actions and policy measures, but within these circular strategies, a crucial role is assigned to sharing systems to facilitate the move from product-focused markets to function-focused markets (Vandermerwe & Rada, 1988; Tukker, 2004; Kjaer et al., 2019).

The environmental benefits of such sharing systems are often taken for granted and most platforms explicitly mention their green credentials (Schor, 2016; Verboven & Vanherck, 2016; Hojnik, 2018). However, this widespread belief is increasingly put into question as studies reveal evidence to the contrary. For example, car-sharing systems may have a negative environmental impact – at least for some types of users – when taking into account increased access to cars, behavioral changes, the full life cycle of cars, and other systemic effects (Jung & Koo, 2018; Ding

[1] Besides differences in focus, platforms can also differ with respect to the types of parties that are involved, ranging from for-profit firms over social enterprises to individual consumers. Following Schor (2016), these sharing economy platforms can be categorized by their market orientation (for-profit vs. non-profit) and their market structure (peer-to-peer, business-to-consumer or business-to-business).

et al., 2019; Chapman et al., 2020). Rebound effects are likely to play a crucial role in determining the net environmental impact of sharing systems (Maxwell et al., 2011; Zink & Geyer, 2017). Lower use costs may result in increased consumption of the shared product or service, or – through an income effect – an increased overall consumption. The platforms are creating new markets that boost the purchasing power of users and expand the volume of commerce. Transportation needs increase and result in a rise of associated externalities. Moreover, mental spillover effects may occur as an uptake in perceived environmentally-friendly consumption can morally liberate individuals to pursue other goals that may be inconsistent with the initial sustainability objective (e.g. Tiefenbeck et al., 2013).

Up to our knowledge, all the studies that have analyzed the environmental effects of sharing platforms have focused on practical implications and empirical cases (e.g. Neunhoeffer & Teubner, 2018, Farajallah et al., 2019, as well as the studies mentioned above). By contrast, we propose to analyze the environmental and economic implications of peer-to-peer sharing systems from a theoretical point of view. In doing so, we aim to address the impact of a sharing system on production decisions and to identify the conditions under which the existence of a sharing system can be beneficial or detrimental for producers, consumers, the environment, and society as a whole. This approach is relevant, not only because it is novel, but also because it provides a framework to understand the fundamentals behind the overall effects of sharing systems: the positive ones, but also the potentially negative side-effects described above.

The interactions between the product (or primary) and the sharing (or secondary) markets give rise to complex effects that should be considered for the sake of a complete analysis, notably to evaluate welfare impacts. In economic terms, the supply in the sharing market is determined by the demand in the product market, as the goods are shared by those who have previously purchased them. In environmental terms, a full analysis requires accounting for the externalities generated during the full life cycle of the product, starting with the production phase, followed by the use phase, and ending with the end-of-life, or disposal, phase of the product.

In the production phase, the option of using a shared product rather than a privately owned one may be attractive to individuals if this is seen as a cheaper and more flexible option (Edbring et al., 2016). This effect potentially reduces demand in the product market and, thus, will affect the production and price strategies of producers (Dalhammar et al., 2021). A sharing market may also have an impact on product design through material selection and product durability. As consumers become suppliers of shared products, they may appreciate durability and repairability more, increasing their willingness to pay for long-lasting products (European Commission, 2018). If firms react by producing more durable goods, this may have two counteracting effects in environmental terms. On the one hand, if goods last longer fewer products are needed to satisfy consumer needs, thus leading to a reduction in production-related pollution and material use. On the other hand, increasing physical durability may imply higher material-intensity (e.g. reusable soda bottles can be twice as material-intensive as single-use bottles (Sunday Times, 2020)), and thus increase pressure on scarce resources. Overall, producing more durable goods can increase or decrease the production externality associated with pollution and resource scarcity.

Regarding the use phase, access to currently unused products is often noted as a key benefit of sharing systems. For example, Neunhoeffer and Teubner (2018) mention that a regular electric drill is used roughly 10 min over its lifetime on average, while the Ellen MacArthur Foundation (2015) states that the European car is parked 92 percent of the time. The more intensive use of durable goods creates value as individuals have access to more product variety, frequently pay less, and do not have to invest resources in buying, maintaining and storing these goods. Yet, the availability of a pay-per-use alternative may give individuals access to goods that they could not afford otherwise (Edbring et al., 2016). For example, urban households may opt to participate in car-sharing systems while they typically would not buy a car and use other mobility options such as public transport instead (Chapman et al., 2020). Overall, product use and consumer/user surplus are expected to increase due to the presence of a sharing market, but possibly generate more environmental externalities.

After the use phase, products need to be disposed of. If sharing leads to increased product durability, this may move the disposal phase forward in time, which can be seen as a societal benefit. However, in some cases, sharing may lead to misuse and increased waste production. For example, Yin et al. (2019) mention growing numbers of broken bikes that need to be disposed of due to the presence of dockless bike-sharing systems in China. When it comes to waste, the dominant means of disposal in the EU are landfilling (38.4%) and recycling (37.9%) (Eurostat, 2018). Landfilling is associated with significant external costs such as land use, soil contamination and air pollution (Dijkgraaf & Vollebergh, 2004).

In this paper, we provide a simple conceptual analysis of all these effects in the framework of a stylized microeconomic model. We assume that a monopolist produces a good and chooses its price and lifespan to maximize profits. Apart from being sold in the primary market, the good is also suitable for rent on a peer-to-peer sharing platform, where owners of the good and potential users meet. The sharing market affects the monopolist in two opposing ways. On the one hand, potential buyers of the good may experience an increase in their willingness to pay for the product, since they can potentially obtain rents by offering the product to others part-time. On the other hand, the monopolist may lose some clients that may instead get access to the good through the sharing platform. We study the monopolist's behavior and its impact on the primary and secondary markets under two alternative scenarios. First, we analyze the scenario where the monopolist is myopic about its possible influence on the sharing market and then we address the scenario where the firm chooses its decision variables strategically taking into account direct and indirect effects. We compare the results of both cases with the situation where the sharing market is absent. Consumers' decisions regarding buying, sharing and using the product paint a complete picture of the welfare effects and environmental damages under each setting.

The first important finding of the interrelation of the two markets is that the monopolist's profit is increasing in the use price. Interestingly, this mechanism opens up the door for the fact that a monopolist can benefit from the presence of a sharing market, despite the consumer-poaching competition effect introduced by the latter. In fact, if the monopolist behaves strategically, it can manipulate its decision variables (product price and lifespan) to induce the largest possible use prices, and hence obtain larger profits. But even a myopic monopolist can benefit from the presence of the sharing market, provided that the conditions in such a market result in a large enough use price.

To assess the environmental impacts, it is useful to compare three key variables in the scenarios with and without sharing: aggregate production, lifespan, and relative use (as a proportion of the overall duration of the product). Regarding the latter, we find the intuitive result that relative use levels are always larger when a sharing market is present than when it is not. The comparison regarding production and lifespan is not that obvious though, but we surprisingly find cases for which overall production is larger with sharing than without sharing. Also, although a strategic monopolist always chooses longer lifespans in combination with larger prices, it may well be the opposite case if the monopolist acts myopically. Considering all these effects, we find many combinations of parameters for which the scenarios with sharing perform worse in the three environmental components than the scenario without sharing.

Regarding economic surplus, owners and users benefit from the presence of a sharing market provided that the monopolist cannot act strategically, i.e., it cannot use its production decisions variables to manipulate the use price and catch a larger proportion of total surplus. This is particularly clear in the case of users, who can only get a positive surplus in the myopic case. Indeed, the presence of a strategic monopolist can make all consumers worse-off with sharing than without sharing. Our analysis reveals that such strategic behavior by the producer tends to generate a conflict between efficiency and equity as a larger surplus can be generated by the monopolist who can also retain a larger proportion of it.

Only a limited set of recent papers have theoretically investigated consumer, producer, and/or platform decisions in peer-to-peer sharing systems, but none of them takes the approach we follow in this paper. In particular, none of them analyzes the environmental effects of these sharing initiatives. Einav et al. (2016) study the design of peer-to-peer markets by looking at search mechanisms matching buyers and sellers, price decisions, and reputational effects. They ask the question of when and how such peer-to-peer markets need to be regulated, although they do not specifically look at producer incentives in the primary market. Later, Jiang and Tian (2018) develop an analytical framework to examine the strategic aspects of product sharing among consumers for the producer of the good. A purchaser of the good can derive different use values across two different use periods. In a period with low self-use value, the consumer may generate some income by renting out her purchased product through a third-party sharing platform. They also investigate the effect of transaction costs on the monopolist's profits and consumer surplus, as well as the firm's price and quality decisions. They show that the monopolist will select a price-quality pair that ensures higher profitability by extracting more surplus from consumers who expect potential income from product sharing. Environmental impacts are not included in this model, nor is the possibility that the firm chooses the duration of the goods (i.e., the number of use periods is fixed in their setting). Benjaafar et al. (2019) focus on the impact of matching frictions (i.e. an owner may not always find a renter for the product or vice versa) and the role of a sharing platform's objective function (i.e. maximize profits or maximize social welfare) on collaborative consumption decisions. They investigate the impact of the rental price, commission rate, costs of ownership, extra wear and tear costs, and inconvenience costs. However, they do not address the impact of the sharing system on producers' decision processes.

The remainder of the paper is organized as follows. In Section 2, we describe the general framework, followed by a discussion of the sharing market in Section 3. In Section 4, we focus on the monopolist's decision process under three scenarios: a first scenario without the presence of a sharing market, a second scenario with a sharing market where the monopolist is assumed to be myopic, and a third scenario where the monopolist acts strategically and takes its impact on the sharing market into account. In Section 5, we present a welfare analysis of the different scenarios, taking into account the economic and environmental components. We conclude in Section 6. All the proofs are in the Appendix.

1. The Model

A monopolist produces a durable consumption good. The firm can choose the lifespan of the good (i.e., the amount of time the good can be used in good shape), denoted as t, as well as the unit price, p. We assume that the lifespan affects the unit production cost as well as the firm's remaining costs (e.g. costs that are not variable in output quantity). Specifically, the marginal cost of production is $c \cdot t$ (with $1 > c > 0$), while the remaining costs the firm faces can be expressed as $\frac{d}{2}t^2$, with $d > 0$. Parameter c is associated with pure production costs, while d refers to the added costs that the firm must assume to make the good last longer (e.g. green design). If the monopolist produces and sells a quantity Q of the good, its profit can be written as

$$\pi = (p - ct)Q - \frac{d}{2}t^2. \tag{1}$$

The demand is characterized by a mass of consumers that differ in terms of the proportion of time they are willing to use the product, denoted as ξ.[2] We assume that ξ is uniformly distributed in the interval $[0,1]$ and each consumer can buy at most one unit of the product. We assume the reservation utility is zero.[3]

[2] There are many products for which individuals show a constant pattern of use ξ, regardless of the specific lifespan t. For example, to ride the car on weekdays, to use the washing machine three times per week, to use the drill twice a year, etc.

[3] We consider this assumption for presentation simplicity. When a sharing market exists, the main implication of this assumption is full demand coverage. This allows us to characterize analytically all the effects of the sharing market on the economy and the environment for the alternative scenarios on the monopolist's behavior considered in the paper.

Once purchased, owners can create value by providing access to other individuals during the time they are not using the product. Due to this double role as a consumer and as an access provider, we refer to the owners of the good as *prosumers*.[4]

Prosumers' (indirect) expected utility can be written as follows:

$$U_P = \xi t + (1 - \xi) t r \alpha - p. \tag{2}$$

The first term in equation (2) is the utility derived from the effective time a prosumer uses the product for her own purposes. We assume that a prosumer is willing to share the good (during the time she is not using it, $1 - \xi$) at any price $r \geq 0$, if she finds partners willing to do so. The second term in equation (2) denotes the expected gains associated with sharing the good at price r, while α refers to the probability to find someone willing to use the good by accessing the sharing market or, alternatively, the expected proportion of time that the good will be successfully shared. Finally, the third term in expression (2) reflects the negative effect of the price of the product on indirect utility. Note that the first and third terms are usual when modeling indirect utility in imperfect competition models. The innovative part is the second term, but we can easily come back to the traditional specification by simply assuming $\alpha = 0$. From expression (2), we can easily infer that the maximum price the monopolist can charge for the product in equilibrium is $p = t$. This is so because $\xi t + (1 - \xi) t r \alpha$ is an increasing function of ξ, and $\xi \in [0,1]$.

We borrow the formulation for prosumers' indirect utility given in (2) from Benjaafar et al. (2019), but there are two main differences between our approach and theirs. The first is that in ours the lifespan of the product, t, is a strategic variable of the monopolist, while Benjaafar et al. (2019) do not model the producer's behavior at all. Hence, they take the lifespan as exogenous and normalized to 1. In order to concentrate on the monopolist behavior and the associated external effects, we simplify the model in other respects. In particular, we do not explicitly model the sharing platform and we normalize the commission rate to zero. In addition, we abstract from any cost the prosumer may suffer from sharing the product (Benjaafar et al. (2019) specifically refer to the *extra wear and tear the user places on the product*).

[4] Starting from the first mention of 'prosumers' by Alvin Toffler (1980), a forward thinker considering societal change from an industrial era to an informational era, several interpretations of this concept have emerged especially related to the process of value co-creation. Recently, Lang et al. (2020, p.3) have proposed the flexible definition of prosumers as 'individuals who consume and produce value, either for self-consumption or consumption by others, and can receive implicit or explicit incentives from organizations involved in the exchange'.

Unlike prosumers, users are individuals who do not purchase the good, but are willing to use it if they find partners (prosumers) in the sharing market. As in Benjaafar et al. (2019), users' (indirect) expected utility is given by:

$$U_U = \beta(\xi t - \xi t r) \tag{3}$$

where β stands for the probability to find providers of the good by accessing the sharing market or, equivalently, the expected proportion of desired time that users will be able to cover at a use price r. Since the reservation utility is zero, expression (3) implies that the use price is upper bounded by $r = 1$, as a higher value would cause users to opt out of this market. We assume that users are willing to share the good at any price $r \leq 1$, including the threshold value $r = 1$, which renders an expected utility equal to zero.

Hence, our model considers two interrelated markets. The first one is the primary product market, where the monopolist meets with potential buyers of the good, and sets the price and lifespan of the product to maximize profits. The second one is the sharing market, where prosumers and potential users of the good interact in a competitive setting, and an equilibrium use price is determined. As a result of this interrelation, on the one hand, the demand for the product in the primary market depends on the use price. On the other hand, the use price depends on both the price and lifespan of the product, as we show below. Parameters α and β summarize possible frictions in the secondary market, such as individuals' lack of familiarity with sharing systems or difficulties accessing the online platform.

2. The sharing market

The first step to compute the market equilibrium is to identify prosumers and users. This is done by finding the individual who is indifferent between buying the good (and being a prosumer) and not buying the good (and, thus, being a potential user). This indifferent consumer is denoted as $\overline{\xi}$, and is identified by equalizing expressions (2) and (3), as follows:

$$\xi t + (1 - \xi) t r \alpha - p = \beta(\xi t - \xi t r), \tag{4}$$

from which we can easily obtain:

$$\overline{\xi} = \frac{p - tr\alpha}{t[1 - \beta + r(\beta - \alpha)]}. \tag{5}$$

Hence, prosumers are those with $\xi \geq \overline{\xi}$, while users are those with $\xi < \overline{\xi}$,[5] provided $r \geq 0$ (prosumers do not supply the good at a price below zero) and $r \leq 1$ (there are no users for a price above one). Since $\xi \in [0,1]$, and assuming that each consumer buys at most one unit of the good, the number of potential units to be supplied in the sharing market (which coincides with the aggregate demand of the good in the product market) is:

$$Q = 1 - \overline{\xi} = 1 - \frac{p - tr\alpha}{t[1 - r\alpha - \beta + r\beta]} = \frac{t(1 - \beta + r\beta) - p}{t[1 - \beta + r(\beta - \alpha)]}. \tag{6}$$

Given that $\xi \in [0,1]$, in equilibrium, we must have $tr\alpha \leq p \leq t(1 - \beta + r\beta)$. Since each unit of the good has a lifespan t, these Q units of the good jointly provide a potential total use time equal to

$$tQ = \mathrm{t}\left(1 - \overline{\xi}\right) = \frac{t(1 - \beta + r\beta) - p}{1 - \beta + r(\beta - \alpha)}. \tag{7}$$

An individual with parameter ξ is willing to use the good for an amount of time ξt him(her)self. Thus, prosumers, i.e. the agents characterized by $\xi \in \left[\overline{\xi}, 1\right]$, will be willing to use a good during an amount of time given by

$$\int_{\overline{\xi}}^{1} t \cdot s \cdot ds = t\left(\frac{1 - \overline{\xi}^2}{2}\right). \tag{8}$$

Thus, the time that prosumers are willing to share the good is given by the difference between the maximum time they have bought as the owner of the good (expression (7)) and the time they use the good for themselves (expression (8)). Therefore, the potential supply, S^P, in the secondary market (in terms of time) is given by

[5] This is so because $U_P - U_U$ is increasing in ξ. Using (2) and (3), we have $\frac{\partial(U_P - U_U)}{\partial\xi} = t[1 - r\alpha - \beta(1 - r)]$. Since r is constrained to be between 0 and 1, we have $\frac{\partial(U_P - U_U)}{\partial\xi} = t(1 - \beta) \geq 0$ evaluated at $r = 0$ and $\frac{\partial(U_P - U_U)}{\partial\xi} = t(1 - \alpha) \geq 0$ evaluated at $r = 1$. Thus, it must be $\frac{\partial(U_P - U_U)}{\partial\xi} \geq 0$ for any admissible value of r except if $\frac{\partial(U_P - U_U)}{\partial\xi}$ is U-shaped in r. This possibility is discarded because $\frac{\partial^2(U_P - U_U)}{\partial\xi\partial r} = t(\beta - \alpha)$, which is constant (either positive, negative or zero) and thus $\frac{\partial(U_P - U_U)}{\partial\xi}$ can only be constant, strictly increasing or strictly decreasing in r.

$$S^P(p,r,t,\alpha,\beta) = t\left(1-\overline{\xi}\right) - t\left(\frac{1-\overline{\xi}^2}{2}\right) = t\left(\frac{\left(1-\overline{\xi}\right)^2}{2}\right), \tag{9}$$

where $\overline{\xi}$ is given by (5). Hence, the "effective supply", S^E, is computed as the potential supply given in (9) multiplied by the probability of successfully accessing the sharing market as a supplier, α.

On the other hand, the potential demand for access to the good is given by the amount of time that consumers are willing to pay for using the shared good, given by

$$D^P(p,r,t,\alpha,\beta) = \int_0^{\overline{\xi}} t \cdot s \cdot ds = t\left(\frac{\overline{\xi}^2}{2}\right), \tag{10}$$

and the effective demand is the potential demand given in (10) multiplied by the probability of successfully accessing the sharing market as a user, β.

The equilibrium use price is obtained from the market clearing condition (effective supply equal to effective demand) plus the boundary conditions $0 \leq r \leq 1$ imposed by the participation constraints of prosumers and users. The corresponding analytical expression is provided in the following lemma and illustrated in Figure 1. [6]

Lemma 1. *Given (p,t,α,β), the equilibrium use price is given by*

$$r = \begin{cases} 0 & if \quad \frac{p}{t} < \frac{(1-\beta)\sqrt{\alpha}}{\sqrt{\alpha}+\sqrt{\beta}} \\ \frac{p}{t\sqrt{\alpha\beta}} - \frac{1-\beta}{\sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)} & if \quad \frac{(1-\beta)\sqrt{\alpha}}{\sqrt{\alpha}+\sqrt{\beta}} \leq \frac{p}{t} \leq \frac{\sqrt{\alpha}\left(\sqrt{\alpha\beta}+1\right)}{\sqrt{\alpha}+\sqrt{\beta}} \\ 1 & if \quad \frac{\sqrt{\alpha}\left(\sqrt{\alpha\beta}+1\right)}{\sqrt{\alpha}+\sqrt{\beta}} < \frac{p}{t} \end{cases} \tag{11}$$

[6] Note that in the case of a corner solution, the sharing market does not necessarily clear, possibly leading to excess supply or demand.

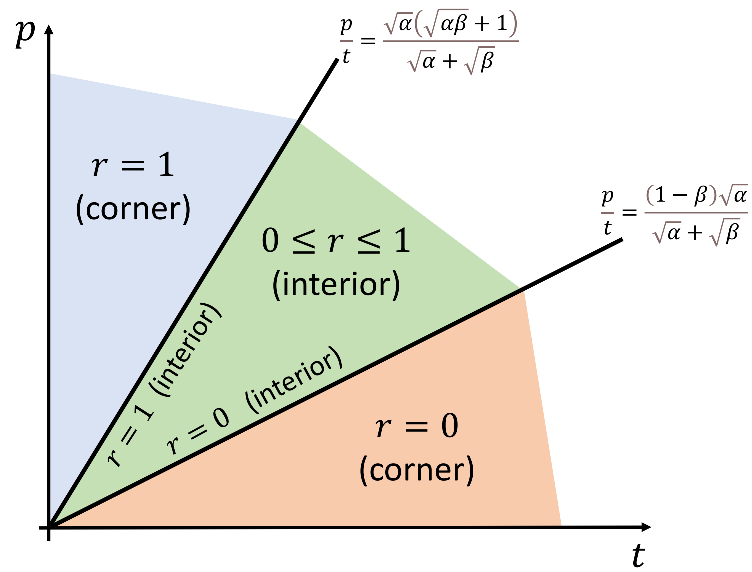

Figure 1: Existence of corner and interior solutions

Hence, the equilibrium use price can be either interior (with $0 \le r \le 1$) or corner ($r = 0$ or $r = 1$). The solution is crucially affected by the ratio $\frac{p}{t}$, which measures the price per unit of available time in the primary market. In the interior region, the equilibrium use price depends positively on the product price p and negatively on the product lifespan t. Both are choice variables of the monopolist, so we can conclude immediately that the monopolist can affect the use price. Ceteris paribus, a higher price reduces the demand in the primary market, and the corresponding reduction of the supply in the secondary market induces a higher use price r. Conversely, a longer lifespan increases, ceteris paribus, the amount of available use time of the good and, consequently, it increases the supply in the secondary market, which naturally leads to a lower equilibrium use price.

3. The monopolist's problem

The monopolist's problem consists of finding the product price and lifespan that maximize profits. We analyze three situations. As a benchmark case, in subsection 4.1 we derive the monopolist's solution when the sharing market is absent. In subsections 4.2 and 4.3, we consider the more interesting situation where the sharing market exists. In subsection 4.2, we study the case of a myopic monopolist that does not consider its possible influence on the sharing market.

However, in subsection 4.3 we analyze the case of a strategic monopolist that takes its influence in the sharing market into account when deriving its optimal choices.

4.1. The sharing market is absent

Going back to expression (2), in the absence of a sharing market, consumers purchase the good as long as $\xi t - p \geq 0$. This determines an aggregate demand for the product equal to $Q = 1 - \frac{p}{t}$ (we can obtain this same expression by substituting $\alpha = \beta = 0$ in expression (6)). The monopolist's problem is the following:

$$\max_{p,t}(p - ct)Q - \frac{d}{2}t^2 = (p - ct)\left(1 - \frac{p}{t}\right) - \frac{d}{2}t^2$$

By solving this problem we can derive the optimal price and lifespan, which in turn determine the overall production and maximum monopolistic profits. In addition, we obtain the total use of the good (u), which is given by the aggregate time that the owners use their products. The corresponding analytical expression is given by (8), with $\bar{\xi} = 1 - Q$. Hence, relative use (i.e., total use as a proportion of the total use time of the product), is defined as:

$$RU := \frac{u}{tQ} = \frac{1 - \bar{\xi}^2}{2Q} = \frac{1 - (1 - Q)^2}{2Q} = \frac{2 - Q}{2} = 1 - \frac{Q}{2}$$

The monopolist's solution is provided in Proposition 1. Superscript N stands for *no sharing market*.

Proposition 1. *In the absence of a sharing market, the monopolist's solution for given cost parameters* (c, d) *is given by* $p^N = \frac{(1+c)(1-c)^2}{8d}$ *and* $t^N = \frac{(1-c)^2}{4d}$. *This results in total production* $Q^N = \frac{1-c}{2}$, *overall monopolist's profits* $\pi^N = \frac{(1-c)^4}{32d}$ *and relative use of the good* $RU^N = \frac{3+c}{4}$.

Note that a larger value of the cost parameter c has the usual implication of reducing the equilibrium output, but the effect on the price is not the same as in a basic monopoly model with linear demand. Indeed, for the relevant range, $0 < c < 1$, the monopolist's price is decreasing rather than increasing in c. The reason is that, in this range, the lifetime of the good, t, is also decreasing (because of the interaction between c and t in the cost function), which makes consumers less willing to pay for the good.[7] An increase in parameter d, which determines the costs not directly related to production, does not have an impact on output and leads to a lower price and shorter lifespan, in such a way that the price per unit of time, $\frac{p}{t}$, is kept constant at $\frac{p}{t} = \frac{(1+c)}{2}$. In other words, when d increases, the monopolist offers a cheaper good with a shorter lifetime, although the price per unit of time is kept independent of d.

4.2. Myopic monopolist

Now, we consider that there exists a sharing market. However, the monopolist ignores its possible influence on the use price, r, and takes it as given. This case can reflect a situation where the monopolist cannot control the secondary market, for example, due to regulations or geographical distance. Taking the demand of the product obtained in (6) into account, the firm solves the problem:

$$\max_{p,t} \left\{(p - ct)Q - \frac{d}{2}t^2\right\} = \max_{p,t} \left\{(p - ct)\left[\frac{t(1 - \beta + r\beta) - p}{t[1 - \beta + r(\beta - \alpha)]}\right] - \frac{d}{2}t^2\right\}$$

In the following lemma, we present the optimal monopolist's strategy as a function of the use price, r.

Lemma 2. *For given parameters (c, d, α, β), and a given use price, r, the profit-maximizing price and lifespan of a myopic monopolist are given by:*

$$p = \frac{(1-\beta+r\beta+c)(1-\beta+r\beta-c)^2}{8d[1-\beta+r(\beta-\alpha)]} \tag{12}$$

$$t = \frac{(1-\beta+r\beta-c)^2}{4d[1-\beta+r(\beta-\alpha)]} \tag{13}$$

Combining equations (12) and (13), we conclude that the price per unit of time set by the monopolist, which is given by $\frac{p}{t} = \frac{(1-\beta+r\beta+c)}{2}$, is smaller than under no sharing (which is given by $\frac{p}{t} = \frac{(1+c)}{2}$), except in the corner region $r = 1$. This effect can be understood as an implication of the competition that the secondary market represents for the producer. In the myopic monopolist

[7] This negative effect between the marginal cost and the product price is also present when the sharing market exists, see Subsections 4.2 – 4.4.

case, the ratio $\frac{p}{t}$ depends positively on the unit cost c and the use price r, and negatively on parameter β. A higher use price softens the competition that the secondary market represents for the monopolist and allows it to push the price upwards. When β increases, it becomes easier for potential users to get access to the good and thus more people are willing to be users and fewer prosumers. This shrink in the primary market demand forces the monopolist to lower the price.

We now combine the optimal monopolist's choices (12) and (13) with the equilibrium condition (11), in order to find the equilibrium values of all the relevant variables: use price, product price, lifespan and overall quantity produced.

The following proposition provides the analytical solution. Superscript M stands for *myopic*.

Proposition 2. *For given parameters* (c, d, α, β)*, the equilibrium in the context of a myopic monopolist is given by the following expressions:*

$$r^M = \begin{cases} 0 & if \quad c \leq \underline{c} \\ \dfrac{(1-\beta)\left(\sqrt{\beta}-\sqrt{\alpha}\right)+c\left(\sqrt{\alpha}+\sqrt{\beta}\right)}{\sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)\left(2\sqrt{\alpha}-\sqrt{\beta}\right)} & if \quad \underline{c} < c < \overline{c} \\ 1 & if \quad \overline{c} \leq c \end{cases}$$

$$p^M = \begin{cases} \dfrac{(1-\beta+c)(1-\beta-c)^2}{8d(1-\beta)} & if \quad c \leq \underline{c} \\ \dfrac{\sqrt{\beta}\left[\alpha(1-\beta)+c\left(\alpha+\sqrt{\alpha\beta}\right)\right]\left[\alpha(1-\beta)+c(\beta-\alpha)\right]}{d\left(\sqrt{\alpha}+\sqrt{\beta}\right)^3\left(2\sqrt{\alpha}-\sqrt{\beta}\right)^2} & if \quad \underline{c} < c < \overline{c} \\ \dfrac{(1+c)(1-c)^2}{8d(1-\alpha)} & if \quad \overline{c} \leq c \end{cases}$$

$$t^M = \begin{cases} \dfrac{(1-\beta-c)^2}{4d(1-\beta)} & if \quad c \leq \underline{c} \\ \dfrac{\sqrt{\beta}\left[\alpha(1-\beta)+c(\beta-\alpha)\right]}{d\left(\sqrt{\alpha}+\sqrt{\beta}\right)^2\left(2\sqrt{\alpha}-\sqrt{\beta}\right)} & if \quad \underline{c} < c < \overline{c} \\ \dfrac{(1-c)^2}{4d(1-\alpha)} & if \quad \overline{c} \leq c \end{cases}$$

$$
Q^M = \begin{cases} \dfrac{1-\beta-c}{2(1-\beta)} & if \quad c \leq \underline{c} \\ \dfrac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}} & if \quad \underline{c} < c < \overline{c} \\ \dfrac{1-c}{2(1-\alpha)} & if \quad \overline{c} \leq c \end{cases}
$$

$where\ \underline{c} := \frac{(1-\beta)(\sqrt{\alpha}-\sqrt{\beta})}{\sqrt{\alpha}+\sqrt{\beta}}\ and\ \ \overline{c} := \frac{\sqrt{\alpha}-(1-2\alpha)\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$.

The proposition identifies the three types of solution mentioned above (one interior and two corner cases) and reveals that the prevailing type of solution depends on the value of the cost parameter c.[8] Both the price and the lifespan of the product are decreasing in the marginal cost of production, as in the case of no sharing presented in the previous subsection. In the interior case, the equilibrium quantity is independent of the cost parameters and is fully determined by α and β. The reason for this is the joint consideration of market clearing in the sharing market and perfect market coverage. [9] This is no longer the case in the corners, where the sharing market does not clear.

In the presence of a sharing market (irrespective of the presence of a myopic or strategic monopolist), total use of the good changes in comparison to the case where the sharing market is absent. The reason is that we have to consider not only the time that owners of the good use it themselves, given by expression (8), but also the time that users have access to the good in the sharing market, given by expression (10), where the latter needs to be multiplied by β to account for effective demand.[10] Summing up, the relative use in the presence of a sharing market is given by

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[8] Note that, depending on the values of α and β, it is not always the case that all three intervals exist. In fact, if $\beta > \alpha$, we have $\underline{c} < 0$, and so the first range does not arise. For the sake of completeness, we focus on the general case where all three ranges are possible.

[9] Using expressions (9) and (10), assuming that the sharing market clears with perfect market coverage results in $\beta t\left(\frac{\overline{\xi}^2}{2}\right) = \alpha t\left(\frac{\left(1-\overline{\xi}\right)^2}{2}\right)$, or, equivalently, $\sqrt{\beta}\,\overline{\xi} = \sqrt{\alpha}\left(1-\overline{\xi}\right)$, from which we can easily get $\overline{\xi} = \frac{\sqrt{\alpha}}{\sqrt{\alpha}+\sqrt{\beta}}$. Hence, $Q = 1-\overline{\xi} = \frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$ no matter what the specific values for the product price, the product lifespan and the use price are.

[10] Note that, in a corner solution, the aggregation of these two terms may be larger than one. This may happen in an excess demand situation where the use time supplied by prosumers is insufficient to cover the users' demand, or even

$$RU = \frac{u}{tQ} = min\left(1, \frac{1 - \bar{\xi}^2 + \beta\bar{\xi}^2}{2Q}\right) = min\left(1, \frac{1 - (1-\beta)(1-Q)^2}{2Q}\right) \qquad (14)$$

We are now curious as to whether the presence of a sharing market is beneficial or detrimental for the monopolist. Two forces going in opposite directions influence the monopolistic profits when the sharing market is present. On the one hand, the presence of a sharing market increases the value prosumers attach to the product (since they can receive a fee for allowing part-time access to the good) and thus are willing to pay more. On the other hand, the sharing market is a competitor for the monopolist, especially attracting consumers with a lower willingness to use the product. The following lemma shows that the resulting impact on equilibrium depends on the use price, and Proposition 3 establishes the existence of a threshold for that price over (below) which the existence of a sharing market is (not) beneficial for the monopolist.

Lemma 3. *The monopolistic profits are strictly increasing in the use price .*

The intuition behind this result is clear and reflects that buying the good in the primary market and renting it in the secondary market are substitutes in consumption. Everything else equal, a larger use price benefits the monopolist since the demand in the primary market will increase. Besides this fact, a higher use price increases prosumers' willingness to pay for the good in the primary market (see the second term of expression (2)). These two effects reinforce each other and hence imply that a higher use price enables the monopolist to make higher profits.

Proposition 3. *Given $\beta < 1$, there exists a threshold equilibrium value of $r \in [0,1]$ (critically influenced by α and β) above which the existence of the sharing market is beneficial for the myopic monopolist.*

A use price close to zero is detrimental to the firm for two reasons. First, prosumers are willing to pay less for the product if they get no revenue in the sharing market. Second, the sharing market is a fierce competitor of the monopolist, and users of the good get a positive indirect utility

a proportion β of it. In this case, the effective relative use of the good is equal to one, which means that total available use time is exhausted and some effective demand may still remain uncovered.

(which becomes the reservation utility for prosumers). However, if the use price is close to one, prosumers' willingness to pay for the product increases because of their ability to share the good in the sharing market at the highest possible price. In this situation,the existence of a secondary market is beneficial for the monopolist. Hence, since the monopolist's profits are increasing in the use price, there must be a threshold value of the use price beyond which the existence of the sharing market is beneficial for the monopolist.

Next, we compare the resulting lifespan, relative use levels and production in the two models (no sharing versus sharing with myopic monopolist). The main conclusion is that, except for the relative use, there is not an obvious ranking in any dimension.

Proposition 4. *Lifespans, relative use and production levels under a myopic monopolist and no sharing are related as follows:*

(i) *There exists a threshold value* $c_t \in (\underline{c}, \overline{c})$ *such that* $t^M \geq t^N$ *if and only if* $c \geq c_t$.

(ii) $RU^M \geq RU^N$ *for any admissible parameter combination, with equality if* $c = \overline{c}$ *and strict inequality otherwise.*

(iii) *There exists a threshold value* $c_Q := \frac{\sqrt{\alpha}-\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}} \in (\underline{c}, \overline{c})$ *such that* $Q^M \geq Q^N$ *if and only if* $c \geq c_Q$.

Apart from the results about lifespan, relative use and output displayed in the proposition, we conclude that there exists a related result for price. Specifically, we have $p^N > p^M$ when $c \leq \underline{c}$ and $p^N < p^M$ when $c \geq \overline{c}$. By continuity, p^N and p^M must cross in the $(\underline{c}, \overline{c})$ interval. Given the complex expressions involved, it cannot be proven, in general, that there is a single crossing point,[11] but this is always the case for all the relevant parameter values. Labelling this crossing point as c_p, we get $p^M \geq p^N$ if and only if $c \geq c_p$ (see the numerical analysis below for an illustration).

Proposition 4 confirms the intuitive result that, with a sharing market, a larger proportion of available time is used. This is a direct consequence of the fact that prosumers can share their goods with users when they are not using them themselves. Nevertheless, this fact does not imply, as one might expect, that total output with a sharing market will always be lower than without it.

[11]Such crossing point(s) is(are) determined by a cubic equation, which, in general, may give rise to up to three real solutions, although this is never the case in the relevant range.

It is perfectly possible that the existence of a secondary market attracts more buyers, who take advantage of the possibility of using a good part of the time and sharing it the rest of the time. This situation is more likely to arise the higher the marginal production cost.

One could also expect that, in the presence of a sharing market, offering longer-lasting products will be attractive for the producer. Proposition 4 shows that this may or may not be the case and this is again linked to the marginal production cost.

4.3. Strategic monopolist

In the myopic case, we have proven that the firm can benefit from the presence of the sharing market, provided that the use price is sufficiently large. Intuitively, when the monopolist takes into consideration its influence on the use price, it will try to induce the largest possible use price ($r = 1$) by choosing the product price and lifespan accordingly.

The firm's optimization problem is now the following:

$$\max_{p,t}(p - ct)Q - \frac{d}{2}t^2$$

subject to (6) and (11)

The solution is provided next. Superscript S stands for *strategic*.

Proposition 5. *For given parameters* (c, d, α, β)*, the equilibrium variables in the context of a strategic monopolist are*

$r^S = 1,$

$$p^S = \begin{cases} \frac{\sqrt{\alpha}(\sqrt{\alpha\beta}+1)[\sqrt{\alpha\beta}+\alpha\beta-c\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta})]}{d(\sqrt{\alpha}+\sqrt{\beta})^3} & if \quad c \leq \bar{c} \\ \frac{(1+c)(1-c)^2}{8d(1-\alpha)} & if \quad c > \bar{c}, \end{cases}$$

$$t^S = \begin{cases} \frac{\sqrt{\alpha\beta}+\alpha\beta-c\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta})}{d(\sqrt{\alpha}+\sqrt{\beta})^2} & if \quad c \leq \bar{c} \\ \frac{(1-c)^2}{4d(1-\alpha)} & if \quad c > \bar{c}, \end{cases}$$

$$Q^S = \begin{cases} \dfrac{\sqrt{\beta}}{\sqrt{\alpha} + \sqrt{\beta}} & if \quad c \leq \overline{c} \\ \dfrac{1-c}{2(1-\alpha)} & if \quad c > \overline{c} \end{cases}$$

where $\overline{c} = \frac{\sqrt{\alpha}-(1-2\alpha)\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$.

As shown in Proposition 5, the strategic monopolist's solution can take two forms depending on the parameter values. If the marginal cost c is below $\overline{c}$, the monopolist chooses a value for the price and the lifespan such that $\frac{p}{t} = \frac{\sqrt{\alpha}(\sqrt{\alpha\beta}+1)}{\sqrt{\alpha}+\sqrt{\beta}}$. This value is just on the frontier between the interior solution case ($0 \leq r \leq 1$) and the corner solution case ($r = 1$) as shown in Lemma 1 (and Figure 1). As we show below, in this range, the monopolist takes advantage of its ability to manipulate the use price to increase its profit above that of the myopic case.

On the other hand, when c is large enough ($c > \overline{c}$), the solution enters a range where the use price has reached its maximum value ($r = 1$) and cannot increase anymore. In this region, the monopolist cannot manipulate market behavior anymore and its ability to take advantage of its strategic behavior is lost. Therefore, in this region, a strategic monopolist behaves exactly in the same way as a myopic monopolist.

Proposition 3, in combination with the fact that the use price is always one when the firm acts strategically, results in the following:

Proposition 6. *The existence of the sharing market is always beneficial for a strategic monopolist.*

4.4 Numerical illustration

In this subsection, we numerically illustrate the solution under the three different scenarios: 'no sharing', 'myopic' monopolist and 'strategic' monopolist. In this way, we can gain additional insight into the sensitivity of the market equilibrium to different values of the marginal cost parameter c in the three possible solution intervals. For illustration purposes, we set the parameter values $d = 0.2$, $\alpha = 0.6$ and $\beta = 0.2$, but our main conclusions do not qualitatively change under alternative values for these parameters.

Figure 2 (first row) illustrates that the strategic monopolist always sets the highest product price and longest lifespan independent of the marginal cost parameter. In the two first solution intervals ($c \leq \overline{c}$), the values preferred by the strategic monopolist are above the ones set by a myopic monopolist. Nevertheless, in the upper range ($\overline{c} < c$), both solutions coincide, as we already know from the analysis in Section 4.2. It is also interesting to see that, if the monopolist is myopic, the product lifespan can be shorter in the presence of a sharing market than without it, as we know from Proposition 4. A possible explanation for this fact is that the lifespan can be used to limit the impact of the sharing market on the monopolist's sales when the firm cannot strategically increase the use price to make the sharing market less attractive to users. Note also that the product price in the myopic case can be below the one that would prevail without a sharing market, provided that the use price is sufficiently small.

Figure 2 (second row) also confirms that, whether the monopolist acts strategically or not, the relative use levels are larger when the sharing market is present as compared to the benchmark situation without sharing. The result regarding output is not so obvious. Intuitively, one may expect that the output should be lower with a sharing market (especially in the strategic case, where the product lifespan is larger). Nevertheless, as we know from the analytical analysis, we get the opposite result when the marginal cost parameter is large enough.

The fact that, when $c \geq \underline{c}$, output and relative use level take the same value regardless of whether the monopolist is myopic or strategic suggests that product price and lifespan can be used by the strategic monopolist to increase its profit, but the channel by which this profit increases is accomplished by increasing the use price and not by modifying output or relative use levels.

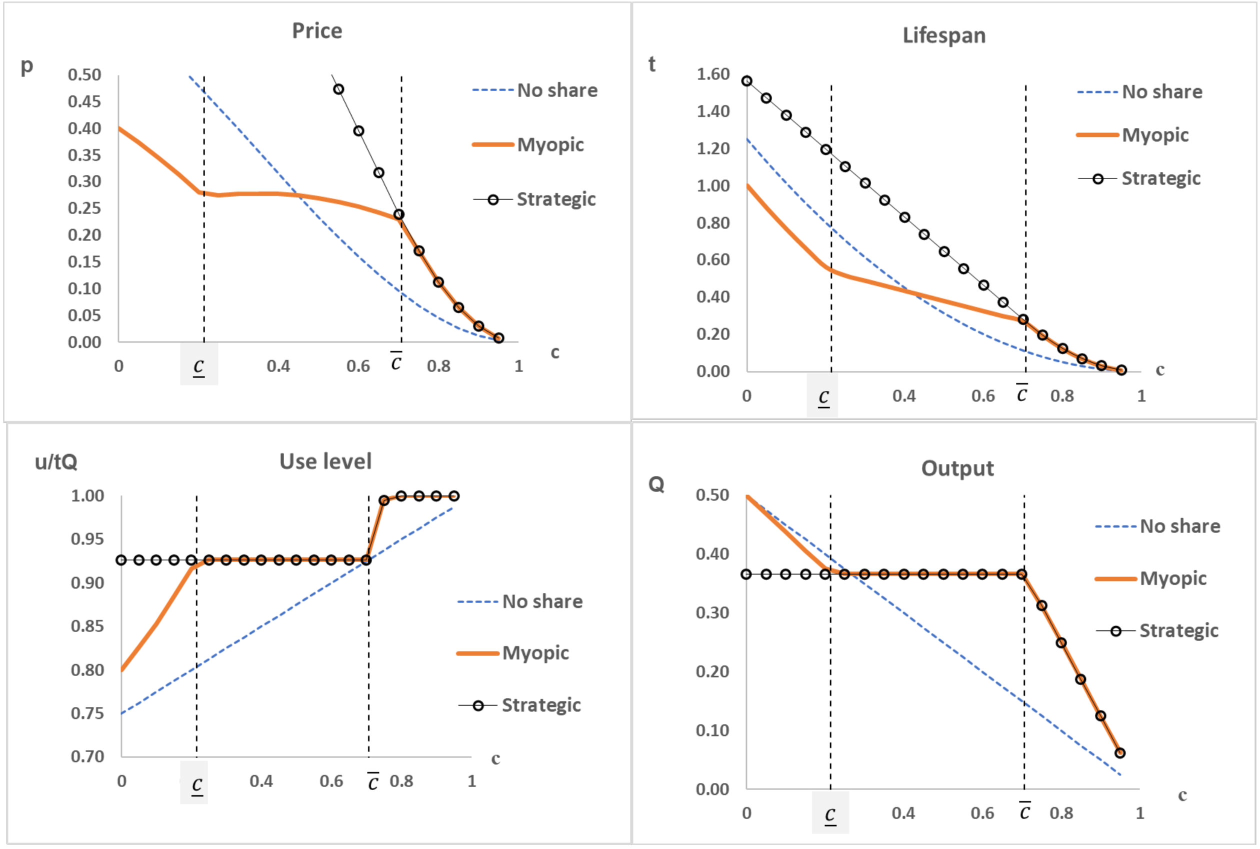

Figure 2: Numerical illustration equilibrium values with $d = 0.2, \alpha = 0.6, \beta = 0.2$

4. Welfare analysis

The analysis of the monopolist's decisions and consumer behavior in the previous sections provides us with some background to assess the welfare impacts of a sharing market considering the different stages of the life cycle. Welfare can be split into two qualitatively different parts that we address separately: on the one hand, the environmental impact of output, use and disposal, and, on the other hand, the purely economic component or agents' surplus.

5.1 Environmental component

The environmental component of welfare reflects the negative externalities associated with the complete life cycle, due to pollution and use of scarce materials during the production phase, the use phase and the (end-of-life) disposal phase of the product. Firstly, we assume that production externalities (E_P) increase with the quantity produced:

$$E_P = e_P.(1 + \delta t).Q$$

where $e_P \geq 0$ is a scale parameter and $\delta \geq 0$ reflects the impact of a longer lifespan on the production phase as, for example, more materials may be needed to allow more intensive use and more externalities may be generated per unit produced. For instance, the material footprint of producing reusable packaging is typically higher than that of single-use packaging (Coelho et al., 2020). Yet, this increased material input is balanced with a longer product lifespan.

Next, we assume use externalities (E_U) are a linear function of the total use *(u)*:

$$E_U = e_U . u$$

Thus, the externalities associated with the use phase of the product depend on the total duration (in hours or days) that the product is used and not on the relative use (as a percentage of the maximum possible use).

Lastly, we assume disposal externalities (E_D) are an increasing function of the quantity produced, but a decreasing function of the lifespan of the product. The latter relationship reflects that the disposal phase is shifted forward in time as the life span increases and thus that the present value of the environmental impact of disposal reduces with the product life span. This gives:

$$E_D = e_D . \left(\frac{1}{1+t}\right) . Q$$

Thus, the aggregate impact of environmental externalities over the total life cycle of the good is captured by the environmental welfare component (E):

$$E = E_P + E_U + E_D = e_P . (1 + \delta t) . Q + e_U . u + e_D . \left(\frac{1}{1+t}\right) . Q$$

Based on this expression, we see that *E* is strictly increasing with the quantity produced and the use of the goods. The effect of increasing the lifespan of the product is, however, ambiguous as the production externalities may increase but the disposal externalities may decrease: $\frac{\partial E}{\partial t} = Q\left(\delta e_P - \frac{e_D}{(1+t)^2}\right) \lesseqgtr 0$.

Obviously, the results about the environmental effects are crucially affected by the values of the parameters, which should reflect the nature of the specific good under consideration and the externalities derived from its production, use and disposal. Figure 3 shows an illustration based on the values $e_P = e_U = e_D = \delta = 1$, and the same values of parameters d, α and β assumed in the previous section. In practice, these parameter values will depend on the specifics of the product and materials of the study.

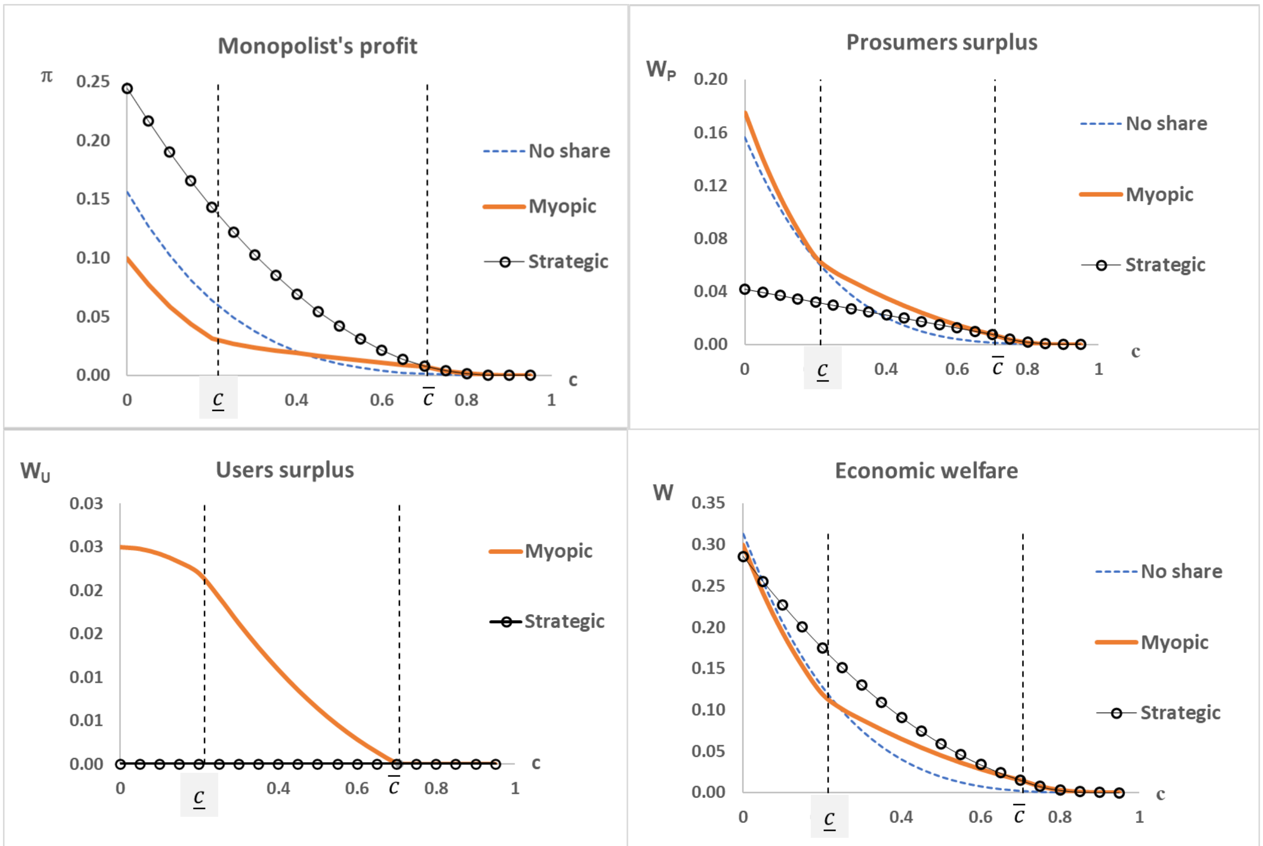

Figure 3: Illustration externalities, $e_P = e_U = e_D = \delta = 1, d = 0.5, \alpha = 0.6, \beta = 0.2$.

Our numerical analysis confirms that the introduction of a sharing market does not automatically lead to a lower environmental impact associated with production and consumption. In fact, the overall externality with sharing tends to be larger than without it. This is illustrated in the last graph of Figure 3, which also shows that the case of a strategic monopolist is the one that tends to generate more externalities. This result is driven by the fact that this setting is the one resulting in more production and use externalities, which is consistent with the fact that a myopic and a strategic monopolist tend to generate more output than in a situation without a sharing market and the strategic one produces goods with a longer lifespan. The latter element causes the disposal externality generated by a strategic monopolist to be lower, in present terms, than that of a myopic one.

5.2 Economic component

The economic surplus of all the economic agents in the industry can be computed by adding up the monopolist's profit and indirect utility of prosumers and users as given by expressions (1), (2) and (3), respectively.

In the absence of a sharing market, there are no users and the indirect utility of each consumer is given by $U_P = \xi t - p$. So, the aggregate surplus of all the active consumers can be computed as

$$W_P^N = \int_{\bar{\xi}}^{1} (\xi t - p) d\,\xi = \frac{t}{2}\left(1 - \bar{\xi}^2\right) - \left(1 - \bar{\xi}\right)p \qquad (14)$$

which, using the equilibrium values of $\bar{\xi}$, t and p presented in Proposition 1, can be written as

$$W_P^N = \frac{(1-c)^4}{32d} \qquad (15)$$

Thus, the total surplus turns out to be

$$W = W_P^N + \pi^N = \frac{(1-c)^4}{32d} + \frac{(1-c)^4}{32d} = \frac{(1-c)^4}{16d} \qquad (16)$$

When the sharing market is present, the aggregate welfare of prosumers is given by

$$W_P = \int_{\bar{\xi}}^{1} [\xi t + (1-\xi) tr\alpha - p] d\,\xi$$

$$= tr\alpha - p + \frac{(1 - r\alpha)t}{2} - (tr\alpha - p)\bar{\xi} - \frac{(1 - r\alpha)t}{2}\bar{\xi}^2$$

and the aggregate welfare of users is

$$W_U = \int_{0}^{\bar{\xi}} [\beta(\xi t - \xi tr)] d\,\xi = \frac{\beta t(1-r)}{2}\bar{\xi}^2$$

As we know, when the monopolist acts strategically, the equilibrium use price is equal to one, which implies that the users' surplus is always zero, but this is not necessarily so when the monopolist acts myopically.

Total economic surplus (or welfare) is the aggregation of prosumers, users and the monopolist surplus, that is:

$$W = W_P + W_U + \pi \tag{16}$$

where the second component is absent if no sharing market exists, and it is zero in the strategic monopolist case.

Figure 4 shows how the different components of economic welfare (profit, prosumers' surplus and users' surplus) and total economic surplus depend on the marginal cost parameter.

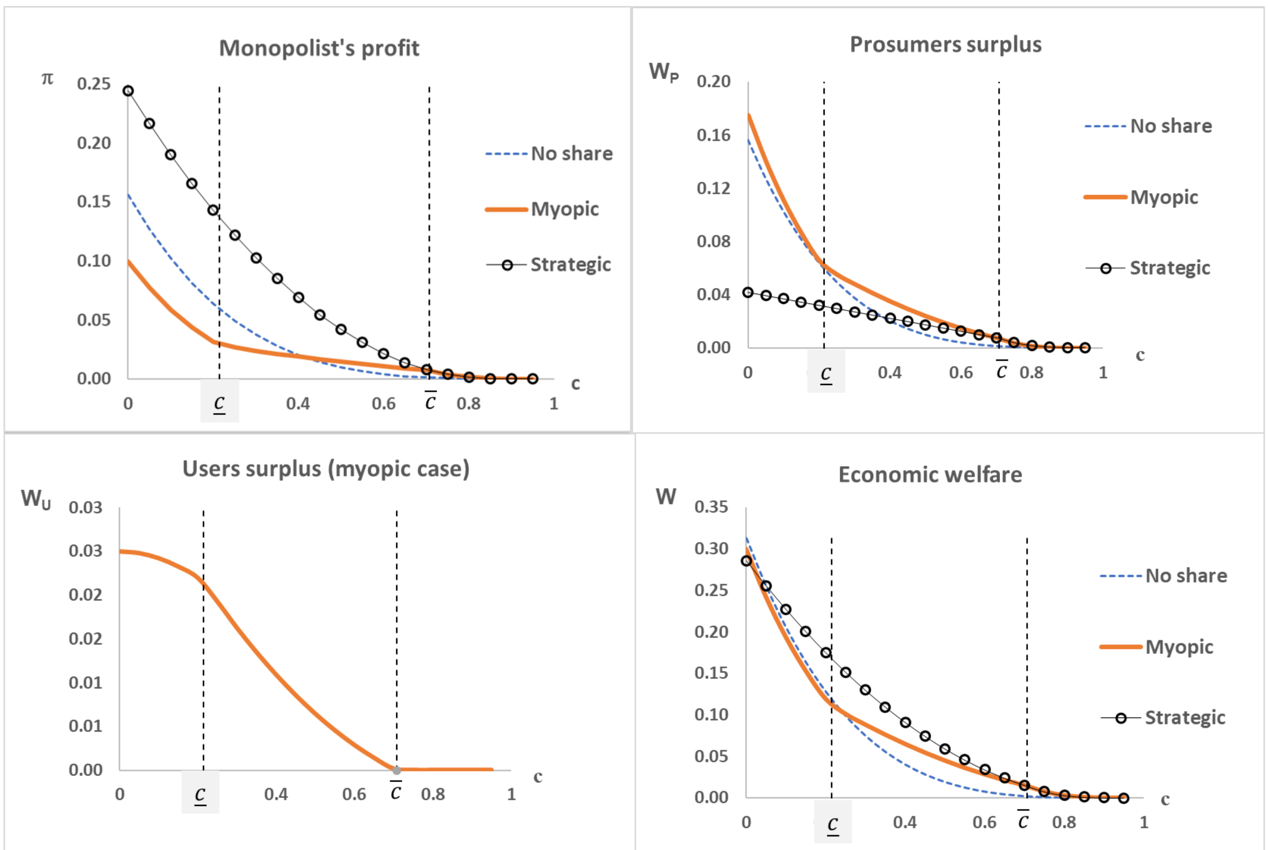

Figure 4: Components of economic welfare with $= 0.2, \alpha = 0.6, \beta = 0.2$.

The first graph in Figure 4 illustrates the fact that the monopolist can always benefit from the presence of the sharing market if it can use its decision variables to affect the use price in a strategic way. The sharing market is also beneficial for a myopic monopolist in the case of a sufficiently large use price, which arises if, in turn, the marginal cost parameter is large enough.

The second graph in Figure 4 shows that prosumers are clearly better-off with a myopic than with a strategic monopolist. Although the fact that $r = 1$ in the strategic case would benefit prosumers considerd on its own, the monopolist's distortions on the price and lifespan that are needed to induce such use price hurt prosumers in net terms. This fact is even more extreme in the case of users, who can only get a positive surplus in the myopic case (and only if $r < 1$). In the strategic case, the fact that $r = 1$ causes their utility to be always zero and, thus, their surplus is not displayed in Figure 4. The presence of strategic sharing can make prosumers even worse-off than with no sharing. Obviously, in the latter case, it is meaningless to talk about prosumers and users, as there would only be consumers.

Hence, the overall effect of a monopolist's strategic behavior on the economic component of welfare (as compared with the myopic case) is ambiguous since one agent (the monopolist) is better-off and the rest of the agents (prosumers and users) are worse-off. The last graph of Figure 4 shows that, in aggregate terms, the strategic behavior of the monopolist tends to improve efficiency in economic terms except for marginal cost values very close to zero. Therefore, there is a trade-off between efficiency and distribution: the strategic monopolist generates the largest aggregate surplus, but it also captures the largest share of these rents due to its market power. The same conclusion follows if one compares the aggregate surplus created in the strategic monopoly with the situation without a sharing market.

In view of these results, one can ask the general question if the mere presence of a sharing market is welfare-improving in economic terms or not. It turns out that the answer is not obvious and depends on how the monopolist behaves. We know that a strategic monopolist is always better-off than without a sharing market, but the result is not so straightforward if the monopolist is myopic, although the latter case is the most beneficial for users and prosumers.

5. Conclusions

In this paper, we have theoretically analyzed a situation where a good produced by a monopolistic firm is suitable to be shared in a perfectly competitive peer-to-peer sharing platform. This study contributes to a recent literature that uses theoretical economic models to investigate consumer, producer and/or platform decisions in peer-to-peer systems (e.g. Einav, 2016; Jiang and Tian, 2018; Benjaafar et al., 2019). Our main contribution to this literature is the joint consideration of price and lifespan decisions in the primary market, and the resulting effects on product output, use prices and use levels, all of which have effects on the economic and environmental components of welfare. We have considered the case where the monopolist can be myopic about its possible influence in the sharing market versus the case where the firm can choose its decision variables strategically. These situations can be understood as two different levels of market power (moderate and full) in the sharing market, which we have compared to the situation where the sharing market is absent.

As an important first conclusion, we have shown that the monopolist can benefit from the presence of a peer-to-peer sharing system under certain conditions. In principle, we may think that the presence of a sharing market could only harm the monopolist, due to the possible loss of clients that may instead opt to gain access to the good in the sharing market. However, *forward-looking* potential buyers of the good may experience an increase in their willingness to pay for the product if they anticipate that they can obtain rents by offering the product to others part-time. We find that the monopolist can benefit from the presence of the sharing market if the use price is sufficiently large. This is surely the case if the monopolist acts strategically since the firm can manipulate its decision variables (product price and lifespan) accordingly to induce the largest possible use price. But the monopolist can also benefit from the presence of the sharing market even if it acts myopically, provided that the conditions in the sharing market result in a sufficiently large use price.

Secondly, both prosumers and users are clearly better-off with a myopic than with a strategic monopolist. Actually, we can ensure that they are better-off if a sharing market exists, provided that the monopolist does not have the ability to manipulate the strategically the use price, i.e., if the market power is moderate. Otherwise, the monopolist's distortions on the price and lifespan to induce a large use price hurt prosumers in net terms and it may be the case that, in these conditions, prosumers are worse with than without a peer-to-peer sharing market. This conclusion is even stronger for users, who can only get a strictly positive surplus in the myopic case.

Thirdly, in terms of the strategic variables, both the product price and lifespan of the product are larger if the monopolist is strategic, compared to the other two scenarios. The presence of a sharing market induces the monopolist to make goods that are more expensive, but also last longer. However, this need not be the case if the monopolist is myopic. In this case, limiting the product lifespan can be used to minimize the impact of the sharing market on the monopolist's sales when it cannot strategically increase the use price to make the sharing market less attractive to users. This limited lifespan may induce a lower product price, as compared to the case without sharing.

Fourthly, as expected, the relative use of the good is higher with sharing, yet this does not necessarily imply a lower level of output and the opposite result can easily arise. One may expect a priori that using the good more intensively reduces the need to produce additional units of output. Nevertheless, the creation of the secondary market also intensifies the economic activity, prosumers are willing to pay more as a result of the potential rents they can extract by sharing the goods, and this second effect may ultimately prevail and give rise to a larger output level.

Finally, our main point is that the presence of a peer-to-peer sharing market need not improve environmental conditions. We have analyzed the implications related to three factors: lifespan of the product, total production, and use levels (in percentage terms). Regarding the first factor, we have seen that a strategic monopolist prefers to produce long-lasting products, while this is not necessarily the case if the firm acts myopically. While increased longevity decreases the externalities associated with disposal, it may simultaneously increase the externalities associated with the use phase. Regarding the second factor, the fact that the total quantity produced may be larger with sharing than without sharing is definitely problematic in environmental terms. Finally, the use levels, both in absolute terms, and as a percentage of the product lifespan are larger with sharing than without sharing, which will definitely increase the externalities associated with the use of the good. Our numerical results illustrate that there are many combinations of parameters for which the presence of sharing hurts the environment in all three components.

Our theoretical model can be considered as a benchmark scenario that may serve as a starting point to analyze other more realistic situations. A first extension would be to explore the working of the sharing market in more detail. For example, by exploring the relevance of network externalities. Second, the model we have presented is static, but some of the decisions made by the agents in our model take are actually dynamic. Although the exercise of developing a dynamic model is surely worthwhile on theoretical grounds, we do not think that our main conclusions are going to change much. Finally, adding (imperfect) competition in the primary market is worth exploring, since the ability to influence the use price, in this case, would be limited for an individual producer. All these extensions deserve further investigation.

Appendix

Proof of Lemma 1. We first assume that there is an interior solution. The equilibrium use price is determined by equalizing effective supply and effective demand. On the one hand, effective supply is α times potential supply, given in (9). Combining this equation with the analytical expression for $1-\bar{\xi}$, given in (6), we obtain:

$$S^E(p,r,t,\alpha,\beta)=\alpha\cdot t\left(\frac{\left(1-\bar{\xi}\right)^2}{2}\right)=\frac{\alpha\cdot t}{2}\left(\frac{t(1-\beta+r\beta)-p}{t[1-\beta+r(\beta-\alpha)]}\right)^2$$

On the other hand, effective demand is β times potential demand, given in (10). Combining this equation with the analytical expression for $\bar{\xi}$, given in (5), we obtain:

$$D^E(p,r,t,\alpha,\beta)=\beta\cdot t\left(\frac{\bar{\xi}^2}{2}\right)=\frac{\beta\cdot t}{2}\left(\frac{p-tr\alpha}{t[1-\beta+r(\beta-\alpha)]}\right)^2$$

We now impose the market clearing condition $S^E(p,r,t,\alpha,\beta)=D^E(p,r,t,\alpha,\beta)$, that is:

$$\frac{\alpha\cdot t}{2}\left(\frac{t(1-\beta+r\beta)-p}{t[1-\beta+r(\beta-\alpha)]}\right)^2=\frac{\beta\cdot t}{2}\left(\frac{p-tr\alpha}{t[1-\beta+r(\beta-\alpha)]}\right)^2$$

or, equivalently:

$$\sqrt{\alpha}[t(1-\beta+r\beta)-p]=\sqrt{\beta}(p-tr\alpha)$$

This expression can be rewritten as follows:

$$\left(\sqrt{\alpha}\beta+\alpha\sqrt{\beta}\right)tr=\left(\sqrt{\alpha}+\sqrt{\beta}\right)p-t(1-\beta)\sqrt{\alpha}$$

And solving this equation for r we obtain the expression for the interior solution case displayed in Lemma 1. By imposing the boundaries in this expression ($r\geq 0$ and $r\leq 1$) we respectively obtain the corner solution expressions displayed in the lemma.

Proof of Proposition 1. The first-order conditions with respect to the price and product lifespan are, respectively:

$$(w.r.p)\qquad 1-\frac{p}{t}-(p-ct)\frac{1}{t}=0;$$

$(w.r.t) \qquad \dfrac{p^2}{t^2} - c - dt = 0.$

From the first condition, we get $p = \frac{(1+c)t}{2}$ which, together with the second condition, results in $p^N = \frac{(1+c)(1-c)^2}{8d}$ and $t^N = \frac{(1-c)^2}{4d}$. Since $Q = 1 - \frac{p}{t}$, total production of the good is $Q^N = \frac{1-c}{2}$, and using the profit function, we get $\pi^N = \frac{(1-c)^4}{32d}$. Total use of the good (in percentage terms), is $RU^N = \frac{1-\bar{\xi}^2}{2Q} = \frac{1-(1-Q)^2}{2Q} = 1 - \frac{Q}{2} = 1 - \frac{1-c}{4} = \frac{3+c}{4}$.

Proof of Lemma 2. The first-order conditions of the monopolist's problem are as follows:

$$(w.r.p) \qquad \frac{(1-\beta+r\beta)}{[1-\beta+r(\beta-\alpha)]} - \frac{p}{t[1-\beta+r(\beta-\alpha)]} - \frac{p-ct}{t[1-\beta+r(\beta-\alpha)]} = 0$$

from which we easily obtain $p = \frac{t(1-\beta+r\beta)+ct}{2}$.

$$(w.r.t) \qquad -c\left\{\frac{(1-\beta+r\beta)}{[1-\beta+r(\beta-\alpha)]} - \frac{p}{t[1-\beta+r(\beta-\alpha)]}\right\} + (p-ct)\frac{p}{t^2[1-\beta+r(\beta-\alpha)]} - dt = 0$$

from which we get:

$$p^2 = ct^2(1-\beta+r\beta) + dt^3[1-\beta+r(\beta-\alpha)]$$

or equivalently:

$$\left(\frac{p}{t}\right)^2 = c(1-\beta+r\beta) + dt[1-\beta+r(\beta-\alpha)]$$

Combining this condition with the former one $p = \frac{t(1-\beta+r\beta)+ct}{2}$, we then find the monopolist's optimal choices displayed in the lemma.

Proof of Proposition 2. Assume first that we are in the interior region. From the proof of Lemma 2 we know $\frac{p}{t} = \frac{1-\beta+r\beta+c}{2}$, and using this expression in (11) we obtain:

$$r = \frac{1-\beta+r\beta+c}{2\sqrt{\alpha\beta}} - \frac{1-\beta}{\sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)}$$

from which we get $r^M = \frac{(1-\beta)(\sqrt{\beta}-\sqrt{\alpha})+c(\sqrt{\alpha}+\sqrt{\beta})}{\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta})(2\sqrt{\alpha}-\sqrt{\beta})}$.

Provided that $2\sqrt{\alpha}-\sqrt{\beta}>0$, we have $r^M \geq 0$ as long as $(1-\beta)\left(\sqrt{\beta}-\sqrt{\alpha}\right) + c\left(\sqrt{\alpha}+\sqrt{\beta}\right) \geq 0$, which is equivalent to $c \geq \frac{(1-\beta)(\sqrt{\alpha}-\sqrt{\beta})}{\sqrt{\alpha}+\sqrt{\beta}} \coloneqq \underline{c}$. In addition, $r^M \leq 1$ requires $(1-\beta)\left(\sqrt{\beta}-\sqrt{\alpha}\right)+c\left(\sqrt{\alpha}+\sqrt{\beta}\right) \leq \sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)\left(2\sqrt{\alpha}-\sqrt{\beta}\right)$, which is equivalent to $c \leq \frac{\sqrt{\alpha}-(1-2\alpha)\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}} \coloneqq \overline{c}$. If these two conditions hold, we can substitute the obtained expression for r^M into the optimal monopolistic choices presented in Lemma 2 and rearrange to get the expressions given in the proposition. These equilibrium expressions can be substituted in the demand expression (6) to obtain $Q^M = \frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$.

If one of the two conditions does not hold, we are in a corner solution. In the case where $c \leq \underline{c}$, we have $r^M = 0$. To obtain the remaining equilibrium variables in this case, we simply substitute $r^M = 0$ in expressions (12) and (13), which result in $p^M = \frac{[1-\beta+c][1-\beta-c]^2}{8d(1-\beta)}$ and $t^M = \frac{(1-\beta-c)^2}{4d(1-\beta)}$. All these expressions can then be substituted in (6) to get the equilibrium quantity $Q^M = \frac{1-\beta-c}{2(1-\beta)}$.

Next, if $c \geq \overline{c}$, we then have $r^M = 1$. Hence, we substitute it in expressions (12) and (13) to obtain $p^M = \frac{(1+c)(1-c)^2}{8d(1-\alpha)}$ and $t^M = \frac{(1-c)^2}{4d(1-\alpha)}$. Using expression (6), we further obtain $Q^M = \frac{1-c}{2(1-\alpha)}$.

Proof of Lemma 3. To see the effect of the use price on the monopolistic profits, we can write:

$$\pi(r) = \left(p(r) - ct(r)\right)Q(p(r), t(r), r) - \frac{d}{2}\left(t(r)\right)^2$$

By the envelope theorem, the effect of the use price on the monopolist's profits is:

$$\frac{d\pi(r)}{dr} = \left(p(r) - ct(r)\right)\frac{\partial Q}{\partial r}.$$

To see whether the sign of $\frac{\partial Q}{\partial r}$ is positive or negative, we plug expressions (12) and (13) in expression (6), to obtain $Q = \frac{t(1-\beta+r\beta)-p}{t[1-\beta+r(\beta-\alpha)]} = \frac{(1-\beta+r\beta)-c}{2[1-\beta+r(\beta-\alpha)]}$. From this expression, we can easily obtain $\frac{\partial Q}{\partial r} = \frac{\alpha(1-\beta)}{2[1-\beta+r(\beta-\alpha)]^2} > 0$. Hence, the monopolist's profit is strictly increasing in the use price.

Proof of Proposition 3. We start by analyzing the case $r^M = 0$ (first case in Proposition 2), where we can easily get $\pi^M = \frac{(1-\beta-c)^4}{32d(1-\beta)^2}$. Since $\pi^N = \frac{(1-c)^4}{32d}$ (Proposition 1), we then have $\pi^M < \pi^N$ for any $\beta > 0$. Next, we look at the case $r^M = 1$ (third case in Proposition 2), where the monopolistic profits are now $\pi^M = \frac{(1-c)^4}{32d(1-\alpha)^2}$. Since $\pi^N = \frac{(1-c)^4}{32d}$, we now have $\pi^M > \pi^N$ for any $\alpha > 0$. Consequently, given $c \geq 0$, there must be a threshold value of $r \in (0,1)$ (critically influenced by α and β, and provided that $\beta < 1$) beyond which the existence of the sharing market is beneficial for the monopolist, since we have shown before in Lemma 3 that the monopolist's profits are increasing in the use price.

Proof of Proposition 4. Comparing the expressions for lifespan, we conclude that that $t^N > t^M$ if $c \leq \underline{c}$ and $t^M > t^N$ if $c \geq \overline{c}$. Thus, by continuity, t^N and t^M must cross in the $(\underline{c}, \overline{c})$ interval an odd number of times. Using the relevant expressions for the interior region and rearranging, we conclude that

$$t^M \geq t^N \Leftrightarrow \Phi(c) \coloneqq 4\sqrt{\beta}[\alpha(1-\beta-c)+c\beta] - (1-c)^2\left(\sqrt{\alpha}+\sqrt{\beta}\right)^2\left(2\sqrt{\alpha}-\sqrt{\beta}\right) \geq 0$$

The previous inequality gives rise to a second-order equation in c, which may have, at most, two real roots such that $\Phi(c) = 0$ in the relevant range $(\underline{c}, \overline{c})$, but since we know that there is an odd number of crossings in the relevant region we conclude that there must exist one single value $c_t \in (\underline{c}, \overline{c})$ *such that* $\Phi(c_t) = 0$ *and thus* $t^M \leq t^N$ *if and only if* $c \leq c_t$.

When a sharing market exists, relative use levels are given by (14), where the boundary value 1 may only arise in the corner $c > \overline{c}$ region. By plugging in (14) the relevant expression for Q^M when

$c \leq \underline{c}$ from Proposition 2, comparing to the expression for RU^N in Proposition 1, and rearranging, we conclude that, in this range,

$$RU^M > RU^N \Leftrightarrow 8(1-\beta) - 2(1-\beta+c)^2 > 2(3+c)(1-\beta+c) \Leftrightarrow 1-\beta+c > 0$$

and the latter inequality always holds for any admissible parameter combination.

Using the interior region expression for Q^M from Proposition 2 in (14), comparing to the expression for RU^N from Proposition 1 and rearranging, we conclude that

$$RU^M \geq RU^N \Leftrightarrow c \leq \frac{2\beta\left(\sqrt{\alpha}+\sqrt{\beta}\right)\left(\sqrt{\alpha}+\sqrt{\beta}\right) - 2\beta + 2\beta^2 + (1-4\beta)\sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)}{\sqrt{\beta}\left(\sqrt{\alpha}+\sqrt{\beta}\right)}$$

where it can be shown that the right-hand side of the last inequality is equal to $\overline{c}$, and therefore the inequality always holds in the interior solution range with equality at the point $c = \overline{c}$.

Finally, if $c \geq \overline{c}$, taking the relevant value for Q^M in Proposition 2 and rearranging, we conclude that the relative use in this range is given by

$$RU^M = min\left(1, \frac{4(1-\alpha)^2 - (1-\beta)(1-2\alpha+c)^2}{4(1-c)(1-\alpha)}\right).$$

When this expression is larger than one, which happens if c is large enough, it is clearly the case that $RU^M = 1 > RU^N = \frac{3+c}{4}$. When it is smaller than one, straight-forward calculations show that

$$RU^M \geq RU^N \Leftrightarrow \frac{4(1-\alpha)^2 - (1-\beta)(1-2\alpha+c)^2}{4(1-c)(1-\alpha)} \geq \frac{3+c}{4}$$

$$\Leftrightarrow -(1-\beta)(1-2\alpha+c)^2 \geq \alpha(1-c)^2$$

$$\Leftrightarrow \ c \geq \frac{\sqrt{\alpha} - (1-2\alpha)\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}} = \overline{c}$$

which always hold in the third solution interval, with equality if $c = \overline{c}$ and with strict inequality at $c > \overline{c}$.

Finally, we compare the quantities under no sharing and the myopic case. By comparing the relevant expressions in Propositions 1 and 2, it is straightforward to conclude that $Q^N > Q^M$ if $c <$

$\underline{c}$ and $Q^M > Q^N$ if $c > \bar{c}$. By comparing the expressions in the interior region we conclude that $Q^M > Q^N$ as long as $c > \frac{\sqrt{\alpha}-\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$, which clearly belongs to the $(\underline{c}, \bar{c})$ interval.

Proof of Proposition 5. Since the profit of the monopolist is increasing in the use price, r, we know that the strategic monopolist will choose the value of its decision variables in such a way that this variable will attain its maximum feasible value $r = 1$. Nevertheless, according to expression (11), this value can be achieved in two different situations: as the limiting case of an interior solution, which happens when $\frac{p}{t} = \frac{\sqrt{\alpha}(\sqrt{\alpha\beta}+1)}{\sqrt{\alpha}+\sqrt{\beta}}$, or in a corner solution with $\frac{p}{t} > \frac{\sqrt{\alpha}(\sqrt{\alpha\beta}+1)}{\sqrt{\alpha}+\sqrt{\beta}}$. In the latter case, the use price achieves a constant value of 1 and is not responsive anymore to changes in the monopolist's decision variables. In this range, the problem of the strategic monopolist is exactly the same as that of a myopic monopolist. According to Proposition 2, this case is relevant when $c \geq \bar{c}$.

Let us consider now the interior case. Since the monopolist takes into account the market clearing condition in the sharing market and how the choice variables p and t affect the use price, the firm can infer that the product market demand, in this case, is inelastic (i.e., independent of the price and the lifespan) and given by $Q = \frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}$ (see our discussion in footnote 9). Hence, the problem becomes

$$\max_{p,t}(p - ct)\left(\frac{\sqrt{\beta}}{\sqrt{\alpha} + \sqrt{\beta}}\right) - \frac{d}{2}t^2$$

$$s.t. \quad \frac{p}{t\sqrt{\alpha\beta}} - \frac{1-\beta}{\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta})} = r = 1$$

The constraint of this problem can be written as $p = K \cdot t$, with $K = \sqrt{\alpha\beta}\left(1 + \frac{1-\beta}{\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta})}\right) = \frac{\sqrt{\alpha}(\sqrt{\alpha\beta}+1)}{(\sqrt{\alpha}+\sqrt{\beta})}$, which is a linear relationship between the price and the lifespan.

Hence, the optimization problem can be written as:

$$\max_t (K-c)t\left(\frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}\right)-\frac{d}{2}t^2$$

from which we get the first order condition $(K-c)\left(\frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}\right)-dt=0$, which results in:

$$t^S=\frac{K-c}{d}\left(\frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}\right)$$

Since $p=K\cdot t$, we further have:

$$p^S=\frac{K(K-c)}{d}\left(\frac{\sqrt{\beta}}{\sqrt{\alpha}+\sqrt{\beta}}\right)$$

Plugging the expression for K into $t^S$and p^S and rearranging we get the expressions in the proposition.

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