Business Model Choice for Heavy Equipment Manufacturers

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Technological advances enable new business models for heavy equipment manufacturers wherein customers access equipment without ownership. We seek to understand the profitability and environmental performance of different emerging business models in light of salient economic and operational factors. We develop a game-theoretic model to identify the optimal choice between a traditional ownership-based business model and two access-based models: servicization and peer-to-peer sharing. After-sales services, equipment characteristics, usage environments, and fuel prices affect this choice. We also provide a novel framework to analyze business models' environmental impact, which incorporates trade-offs between economic value and environmental costs and shows that all models may create win-win situations for the manufacturer and the environment.

Key words: business model innovation; environmental impact; sharing economy; after-sales; durable goods

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1. Introduction

Firms must make critical decisions about their business models: how they provide products to customers and capture the resulting value (Kaplan 2012). New technologies like the Internet of Things (IoT) and online marketplaces enable novel business models by seamlessly measuring usage and matching supply and demand. Thus, firms can provide an asset as a service (Rymaszewska et al. 2017), charging customers only for actual use. New technologies are also central to the emergent sharing economy in which "peers" provide products to others via sharing platforms (Benjaafar et al. 2019). Such platforms match owners of idle assets with non-owners seeking access in customer-to-customer (e.g., Getaround) and business-to-business (e.g., Yard Club) settings.

In light of this trend, we investigate the business model choice of a *heavy equipment* manufacturer. Traditionally, heavy equipment manufacturers rely on business models combining sales and after-sales services (SA). However, they increasingly turn to new models based on servicization (SV) or sharing platforms (SP). This paper aims to further our understanding of how a manufacturer should design and choose between different business models to benefit from novel ways of equipment use. At the same time, we consider the environmental impact of the manufacturer's choices.

We focus on the heavy equipment industry because it is a highly concentrated industry with enormous economic significance—the construction equipment market alone was valued at US$ 196B in 2021 (Chinchane and Mutreja 2023). More importantly, the heavy equipment industry's *unique characteristics* lead to significantly different insights than those found in the extant literature on sharing and servicization and therefore allow us to add to the existing theory.

First, manufacturers heavily rely on *after-sales services*—activities to maintain and repair equipment—for revenues. They generate up to 60% of their revenues in the after-sales market (Allied Market Research 2022), averaging 2.5 times the margins of new equipment sales (Ambadipudi et al. 2017). Second, the industry is an early adopter of access-based business models in the form of servicization, which is used by all major manufacturers.[1] The leading heavy equipment manufacturer, Caterpillar also has acquired the sharing platform Yard Club, where equipment owners and dealers provide usage to non-owners (Lawler 2017). Third, the industry is experiencing increasing pressures to adapt in reaction to environmental concerns (Nosratabadi et al. 2019).

The trade-offs when choosing between business models are complex. An ownership-based model (SA) allows a manufacturer to extract revenues from sales and after-sales but excludes customers with low usage requirements. On the other hand, servicization (SV) and sharing (SP) enable pooling demand so that these customers can be included profitably in the market, but only if demand and supply are matched effectively. With SV, the manufacturer directly controls the availability of equipment accessed by non-owners. Because providing this form of access is generally costly, it must strike a balance between owners and non-owners. With SP, non-owners access owners' equipment, increasing the potential for pooling. On the other hand, the manufacturer needs to induce owners to supply access. This implies that after-sales fees charged by the manufacturer are limited: Charging higher fees would disincentivize owners from increasing utilization by sharing their equipment. Overall, the three business models all bring advantages and disadvantages, and there is no obvious strategy to select from them. Similarly, it is difficult to directly infer the impact of different business model choices on the environment: Access-based models lead to higher overall usage due to price segmentation but may lead to lower production quantities due to pooling.

We provide an analytical model that helps managers derive actionable insights around the optimal design and choice of business models. We find that SA, SV, and SP can all be optimal, depending on the production and after-sales service costs. We then relate combinations of these factor for which each business model is optimal to prototypical equipment types and usage environments.

We further analyze how a change in fuel prices affects this choice: A recent rise has drastically threatened heavy equipment customers' profitability and intensified discussions around electrification (Chergui 2023). Our results show that SP becomes less relevant as fuel costs increase and more relevant with electrification, associated with lower energy but higher manufacturing costs.

Moreover, we answer whether the manufacturer's choice benefits the environment. We extend the literature assessing the impact of individual access-based models compared to ownership-based ones by comparing SP with SV. We find that enabling sharing is environmentally beneficial if it leads to a switch away from SV. This approach to analyzing the environmental impact considers a manufacturer's prior business model as the benchmark. We additionally introduce a benchmark that accounts for the environmental and overall economic impact of business activities to deduce a socially acceptable level of the latter. We find that the manufacturer, choosing a business model based on profits, does not always have a higher environmental impact than this benchmark: Its impact could be lower with multiple business models and, under SP, the manufacturer may inadvertently induce the same market behavior (and environmental impact) as the benchmark.

Our key findings persist when considering secondary markets, which have not been studied in the servicization or sharing context. While secondary markets subtly impact business model design, they do not qualitatively affect the choice between models or their environmental impact.

In sum, our paper contributes to an emerging literature on novel business models. We provide a holistic view by studying multiple models simultaneously. Incorporating after-sales, secondary markets, and endogenous service levels allows us to both test the robustness of results and provide new insights. We also extend environmental impact analyses by studying the choice between servicization and sharing as well as providing a comparison of two different benchmarks. We hope this comparison sparks explorations for a broader environmental analysis of business models.

2. Literature review

Our work is related primarily to the emerging literature studying business models from an economic and environmental perspective. It also draws on the durable goods literature.

Servicization is more established in the literature on access-based business models, with choices such as the service region (He et al. 2017), product efficiency (Agrawal and Bellos 2017, Bellos et al. 2017), durability (Örsdemir et al. 2019), and cost accounting (Ladas et al. 2022) analyzed. While traditionally focused on profit-maximization (e.g., Toffel 2008), authors are increasingly concerned with the environmental impact of the business model (e.g., Örsdemir et al. 2019).

We use some of the modeling approaches as outlined in the model discussion. In contrast to the existing literature, we consider the specific context of heavy equipment and the critical role after-sales services play (see, e.g., Dombrowski and Malorny 2014). We also endogenize the service level: while customer segmentation remains similar to the prior literature, customer density affects prices. The business model choice also differs, e.g., after-sales services reduce the potential of servicization.

In contrast to servicization, product sharing enables access to equipment owned by other customers rather than the manufacturer. This difference is important—only accessing customers are affected by servicization, while sharing also affects owners. Sharing is enabled by peer-to-peer marketplaces, or *sharing platforms*. A recent stream of literature focuses on the impact of sharing on market outcomes (Fraiberger and Sundararajan 2017, Jiang and Tian 2018, Benjaafar et al. 2019, Benjaafar and Pourghannad 2019, Filippas et al. 2020), supply chains (Tian and Jiang 2018), the (financial) performance of sharing platforms (Benjaafar et al. 2019, 2022), and the strategic options a firm may pursue (Abhishek et al. 2021). Benjaafar and Hu (2020) provide an overview and outline key questions, while Chen et al. (2020) describe additional research opportunities.

Again, we draw on some of the modeling ideas but extend the inquiry into after-sales services. Notably, when these are sufficiently beneficial, the manufacturer might lower its equipment price after the introduction of sharing, contrary to the price increase observed without after-sales services.

Our work compares a range of business models rather than comparing only servicization or sharing with an ownership-based model. The literature shows that servicization is ineffective when production costs are high (Ladas et al. 2022). We add that sharing fills a gap by allowing equipment pooling when production costs are high, and pooling is most desirable. Benjaafar et al. (2019) and Abhishek et al. (2021) also address differences between the two access-based models. However, the former do not take the manufacturer's perspective, while the latter do not endogenize matching frictions. Chen et al. (2020) consider search and matching frictions an important risk factor that may lead to sharing platform failure. Hence, we make matching mechanisms comparable across models and show that the impact of frictions differs between sharing and servicization.

Adding to previous analyses, we also link optimality regions with different types of equipment and usage environments encountered in practice. We further include an analysis of how the business model choice is affected by rises in fuel prices and electrification, allowing us to contribute to an important discussion in practice. Finally, we expand the analysis of business models' environmental impact, finding that a move from a world of ownership-based models and servicization (as is mostly the case in heavy equipment up to now) to one with sharing means that environmental impacts are reduced exactly when manufacturers prefer to replace servicization by sharing. We also derive a novel framework to assess business models' environmental impact by considering a benchmark trading off economic value and environmental costs. This is in line with the perspective of a regulator and extends our understanding of the role novel business models play in enabling more sustainable operations—an open research question highlighted by Agrawal et al. (2019).

Finally, we draw on the durable goods literature to model after-sales services and secondary markets, which have so far not been considered in the context of sharing and servicization. After-sales services are studied extensively due to their profitability and increasing importance for manufacturers (e.g., Durugbo 2020, identify 249 articles between 1970 and 2018). This includes analyses of inventory management (Alptekinoğlu et al. 2013), service differentiation (Guajardo and Cohen 2018), contracting (Bakshi et al. 2015), and technology adoption (Kundu and Ramdas 2022). Research increasingly examines the role of the Internet of Things (IoT) in enabling condition monitoring and preventative maintenance (Olsen and Tomlin 2020, Li and Tomlin 2022). We take into account the manufacturers' competitive benefits from IoT, but abstract from the details of after-sales service delivery. This allows us to model the broad impact of after-sales service profitability on the business model choice through implicit shifts in production and usage patterns. Secondary markets (Anderson and Ginsburgh 1994, Chen et al. 2013) also impact business model design: We find that the manufacturer may incentivize servicization or sharing to avoid their emergence.[2]

3. Model

This section develops the mathematical model, introducing the different actors and the sequence of events. Table 1 at the end of the section summarizes the notation.

Heavy equipment manufacturer. We consider a profit-maximizing heavy equipment manufacturer producing equipment at marginal cost γ in one of infinitely many periods of unit length. Equipment has one usage period in which it can generate revenues at rate 1 if it is maintained to avoid deterioration. In particular, if the equipment is used for a fraction θ of the period, maintenance (or "after-sales") at cost $\kappa\theta$ retains the rate of revenue generation of 1, where $\kappa < 1 - \gamma$. Without maintenance, the revenue generation rate drops to $\nu < 1$. When we turn to the manufacturer's environmental impact (Section 5), we assume that the production of one equipment unit has an environmental cost e_p, while equipment usage for one period has an environmental cost e_u.

Customers and equipment usage. There are $n \geq 2$ risk-neutral profit-maximizing customers. We normalize the market size to 1 for intuitive illustrations, so n can be interpreted as the market density. Customers are heterogeneous in the available business opportunities: A customer's type, or *usage requirement*, θ, indicates the percentage of a period they can generate revenue with the equipment. We assume that θ is period-invariant and follows a uniform distribution on $[0,1]$, this distribution is common knowledge but each customer's usage requirement is private information.

Customers can obtain equipment usage in three ways. First, they may buy equipment at a price p from the manufacturer and use it as required. For maintenance, they pay m per unit of usage. Second, if the manufacturer servicizes the equipment, they can access it for u per unit of usage. Third, if the manufacturer sets up a sharing platform, they can access other customers' equipment for r per unit of usage.[3] We normalize customers' outside options to zero.

To provide access to non-owners, the provider (the manufacturer in the case of servicization or an equipment owner in the case of sharing) incurs inconvenience costs μ per unit of usage. The manufacturer sets the prices u and r, the sharing platform commission c, and the quantity S_{SV} of servicized equipment. As a result of these choices, there is a demand D and supply S for access-based usage. A percentage $\phi = \frac{n}{n+1}\min\{1, S/D\}$ of each customer's access demand is met in equilibrium. The functional form of this *service level* ensures mismatches are less severe when supply is sufficient ($S \geq D$) and when the market is more dense (high n).

Sequence of events. The manufacturer determines the available options and prices, while customers discover their type, θ. Then, at the start of each period, customers decide whether to buy (and possibly maintain) equipment, access it through servicization or sharing, or abstain. As a result of these decisions, an equilibrium service level emerges. We denote the manufacturer's steady-state per-period profit with Π and customer θ's steady-state per-period profit with π_θ.

3.1. Model discussion

A significant share of heavy equipment manufacturers' profits stems from after-sales activities such as maintenance (Cohen et al. 2006, Chinchane and Mutreja 2023). We make two assumptions regarding these activities. First, the manufacturer exclusively performs maintenance. This is based on the increasing prevalence of IoT technologies within equipment enabling significant advantages in manufacturer-led predictive and preventive maintenance (Corner 2017, Li and Tomlin 2022) and other advantages stemming from intellectual property rights, proprietary diagnostic tools, or exclusive access to software (Wiens 2018, Shah 2019). Second, to emphasize that heavy equipment is too costly to use without maintenance, we assume that $\nu < \gamma/2$.[4] Indeed, 70-100% of industrial equipment sold directly to customers is combined with service contracts (Ambadipudi et al. 2017).[5]

A key difference between sales and after-sales is the dependence on usage: While the profitability of a sale is not affected by the eventual usage, the need for after-sales services is. Therefore, we emphasize insights that follow from differences in utilization and resulting differences in after-sales requirements. Hence, as in the case of Benjaafar et al. (2019), we assume customer heterogeneity is reflected in the usage requirement rather than the rate of revenue generation.

Heterogeneity in usage requirements also drives interest in new access-based business models (Örsdemir et al. 2019). While such models can help fulfill the demand of low usage customers, they imply administrative and operational costs, such as from contracting, insurance, and equipment relocation. Our discussions with experts reveal that logistical challenges of providing equipment access can be significant. We capture this by restricting the per-period cost μ to $(\nu, 1)$. The value ν provides a useful lower bound, because it implies that it is not economical to provide equipment for access in a second usage period, when we extend our model to the case of secondary markets. A smaller value of μ would also render a traditional ownership-based business model obsolete even for small values of n, even though it is widely observed in practice.

The impact of matching frictions on access-based business models is captured by $\phi(S, D, n)$. Our functional form ensures consistency of matching dynamics with queueing approximations in the servicization literature (Bellos et al. 2017). At the same time, its relative simplicity enables us to endogenize the service level. To simplify exposition, we also assume that $n > \frac{1-\kappa-2\gamma-\mu}{2\gamma}$.[6]

In the case of sharing, the manufacturer profits from customers accessing the equipment through the sharing platform with a commission. In practice, the commission is commonly a fixed percentage of the sharing price (Hu 2021). For simplicity, we define the commission c as a price per unit of usage time, corresponding directly to a percentage fee in equilibrium.

Table 1 Decision, equilibrium outcome, and parameter notation.

Decision	Description
p	equipment sales price
m	maintenance fee
u	per-usage price of servicization
r	per-usage price of shared equipment
c	sharing platform commission
S_{SV}	equipment supplied for servicization

Outcome	Description
$\phi \in [0,1]$	service level of servicization and sharing
$\eta \in [0,1]$	utilization of servicized or shared assets
$D \in [0,1]$	demand for access-based usage
$S \in [0,1]$	supply of access-based usage
$p_s \geq 0$	secondary market price

Parameter	Description
$\gamma \geq 0$	equipment production cost
$\kappa \geq 0$	cost of after-sales services
$\nu \in [0, \gamma/2)$	usage value of unmaintained equipment
$\mu \in (\nu, 1)$	per-usage cost to provide access
$n \geq 2$	customer density
$\theta \in [0,1]$	required usage, with cdf $F(\cdot)$ and pdf $f(\cdot)$
$e_p \geq 0$	environmental cost of production
$e_u \geq 0$	environmental cost of usage

Note. Outcome η (resp. p_s) is introduced in Section 4.3 (resp. Section 6).

We initially assume equipment has a single usage period. We relax this assumption in Section 6, but note that the base case corresponds to a practical scenario where target customers prefer to buy the newest equipment version, for example, due to efficiency considerations or to stay within the warranty period (Caterpillar 2016). After the main usage period, the equipment may be sold to an entirely different group of customers (e.g., customers in developed markets might sell old equipment to emerging markets; Digvijay and Mutreja 2022, TechNavio 2022). In other cases, old equipment remains relevant for target customers and is traded on secondary markets. We characterize how the possibility of secondary markets affects the manufacturer's business models. While an analytical comparison of business models is intractable in this case, an exhaustive numerical search over the parameter space shows that the critical insights regarding such a comparison remain unchanged.

Finally, we adopt the notion of rational expectations (Muth 1961)—that customers correctly anticipate the service level to achieve equilibrium outcomes—which is frequently applied in the operations literature (see, e.g., Su and Zhang 2008) and found in the context of sharing (e.g., Abhishek et al. 2021). As the latter authors, we also consider only static equilibria. Consequently, optimizing per-period profits and the net present value over an infinite horizon are equivalent.

4. The manufacturer's business model choice

We derive the optimal design of each business model before comparing them.[7] In doing so, we highlight both the similarities and differences arising from the heavy equipment context with the extant literature on each business model. Proofs for this section are found in Appendix B.

4.1. An ownership-based business model: Sales and after-sales (SA)

In a traditional business model where the manufacturer sells equipment and provides after-sales services, a customer θ may follow one of three strategies in equilibrium:

- $d_\theta = O$: Buy new equipment at the start of the period, then use it without maintenance.
- $d_\theta = M$: Buy new equipment at the start of the period, then use it with maintenance.
- $d_\theta = A$: Abstain.

We assume, wlog, that indifferent customers prefer M to O, and M or O to A.

The manufacturer profits from equipment sales (net of production costs) to customers following O or M and from maintenance fees (net of maintenance costs) for customers following M:

$$\Pi^{SA} = \max_{p,m\geq 0} \int_0^1 \mathbb{1}_{\{d_\theta = O\}}[p-\gamma] + \mathbb{1}_{\{d_\theta = M\}}\left[p-\gamma+(m-\kappa)\theta\right] d\theta.$$

Lemma 1. *The manufacturer maximizes its profit from the SA business model by inducing customers $\theta \in [0, \theta_1)$ to abstain and customers $\theta \in [\theta_1, 1]$ to buy and maintain the equipment. The threshold and profit, respectively, are $\theta_1^{SA} = \frac{\gamma+\nu}{1-\kappa+\nu}$ and $\Pi^{SA} = \frac{(1-\kappa-\gamma)^2}{2(1-\kappa+\nu)}$.*

The manufacturer subsidizes sales to generate maintenance revenues, with the sales price decreasing as maintenance margins increase. There are more purchases than if customers were to obtain maintenance in a competitive market. These observations align with anecdotal evidence that manufacturers incur losses on equipment sales, relying on the after-sales market for profits. Indeed, some manufacturers generate more than half of their revenue from high-margin after-sales services (Allied Market Research 2022). However, the extent of value extraction through after-sales services is limited because buyers can still obtain revenues with unmaintained equipment.

4.2. An established access-based business model: Servicization (SV)

The manufacturer may retain ownership of some equipment and charge its customers a price u per unit of usage. Customers may still buy the equipment for price p and choose to obtain maintenance at per unit price m. A customer θ may thus follow one of the strategies from before or:

- $d_\theta = \tilde{R}$: access maintained equipment through servicization.

We assume that, wlog, $\tilde{R}$ is preferred to M, O, and A. Due to the inconvenience cost incurred by servicizing the equipment, it is easy to see that any servicized equipment must be maintained.

The manufacturer profits from sales to customers O and M, and maintenance for customers M, as in the case of SA. In addition, it profits from providing usage to customers following $\tilde{R}$ through the per-usage price but needs to pay for inconvenience and maintenance costs. Moreover, the manufacturer pays for the production of equipment required to fulfill this usage:

$$\Pi^{SV} = \max_{p,m,u,S_{SV}\geq 0} \int_0^1 \Big(\mathbb{1}_{\{d_\theta=O\}}[p-\gamma] + \mathbb{1}_{\{d_\theta=M\}}\left[p-\gamma+(m-\kappa)\theta\right]$$
$$+ \phi \mathbb{1}_{\{d_\theta=\tilde{R}\}}\theta\left[u-\kappa-\mu\right] \Big) d\theta - S_{SV}\gamma,$$

where $\phi = \frac{n}{n+1}\min\left\{1, \frac{S_{SV}}{\int_0^1 \mathbb{1}_{\{d_\theta=\tilde{R}\}}\theta d\theta}\right\}$ is the equilibrium service level of the servicization market.

In presenting the optimal strategy of the manufacturer, we assume that $\frac{n}{n+1}(1-\kappa-\mu) > \gamma$. This is without loss of generality: If the condition did not hold, matching frictions and inconvenience costs would be too high to justify servicization, and SA would be preferred to SV.

Lemma 2. *The manufacturer maximizes its profit from the SV business model by inducing customers $\theta \in [0, \theta_1]$ to access the equipment through servicization and customers $\theta \in (\theta_1, 1]$ to buy and maintain the equipment. The threshold and profit, respectively, are $\theta_1^{SV} = \frac{\gamma+\nu}{1-\kappa+\gamma+\nu-\frac{n}{n+1}(1-\kappa-\mu)}$ and $\Pi^{SV} = \frac{1}{2}\left[1-\kappa-2\gamma-\nu+\frac{(\gamma+\nu)^2}{1-\kappa+\gamma+\nu-\frac{n}{n+1}(1-\kappa-\mu)}\right]$.*

By pooling customers' usage, servicization allows the manufacturer to provide access to low-usage customers profitably. The extent of servicization crucially depends on μ and n: A higher inconvenience cost μ reduces the profitability of such customers. In contrast, a higher customer density n means the manufacturer can provide the same usage for access with fewer units of equipment due to reduced frictions. It follows that the manufacturer decreases (resp. increases) its sales price as μ (resp. n) increases in order to shift the threshold θ_1^{SV} lower (resp. higher). A crucial difference to the existing servicization literature (e.g., Bellos et al. 2017) is the endogenization of the service level, which leads to the equipment price increasing in the customer density.

4.3. A novel access-based business model: Sharing platform (SP)

Finally, the manufacturer may establish a sharing platform for its customers. Aside from sales and maintenance prices, the manufacturer chooses the per-usage price of shared equipment r and the commission of the platform c. Based on the manufacturer's prices, customers form expectations about the equilibrium service level ϕ. A customer θ may follow a strategy from the SA model or:

- $d_\theta = R$: access maintained equipment through the sharing platform.

We assume, wlog, that indifferent customers prefer R to other strategies. A customer θ owning the equipment may further choose to generate additional income by sharing it for a percentage of time $y_\theta \in [0, 1-\theta]$. We assume that frictions in the sharing market affect all equipment owners proportionally. That is, if the total supply of usage for access is S and the fulfilled demand is ϕD, buyers sharing (maintained) equipment obtain $y_\theta \eta(r - m - c - \mu)$, where $\eta = \frac{\phi D}{S}$. As in the case of SV, it is easy to show that access is limited to maintained equipment due to the associated inconvenience cost. That is, a customer following strategy O never shares their equipment.

The manufacturer profits from sales to customers O and M, and maintenance for customers M, as in the case of SA. In addition, it profits from the usage provided to customers following R in two ways: through the commission of the sharing platform and (indirectly) the additional maintenance fees borne by the owners of the shared equipment. The definition of ϕ guarantees the equivalence $\int_0^1 \mathbb{1}_{\{d_\theta = M\}} y_\theta d\theta = \phi \int_0^1 \mathbb{1}_{\{d_\theta = R\}} \theta d\theta$ in equilibrium. Hence, we can write

$$\Pi^{SP} = \max_{p,m,c,r \geq 0} \int_0^1 \left(\mathbb{1}_{\{d_\theta = O\}} [p - \gamma] + \mathbb{1}_{\{d_\theta = M\}} [p - \gamma + (m - \kappa)\theta] + \phi \mathbb{1}_{\{d_\theta = R\}} (c + m - \kappa)\theta \right) d\theta.$$

LEMMA 3. *The manufacturer maximizes its profit from the SP business model by inducing customers $\theta \in [0, \theta_1]$ to access the equipment through the sharing platform and customers $\theta \in (\theta_1, 1]$ to buy and maintain the equipment. The threshold and profit, respectively, are*

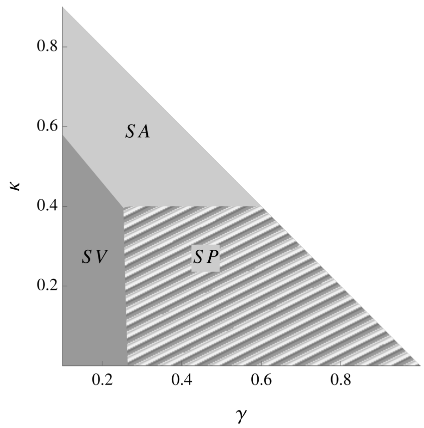
$$\theta_1^{SP} = \begin{cases} \frac{(2n+1)\mu - n(1-k-\gamma)+\gamma}{1-\kappa+(2n+1)\mu}, \\ 1/2, \end{cases} \quad \textit{and} \quad \Pi^{SP} = \begin{cases} \frac{(n+1)(1-\kappa-\gamma)^2}{2(1-\kappa+(2n+1)\mu)}, & \textit{if } \gamma > \frac{2n+1}{2(n+1)}(1-\kappa-\mu), \\ \frac{4(n+1)(1-\kappa-\gamma)-(2n+1)\mu-(1-\kappa)}{8(n+1)}, & \textit{otherwise.} \end{cases}$$

Because usage by non-owners comes at an added cost, more value is created when high-usage customers, rather than low-usage customers, buy the equipment. For a sharing market to exist, however, such buyers must be willing to share their equipment when it is idle. Added utilization from accessing customers leads to an increase in the maintenance need of the equipment. At the same time, the demand of multiple customers can be fulfilled with the same equipment. The manufacturer compensates buyers for the former effect by dropping the commission while capturing rents generated from the latter by extracting revenues through after-sales services.

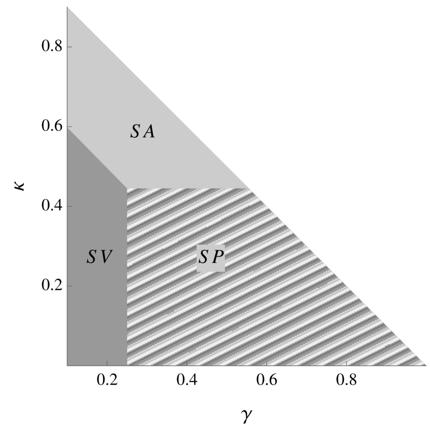
Sharing is also crucially affected by μ and n. As with SV, the profit decreases in μ and increases in n. In sharp contrast, however, the manufacturer reacts to an increase in μ (resp. n) by an *increase* (resp. *decrease*) in the sales price, and, thus, the threshold θ_1^{SP}. A higher μ means the manufacturer must reduce its maintenance fees. Otherwise, owners are unwilling to incur added maintenance from sharing their equipment. However, this reduces the value that the manufacturer can extract from owners' usage. For n, we note that the sharing market induced by the manufacturer is supply-constrained (in the first case) or has supply equalling demand (in the second case). The sales price is only affected by n in the first case: A higher n means that more of each owner's extra capacity supplied to the sharing market can be matched to a user. Hence, by reducing the threshold, the manufacturer can increase total usage—the base on which it extracts after-sales revenues.

That the sales price is increasing in μ also leads to an important observation when comparing SP and SA: If μ is high, there is little extraction through after-sales services under SP. Then, the sales price is higher than under SA, in line with prior studies in the sharing economy (Jiang and Tian 2018, Abhishek et al. 2021). Conversely, if μ is low and the manufacturer benefits from after-sales services of shared equipment, the price may be lower under SP than under SA.

Figure 1 Comparison between the SA, SV, and SP business models.



(a) $n = 5$



(b) $n = 50$

Note. Business models are preferred by the manufacturer in the different regions as indicated by their abbreviations. The equipment cannot be used economically beyond the diagonal cut-off. Other parameters are $\nu = 0.05$ and $\mu = 0.3$.

4.4. Comparison of business models

The parameter regions where each business model is the optimal choice for the manufacturer are characterized in Proposition 1. Figure 1 visualizes the business model choice as a function of the production cost γ and per-usage maintenance cost κ.

PROPOSITION 1. *The manufacturer's optimal choice of business model is:*

- *SV, if* $\gamma \leq \frac{n}{n+1}(1-\kappa-\mu)$ *and* $\gamma \leq \overline{\gamma}$*, for some* $\overline{\gamma} \in \left(\mu-\nu, \mu-\nu+\frac{1-\kappa-\mu}{3n}\right)$.
- *SP, if* $\overline{\gamma} < \gamma$*, and* $\kappa \leq \overline{\kappa}$ *for some* $\overline{\kappa} \in \left(1-\mu-(\mu-\nu)\frac{3(n+1)}{3n-1}, 1-\mu-(\mu-\nu)\frac{n+1}{n}\right]$.
- *SA, otherwise.*

We first note that considering only SV, one would conclude that access-based models are suboptimal when production costs are high (see, e.g., Ladas et al. 2022). This highlights the importance of studying multiple access-based models simultaneously: SP fills a business model gap.

When access-based models (SV, SP) are chosen, they enable the pooling of shared resources. This, in turn, allows for market segmentation, bringing in low-usage customers who would not have purchased equipment under SA. This increases total usage, leading to more maintenance. Thus, when maintenance costs (κ) are high, the manufacturer prefers SA over access-based models.

Conversely, SV and SP, are preferred when maintenance costs are low. The choice between them is driven by how each provides access. SP allows for more pooling since the usage of multiple non-owners and an owner is borne by the same piece of equipment. This is in contrast to SV, where only the usage of non-owners is pooled using dedicated equipment. One may thus intuit that SP is always the better business model. However, after-sales pricing is more constrained under SP because the manufacturer cannot discriminate between the usage of an owner and the usage of non-owners accessing the owner's equipment, although only the latter incurs inconvenience costs. Hence, SP dominates when the manufacturing costs (γ), and thus the benefits of pooling, are high.

The parameters γ and κ are directly linked to different types of equipment and usage environments. More powerful equipment tends to be more expensive to produce (higher γ). Meanwhile, maintenance costs (κ) are higher in harsher environments such as in mining (MacAllister 2021). Consider the differences between bulldozers and two types of excavators. Bulldozers perform flattening and clearing tasks for which they are equipped with powerful engines. Excavators, which perform digging tasks, employ less powerful engines.[8] Thus, bulldozers are associated with higher production costs compared to excavators. In addition to usage environment, the propulsion system —wheels or tracks—utilized by excavators influence their maintenance costs. Crawler excavators, which use tracks, are better suited for wet, rough and irregular terrain due to their superior traction but are more complex than wheeled excavators, and have higher maintenance costs. Putting these equipment features together, our results indicate that bulldozers are ideal candidates for an SP business model due to higher production but lower maintenance costs. Wheeled excavators—with lower production and lower maintenance costs—are a good match for SV. Finally, crawler excavators—with lower production but higher maintenance costs—are more suited for SA.[9]

In Appendix A.1, we relax our assumption that the inconvenience costs for sharing and servicization are identical. When their difference is sufficiently large, the manufacturer may choose a joint business model combining servicization and sharing. As outlined there, this joint business model is optimal in the area where access-based models are preferred (low κ). When the dedicated equipment for an SV model is relatively cheap (low γ), the manufacturer continues to prefer SV. As γ increases, it first shifts to a combined SV/SP model, before finally shifting to SP (high γ).

4.5. Effects of fuel price shocks on the business model comparison

We next discuss how the optimal choice between business models changes when customers' fuel costs change. Fuel costs are the most important operating costs and can make up half the total ownership costs (Jackson 2016). This analysis is of particular importance in light of two interlinked debates in the industry: the drastic increase in fuel prices in recent years and the increasing prevalence of electric engines, which are assumed to reduce fuel costs at the price of increased production costs (Chergui 2023). Given that fuel prices are heavily auto-correlated (Alvarez-Ramirez et al. 2002), and a switch to electric engines also represents a long-term trend, it is reasonable to assume that a manufacturer responds to both trends by adjusting its business model.

Thus far, the rates of revenue generation, standardized to 1 or ν, are assumed to be net of fuel costs. The proposed analysis corresponds to replacing these rates by $1-\psi$, respectively $\nu-\psi$ for some value ψ, where an increase in fuel prices is represented by $\psi > 0$. We observe the following adjustments in the business model choice, where we assume $n \to \infty$ for clarity:

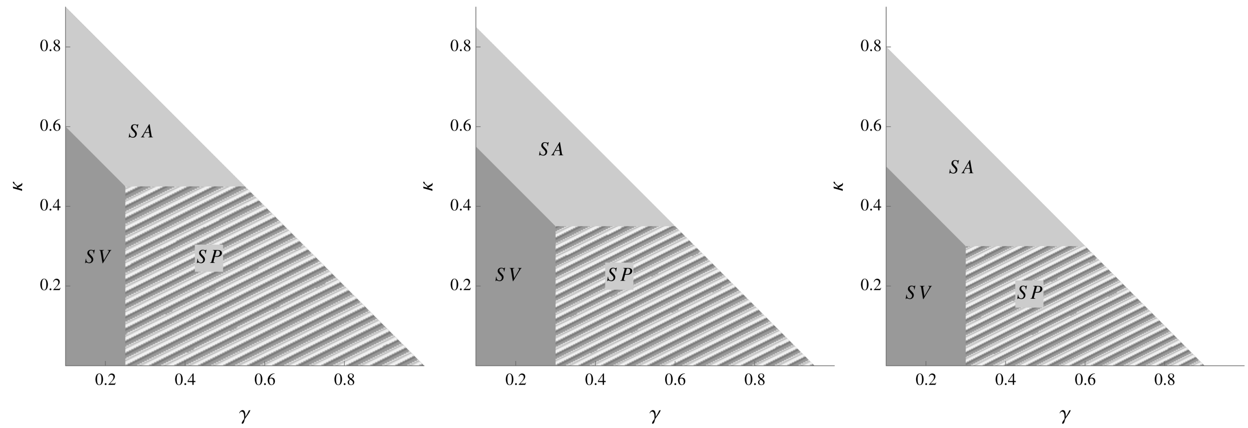
Corollary 1. *Take any feasible tuple of parameters $(\gamma, \kappa, \nu, \mu)$ and assume $n \to \infty$. If the rate of revenue generation is reduced by $\psi > 0$, the optimal business model choice changes as follows:*

- *From SA to SA or inactivity.*
- *From SV to SV, SA, or inactivity.*
- *From SP to any business model or inactivity.*

While a lower rate of revenue generation (higher ψ) hurts all business models, Corollary 1 indicates that the manufacturer's preference shifts away from SP toward SV and SA. When SA is the preferred business model, an increase in ψ induces the manufacturer to lower either the equipment price p (for low ψ) or the maintenance fee m (for high ψ). This is still the SA business model, albeit with lower value extracted from each customer. When ψ is too high, there comes a point when it becomes unprofitable to induce any customers to purchase equipment.

When SV is the preferred business model, in addition to treating buying customers similarly to SA, the manufacturer must reduce the per-usage fee u as ψ increases. When u is too low, it is unprofitable to induce accessing customers to join the market, and the firm reverts to SA.

Figure 2 Business model comparison for different levels of ψ.



(a) $\psi = 0$ (b) $\psi = 0.05$ (c) $\psi = 0.1$

Note. Business models are preferred by the manufacturer in the different regions as indicated by their abbreviations. Other parameters are $\nu = 0.05$ and $\mu = 0.3$, while $n \to \infty$.

To understand the manufacturer's move away from SP, note that it needs to induce owners to share their equipment. However, the price r they obtain from sharing decreases in ψ. To compensate owners, the maintenance fee m must be reduced—even for low ψ, where m is unchanged under SA and SV—making SP less attractive and eventually inducing a switch to SV, SA, or inactivity.

The inverse holds for $\psi < 0$. We skip a formal result for brevity, but we point out the key impact of electrification on business model choice: Electric heavy equipment is commonly associated with lower energy costs ($\psi < 0$) and increased production costs (increase in γ), both favoring SP. The shifts in the optimal business model choice are also displayed in Figure 2.

5. The manufacturer's environmental impact

In this section, we study the environmental impact of the heavy equipment manufacturer. Following Agrawal and Bellos (2017), we assign environmental cost e_p (resp. e_u) to the production of one unit of the equipment (resp. usage for an entire period). For improved clarity, but without qualitatively affecting our results, we assume that $n \to \infty$. All proofs are found in Appendix C.

5.1. Access-based business models compared to an ownership-based business model

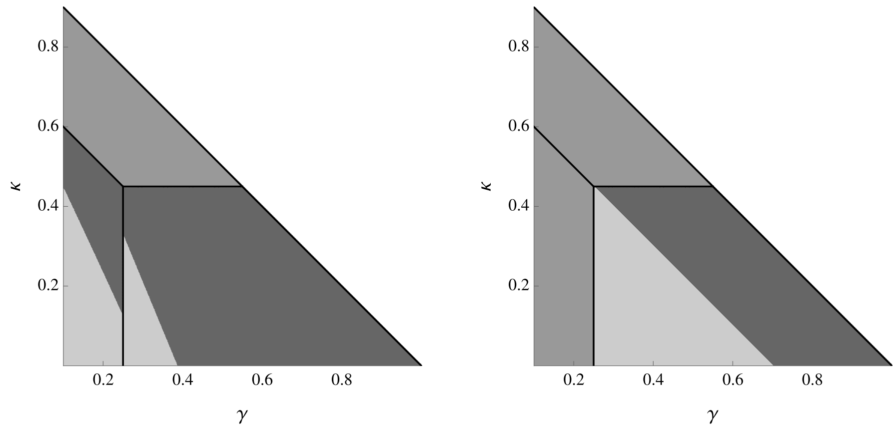
We start by analyzing how a move to access-based business models from an ownership-based one affects the manufacturer's environmental impact in Lemma 4. Figure 3a displays regions where the impact is higher, lower, or unchanged.

LEMMA 4. *There exists $\bar{e}_u$ such that adopting the SV (resp. SP) business model increases the environmental impact for all $e_u \geq \bar{e}_u$. If and only if $(\gamma+\mu+\nu)\left[2(\gamma+\mu)-(1-\kappa-\nu)\right] < \mu(1-\kappa+\nu)$ (resp. $2\gamma < 1-\kappa-\nu$), there exists $\bar{e}_p$ such that adopting the SV (resp. SP) business model reduces the environmental impact for all $e_p \geq \bar{e}_p$.*

Moving from SA to SV (bottom left of Figure 3a), customers' total equipment usage is higher due to new customers accessing the equipment without ownership. At the same time, these customers' usage is pooled. In particular, an increase in γ means more customers are accessing the equipment rather than buying it. Hence, one may expect a high γ to be associated with reducing the total equipment produced. However, an increase in γ also reduces the equipment produced under SA —more quickly than under SV, where pooling effects moderate the increased production costs. As a result, it is only for low values of γ, when few customers access the equipment, that the manufacturer produces less under SV and may have a lower environmental impact. For high values of γ, both production and usage are higher under SV, so the environmental impact is higher. The threshold in γ is decreasing with κ: Under SA, a higher κ means that some customers can no longer be served profitably and are priced out of the market, lowering production. Under SV, non-owners access the equipment and both segments of the market incur maintenance costs. Hence, a change in κ does not affect the trade-off between ownership and access, and production remains unchanged.

Moving from SA to SP (bottom right of Figure 3a), total usage also increases due to new customers accessing the equipment. However, production is affected differently in the two cases of Lemma 3. In the second case, when γ and κ are sufficiently low, the manufacturer induces a sharing market where supply equals demand, implying that production is unaffected by a change in those costs. Meanwhile, production under SA is decreasing in γ and κ. Hence, for small enough costs,

Figure 3 Environmental impact of the optimal business model compared to:



(a) The SA business model. (b) The SA or SV business model.

Note. The environmental impact is lower/unchanged/higher under the optimal business model in the light/medium/dark gray region. Black lines indicate the boundaries between business model choices. Other parameters are $\nu = 0.05$, $\mu = 0.3$, $e_p = 0.05$, and $e_u = 0.05$.

the manufacturer produces less under SP and may have a lower environmental impact. As costs increase, the production under SP eventually exceeds that under SA. Given that usage is always higher under SP, the environmental impact is now higher under SP. Once costs are sufficiently high, i.e., in the first case of Lemma 3, the manufacturer induces an equilibrium with fewer owners than non-owners by increasing the sales price. However, as the manufacturer incentivizes owners to share with a reduced maintenance fee under SP, more customers are owners relative to SA. Usage remains higher (while SP is preferred to SA), so the environmental impact remains higher, too.

That the production and environmental impact may be lower under access-based models when production costs are low (and higher when production costs are high) is consistent with the prior literature on servicization and sharing (see, e.g., Agrawal and Bellos 2017, Benjaafar et al. 2019).

5.2. The SP business model compared to the incumbent business model

Having shown the consistency of our model with prior work, we move to the (novel) comparison between access-based models. Given that SV is more established than SP, we take the situation faced by a manufacturer that previously made an optimal choice between SA and SV and now considers a move to SP. As the following proposition shows, this benefits the environment exactly when SP replaces SV, independent of the values of e_p and e_u. This is shown in Figure 3b and can have important implications for regulators considering whether to simplify a move to SP.

PROPOSITION 2. *Adopting the SP business model reduces the environmental impact if and only if SV was the optimal choice beforehand.*

Under SP, the manufacturer induces a sharing market wherein supply equals (rather than exceeds) demand exactly when SV dominates SA. In this case (in the light gray region of Figure 3b), the total usage fulfilled is the same under SV and SP. At the same time, because owners' equipment is used for non-owners' usage under SP (as opposed to dedicated equipment under SV), the total production quantity is lower.

5.3. The manufacturer's business model choice compared to the triple bottom line

Environmental impacts are frequently managed as a result of pressures from various stakeholders such as customers, investors, or governments. For example, many governments have pledged to reduce their net emissions to zero by 2050. However, the same governments have economic growth targets, meaning they must search for beneficial trade-offs between the economic value generated and the resulting environmental impact. Therefore, we provide an additional analysis that compares the environmental impact of the manufacturer's choices—purely driven by a profit motive—to those of a hypothetical "social planner" that aims to optimize the triple bottom line of manufacturer profit, customer profit, and environmental impact. We summarize the social planner's optimal choices in Lemma 5 and compare the environmental outcome of the manufacturer's choice to that of the social planner in Proposition 3 and Figure 4. Interestingly, the manufacturer's profit-driven choices can lead to higher, lower, or the same environmental outcome as the social planner's.

LEMMA 5. *A social planner optimizing the triple bottom line would choose the following:*

- *If* $1-\kappa-\gamma-e_p-e_u \le 0$*, all customers abstain. Otherwise;*
- *if* $1-\kappa-\mu-e_u \le 0$*, customers* $\theta \in [0,\theta_1)$ *abstain while customers* $\theta \in [\theta_1,1]$ *own and use equipment for some* $\theta_1 \in (0,1)$*;*

- *if* $1 - \kappa - \mu - e_u > 0$*, customers* $\theta \in [0, \theta_1)$ *obtain usage through the sharing platform while customers* $\theta \in [\theta_1, 1]$ *own and use equipment for some* $\theta_1 \in (0, 1)$*.*

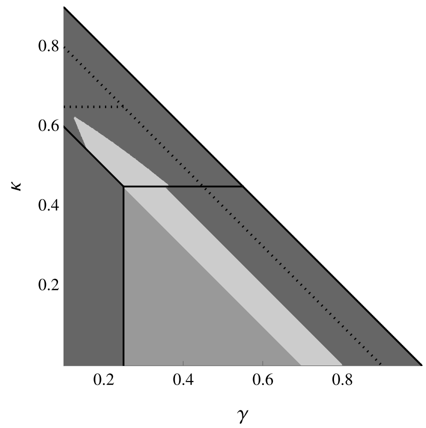
Appendix C.2 explicates all assumptions. The structure of the social planner's solution is similar to that of the manufacturer: When κ is high, it follows an SA-like strategy. On the other hand, when κ is sufficiently low, it enables access (and, thus, pooling). The critical difference is that this bound on κ now decreases with the environmental impact of usage, e_u. This is intuitive, as enabling access necessarily increases the total usage. Compared to the manufacturer, however, the social planner never uses servicization. To see why, recall that the manufacturer might prefer servicization because it limits the extraction from after-sales services less than sharing. Considering both manufacturer and customer profits, the social planner is not constrained in such a way. Hence, it always follows an SP-like strategy for a sufficiently low value of κ.

Proposition 3. *Under any business model optimally chosen by the manufacturer, there is a range of parameters such that the manufacturer's environmental impact is lower than that of a social planner optimizing the triple bottom line. In particular,*

- *if SA is the optimal business model choice, the manufacturer's impact is lower if and only if* $e_p \leq \bar{e}_p$ *for some* $\bar{e}_p \in (0, 1-\kappa-\gamma)$ *and* $e_u \in E_u$*, where* E_u *is a non-empty subset of* $[0, 1-\kappa-\gamma)$*;*
- *If SV is the optimal business model choice, the manufacturer's impact is lower if and only if* $e_u \leq \bar{e}_u$ *for some* $\bar{e}_u > 1 - \kappa - \mu$ *and* $e_p \in E_p \subseteq \left[0, \mu(\gamma+\nu)\frac{\gamma+\nu+2\mu}{2(\gamma+\nu+\mu)^2} - \gamma\right)$*;*
- *if SP is the optimal business model choice, the manufacturer's impact is lower if and only if* $1 - \kappa - \gamma - \mu < 0$*,* $e_u < 1 - \kappa - \mu$*, and* $e_u + e_p < \frac{1-\kappa-\gamma}{2}$*.*

Figure 4 compares the environmental impact of the manufacturer's business model to the triple bottom line. The manufacturer's (resp. social planner's) decision is indicated through solid (resp. dotted) lines. Recall from Figure 3a that a transition away from SA reduces the environmental impact in the bottom left part. In contrast, Figure 4 shows an increase relative to the triple bottom line. Hence, conclusions regarding the environmental benefits of new business models are highly dependent on the benchmark chosen and careful thought should be given to this choice.

Figure 4 Environmental impact of the manufacturer's business model compared to the social planner's strategy.



Note. The environmental impact is lower/unchanged/higher under the profit-maximizing business model in the light/medium/dark gray region. Solid (resp. dotted) black lines indicate the boundaries between business model choices (resp. the social planner's strategies). Other parameters are $\nu = 0.05$, $\mu = 0.3$, $e_p = 0.05$, and $e_u = 0.05$.

We highlight three key observations from Figure 4. First, the social planner is inactive above the dotted diagonal line because the environmental costs of production and usage outweigh the economic benefits, which are low when γ and κ are high. Not considering environmental costs, the manufacturer remains active above the dotted diagonal line, with a higher environmental impact.

Second, the manufacturer's choices can lead to an environmental impact below the benchmark. For example, the SP model can be environmentally friendlier than an SP-like strategy chosen by the social planner (corresponding to the light gray area in the SP-part of Figure 4). Compared to the manufacturer, the social planner's consideration of the environment pushes it towards an outcome with lower production and usage, that is, with a higher threshold between access and ownership. On the other hand, taking into account both manufacturer and customer profits, there is an economic incentive to increase production and usage compared to the manufacturer. When γ and κ are not too high, economic incentives outweigh environmental ones and the social planner induces more production and usage, leading to a higher environmental impact.[10]

Third, despite their different objectives, environmental outcomes may coincide when the manufacturer and the social planner induce a sharing market where supply equals demand (medium gray region of Figure 4), at intermediate values of γ. In this case, all usage demand is fulfilled with the minimum possible production quantity. The environmental outcomes differ for higher or lower γ. If γ is high, both induce a sharing market with less supply than demand to reduce the total production quantity, but set different thresholds. If γ is low, the manufacturer induces SV, while the social planner continues to induce a sharing market.

6. Robustness of results in the face of secondary markets

We extend our analysis to the case where equipment may generate revenues over two periods, in line with the durable goods literature (Desai and Purohit 1998). In particular, after the equipment generates revenues at a rate of 1 (resp. ν) in the first period if it is maintained (resp. not maintained), we assume that it always generates revenues at the rate of ν in the second period.

At the start of each period, customers who own equipment used during the previous period can sell it on a secondary market with zero transaction costs. Other customers may decide to buy that equipment. We assume equipment is sold on the secondary market for the equilibrium price p_s. In the following, we outline only the key results, while the details are relegated to Appendix D.

6.1. SA-like business models with secondary markets

When the manufacturer offers the equipment for sale, a secondary market emerges, where high-usage customers sell the equipment after one period, and intermediate-usage customers buy it. There are two (sub-)business models to consider, based on how many customers the manufacturer induces to buy on the primary market (and maintain their equipment). If the number is low, the secondary market demand exceeds supply, and customers with low usage are excluded. We call this model ASM (customers follow strategies A, S, and M, where S means that a customer buys used equipment through the secondary market). This presents a direct continuation of SA. The only difference is that some customers that abstained from the market under SA, and some of the lower-usage buying customers now buy on the secondary market. The business model also displays the same structure as that found in Anderson and Ginsburgh (1994), with the critical difference that equipment sales are subsidized to generate after-sales revenues.

When production and maintenance costs are relatively low, the manufacturer may induce sufficient customers to buy new, such that the secondary market supply exceeds demand, driving the price to zero. In this model, called SM (customers follow strategies S and M), all usage requirement is fulfilled, while the manufacturer only extracts profits through maintenance.[11]

6.2. SV-like business models with secondary markets

Consider a manufacturer offering servicization. It could sell equipment accessed in one period to the secondary market in the next. Taking this into account makes the manufacturer's problem intractable. However, an exhaustive numerical search reveals that this is never optimal when servicization is optimal. Hence, we assume that all secondary equipment originates from owners.[12]

As before, customers with intermediate levels of usage buy through the secondary market, resulting in a direct extension to SV: the business model $\tilde{\text{R}}$SM (customers follow strategies $\tilde{R}$, S, and M). The manufacturer chooses this model if κ and γ are sufficiently high. Compared to the case without a secondary market, some customers with intermediate usage deviate from the strategies $\tilde{R}$ and M to buy on the secondary market (S). While the manufacturer loses out on these customers, it raises its price to extract some of the surplus that buying customers generate by selling their used equipment. Nevertheless, the secondary market comes at a cost, so it might be beneficial to hinder its emergence. The manufacturer can do so in two ways:

First, by providing accessing customers with a sufficient surplus not to buy secondary equipment, leading to business model $\tilde{\text{R}}$M. While the customers' strategies are identical to those under SV (in the absence of a secondary market), the business model is fundamentally different because of the surplus required by accessing customers in order not to pick up used products from the secondary market (at price zero). The manufacturer also needs to lower its maintenance fee sufficiently to provide more surplus to buying customers to avoid them deviating to strategy $\tilde{R}$.

Second, the business model $\tilde{\text{R}}$, wherein the manufacturer does not provide equipment to buy, avoids deviations even when all surplus is extracted from accessing customers. This is always feasible, but comes at the cost of incurring inconvenience costs and matching frictions on all usage.

6.3. SP-like business models with secondary markets

When the manufacturer provides a sharing platform, the situation is similar: Customers with intermediate usage buy the equipment on the secondary market, while low-usage customers continue to access equipment shared by high-usage owners. This is business model RSM (customers follow strategies R, S, and M), which directly extends the SP business model to the case of secondary markets and is generally chosen by the manufacturer if κ and γ are sufficiently high.

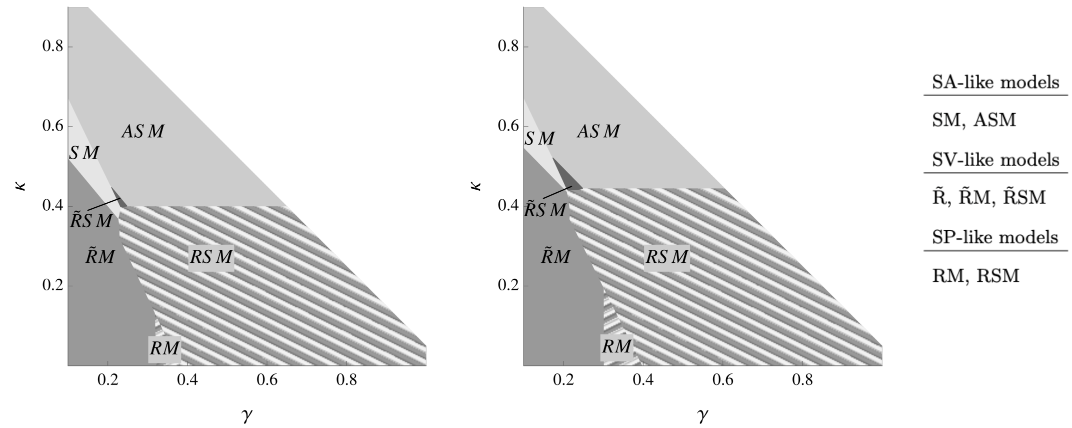
As with servicization, the secondary market comes at a cost to the manufacturer. Thus, it may choose a lower price for equipment access that leaves accessing customers with sufficient surplus to avoid deviation (business model RM). While the business model RM is reminiscent of the business model SP (without a secondary market), the fundamental difference again lies in the customer surplus. Accessing customers are provided with a surplus to avoid their deviation to the secondary market, and owners' surplus is increased accordingly to avoid them deviating to strategy R.

6.4. The effect of a secondary market on the comparison of business models

Through a numerical search, we find that the key structure of the optimal business model choice is unchanged in the presence of a secondary market. In particular, a pure ownership-based model is prevalent for high values of κ. For low values of κ, the manufacturer chooses either a servicization business model (if γ is low) or a sharing business model (if γ is high). As seen in Figure 5, the choice at intermediate values of κ and γ can be more complex due to the different business models within each category (e.g., RM and RSM in the case of sharing).

We make an important observation regarding the (sub-)business models: when κ or γ are higher, segmenting customers into more groups is more attractive. For access-based models, this means not suppressing the secondary market, thus needing less equipment and after-sales services. For a traditional model, this involves inducing some customers to abstain (in addition to those buying new and old equipment), with similar effects. We also verify through a numerical search that our results regarding the environmental impact remain robust. Appendix D.4 provides more details.

Figure 5 Comparison between the SA-like, SV-like, and SP-like (sub-)business models.



(a) $n = 5$ (b) $n = 50$

Note. Business models are preferred by the manufacturer in the different regions as indicated by their abbreviations. The equipment cannot be used economically beyond the diagonal cut-off. Other parameters are $\nu = 0.05$ and $\mu = 0.3$.

7. Conclusion

Technological advances enable customers to access products in new ways. Servicization allows manufacturers to pool the demands of multiple customers and offer usage-based pricing. With sharing platforms, customers make use of other customers' products. In light of these options to obtain usage without ownership, we study the business model choices available to heavy equipment manufacturers and the environmental impact of their choices. The heavy equipment industry is distinct in the role after-sales services play for manufacturers' profitability.

We identify operational characteristics of heavy equipment that drive a manufacturer's choice among an ownership-based business model of sales and after-sales services (SA) and the access-based business models servicization (SV) and sharing (SP). Access-based models allow including low-usage customers through equipment pooling. This is desirable when the costs of providing after-sales services are relatively low, e.g., for equipment used in non-demanding environments. Among these models, sharing enables more demand pooling but constrains the profitability of after-sales services. As a result, servicization is preferable when production costs are low, and, consequently, the benefits from pooling are modest. This corresponds, e.g., to equipment with relatively low power. In contrast, high-powered or electric equipment tends to be more costly to produce and is more amenable to sharing. We discuss how this comparison evolves under increasing fuel costs, a topic that has recently garnered attention in practice. Combining these results, we find that a move to electric equipment would particularly favor a sharing business model.

We also discuss the environmental impact of the business model choice. Consistent with the literature, access-based models increase usage compared to an ownership-based model but can sometimes reduce the production quantity, thus potentially benefiting the environment overall. Our three-way analysis further enables a comparison of access-based models: When SP is introduced where SV was previously the optimal business model choice, the environmental impact is reduced.

The benchmark in this analysis is a prior business model of the profit-maximizing manufacturer. We further propose a new benchmark trading off the triple bottom line of manufacturer profits, customer profits, and environmental costs. As expected, the manufacturer's impact often exceeds this benchmark. However, it may also be lower because conflicts between manufacturer and customer profits can imply that the manufacturer induces relatively lower production and usage. Finally, the manufacturer may induce the same market outcomes as the benchmark, but only under SP.

Our key results regarding the profitability and environmental impact of different business models are robust in the face of secondary markets. Such markets imply a proliferation of (sub-)business models because they can lead to further customer segmentation. However, the manufacturer may strategically use servicization or sharing to suppress secondary markets.

In summary, our paper contributes to an emerging literature on novel business models and their role in creating more profitable and environmentally friendly options for manufacturers. We study multiple novel business models simultaneously, enabling a holistic view for manufacturers and regulators. Moreover, we consider critical characteristics of the heavy equipment industry that are also important for other durable goods: a focus on after-sales, a proliferation of new types of access, the presence of secondary markets, and sensitivity to fuel prices. We highlight how considering these characteristics and multiple models enables new insights concerning business model design and choice. Finally, we extend the study of business models' environmental impact by providing a benchmark that explicitly considers economic and environmental trade-offs. We hope this can serve as a starting point for further analyzing business models in the context of sustainability.

Endnotes

1. See, e.g., https://tinyurl.com/bdz7c564, https://tinyurl.com/53vxef5k.

2. Leasing, discussed extensively within the durable goods literature (see, e.g., Desai and Purohit 1998), may seem similar to servicization. However, products are dedicated to users, and payments not linked to usage (Bellos et al. 2017). Hence, leasing provides the same trade-offs as an ownership-based model in our context. The only exception is that it may, similar to access-based models, prevent a secondary market from emerging (Waldman 1997). This has been studied in the prior literature, so we do not investigate it further.

3. It is easy to show that all equipment used for access is maintained.

4. We only need $\nu < \gamma$ here. However, this changes to $\nu < \gamma/2$ when equipment can generate revenues after one period (Section 6). The stricter assumption has no bearing on the earlier results, so, we use it throughout.

5. For an example, see https://tinyurl.com/y2dxjwwy.

6. The inequality has a very low or negative right-hand side and is, thus, easy to satisfy. Moreover, assuming it holds reduced the number of comparisons that need to be made within and across business models.

7. Customers make various choices that are affected by different prices, providing an analytical challenge. A key observation is that each strategy corresponds to a unique (possibly empty) subinterval of $[0, 1]$, and an equilibrium to a sequence of such subintervals. This allows us to focus on a limited number of equilibria, although this number is increased by the minimum in the service level function. Moreover, directly optimizing over the prices is challenging, as the resulting profit function is non-concave. This is mainly caused by buying customers: different from the pay-per-use literature, they face both a fixed price and a usage-dependent price. Hence, we derive the minimum profits for customers in a subinterval not to deviate from the subinterval's strategy. We then upper-bound the manufacturer's profit for arbitrary subinterval thresholds and optimize the threshold locations. Finally, we derive prices that induce customers to follow strategies in line with the optimal thresholds and show that the prices lead to obtaining the upper bound on profits.

8. Discussions with industry insiders reveal that medium-sized bulldozers have more than 200 hp. and sell for US$ 250–400k, while medium-sized excavators have 175–200 hp. and sell for US$ 150–300k.

9. Both costs are positively associated with the equipment size (MacAllister 2021). Meanwhile, size poses a physical constraint for access-based business models: Customers can more easily access small and medium-sized equipment as it needs to be transported by trucks. Hence, access-based models are less feasible in the top and right parts of the graph. This may explain why sharing is observed less than other models in practice: in some regions where it is the preferred business model, physical constraints may hamper its emergence. When discussing the environmental impact of the business model choice in Section 5.1, we find that access-based models can have a lower impact for equipment with low costs and, thus, size.

10. The manufacturer's environmental impact with SP or SA can be lower than the social planner's when the latter induces a different threshold with an analogous "business model". It can also be lower with SA or SV when the social planner induces a different model (e.g., the light gray area in the SA-part of Figure 4).

11. We note that the secondary market price dropping to the transaction cost is an outcome also reflected in the durable goods literature in economics (Anderson and Ginsburgh 1994).

12. Our discussions with industry insiders reveal that, in practice, OEMs sell such used equipment to less developed markets to avoid disposal costs.

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Appendix A: Additional robustness checks

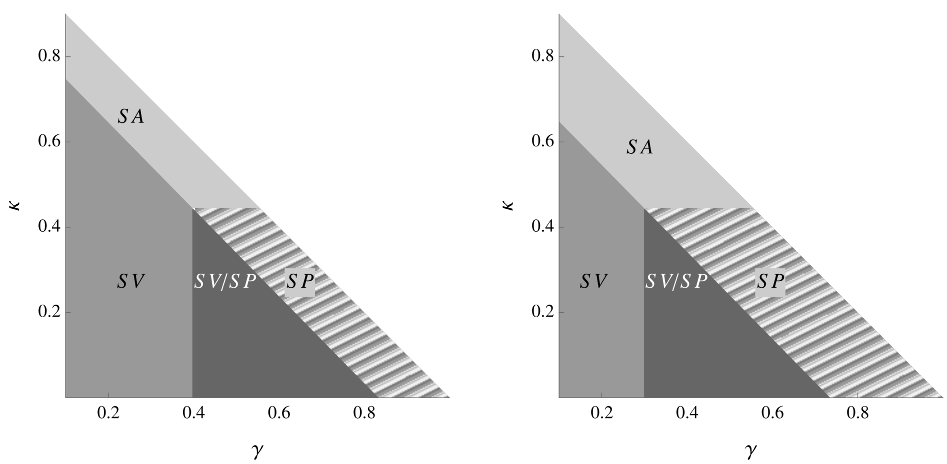
A.1. A business model combining sharing and servicization

Combining sharing and servicization is never optimal under the assumption that the inconvenience cost μ is equal for both. This is the case even when we assume—most favorably for the manufacturer—that customers access whatever equipment they can first so that all equipment for access is supplied in a joint queue. To see why, note that the key advantage of servicization over sharing is that it enables access without further limiting the manufacturer's ability to extract revenues from buyers through after-sales services. To sustain a sharing market, however, a reduction in maintenance fees is necessary, defeating this advantage of servicization.

The situation changes if we modify our assumptions such that servicization and sharing have different inconvenience costs, μ_{SV} and μ_{SP}. In particular, providing access centrally under servicization may be more efficient than the decentral provision under sharing. If the difference is sufficiently large, that is, if $2n(\mu_{SP} - \mu_{SV}) > 1 - \kappa - \mu_{SP}$, a combined business model can emerge, wherein low-usage customers access equipment that is either provided by the manufacturer or by other customers and high-usage customers buy, maintain, and share equipment.

This combined business model ("SV/SP") is optimal when SV and SP each dominate SA. Moreover, when it is optimal, SV/SP always replaces SP. This is not surprising, given that $\mu_{SV} < \mu_{SP}$ means servicization provides a cost advantage. However, SV/SP cannot replace SP when γ is high. In this region, servicization is inefficient because the costs of providing servicized products outweigh the benefits: SA dominates SV. Figure 6 compares the business models, holding μ_{SP} fixed and varying μ_{SV}. We note that analytical results can be obtained in line with the ones in the baseline

Figure 6 Comparison between the SA, SV, SP, and combined SV/SP business models.



(a) $\mu_{SV} = 0.15$ (b) $\mu_{SV} = 0.25$

Note. Business models are preferred by the manufacturer in the different regions as indicated by their abbreviations. Other parameters are $\nu = 0.05$, $\mu_{SP} = 0.3$, and $n = 50$.

case if we assume that the special case of $S > D$ does not appear. However, we can exclude the optimality of this special case through an exhaustive numerical search.

Qualitatively, the regions of other business models align with the previous results, with SV expanding with a decrease in μ_{SV}. The hybrid business model SV/SP can be found between SV and SP. It is worth noting that where SV/SP replaces SP, its environmental impact is unchanged. Hence, the picture regarding business models' environmental impact is the same, save for the changes induced by an expansion of the SV region. As a social planner will also switch to an SV/SP-like strategy, the comparison here remains qualitatively unchanged.

A.2. An alternative assumption on the usage distribution

In practice, usage requirements may not be distributed uniformly. For example, during an economic downturn, usage could be bottom-heavy; conversely, it could be top-heavy during a boom. This is expected in the case of the highly pro-cyclical construction industry (Sun et al. 2013). Further, when heavy equipment customers are price-takers, such as in commodity mining (Olofsson 2022), one may expect a top-heavy distribution, as customers are left with an increase in quantities to expand profits. We can take such scenarios into account with a trapezoidal distribution. We note that the total usage requirement remains the same as under a uniform distribution ($1/2$) only when the trapezoidal distribution is symmetric, in line with the economic downturn/boom interpretation.

In Figure 7, we show the optimal business model choice in these three scenarios, denoting the lower (resp. upper) discontinuity of the trapezoidal distribution with $\underline{\theta}$ (resp. $\overline{\theta}$). The optimal choice remains qualitatively the same, with slight shifts in the regions where different business models are preferred. In particular, SP benefits strongly from a centering of usage requirements. Similarly, but to a lesser degree, when usage requirements are skewed to the left (and total usage is reduced), SP is chosen more frequently. However, when usage requirements are right-skewed (and total usage is increased), the comparison remains essentially unchanged.

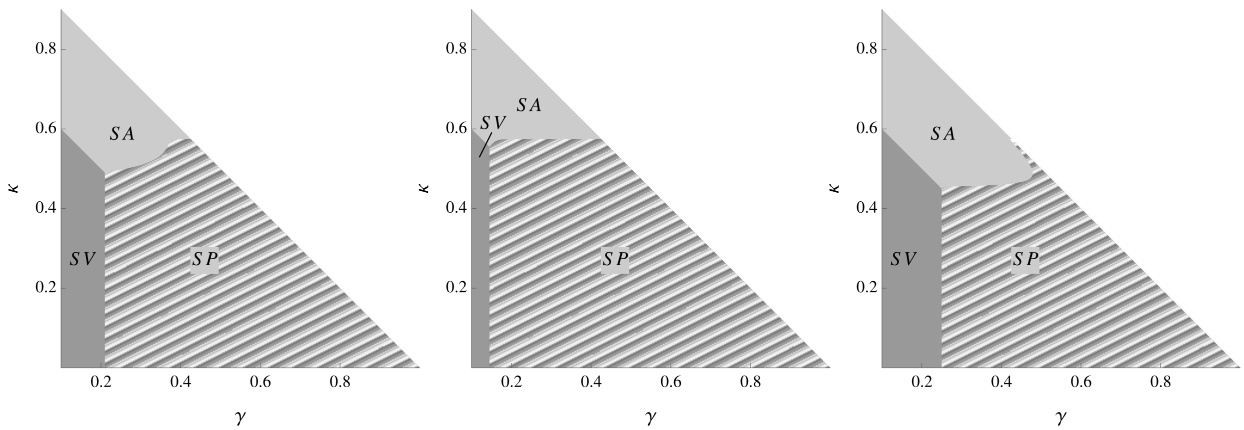
Through numerical experiments, we also find that comparisons concerning the environmental impact are qualitatively unchanged regarding positions within the plot but with the size of the different regions growing or shrinking depending on the distributional assumptions. We have not included those figures for brevity, but they are available from the authors upon request.

Appendix B: Proofs related to business model design and choice

B.1. Sales and after-sales (SA)

Proof of Lemma 1. Assume a customer $\theta_1 \in [0,1]$ chooses strategy O. This customer's profit is $\pi_{\theta_1} = \nu\theta_1 - p$ and we must have $\nu\theta_1 - p > (1-m)\theta_1 - p$, the profit from strategy M. However, this implies that $\nu > 1-m$, so no customer will choose strategy M. Secondly, assume that $\nu\theta_1 - p > 0$ (resp. $(1-m)\theta_1 - p > 0$) for some $\theta_1 \in [0,1]$. Then $\nu\theta - p > 0$ (resp. $(1-m)\theta - p > 0$) for all $\theta > \theta_1$.

Figure 7 Comparison between the SA, SV, and SP business models if usage requirements follow a trapezoidal distribution.



(a) $\underline{\theta}=0.1,\ \overline{\theta}=0.9,\ E\theta=0.5$ (b) $\underline{\theta}=0.01,\ \overline{\theta}=0.5,\ E\theta=0.39$ (c) $\underline{\theta}=0.5,\ \overline{\theta}=0.99,\ E\theta=0.61$

Note. Business models are preferred by the manufacturer in the different regions as indicated by their abbreviations. Other parameters are $\nu=0.05$, $\mu=0.3$, and $n=50$.

It follows that we need to consider two possible equilibria: AO and AM, where each equilibrium is denoted by the relevant strategies in the different subintervals. We next identify the optimal prices within either equilibrium, such that the equilibrium in question is the only one that may emerge:

Equilibrium AO. This can always be induced by setting the maintenance fee m sufficiently high. Customers with $\theta \geq \frac{p}{\nu}$ will buy the equipment. Hence, the manufacturer's problem becomes $\Pi^{AO} = \max_{p\leq\nu}\left(1-\frac{p}{\nu}\right)(p-\gamma)\,d\theta$. Note that $\nu<\gamma$. Hence, the second term is always negative in the feasible range, and the manufacturer will never induce the equilibrium.

Equilibrium AM. Assume $\theta_1\in[0,1]$ is the threshold between customers abstaining and those buying the equipment. Consider the centralized problem. Buyers generate net-revenues per period of $(1-\kappa)\frac{1-\theta_1^2}{2}$, while production costs are $\gamma(1-\theta_1)$. Hence, the total surplus generated is $\mathcal{P} = (1-\kappa)\frac{1-\theta_1^2}{2}-\gamma(1-\theta_1)$. To avoid deviation, customers of type θ following strategy M need to obtain profits of at least $\nu(\theta-\theta_1)$. We can thus upper-bound the manufacturer's profit by $\mathcal{P}-\nu\frac{(1-\theta_1)^2}{2}$. Optimize this upper bound over θ_1: it is always concave and takes its maximum at $\theta_1^{AM}=\frac{\gamma+\nu}{1-\kappa+\nu}\in(0,1)$. In this case, the upper-bound becomes $\Pi^{AM}=\frac{(1-\kappa-\gamma)^2}{2(1-\kappa+\nu)}$.

Next, assume $m=1-\nu$ and $p=\nu\frac{\gamma+\nu}{1-\kappa+\nu}$. As $1-m\geq\nu$, AM is indeed the only feasible equilibrium with these prices. Note that $\theta_1=\theta_1^{AM}$. Moreover, $\Pi=\Pi^{AM}$. □

B.2. Serviziation (SV)

Proof of Lemma 2. We first show that if any customer follows $\tilde{R}$, exactly customers $\theta\in[0,\theta_1]$ follow $\tilde{R}$, for some $\theta_1\in(0,1]$. First, if customer $\theta_1>0$ follows $\tilde{R}$, then $\phi(1-u)\theta_1\geq 0$, so $\phi(1-u)\geq 0$ and, hence, $\phi(1-u)\theta\geq 0\ \forall\theta\geq 0$, so we exclude A. Second, say, to the contrary, that customer θ_2

follows $\tilde{R}$, obtaining $\phi(1-u)\theta_2$, and customer $\theta_1 < \theta_2$ follows strategy O or M. The latter customer obtains profit $a\theta_1 - p$ for some constant $a > 0$. Consider now customer $\theta = 0$. By following the strategy of θ_1, they obtain profits of $-p$. By following the strategy of θ_2, they obtain profits of 0. The customer thus weakly prefers servicization. Recall that in equilibrium, each strategy must correspond to a unique (possibly empty) subinterval on $[0,1]$. Hence, we have a contradiction.

In total, there are two equilibria to consider: $\tilde{R}O$ and $\tilde{R}M$. We note that it is never optimal for the manufacturer to have $S_{SV} > D = \int_0^1 \mathbb{1}_{\{d_\theta = \tilde{R}\}} \theta d\theta$ (any unit of equipment held for servicization beyond D has a cost of γ and no benefit). Hence, we can use $\phi = \frac{n}{n+1} \frac{S_{SV}}{\int_0^1 \mathbb{1}_{\{d_\theta = \tilde{R}\}} \theta d\theta}$.

Equilibrium $\tilde{R}O$*.* The manufacturer's profit for a threshold θ_1 is $(p-\gamma)(1-\theta_1) + \phi\frac{\theta_1^2}{2}(u - \kappa - \mu) - \phi\frac{n+1}{n}\frac{\theta_1^2}{2}\gamma$. As no customer's profit can be higher than $\nu - p$, we have $p \le \nu < \gamma$, and the manufacturer's profit is (strictly) upper-bounded by $\phi\frac{\theta_1^2}{2}\left(u - \kappa - \mu - \frac{n+1}{n}\gamma\right)$. This, in turn, is upper-bounded by $\frac{\phi}{2}\left(u - \kappa - \mu - \frac{n+1}{n}\gamma\right)$, the profit obtainable if the manufacturer only offers servicization. We will consider this as a special case of $\tilde{R}M$ and can, thus, exclude the present equilibrium.

Equilibrium $\tilde{R}M$*.* Assume $\theta_1 \in [0,1]$ is the threshold between customers using servicization and those buying the equipment. Consider the centralized problem. Buyer revenues and associated costs, are as in AM. In addition, servicization generates revenues $\phi\frac{\theta_1^2}{2}[1-\kappa-\mu] - S_{SV}\gamma = \frac{n}{n+1}\frac{2S_{SV}}{\theta_1^2}\frac{\theta_1^2}{2}[1 - \kappa - \mu] - S_{SV}\gamma = \frac{n}{n+1}S_{SV}\left[1 - \kappa - \mu - \frac{n+1}{n}\gamma\right]$. Assume first that the term in parentheses is negative. In this case, it is always better for the manufacturer to replace any servicization by abstention (by setting u high enough). Hence, we can assume wlog for the remainder of this proof that the term is positive. But then, $S_{SV} = \frac{\theta_1^2}{2}$ is optimal for any choice of θ_1.

Consider now the centralized problem under the assumption that $S_{SV} = \frac{\theta_1^2}{2}$. Total surplus is $\mathcal{P} = (1-\kappa)\frac{1-\theta_1^2}{2} - \gamma(1-\theta_1) + \frac{n}{n+1}\frac{\theta_1^2}{2}\left[1 - \kappa - \mu - \frac{n+1}{n}\gamma\right]$. To avoid deviation, customers of type θ following strategy M need to obtain a higher profit than if they were to follow strategies $\tilde{R}$ or O. We thus upper-bound the manufacturer's profit by $\mathcal{P} - \nu\frac{(1-\theta_1)^2}{2}$. Optimize this upper bound over θ_1: it is always concave and takes its maximum at $\theta_1^{\tilde{R}M} = \frac{\gamma+\nu}{1-\kappa+\gamma+\nu-\frac{n}{n+1}(1-\kappa-\mu)} \in (0,1)$. In this case, the upper-bound becomes $\Pi^{\tilde{R}M} = \frac{1}{2}\left[1 - \kappa - 2\gamma - \nu + \frac{(\gamma+\nu)^2}{1-\kappa+\gamma+\nu-\frac{n}{n+1}(1-\kappa-\mu)}\right]$.

Next, assume $m = 1-\nu$, $p = \nu\theta_1^{\tilde{R}M}$, $u = 1$, and $S_{SV} = \frac{\theta_1^{\tilde{R}M}}{2}$. As $1 - m \ge \nu$ and $u \ge 1$, $\tilde{R}M$ is indeed the only feasible equilibrium with these prices. Moreover, $\theta_1 = \theta_1^{\tilde{R}M}$ and $\Pi = \Pi^{AM}$. □

B.3. Sharing platform (SP)

Proof of Lemma 3. First, if any customer $\theta_1 \in (0,1]$ follows R in equilibrium, no customer will abstain, because $\phi > 0$ if a sharing market exists, so $\phi(1-r)\theta_1 \ge 0 \Rightarrow \phi(1-r)\theta \ge 0 \ \forall \theta \in (0,1]$ (and a customer with $\theta = 0$ will choose R by the assumption regarding indifferent customers).

Second, customers owning the equipment and maintaining it gain $y_\theta \eta(r - c - m - \mu)$ from sharing remaining usage, where $\eta = \frac{\phi D}{S}$ is the percentage of time their equipment is actually matched to a user. As $r-c-m-\mu$ is independent of the type, the additional profit is linear in y_θ, so $y_\theta \in \{0,1\}$ with an identical choice for all customers choosing M. Then, for a sharing market to exist, there need to be customers that follow strategy M, and we also require $r-c-m-\mu \geq 0$ (so that they share their equipment). A customer of type θ following M obtains $\pi_\theta^M = (1-m)\theta - p + \eta(1-\theta)(r-c-m-\mu)$. A customer of type θ following O obtains $\pi_\theta^O = \nu\theta - p$. Because $r-c-m-\mu \geq 0$, if $1-m \geq \nu$, no customer follows strategy O. Hence, assume that $1-m < \nu$. However, because also $r \leq 1$ for any customer to follow R, we then have that $r-c-m-\mu < 1-c-(1-\nu)-\mu = \nu - c - \mu < 0$. Hence, there cannot be a sharing equilibrium with customers following strategy O. This leaves two equilibria to consider: MR and RM.

Equilibrium MR. Assume the equilibrium holds. A customer θ following M obtain profits $\pi_\theta^M = (1-m)\theta - p + \eta(1-\theta)(r-c-m-\mu)$, while they obtain profits $\pi_\theta^R = \phi(1-r)\theta$ if following R. Substitute $\epsilon_2 = \phi(1-r)$ and $\epsilon_1 = 1-m-\eta\left(1-m-c-\mu-\frac{\epsilon_2}{\phi}\right)$. We then have $\pi_\theta^M = \epsilon_1\theta + K$ for some constant K, and $\pi_\theta^R = \epsilon_2\theta$. In particular, $\epsilon_2 \geq \epsilon_1$ is required to avoid deviations from equilibrium strategies. Moreover, for owners to share, $r-c-m-\mu \geq 0$, and for the manufacturer to not potentially make an infinite loss, $c \geq 0$. Substituting r and c appropriately, this can be rewritten as $m \leq 1-\epsilon_1$ and $m \geq \frac{\phi(1-\epsilon_1)+\eta\epsilon_2-\eta\phi(1-\mu)}{\phi(1-\eta)}$, respectively. However, because $\epsilon_1 \leq \epsilon_2$, $1-\epsilon_1 - \frac{\phi(1-\epsilon_1)+\eta\epsilon_2-\eta\phi(1-\mu)}{\phi(1-\eta)} = \eta\frac{\phi(\epsilon_1-\mu)-\epsilon_2}{\phi(1-\eta)} < 0$, so there is no feasible value of m.

Equilibrium RM. Assume $\theta_1 \in [0,1]$ is the threshold between customers accessing through the sharing platform, and those buying the equipment. Then, demand for access is $D = \frac{\theta_1^2}{2}$, supply is $S = \frac{(1-\theta_1)^2}{2}$, and the service level is $\phi = \frac{n}{n+1}\min\left\{1, \frac{(1-\theta_1)^2}{\theta_1^2}\right\}$. The manufacturer solves the problem $\Pi^{SP} = \max_{p,m,c,r}(m-\kappa)\frac{1-\theta_1^2}{2} + (p-\gamma)(1-\theta_1) + \phi\frac{\theta_1^2}{2}(m+c-\kappa) = (m-\kappa)\frac{1-\theta_1^2}{2} + (p-\gamma)(1-\theta_1) + \frac{n}{n+1}\min\left\{\theta_1^2,(1-\theta_1)^2\right\}\frac{m+c-\kappa}{2}$, subject to a number of constraints. In particular, (i) θ_1 must solve $\phi(1-r)\theta_1 = (1-m)\theta_1 - p + \frac{\phi D}{S}(1-\theta_1)(r-c-m-\mu) \Leftrightarrow \frac{n}{n+1}\frac{1}{\theta_1^2}\min\left\{\theta_1^2,(1-\theta_1)^2\right\}(1-r)\theta_1 = (1-m)\theta_1 - p + \frac{n}{n+1}\min\left\{\theta_1^2,(1-\theta_1)^2\right\}\frac{1}{1-\theta_1}(r-c-m-\mu)$, (ii) accessing customers must prefer strategy R to strategy A, that is, $r \leq 1$, and (iii) owners must be willing to share their equipment, that is, $r-c-m-\mu \geq 0$. There are additional constraints to avoid deviation: customers following strategy R (resp. M) need to prefer this to strategies M and O (resp. R and O). However, we will show that these constraints hold implicitly even if we optimize the manufacturer's profit only over constraints (i)-(iii). It follows that the optimal result is identical when the constraints are added.

Consider now the optimization problem with only (i)-(iii). Using constraint (i), substitute $p = \theta_1(1-m) - \frac{n}{n+1}\frac{\min\left\{\theta_1^2,(1-\theta_1)^2\right\}}{\theta_1(1-\theta_1)}\left[1-r-\theta_1(1-c-m-\mu)\right]$ into the profit function Π, and denote $\Pi(m,c,r) = \frac{1}{2}\Big((1-\theta_1)\left[\theta_1(2-m-\kappa)+m-\kappa-2\gamma\right] + \frac{n}{n+1}\frac{\min\left\{\theta_1^2,(1-\theta_1)^2\right\}}{\theta_1}\left[\theta_1\left(2(1-\mu)-m-c-\kappa\right)-2(1-r)\right]\Big)$. We then have $\frac{d\Pi(m,c,r)}{dr} = \frac{n}{n+1}\frac{\min\left\{\theta_1^2,(1-\theta_1)^2\right\}}{\theta_1} > 0$. As increasing r allows to increase the prices c and m due to constraint (iii), we have $r^* = 1$ and can rewrite $\Pi(m,c) = \Pi(m,c,1) = \frac{1}{2}\Big((1-\theta_1)\left[\theta_1(2-m-\kappa)+m-\kappa-2\gamma\right] + \frac{n}{n+1}\min\left\{\theta_1^2,(1-\theta_1)^2\right\}\left[2(1-\mu)-m-c-\kappa\right]\Big)$. Note that $\frac{d\Pi(m,c)}{dc} = -\frac{n}{n+1}\frac{\min\left\{\theta_1^2,(1-\theta_1)^2\right\}}{2} < 0$, while $\frac{d\Pi(m,c)}{dm} = \frac{1}{2}\left((1-\theta_1)^2 - \frac{n}{n+1}\min\left\{\theta_1^2,(1-\theta_1)^2\right\}\right) > 0$. At the same time, in constraint (iii), m and c have a rate of substitution of 1. It follows that $c^* = 0$ and $m^* = 1-\mu$.

Letting $r^* = 1$, $c^* = 0$, and $m^* = 1-\mu$, constraints (ii) and (iii) are fulfilled. Constraint (i) can be rewritten as $p = \mu\theta_1$, and the profit can be rewritten, in consequence, as $\Pi(p) = (1-\mu-\kappa)\frac{1-\left(\frac{p}{\mu}\right)^2}{2} + (p-\gamma)\left(1-\frac{p}{\mu}\right) + \frac{n}{n+1}\min\left\{\left(\frac{p}{\mu}\right)^2, \left(1-\frac{p}{\mu}\right)^2\right\}\frac{1-\mu-\kappa}{2}$. We need to consider three cases when optimizing over p: (a) $\theta_1 = \frac{p}{\mu} > 1/2$, (b) $\theta_1 = \frac{p}{\mu} = 1/2$, and (c) $\theta_1 = \frac{p}{\mu} < 1/2$. Before, however, we show that no customer has an incentive to deviate with the given prices. First, we have that $\pi^O_\theta = \nu\theta - p^*$. For any customer $\theta \le \theta_1$, this is upper-bounded by $\nu\theta_1 - p^* = \nu\frac{p^*}{\mu} - p^*$. But $\nu < \mu$, so the upper bound is negative. For any customer $\theta > \theta_1$, we have that $\pi^O_\theta < \pi^M_\theta \Leftrightarrow \nu\theta - p^* < \mu\theta - p^* \Leftrightarrow \nu < \mu$, which also holds. Moreover, $\pi^M_\theta - \pi^R_\theta = \mu\theta - p^*$, which is increasing in θ, and no customer will deviate from the assumed equilibrium strategy.

Consider case (a). We rewrite $\Pi(p) = (1-\mu-\kappa)\frac{1-\left(\frac{p}{\mu}\right)^2}{2} + (p-\gamma)\left(1-\frac{p}{\mu}\right) + (1-\mu-\kappa)\frac{n}{n+1}\frac{\left(1-\frac{p}{\mu}\right)^2}{2}$. This is concave in p, and the first-order condition is fulfilled at $p^* = \mu\frac{n(\gamma+2\mu-(1-\kappa))+\gamma+\mu}{1-\kappa+\mu(2n+1)}$, where we have $\Pi(p^*) = \frac{(n+1)(1-\kappa-\gamma)^2}{2(1-\kappa+\mu(2n+1))}$. The condition $\frac{p^*}{\mu} > 1/2 \Leftrightarrow 2n(\gamma+2\mu-(1-\kappa)) + 2\gamma + 2\mu > 1-\kappa+\mu(2n+1) \Leftrightarrow \gamma > (2n+1)(1-\kappa-\gamma-\mu)$ also implies that $p \ge 0$. Assume that the condition does not hold. Then, case (b) must be strictly dominant over any choice of p that enables case (a). Similarly, if the condition does hold, case (a) must lead to a higher profit than case (b).

Next, consider (b). Here, $p^* = \frac{\mu}{2} \ge 0$, and $\Pi(p^*) = \frac{4(n+1)(1-\kappa-\gamma)-(2n+1)\mu-(1-\kappa)}{8(n+1)}$. Finally, consider (c). We rewrite $\Pi(p) = (1-\mu-\kappa)\frac{1-\left(\frac{p}{\mu}\right)^2}{2} + (p-\gamma)\left(1-\frac{p}{\mu}\right) + (1-\mu-\kappa)\frac{n}{n+1}\frac{\left(\frac{p}{\mu}\right)^2}{2}$. This is concave in p, and the first-order condition is fulfilled at $p^* = \mu\frac{(n+1)(\gamma+\mu)}{1-\kappa+\mu(2n+1)}$. The condition $\frac{p^*}{\mu} < 1/2 \Leftrightarrow n \le \frac{1-\kappa-\mu-2\gamma}{2\gamma}$ can never be fulfilled, so we can exclude the case. □

B.4. Comparison of business models

Proof of Proposition 1. First, compare SV and SA: $\Pi^{SV} - \Pi^{SA} = \frac{(\gamma+\nu)^2\left(\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right)}{2(1-\kappa+\nu)\left(1-\kappa+\gamma+\nu-\frac{n}{n+1}(1-\kappa-\mu)\right)}$. This is positive for the entire relevant range of SV, that is, whenever $\frac{n}{n+1}(1-\kappa-\mu) > \gamma$.

Next, compare SP(a) and SA: $\Pi^{SP(a)} - \Pi^{SA} = \frac{(1-\kappa-\gamma)^2}{2(1-\kappa+\nu)(1-\kappa+(2n+1)\mu)}\left[n(1-\kappa-\mu)-(n+1)(\mu-\nu)\right]$. This is positive if and only if $n(1-\kappa-\mu) > (n+1)(\mu-\nu)$.

Third, compare SV and SP(b): $\frac{d\left(\Pi^{SP(b)}-\Pi^{SV}\right)}{d\gamma} = \frac{(1-\kappa+n\mu)^2}{2(1-\kappa+(n+1)(\nu+\gamma)+n\mu)^2} > 0$. Let $\overline{\gamma}$ be the unique value such that $\Pi^{SP(b)} = \Pi^{SV}$. Some algebra reveals $\frac{d\overline{\gamma}}{dn} < 0$, $\overline{\gamma} < \mu-\nu+\frac{1-\kappa-\mu}{3n}$ and $\lim_{n\to\infty}\overline{\gamma} = \mu-\nu$.

The condition for case (a) of SP to be feasible is not fulfilled at the boundary $\overline{\gamma}$. In particular, case (a) is the relevant SP-case if and only if $\gamma > \frac{2n+1}{2(n+1)}(1-\kappa-\mu)$. Assume that case (a) is feasible at the boundary between SV and SP(b), that is, $\overline{\gamma} > \frac{2n+1}{2(n+1)}(1-\kappa-\mu)$, and that SV is actually relevant (in that it dominates SA), that is, $\frac{n}{n+1}(1-\kappa-\mu) > \overline{\gamma}$. Then, we have $\overline{\gamma} > \frac{2n+1}{2n}\frac{n}{n+1}(1-\kappa-\mu) > \frac{2n+1}{2n}\overline{\gamma}$, which is a contradiction. It follows that it is never necessary to compare SP(a) and SV and that SV is the dominant case if and only if $\gamma < \min\left\{\overline{\gamma}, \frac{n}{n+1}(1-\kappa-\mu)\right\}$.

Finally, compare SP(b) and SA: Note that, purely algebraically, the function $\Pi^{SP(a)} \geq \Pi^{SP(b)}$, even when SP(a) is, strictly speaking, not feasible. Hence, we can use $\Pi^{SP(a)}$ as an upper bound. Because $\Pi^{SP(a)} < \Pi^{SA} \Leftrightarrow 1-\mu-(\mu-\nu)\frac{n+1}{n} < \kappa$, we know that SP(b) is dominated by SA for that same range. Moreover, if $\gamma \leq \frac{n}{n+1}(1-\kappa-\mu)$, we have SV dominating SA, so SP(b), if already dominating SV, will dominate SA by transitivity.

Hence, we need to compare SP(b) and SA only for $\gamma > \frac{n}{n+1}(1-\kappa-\mu)$ and $\kappa \leq 1-\mu-(\mu-\nu)\frac{n+1}{n}$. In particular, $\Pi^{SP(b)} - \Pi^{SA} = \frac{1}{8(1-\kappa+\nu)(n+1)}\left[4(n+1)(\gamma+\nu)(1-\kappa-\gamma)-(1-\kappa+\nu)(1-\kappa+(2n+1)\mu)\right]$. We show that the term in square parentheses is always decreasing in κ within this range: $\frac{d}{d\kappa}4(n+1)(\gamma+\nu)(1-\kappa-\gamma)-(1-\kappa+\nu)(1-\kappa+(2n+1)\mu) < 0 \Leftrightarrow 2(1-\kappa)+\nu+(2n+1)\mu-4(n+1)\nu < 4(n+1)\gamma$. We can lower-bound γ, using $\gamma > \frac{n}{n+1}(1-\kappa-\mu)$ to arrive at the sufficient condition $2(2n-1)\kappa < 4\nu(n+1)-\nu-(6n+1)\mu+2(2n-1)$. Here, we can upper-bound κ using $\kappa \leq 1-\mu-(\mu-\nu)\frac{n+1}{n}$ to arrive at the sufficient condition $-\nu(2+n)-\mu(2n^2-n-2) < 0$. The term $2n^2-n-2$ is positive for any $n \geq 2$, so $\Pi^{SP(b)} - \Pi^{SA}$ can cross zero at most once as κ is reduced.

Consider the upper bound on κ: $\Pi^{SP(b)} - \Pi^{SA}|_{\kappa=1-\mu-(\mu-\nu)\frac{n+1}{n}} = \frac{-[\mu-\nu+2n(\mu-\nu-\gamma)]^2}{8n((2n+1)\mu-\nu)} \leq 0$. Moreover, let $\tilde{\kappa} = 1-\mu-(\mu-\nu)\frac{3(n+1)}{3n-1}$ and $\Delta = \Pi^{SP(b)} - \Pi^{SA}|_{\kappa=\tilde{\kappa}}$, with $\frac{d^2\Delta}{d\gamma^2} = -4(3n-1)^2$. Hence, $\Delta \geq 0$ if this is true at the bounds of γ. In particular, we have $\gamma > \frac{n}{n+1}(1-\tilde{\kappa}-\mu) = \frac{3n(\mu-\nu)}{3n-1}$ and, for case (b) to be relevant, $\gamma \leq \frac{2n+1}{2(n+1)}(1-\tilde{\kappa}-\mu) = \frac{3(2n+1)(\mu-\nu)}{2(3n-1)}$. Note that $\Delta|_{\gamma=\frac{3n(\mu-\nu)}{3n-1}} = \frac{\mu(\mu-\nu)}{8((3n+1)\mu-2\nu)} > 0$ and $\Delta|_{\gamma=\frac{3(2n+1)(\mu-\nu)}{2(3n-1)}} = \frac{(\mu-\nu)((6n+1)\mu-3\nu)}{16(3n-1)((3n+1)\mu-2\nu))} > 0$. Thus, $\Pi^{SP(b)} - \Pi^{SA}|_{\kappa=\tilde{\kappa}} \geq 0$, and the result follows. □

Proof of Corollary 1. If $n \to \infty$, the manufacturer's business model choice simplifies as follows:

- SV, iff $\gamma \leq 1-\kappa-\mu$ and $\gamma \leq \mu-\nu$,
- SP, iff $\mu-\nu < \gamma \leq 1-\kappa$ and $\kappa \leq 1+\nu-2\mu$,
- SA, iff $1-\kappa-\mu < \gamma \leq 1-\kappa$ and $\kappa > 1+\nu-2\mu$.

The manufacturer is optimally inactive for any other parameter combination.

A reduction in the rate of revenue generation by $\psi < 1$ for maintained equipment can easily reflected by replacing all occurrences of 1 by $1-\psi$, including in the boundary conditions. For a reduction in the revenue generation from unmaintained equipment, we need to consider the fact that this cannot become negative. In particular, if $\psi > \nu$, then using unmaintained equipment cannot be efficient, even if the equipment comes for free. This corresponds to $\nu = 0$. For our results regarding SA and SV to hold under $\nu = 0$, we require $m = 1-\epsilon$ (or $m = 1-\psi-\epsilon$) for arbitrarily small $\epsilon > 0$. Hence, we can approximate the comparison results arbitrarily well by letting $\epsilon = 0$ and replacing all occurrences of ν by $(\nu-\psi)^+$. After adjustments, we thus have

- SV, iff $\gamma \leq 1-\psi-\kappa-\mu$ and $\gamma \leq \mu-(\nu-\psi)^+$,

- SP, iff $\mu-(\nu-\psi)^+<\gamma\leq 1-\psi-\kappa$ and $\kappa\leq 1-\psi+(\nu-\psi)^+-2\mu$,
- SA, iff $1-\psi-\kappa-\mu<\gamma\leq 1-\psi-\kappa$ and $\kappa>1-\psi+(\nu-\psi)^+-2\mu$.

Otherwise, the manufacturer is inactive. The result follows from a geometric comparison. □

Appendix C: Proofs related to the environmental impact

C.1. Comparisons between business models

Proof of Lemma 4. Under SA, the total production quantity is $prod_{SA}=1-\theta_1^{SA}$, while under SV, the total production quantity is $prod_{SV}=1-\theta_1^{SV}+S^{SV}$, where S^{SV} is the quantity produced for servicization customers and equals $\frac{\left(\theta_1^{SV}\right)^2}{2}$. Thus, the difference is $prod_{SV}-prod_{SA}=\frac{1}{2}\frac{\gamma+\nu}{(1-\kappa+\nu)(\gamma+\nu+\mu)^2}\left[(\gamma+\mu+\nu)\left(2(\gamma+\mu)-(1-\kappa-\nu)\right)-\mu(1-\kappa+\nu)\right]$. Assume that SV is the optimal business model compared to SA, that is, we have $1-\kappa-\gamma-\mu>0$ and $\gamma<\mu-\nu$. The difference in production quantities can be positive or negative: for example, if $\kappa=0.1$, $\gamma=0.2$, $\mu=0.5$, and $\nu=0.1$, the difference is -0.02. On the other hand, if $\nu=0.2$, the difference is 0.08.

Under SA, the total usage is $usage_{SA}=\int_{\theta_1^{SA}}^1\theta d\theta=\frac{1-\left(\theta_1^{SA}\right)^2}{2}$, while under SV, it is $usage_{SV}=\int_{\theta_1^{SV}}^1\theta d\theta+\phi^{SV}\int_0^{\theta_1^{SV}}\theta d\theta=\frac{1}{2}$. Thus, the difference is $usage_{SV}-usage_{SA}=\frac{(\gamma+\nu)^2}{2(1-\kappa+\nu)^2}>0$.

Because the usage under SV is always higher than under SA, there must be an environmental cost of usage beyond which total environmental impact of the SV business model is higher than for the SA business model. On the other hand, for the environmental impact under the SV model to be lower, the production quantity must be less, i.e., $(\gamma+\mu+\nu)\left(2(\gamma+\mu)-(1-\kappa-\nu)\right)<\mu(1-\kappa+\nu))$, and the environmental cost of production must be sufficiently large.

Consider now SP. Assume first that SP (case a) is optimal, that is, $\mu>1-\kappa-\gamma$ and $1-\kappa-\mu>\mu-\nu$. The production quantity under the SP model is $prod_{SP(a)}=1-\theta_1^{SP(a)}$, so we have $prod_{SP(a)}-prod_{SA}=\frac{(1-\kappa-\gamma)(1-\kappa-\mu-(\mu-\nu))}{2\mu(1-\kappa+\nu)}$. Within the range considered, this is always positive.

Usage is $usage_{SP(a)}=\int_{\theta_1^{SP(a)}}^1\theta d\theta+\phi^{SP(a)}\int_0^{\theta_1^{SP(a)}}\theta d\theta$. Hence, $usage_{SP(a)}-usage_{SA}=\frac{(1-\kappa-\gamma)[(1-\kappa+\nu)(1-\kappa-\mu-(\mu-\nu))+\mu(1-\kappa-\gamma)]}{2\mu(1-\kappa+\nu)^2}$. Again, within the range considered, this is positive. As both the production quantity and the usage are higher under SP when case a is the optimal choice, the environmental impact is always higher.

Assume now that SP (case b) is optimal, that is, $\mu\leq 1-\kappa-\gamma$ and $\gamma>\mu-\nu$. We have $prod_{SP(b)}=1-\theta_1^{SP(b)}$, so $prod_{SP(b)}-prod_{SA}=\frac{2\gamma-(1-\kappa-\nu)}{2(1-\kappa+\nu)}$. This difference can be positive or negative: for example, if $\kappa=0.1$, $\mu=0.3$, $\nu=0.1$, and $\gamma=0.3$ (resp. $\gamma=0.5$), the difference is -0.2 (resp. 0.2).

Usage is $usage_{SP(b)}=\int_{\theta_1^{SP(b)}}^1\theta d\theta+\phi^{SP(b)}\int_0^{\theta_1^{SP(b)}}\theta d\theta=\frac{1}{2}$, as under SV, so the comparison with SA follows as in the proof of Lemma 4. Because usage is always higher under SP case b than under SA, but production can be lower or higher, we can draw the same conclusions regarding the environmental impact. To complete the proof, note that $\frac{1-\kappa-\nu}{2}\leq 1-\kappa-\mu\Leftrightarrow\mu-\nu\leq 1-\kappa-\mu$. As the latter condition is required for SP to be optimal, $\gamma<\frac{1-\kappa-\nu}{2}$ implies that we are in case b. □

Proof of Proposition 2. In the absence of SP, SV constitutes the optimal choice if and only if $\mu < 1-\kappa-\gamma$. Hence, we only need to compare SV with SP (case b). We have $prod_{SP(b)} - prod_{SV} = -\frac{\mu^2}{2(\gamma+\mu+\nu)^2} < 0$ and $usage_{SP(b)} - usage_{SV} = 0$. Together with the comparison between SA and SP (case a) in the proof of Lemma 4, the result follows. □

C.2. Comparison with the triple bottom line

Proof of Lemma 5. We assume that the social planner produces $S = S_M + S_{\tilde{R}}$ units of equipment. It allocates S_M to customers that become owners, and can use the equipment to fulfill their usage requirements. The equipment used will always be maintained, because $1-\kappa > \nu$. Moreover, remaining usage of this equipment can be allocated to fulfill non-owner demand, incurring the extra cost μ. The social planner also retains $S_{\tilde{R}}$ units to fulfill further customer demands of non-owners, incurring the extra cost μ. We further assume that the demand by non-owners (whether served form the S_M units distributed or from the $S_{\tilde{R}}$ units kept) is fulfilled according to the queueing system outlined in Section 3, where demands from all non-owners are combined.

The social planner considers all revenues by customers, all costs to incur the revenues, as well as the environmental impact. Hence, the social planner solves the following problem:

$$PPP = \max_{\substack{S_M, S_{\tilde{R}}, \\ \Theta_{\tilde{R}}, \Theta_R, \Theta_M}} \int_{\Theta_{\tilde{R}} \cup \Theta_R} \phi[1-\kappa-\mu-e_u]\theta d\theta + \int_{\Theta_M} [1-\kappa-e_u]\theta d\theta - (S_M + S_{\tilde{R}})(\gamma + e_p)$$

$$s.t. \phi \int_{\Theta_R} \theta d\theta \leq \int_{\Theta_M} (1-\theta) d\theta, \quad \int_{\Theta_M} d\theta \leq S_M,$$

$$\phi = \min\left\{1, \frac{S_M - \int_{\Theta_M} \theta d\theta + S_{\tilde{R}}}{\int_{\Theta_{\tilde{R}} \cup \Theta_R} \theta d\theta}\right\},$$

$$\Theta_i \subseteq [0,1], \quad \Theta_i \cap \Theta_j = \emptyset \ \forall i,j \in \tilde{R}, R, M.$$

As in the case of profit-maximization, each customer strategy has a contribution that is linear in θ, so an optimal allocation consists of a sequence of strategies (A, $\tilde{R}$, R, or M) on the unit interval corresponding to usage requirements, without repetitions. If the contribution of an individual strategy is positive, moreover, its contribution is non-decreasing in the level of usage. Also, the slope for M-customers is largest ($1-\kappa-e_u$ versus $\phi(1-\kappa-\mu-e_u)$ for $\tilde{R}$- and R-customers), so the optimal allocation is of the form A for the lowest usage requirements, R or $\tilde{R}$ for intermediate usage requirements, and M for high usage requirements (not all strategies have to necessarily exist in the optimal allocation). Finally, while the slope is the same for strategies R and $\tilde{R}$, R-customers do not cause additional costs from extra equipment, as they use equipment S_M produced for M-customers. On the other hand, $\tilde{R}$-customers require extra equipment to be produced. As a result, there can only be $\tilde{R}$-customers if all remaining usage of equipment S_M is used by R-customers. In total, we consider the following allocations: $A\tilde{R}$, AM, ARM, $AR\tilde{R}M$, and $A\tilde{R}RM$.

Allocation $A\tilde{R}$. The problem simplifies to $PPP = \max_{\theta_1, S_{\tilde{R}}} \min\left\{1, \frac{S_{\tilde{R}}}{\int_{\theta_1}^1 \theta d\theta}\right\} \int_{\theta_1}^1 (1-\kappa-\mu-e_u)\theta d\theta - S_{\tilde{R}}(\gamma+e_p) = \max_{\theta_1, S_{\tilde{R}}} \min\left\{\frac{1-\theta_1^2}{2}, S_{\tilde{R}}\right\}(1-\kappa-\mu-e_u) - S_{\tilde{R}}(\gamma+e_p)$. It is clear that it can never be optimal to have $S_{\tilde{R}} > \frac{1-\theta_1^2}{2}$. At the same time, the result is linear in $S_{\tilde{R}}$ for any choice of $S_{\tilde{R}} \leq \frac{1-\theta_1^2}{2}$. If $1-\kappa-\gamma-\mu-e_u-e_p < 0$, abstention is preferred. Otherwise, $\theta_1^* = 0$ (to maximize $S_{\tilde{R}}$), resulting in $PPP^{\tilde{R}} = \frac{1-\kappa-\gamma-\mu-e_u-e_p}{2}$.

Allocation AM. The problem simplifies to $PPP = \max_{\theta_1, S_M} \frac{1-\theta_1^2}{2}(1-\kappa-e_u) - S_M(\gamma+e_p)$ *s.t.* $1-\theta_1 \leq S_M$. It is easy to see that $S_M = 1-\theta_1$ at optimum. If $1-\kappa-\gamma-e_u-e_p < 0$, abstention is preferred. Otherwise, $\theta_1^* = \frac{\gamma+e_p}{1-\kappa-e_u}$ and $PPP^{AM} = \frac{\left(1-\kappa-\gamma-e_u-e_p\right)^2}{2(1-\kappa-e_u)}$.

Allocation ARM. The problem simplifies to $PPP = \max_{\theta_1, \theta_2, S_M} \min\left\{\frac{\theta_2^2-\theta_1^2}{2}, S_M - \frac{1-\theta_2^2}{2}\right\}(1-\kappa-\mu-e_u) + \frac{1-\theta_2^2}{2}(1-\kappa-e_u) - S_M(\gamma+e_p)$ *s.t.* $\min\left\{\frac{\theta_2^2-\theta_1^2}{2}, S_M - \frac{1-\theta_2^2}{2}\right\} \leq \frac{(1-\theta_2)^2}{2}, \quad 1-\theta_2 \leq S_M$.

First, assume that θ_1 and θ_2 are set such that $\frac{\theta_2^2-\theta_1^2}{2} \geq S_M - \frac{1-\theta_2^2}{2}$. Then, S_M influences the objective function in a linear manner. Either $1-\kappa-\gamma-\mu-e_u-e_p > 0$, in which case S_M will be as high as possible (that is $S_M = \frac{(1-\theta_2)^2}{2} + \frac{1-\theta_2^2}{2} = 1-\theta_2$). Alternatively, $1-\kappa-\gamma-\mu-e_u-e_p \leq 0$, in which case S_M is at the lower bound, that is, again, $S_M = 1-\theta_2$. We can thus rewrite the objective function as $(1-\theta_2)\frac{2(1-\kappa-\gamma-\mu-e_u-e_p)+\mu(1+\theta_2)}{2}$ and the case constraint as $\theta_2 \geq \frac{1+\theta_1^2}{2}$. Because the objective is independent of θ_1 and the constraint becomes tighter as θ_1 grows, we can assume wlog that $\theta_1 = 0$. The objective is concave in θ_2. Hence, there are two possible options: the interior solution $\theta_2 = -\frac{1-\kappa-\gamma-\mu-e_u-e_p}{\mu}$ and the boundary solution $\theta_2 = 1/2$. The former is feasible if and only if $\theta_2 \geq 1/2 \Leftrightarrow 2(\gamma+e_p) \geq 2(1-\kappa-e_u) - \mu$ and $\theta_2 \leq 1 \Leftrightarrow 1-\kappa-\gamma-e_u-e_p \geq 0$ (where the latter condition is necessary for the social planner not to prefer abstention over any allocation). We then have $PPP^{RM(a)} = \frac{(1-\kappa-\gamma-e_u-e_p)^2}{2\mu}$ and $PPP^{RM(b)} = \frac{4(1-\kappa-\gamma-e_u-e_p)-\mu}{8}$, respectively.

Finally, assume that θ_1 and θ_2 are set such that $\frac{\theta_2^2-\theta_1^2}{2} \leq S_M - \frac{1-\theta_2^2}{2}$. Clearly, again, $S_M = 1-\theta_2$ is optimal. We can then rewrite the objective function as $\frac{(1-\kappa-e_u)(1-\theta_1^2)-2(\gamma+e_p)(1-\theta_2)-\mu(\theta_2^2-\theta_1^2)}{2}$ and the (case, respectively first) constraint as $\theta_2 \leq \frac{1+\theta_1^2}{2}$.

The Hessian of the objective function with respect to θ_1 and θ_2 is $\begin{pmatrix} -(1-\kappa-\mu-e_u) & 0 \\ 0 & -\mu \end{pmatrix}$, so the objective is concave if $1-\kappa-\mu-e_u > 0$ (which is a necessary condition for the contribution from R-customers to be positive and can thus be assumed wlog). The boundary solution $\frac{\theta_2^2-\theta_1^2}{2} = S_M - \frac{1-\theta_2^2}{2}$ has already been covered. Hence, assume the interior solution: $\theta_1 = 0$, $\theta_2 = \frac{\gamma+e_p}{\mu}$. This is feasible if and only if $\theta_2 \leq \frac{1}{2} \Leftrightarrow 2(\gamma+e_p) \leq \mu$, in which case, we have $PPP^{RM(c)} = \frac{1-\kappa-e_u-2(\gamma+e_p)}{2} + \frac{(\gamma+e_p)^2}{2\mu}$.

Allocations $AR\tilde{R}M$ and $A\tilde{R}RM$. Say customers $\theta \in [0, \theta_1)$ are allocated to A, customers $\theta \in [\theta_1, \theta_2)$ to R or $\tilde{R}$, and customers $\theta \in [\theta_2, 1]$ to M. As in the previous cases, we can show that $S_M = 1-\theta_2$ must be optimal. We can, thus, rewrite the objective as $\max_{\theta_1, \theta_2, S_{\tilde{R}}} \min\left\{\frac{\theta_2^2-\theta_1^2}{2}, \frac{(1-\theta_2)^2}{2} + S_{\tilde{R}}\right\}(1-\kappa-\mu-e_u) + \frac{1-\theta_2^2}{2}(1-\kappa-e_u) - (1-\theta_2+S_{\tilde{R}})(\gamma+e_p)$.

The second constraint holds due to the aforementioned equality. The first constraint is automatically fulfilled, because $\int_{\Theta_R} \theta d\theta = \frac{\theta_2^2-\theta_1^2}{2} \frac{\frac{(1-\theta_2)^2}{2}}{\frac{(1-\theta_2)^2}{2}+S_{\tilde{R}}}$, so, $\phi \int_{\Theta_R} \theta d\theta = \min\left\{\frac{\frac{\theta_2^2-\theta_1^2}{2}}{\frac{(1-\theta_2)^2}{2}+S_{\tilde{R}}}, 1\right\} \frac{(1-\theta_2)^2}{2}$, which must be smaller or equal to the righ-hand side, $\frac{(1-\theta_2)^2}{2}$.

Assume first that $\frac{\theta_2^2-\theta_1^2}{2} \geq \frac{(1-\theta_2)^2}{2} + S_{\tilde{R}}$. We can rewrite the objective as $(1-\theta_2+S_{\tilde{R}})(1-\kappa-\gamma-e_u-e_p) - \mu\left[S_{\tilde{R}} + \frac{(1-\theta_2)^2}{2}\right]$. This is linear in $S_{\tilde{R}}$ and the cross-partial derivative to $S_{\tilde{R}}$ and θ_2 is zero. Hence, it must be optimal to have $S_{\tilde{R}} = \frac{\theta_2^2-\theta_1^2}{2} - \frac{(1-\theta_2)^2}{2} = \frac{-1+2\theta_2-\theta_1^2}{2}$ (or return to another allocation entirely). Because θ_1 does not influence the objective function, but a lower θ_1 implies a higher $S_{\tilde{R}}$, we have $\theta_1 = 0$ and $S_{\tilde{R}} = \theta_2 - 1/2$. Plugging this into the objective function, the derivative to θ_2 is $-\mu\theta_2$. But with $\theta_2 = 0$, we get to the allocation M, which is weakly dominated by AM.

Assume next that $\frac{\theta_2^2-\theta_1^2}{2} \leq \frac{(1-\theta_2)^2}{2} + S_{\tilde{R}}$. The objective can be rewritten as $\frac{(1-\kappa-e_u)(1-\theta_1^2)-2(\gamma+e_p)(1-\theta_2+S_{\tilde{R}})-\mu(\theta_1+\theta_2)(\theta_2-\theta_1)}{2}$. Again, this is linear in $S_{\tilde{R}}$, while the cross-partial derivatives to $S_{\tilde{R}}$ and θ_1 (resp. θ_2) are zero. In particular, the derivative to $S_{\tilde{R}}$ is $-\gamma-e_p$, so $S_{\tilde{R}}$ will be at the lower bound, that is, $S_{\tilde{R}} = \frac{\theta_2^2-\theta_1^2}{2} - \frac{(1-\theta_2)^2}{2}$. Plugging this into the objective function, the derivatives to θ_1 and θ_2 are $-\theta_1(1-\kappa-\gamma-\mu-e_u-e_p)$ and $-\mu\theta_2$, respectively. Hence, it must be optimal to have $\theta_2 = \theta_1$, which corresponds to the case AM.

Comparison. For any allocation to be preferable to abstention, we require that $1-\kappa-\gamma-e_u-e_p \geq 0$, so we will assume this wlog. First, we note that $RM(b)$ is always feasible. $PPP^{RM(b)} - PPP^{\tilde{R}} = \frac{3\mu}{8}$, so $\tilde{R}$ can never be optimal. Second, $RM(a)$ and $RM(c)$ (interior solutions) must be preferred to $RM(b)$ (a boundary solution), whenever they are feasible. Third, some algebra shows that $RM(a)$ and $RM(c)$ dominate AM whenever $1-\kappa-\mu-e_u > 0$. However, when this is the case, we have $2(1-\kappa-e_u)-\mu > \mu$. Note that $RM(a)$ is feasible only if $2(\gamma+e_p) \geq 2(1-\kappa-e_u)-\mu$, while $RM(c)$ is feasible only if $2(\gamma+e_p) \leq \mu$, so only one of the two can be feasible. Finally, assume $1-\kappa-\mu-e_u > 0$, but that neither $RM(a)$ nor $RM(c)$ are feasible. That is, we must have $\mu < 2(\gamma+e_p) < 2(1-\kappa-e_u)-\mu$. However, $PPP^{RM(b)} - PPP^{AM} = \frac{(\gamma+e_p)\left[2(1-\kappa-e_u)-\mu-2(\gamma+e_p)\right]+(1-\kappa-\gamma-e_u-e_p)\left[2(\gamma+e_p)-\mu\right]}{8(1-\kappa-e_u)}$, which then is positive. □

Proof of Proposition 3. First, note that when $1-\kappa-\gamma-e_u-e_p < 0$, the social planner will abstain, so the environmental impact of the manufacturer must be worse. Thus, assume $1-\kappa-\gamma-e_u-e_p \geq 0$ and consider the different business models of the manufacturer in turn:

Business model SA: $1-\kappa-\gamma-\mu \leq 0$ and $1-\kappa-\mu-(\mu-\nu) \leq 0$. Say $1-\kappa-\mu-e_u \leq 0$ (social planner chooses AM). $prod^{SA} - prod^{AM} = \frac{e_p(1-\kappa+\nu)+e_u(\gamma+\nu)-\nu(1-\kappa-\gamma)}{(1-\kappa-e_u)(1-\kappa+\nu)}$ and $usage^{SA} - usage^{AM} = \frac{1}{2}\frac{(e_p+\gamma)^2(1-\kappa+\nu)^2-(\gamma+\nu)^2(1-\kappa-e_u)^2}{(1-\kappa-e_u)^2(1-\kappa+\nu)^2}$. Both terms are positive if either e_p or e_u is sufficiently large.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \geq 2(1-\kappa-e_u)-\mu$ (social planner chooses $RM(a)$). $prod^{SA} - prod^{RM(a)} = \frac{\mu(1-\kappa-\gamma)-(1-\kappa+\nu)\left(1-\kappa-\gamma-e_p-e_u\right)}{\mu(1-\kappa+\nu)}$ and $usage^{SA} - usage^{RM(a)} = \frac{1}{2}\left[\frac{\mu-2(1-\kappa-\gamma-e_u-e_p)}{\mu} - \frac{(\gamma+\nu)^2}{(1-\kappa+\nu)^2}\right]$. Again, both terms are positive if either e_p or e_u is sufficiently large.

Say $\mu < 2(\gamma + e_p) < 2(1-\kappa-e_u)-\mu$ (social planner chooses $RM(b)$). $prod^{SA} - prod^{RM(b)} = \frac{1-\kappa-\nu-2\gamma}{2(1-\kappa+\nu)}$ and $usage^{SA} - usage^{RM(b)} = -\frac{(\gamma+\nu)^2}{2(1-\kappa+\nu)^2}$. Usage is always less. Hence, for the manufacturer to have a higher environmental impact, $2\gamma > 1-\kappa-\nu$ is needed, as well as high e_p and low e_u.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \le \mu$ (social planner chooses $RM(c)$). $prod^{SA} - prod^{RM(c)} = \frac{(\gamma+e_p)(1-\kappa+\nu)-\mu(\gamma+\nu)}{\mu(1-\kappa+\nu)}$ and $usage^{SA} - usage^{RM(c)} = -\frac{(\gamma+\nu)^2}{2(1-\kappa+\nu)^2}$. Hence, for the manufacturer to have a higher impact, e_p needs to be high (and e_u low).

To complete the proof for SA, note that if $e_u < 1-\kappa-\mu$, the social planner chooses $RM(a)$, $RM(b)$, or $RM(c)$. In particular, $RM(c)$ if $e_p < \frac{\mu}{2}-\gamma$, $RM(b)$ if $e_p \ge \frac{\mu}{2}-\gamma$ and $e_p+e_u \le 1-\kappa-\gamma-\frac{\mu}{2}$, and $RM(a)$ otherwise. That is, for any e_u, the social planner would select $RM(c)$ for low e_p, $RM(b)$ for intermediate e_p, and $RM(a)$ for high e_p. In all cases, if the environmental impact is higher for the manufacturer for a given e_p, it remains higher for higher values of e_p. In the case of $RM(a)$, the same holds true for e_u. For $RM(b)$ and $RM(c)$, if the environmental impact is lower for the manufacturer for a given e_u, it remains lower for a higher level of e_u. Moreover, the impact of each case is identical at the boundaries. Then, we note that the environmental impact of the manufacturer must be better than that of the social planner if $e_p \approx 0$, because of the lower usage under $RM(b)$ and $RM(c)$, one of which is always chosen by the social planner when $e_p \approx 0$.

Second, consider $e_u = 0$ and $1-\kappa-\mu \le 0$ (so $e_u \ge 1-\kappa-\mu$). In this case, $prod^{SA} - prod^{AM} |_{e_p=0,e_u=0} = \frac{-\nu(1-\kappa-\gamma)}{(1-\kappa)(1-\kappa+\nu)} < 0$ and $usage^{SA} - usage^{AM} |_{e_p=0,e_u=0} = \frac{1}{2}\left(\frac{\gamma^2}{(1-\kappa)^2} - \frac{(\gamma+\nu)^2}{(1-\kappa+\nu)^2}\right) < 0$.

Business model SV: $1-\kappa-\gamma-\mu > 0$ *and* $\gamma \le \mu-\nu$. Say $1-\kappa-\mu-e_u \le 0$. $prod^{SV} - prod^{AM} = \frac{(\gamma+e_p)}{(1-\kappa-e_u)} - \frac{(\gamma+\nu)(\gamma+2\mu+\nu)}{2(\gamma+\mu+\nu)^2}$ and $usage^{SV} - usage^{AM} = \frac{(\gamma+e_p)^2}{2(1-\kappa-e_u)^2}$. The difference in impact $\Delta = e_P \times (prod^{SV} - prod^{AM}) + e_U \times (usage^{SV} - usage^{AM})$ is increasing in e_u and μ, and convex in e_p.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \ge 2(1-\kappa-e_u)-\mu$. $prod^{SV} - prod^{RM(a)} = \frac{\mu-2(1-\kappa-\gamma-e_p-e_u)}{2\mu} + \frac{\mu^2}{2(\gamma+\mu+\nu)^2}$ and $usage^{SV} - usage^{RM(a)} = \frac{\mu-2(1-\kappa-\gamma-e_p-e_u)}{2\mu}$. Because both usage and production costs are always higher, so is the environmental impact of the manufacturer.

Say $\mu < 2(\gamma+e_p) < 2(1-\kappa-e_u)-\mu$. $prod^{SV} - prod^{RM(b)} = \frac{\mu^2}{2(\gamma+\mu+\nu)^2}$ and $usage^{SV} - usage^{RM(b)} = 0$, so the impact of the manufacturer is always higher.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \le \mu$. $prod^{SV} - prod^{RM(c)} = \frac{\gamma+e_p}{\mu} - \frac{\gamma+\nu}{2(\gamma+\mu+\nu)}\left(2 - \frac{\gamma+\nu}{\gamma+\mu+\nu}\right)$ and $usage^{SV} - usage^{RM(c)} = 0$. At $e_p = 0$, the production difference can be positive or negative. At $e_p = \frac{\mu}{2}-\gamma$, the production difference is $\frac{\mu^2}{2(\gamma+\mu+\nu)^2}$. Hence, the manufacturer's impact is higher when e_p is sufficiently large, but the difference does not depend on e_u.

To complete the proof for SV, we first observe that, under the case conditions, there are two options for the strategies of the social planner. Either $2\gamma \ge \mu$, in which case $RM(c)$ is never optimal, or $2\gamma < \mu$, in which case there are values of e_p and e_u such that any strategy can be optimal.

We first show that if $2\gamma \ge \mu$ (i.e., $RM(c)$ is never optimal), SV can never have a lower impact than AM. In particular, because the difference in impacts, Δ, is decreasing in both e_u and μ, it can be lower-bounded by letting $e_u = 1-\kappa-\mu$. We know that the usage-difference is always positive, so focus on the production difference. At this value of e_u, it is $\frac{2(e_p+\gamma)(\gamma+\nu+\mu)^2-\mu(\gamma+\nu)(\gamma+\nu+2\mu)}{2\mu(\gamma+\nu+\mu)^2} \geq \frac{2\gamma(\gamma+\nu+\mu)^2-\mu(\gamma+\nu)(\gamma+\nu+2\mu)}{2\mu(\gamma+\nu+\mu)^2}$. Then, noting that $\frac{d}{d\gamma}\left(2\gamma(\gamma+\nu+\mu)^2-\mu(\gamma+\nu)(\gamma+\nu+2\mu)\right) = 2(3\gamma+\nu)(\gamma+\nu+\mu) > 0$, consider the numerator of the lower bound at $\gamma = \frac{\mu}{2}$: here, it is μ^3, implying that the production-difference can be lower-bounded by a positive term.

Hence, assume $2\gamma < \mu$. The social planner chooses $RM(c)$ if $e_u < 1-\kappa-\mu$ and $e_p < \frac{\mu}{2}-\gamma$, and it chooses AM if $e_u \geq 1-\kappa-\mu$. In the former case, we have established that the manufacturer's environmental impact is lower iff $e_p < \mu(\gamma+\nu)\frac{\gamma+\nu+2\mu}{2(\gamma+\nu+\mu)^2}-\gamma$ (independent of e_u). Consider now the impact difference between SV and AM at the boundary, that is at $e_u = 1-\kappa-\mu$, and recall that it is higher for any higher value of e_u and the same value of e_p. In particular, denote this (lower bound) by $\tilde{\Delta}$ and note that $\tilde{\Delta}\mid_{e_p=0} = \frac{\gamma^2(1-\kappa-\mu)}{2\mu^2} > 0$. We can rewrite $\tilde{\Delta} = \frac{(e_p+\gamma)^2(1-\kappa-\mu)}{2\mu^2} - \frac{e_p}{\mu}\left[\mu(\gamma+\nu)\frac{\gamma+\nu+2\mu}{2(\gamma+\nu+\mu)^2}-\gamma-e_p\right]$. Hence, if there is no range in which the social planner chooses $RM(c)$ and the manufacturer's impact is lower, then there is also no range in which it chooses AM and the manufacturer's impact is lower. If such a range exists, and $e_u \geq 1-\kappa-\mu$ is sufficiently small, than there can be a convex subset $E_p \subseteq \left(0, \mu(\gamma+\nu)\frac{\gamma+\nu+2\mu}{2(\gamma+\nu+\mu)^2}-\gamma\right)$ such that the social planner chooses AM and the manufacturer's impact is smaller iff $e_p \in E_p$. The fact that this set can indeed exist can be shown by letting $\kappa = \frac{225}{1024}$, $\gamma = \frac{53}{2048}$, $\mu = \frac{3}{4}$, $\nu = \frac{3}{256}$, $e_u = \frac{1}{32}$, and $e_p = \frac{3}{1024}$.

Business model SP, case a: $1-\kappa-\gamma-\mu < 0$ *and* $1-\kappa-\mu-(\mu-\nu) > 0$. Say $1-\kappa-\mu-e_u \leq 0$. $prod^{SP(a)} - prod^{AM} = \frac{(1-\kappa-\mu-(\mu-\nu))(1-\kappa-e_u)-(1-\kappa-e_u-\mu)(\gamma+\nu)+\mu(\gamma-\nu+2e_p)}{2\mu(1-\kappa-e_u)} > 0$ and $usage^{SP(a)} - usage^{AM} = \left(prod^{SP(a)} - prod^{AM}\right) + \frac{(1-\kappa-\gamma-e_u-e_p)^2}{2(1-\kappa-e_u)^2} > 0$. Hence, the manufacturer's impact is higher.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \geq 2(1-\kappa-e_u)-\mu$. $prod^{SP(a)} - prod^{RM(a)} = usage^{SP(a)} - usage^{RM(a)} = \frac{2(e_p+e_u)-(1-\kappa-\gamma)}{2\mu}$, so the manufacturer's impact is lower iff $e_p+e_u < \frac{1-\kappa-\gamma}{2}$.

Say $\mu < 2(\gamma+e_p) < 2(1-\kappa-e_u)-\mu$. $prod^{SP(a)} - prod^{RM(b)} = usage^{SP(a)} - usage^{RM(b)} = \frac{1-\kappa-\gamma-\mu}{2\mu} < 0$. Hence, the manufacturer's impact is always lower.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \leq \mu$. For this to be feasible, we need that $\gamma \leq \frac{\mu}{2}$. But then, $0 < 1-\kappa-\mu-(\mu-\nu) \leq 1-\kappa-2\gamma-(\mu-\nu) = 1-\kappa-\gamma-\mu-(\gamma-\nu) < 0$, leading to a contradiction.

Business model SP, case b: $1-\kappa-\gamma-\mu \geq 0$ *and* $\gamma > \mu-\nu$. Say $1-\kappa-\mu-e_u \leq 0$. $prod^{SP(b)} - prod^{AM} = \frac{e_u+2e_p-(1-\kappa-2\gamma)}{2(1-\kappa-e_u)}$, $usage^{SP(b)} - usage^{AM} = \frac{(\gamma+e_p)^2}{2(1-\kappa-e_u)^2}$. Also, $e_u+2e_p-(1-\kappa-2\gamma) \geq (1-\kappa-\mu)+0-(1-\kappa-2\gamma) = 2\gamma-\mu > \gamma-(\mu-\nu) > 0$, so the manufacturer's impact is always higher.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \geq 2(1-\kappa-e_u)-\mu$. $prod^{SP(b)} - prod^{RM(a)} = usage^{SP(b)} - usage^{RM(a)} = \frac{2(\gamma+e_p)-2(1-\kappa-e_u)+\mu}{2\mu}$, so the manufacturer's impact is always higher.

Say $\mu < 2(\gamma+e_p) < 2(1-\kappa-e_u)-\mu$. $prod^{SP(b)} - prod^{RM(b)} = usage^{SP(b)} - usage^{RM(b)} = 0$.

Say $1-\kappa-\mu-e_u > 0$ and $2(\gamma+e_p) \leq \mu$. For this to be feasible, we need that $2\gamma \leq \mu$. But then, $\gamma > \mu-\nu \geq 2\gamma-\nu$. Because $\gamma > \nu$, this is a contradiction.

To complete the proof regarding SP, we only need to consider case a ($1-\kappa-\gamma-\mu<0$). Clearly, a necessary condition for the manufacturer's impact to be lower is $e_u < 1-\kappa-\mu$. In that case, the social planner will either choose $RM(a)$ or $RM(b)$ (recall that the conditions for $RM(c)$ to be feasible are contradictory to the ones for SP to be feasible). In particular, the social planner will choose $RM(b)$ if $e_p+e_u<1-\kappa-\gamma-\frac{\mu}{2}$, and $RM(a)$ otherwise. Moreover, $1-\kappa-\gamma-\frac{\mu}{2}<\frac{1-\kappa-\gamma}{2} \Leftrightarrow 1-\kappa-\gamma-\mu<0$, which is part of the case conditions. The result follows. □

Appendix D: Results and proofs related to the secondary market

D.1. The effect of a secondary market on ownership-based models

A customer may follow one of six strategies in a static equilibrium:

- Buy new equipment when none is owned. Then,
  - — $d_\theta = O$: use it without maintenance for one period and sell it on the secondary market in the next,
  - — $d_\theta = O'$: use it without maintenance for two periods,
  - — $d_\theta = M$: use it with maintenance for one period and sell it on the secondary market in the next,
  - — $d_\theta = M'$: use it with maintenance for one period and without maintenance for the next.
- $d_\theta = S$: Buy equipment on secondary market and use it for one period.
- $d_\theta = A$: Abstain.

We denote the strategy chosen by customer θ with d_θ and, for the case of indifference and wlog, we assume that owning equipment from the current period is preferred to owning equipment from the previous period, which is preferred to abstaining. We first exclude two strategies:

LEMMA 6. *No customer chooses strategies O' or M' in equilibrium.*

Proof. If customer θ chooses O', then it must outperform O and S, so $\nu\theta - \frac{p}{2} \geq \nu\theta - p + p_s \Leftrightarrow p \geq 2p_s$ and $\nu\theta - \frac{p}{2} \geq \nu\theta - p_s \Leftrightarrow p \leq 2p_s$. Hence, O' can only be weakly preferred, at $2p_s = p$, in which case the assumption that indifferent customers choose more recent goods will favor O. If customer θ chooses M', then it must outperform M, so $(1-m)\theta - p + p_s \leq 1/2\,[(1-m)\theta + \nu\theta - p] \Leftrightarrow 1/2\,[(1-m)\theta - p] \leq 1/2\nu\theta - p_s$. But then, $1/2\,[(1-m)\theta + \nu\theta - p] \leq \nu\theta - p_s$, so strategy S is preferred over strategy M'. Hence, M' can only be weakly preferred, in which case the assumption that indifferent customers choose more recent goods will favor M. □

The manufacturer generates revenue from the sale of equipment and from maintenance fees. It solves the problem: $\Pi^{SA} = \max_{p,m} \int_0^1 \mathbb{1}_{\{d_\theta=O\}}[p-\gamma] + \mathbb{1}_{\{d_\theta=M\}}\,[p-\gamma+(m-\kappa)\theta]\,d\theta$, subject to a feasible secondary market outcome. That is, there must be at least as much supply as there is fulfilled demand, i.e. $\int_0^1 \mathbb{1}_{\{d_\theta=M\}} d\theta \geq \int_0^1 \mathbb{1}_{\{d_\theta=S\}} d\theta$ (with equality if $p_s > 0$).

As in the case without a secondary market, any equilibrium must correspond to a sequence of strategies, such that all customers with θ between zero and a first threshold follow the first strategy, all customers with θ between the first threshold and a second one follow the second strategy, etc., up to $\theta = 1$. However, not all permutations of strategies may be attained in equilibrium:

LEMMA 7. *The manufacturer will only induce the following equilibria, or business models:*

- *SM: Customers $\theta \in [0, \theta_1)$ follow strategy S, customers $\theta \in [\theta_1, 1]$ follow strategy M, for some $0 < \theta_1 < 1$.*
- *ASM: Customers $\theta \in [0, \theta_1)$ follow strategy A, customers $\theta \in [\theta_1, \theta_2)$ follow strategy S, customers $\theta \in [\ \theta_2, 1]$ follow strategy M, for some $0 \leq \theta_1 < \theta_2 < 1$.*

Proof. Assume a customer chooses strategy O or M, but that there are no customers choosing S. Then, $p_s = 0$, so no customer will abstain. Moreover, note that if one customer prefers strategy O to S (resp. S to O), then all others do so, as well. This is because customer θ prefers O to S if and only if $\nu\theta - p + p_s \geq \nu\theta - p_s \Leftrightarrow 2p_s \geq p$, while prices p and p_s are identical for all customers. The same holds true for strategies O and M. In summary, it follows that we need to consider six possible equilibria: AMS, ASM, SM, MS, O, M.

Equilibria AMS and MS. For either to be feasible, $p \geq 2p_s$ is required, otherwise O is preferred to S for all customers. Consider customer θ' that is indifferent between M and S: $(1-m)\theta' - p + p_s = \nu\theta' - p_s \Leftrightarrow \theta' = \frac{p-2p_s}{1-m-\nu}$. For $\theta' \in (0, 1]$, we require $1 - m - \nu \geq 0$. However, if also $(1-m)\theta' - p + p_s = \nu\theta' - p_s$, then $(1 - m - v)(\theta - \theta') \geq 0$ for all $\theta \geq \theta'$, and no customer prefers S over M.

Equilibrium O. For this to be feasible, $p = 0$ is needed. The manufacturer's profit in this case is $\Pi = -\gamma$, so they will prefer to stay out of the market altogether.

Equilibrium M. For this to be feasible, $p = 0$ is needed. Moreover, $m \leq 1 - \nu$, or customers deviate to O. If, for example, $m = 1 - \nu$, M is the preferred strategy for all customers, so the equilibrium emerges, and the manufacturer's profit is $\frac{1-\kappa-\nu}{2} - \gamma$, which may be positive. This is also the maximum profit due to the upper bound on m, so $\Pi^M = \frac{1-\kappa-\nu}{2} - \gamma$.

Equilibrium ASM. Let $m = 1 - \nu - \epsilon$ for some $\epsilon \in (0, 1 - \nu]$ and $p = \frac{2\nu(2\gamma+5\nu-(1-\kappa))+\epsilon(8\nu+\gamma)+\epsilon^2}{1-\kappa+7\nu+\epsilon}$, and assume $2\gamma + 5\nu > 1 - \kappa$ (so $p > 0$). Strategy M is preferred to O because $1 - m \geq \nu$. For the same reason, if there are customers choosing S and customers choosing M, then those choosing S must have lower usage requirements. Assume first that $p_s = 0$ is the market clearing price. Then, there must be a threshold θ_1 such that customers $\theta \in [0, \theta_1)$ follow strategy S and customers $\theta \in [\theta_1, 1]$ follow M. Profits must be equal at θ_1, so we find that $\theta_1 = {}^{p}/_{\epsilon}$. However, $\theta_1 > {}^{1}/_{2} \Leftrightarrow 2\gamma + 5\nu + \epsilon > 1 - \kappa$, which contradicts the assumption that $p_s = 0$ (there is less supply than demand for secondary equipment). Hence, $p_s > 0$ must be the market clearing price, and the customers with the lowest usage requirement abstain. We can find the threshold θ_1 (resp. θ_2) that equalizes profits of A

and S (resp. S and M) as a function of p_s. Our equilibrium concept then implies that p_s solves $\theta_2-\theta_1=1-\theta_2$. This is the case at $p_s=\frac{\nu(2\gamma+5\nu-(1-\kappa)+\epsilon)}{1-\kappa+7\nu+\epsilon}$, which is positive by assumption. Moreover, we have $\theta_1=\frac{2\gamma+5\nu-(1-\kappa)+\epsilon}{1-\kappa+7\nu+\epsilon}$ and $\theta_2=\frac{\gamma+6\nu+\epsilon}{1-\kappa+7\nu+\epsilon}$. It is easy to verify that $0<\theta_1<\theta_2<1$, so the equilibrium is consistent with expectations and no customer prefers to deviate. The manufacturer, in turn, receives a profit of $\Pi^{ASM(\epsilon)}=\frac{(1+\nu-\kappa-\gamma)^2}{2(1-\kappa+7\nu+\epsilon)}>0$, so it does not deviate either.

Equilibrium SM. Let $m=1-\nu-\epsilon$ for some $\epsilon\in(0,1-\nu]$ and $p=\frac{\gamma\epsilon}{1-\kappa-\nu}$ and assume $2\gamma<1-\kappa-\nu$. As before, M is preferred to O and customers choosing S must have lower usage requirements. Assume first that $p_s>0$ is the market clearing price. We can find the threshold θ_1 (resp. θ_2) that equalizes profits of A and S (resp. S and M) as a function of p_s. Our equilibrium concept then implies that p_s solves $\theta_2-\theta_1=1-\theta_2$. This is the case at $p_s=\frac{\epsilon\nu(2\gamma-(1-\kappa-\nu))}{(1-\kappa-\nu)(4\nu+\epsilon)}$, which is negative by assumption, leading to a contradiction. Hence, $p_s=0$. It follows that customers $\theta\in[0,\theta_1)$ choose strategy S and customers $\theta\in[\theta_1,1]$ choose M for a threshold θ_1 which equalizes both. We have $\theta_1=\frac{\gamma}{1-\kappa-\nu}<1/2$, so the equilibrium is consistent with expectations and no customer prefers to deviate. The manufacturer, in turn, receives a profit of $\Pi^{SM(\epsilon)}=\frac{(1-\kappa-\nu-\epsilon)(1-\kappa-\nu-\gamma)^2}{2(1-\kappa-\nu)^2}$, so it does not deviate either, as long as ϵ is chosen sufficiently small.

Comparing equilibria. We exclude M as follows, noting that $\epsilon>0$ was chosen arbitrarily small: Assume first that $2\gamma<1-\kappa-\nu$. We have $\Pi^{SM(0)}>\Pi^M\Leftrightarrow(1-\kappa-\nu)^2-2\gamma(1-\kappa-\nu)+\gamma^2>(1-\kappa-\nu)^2-2\gamma(1-\kappa-\nu)$, which is true. Assume next that $2\gamma\geq 1-\kappa-\nu$. We have $\Pi^{ASM(0)}>\Pi^M\Leftrightarrow(\gamma+2\nu)^2+4\nu\left[2\gamma-(1-\kappa-\nu)\right]>0$, which is again true.

Finally, note that $\Pi^{ASM(0)}\geq\Pi^{SM(0)}$ if $2\gamma\geq 1-\kappa-\nu$. If $2\gamma<1-\kappa-\nu$, then $\Pi^{ASM(0)}\geq\Pi^{SM(0)}\Leftrightarrow\gamma\geq\frac{3(1-\kappa-\nu)-\sqrt{(1-\kappa-\nu)(1-\kappa+7\nu)}}{4}$ (in which case also $1-\kappa-5\nu-2\gamma<0$). □

We can now show the optimal strategies in each of these sub-business models. Unless $2\gamma+5\nu>1-\kappa$, ASM degenerates to SM, so we will assume this without loss of generality.

Lemma 8. *The manufacturer maximizes its profit from the ASM business model by inducing customers $\theta\in[0,\theta_1)$ to abstain, customers $\theta\in[\theta_1,\theta_2)$ to buy used equipment, and customers $\theta\in[\theta_2,1]$ to buy new equipment and sell it on the secondary market after one period. The thresholds and profit, respectively, are $\theta_1^{ASM}=\frac{2\gamma+5\nu-(1-\kappa)}{1-\kappa+7\nu}$, $\theta_2^{ASM}=\frac{1+\theta_1^{ASM}}{2}$, and $\Pi^{ASM}=\frac{\left(1-\left(\theta_2^{ASM}\right)^2\right)[1-\kappa-\nu]}{2}-(1-\theta_2^{ASM})\,\gamma+\theta_1\,(1-\theta_1^{ASM})\,\nu$.*

Proof. Consider the centralized problem. Buyers of new equipment generate net-revenues per period of $(1-\kappa)\frac{1-\theta_2^2}{2}$, secondary market participants generate $\nu\frac{\theta_2^2-\theta_1^2}{2}$, and production costs are $\gamma\,(1-\theta_2)$. Hence, the total surplus generated is $\mathcal{P}=(1-\kappa)\frac{1-\theta_2^2}{2}+\nu\frac{\theta_2^2-\theta_1^2}{2}-\gamma\,(1-\theta_2)$. To avoid deviation, customers of type θ following strategy S need to obtain profits of at least $\nu(\theta-\theta_1)$, and customers following strategy M need to obtain a higher profit than if they were to follow strategy S. We can thus upper-bound the manufacturer's profit by $\mathcal{P}-\nu\frac{(1-\theta_1)^2}{2}$. Rewrite θ_1 as a function of θ_2 (using the secondary market equilibrium $\theta_2 - \theta_1 = 1 - \theta_1$) and optimize the upper bound over θ_2. It is always concave in θ_2 and takes its maximum at $\theta_2^{ASM} = \frac{6\nu+\gamma}{1-\kappa+7\nu} < 1$. This is larger $1/2$ (required for a feasible secondary equilibrium) iff $1-\kappa < 5\nu + 2\gamma$. If $1-\kappa \geq 5\nu + 2\gamma$, the only option is $\theta_2 = 1/2$, leading to SM. Thus, we can assume $1-\kappa < 5\nu + 2\gamma$, and we see that $\Pi^{ASM(\epsilon)} \leq \Pi^{ASM} = \frac{(1+\nu-\kappa-\gamma)^2}{2(1-\kappa+7\nu)}$. In particular, with the prices from the proof of Lemma 7 and $\epsilon \to 0$, we have that $\Pi^{ASM(\epsilon)} \to \Pi^{ASM}$, while ASM is indeed the only feasible equilibrium. As ϵ can be arbitrarily close to zero, we will simply write $\Pi = \Pi^{ASM}$. □

Finally, consider the business model SM:

LEMMA 9. *The manufacturer maximizes its profit from the SM business model by inducing customers $\theta \in [0, \theta_1)$ to buy used equipment, and customers $\theta \in [\theta_1, 1]$ to buy new equipment and sell it on the secondary market after one period. The threshold and profit, respectively, are* $\theta_1^{SM} = \min\left\{\frac{\gamma}{1-\kappa-\nu}, \frac{1}{2}\right\}$ *and* $\Pi^{SM} = \frac{\left(1-\left(\theta_1^{SM}\right)^2\right)[1-\kappa-\nu]}{2} - (1-\theta_1^{SM})\gamma$.

Proof. Consider the centralized problem. New equipment buyers generate net-revenues per period of $(1-\kappa)\frac{1-\theta_1^2}{2}$, secondary market buyers generate $\nu\frac{\theta_1^2}{2}$, and production costs are $\gamma(1-\theta_1)$. Hence, the total surplus generated is $\mathcal{P} = (1-\kappa)\frac{1-\theta_1^2}{2} + \nu\frac{\theta_1^2}{2} - \gamma(1-\theta_1)$. To avoid deviation, customers of type θ following strategy S need to obtain profits of at least $\nu\theta$, and customers following M need to obtain a higher profit than if they were to follow S. Thus, an upper bound on the manufacturer's profit is $(1-\kappa)\frac{1-\theta_1^2}{2} + \nu\frac{\theta_1^2}{2} - \gamma(1-\theta_1) - \nu\frac{1}{2}$. This is strictly concave in θ_1. Because SM can only emerge when $1-\theta_1 \geq \theta_1 \Leftrightarrow \theta_1 \leq 1/2$, the term is maximized at

$$\theta_1^{SM} = \begin{cases} \frac{\gamma}{1-\kappa-\nu}, & \text{if } 2\gamma < 1-\kappa-\nu, \\ 1/2, & \text{otherwise.} \end{cases} \text{ with } \Pi^{SM} = \begin{cases} \frac{(1-\kappa-\nu-\gamma)^2}{2(1-\kappa-\nu)}, & \text{if } 2\gamma < 1-\kappa-\nu, \\ \frac{3(1-\kappa-\nu)-4\gamma}{8}, & \text{otherwise.} \end{cases}$$

Assume $2\gamma < 1-\kappa-\nu$. With the prices as given in the proof of Lemma 7 and $\epsilon \to 0$, we have $\Pi^{SM(\epsilon)} \to \Pi^{SM}$, while SM is the only feasible equilibrium. We will simply write $\Pi = \Pi^{SM}$, as ϵ can be arbitrarily close to zero. Alternatively, if $2\gamma \geq 1-\kappa-\nu$, it is easy to verify that the prices $m = 1-\nu-\epsilon$ and $p = \frac{\epsilon}{2}$ lead to the unique equilibrium SM with $\Pi^{SM(\epsilon)} \to \Pi^{SM}$ as $\epsilon \to 0$. □

D.2. The effect of a secondary market on servicization

The manufacturer retains ownership of some equipment and charges its customers a price per unit of usage, denoted by u. Customers further retain the option to buy their own equipment. A customer may thus follow one of the strategies from before, or this additional one:

- $d_\theta = \tilde{R}$: access new equipment through servicization.

We add to the prior assumptions about indifferent customers, wlog, that they prefer access to ownership. Lemma 6 continues to hold, so we exclude strategies M' and O'. Moreover, we can exclude servicization without maintenance and strategy A as in the case without secondary market.

The manufacturer generates revenue from the sale of equipment, maintenance fees, and from servicizing equipment. It solves $\Pi^{SV} = \max_{p,m,u,S_{SV}} \int_0^1 \mathbb{1}_{\{d_\theta = O\}}[p-\gamma] + \mathbb{1}_{\{d_\theta = M\}}[p-\gamma+(m-\kappa)\theta]\, d\theta + \frac{n}{n+1}\min\left\{S_{SV}, \int_0^1 \mathbb{1}_{\{d_\theta=\tilde{R}\}} d\theta\right\}[u-\kappa-\mu] - S_{SV}\gamma$, subject to a feasible secondary market outcome.

We first present the feasible equilibria, assuming that $\frac{n}{n+1}(1-\kappa-\mu) > \gamma$. As in the case without a secondary market, this is without loss of generality, because SA is always preferred to SV otherwise.

Lemma 10. *The manufacturer will only induce the following equilibria, or business models:*

- *$\tilde{R}$: All customers follow strategy $\tilde{R}$.*
- *$\tilde{R}M$: Customers $\theta \in [0,\theta_1)$ follow strategy $\tilde{R}$, customers $\theta \in [\theta_1, 1]$ follow strategy M, for some $0 < \theta_1 < 1$.*
- *$\tilde{R}SM$: Customers $\theta \in [0,\theta_1]$ follow strategy $\tilde{R}$, customers $\theta \in (\theta_1,\theta_2)$ follow strategy S, customers $\theta \in [\theta_2, 1]$ follow strategy M, for some $0 \le \theta_1 < \theta_2 < 1$.*

Proof. As without a secondary market, we can show that if any customer follows $\tilde{R}$, exactly customers with $\theta \in [0,\theta_1]$ follow $\tilde{R}$, for some $\theta_1 \in (0,1]$, and that it is never optimal for the manufacturer to have $S \neq D = \int_0^1 \mathbb{1}_{\{d_\theta=\tilde{R}\}} d\theta$. Moreover, if one customer prefers strategy O to S (resp. S to O), then all others do so, as well, and the same holds true for strategies O and M. Hence, we let $S = \frac{\theta_1^2}{2}$ and $\phi = \frac{n}{n+1}$, and there are five equilibria to consider: $\tilde{R}MS$, $\tilde{R}SM$, $\tilde{R}M$, $\tilde{R}O$, $\tilde{R}$.

Equilibrium $\tilde{R}MS$. This can be excluded in the same way as equilibrium AMS.

Equilibrium $\tilde{R}$. The equilibrium can always be induced with sufficiently high p and servicization fee $u \le 1$. The manufacturer's profit is $\frac{\frac{n}{n+1}(u-\kappa-\mu)-\gamma}{2}$, which is maximized at $\Pi^{\tilde{R}} = \frac{\frac{n}{n+1}(1-\kappa-\mu)-\gamma}{2}$.

Equilibrium $\tilde{R}O$. Without secondary market, customers weakly prefer O' over O. Under the former, the maximum price such that any customer chooses to buy the equipment is $p = 2\nu$. Hence, equilibrium $\tilde{R}O$ requires $p \le 2\nu$. Consider the manufacturer's profit given a threshold θ_1: $\frac{\theta_1^2}{2}\left[\frac{n}{n+1}(u-\kappa-\mu)-\gamma\right] + (p-\gamma)(1-\theta_1)$. Because $p \le 2\nu < \gamma$, this is (strictly) upper-bounded by $\frac{\theta_1^2}{2}\left[\frac{n}{n+1}(u-\kappa-\mu)-\gamma\right]$. It follows that the manufacturer always prefers equilibrium $\tilde{R}$.

Equilibrium $\tilde{R}SM$. The argument follows along similar lines as for equilibrium ASM. In particular, we let $m = 1-\nu-\epsilon$ for some $\epsilon \in (0, 1-\nu]$, $u = 1$, and $p = \frac{2(n+1)\nu[2\gamma+5\nu-(1-\kappa)]+\epsilon[3(n+1)(\gamma+2\nu)-2n(1-\kappa-\mu)]}{4(1-\kappa-\mu)+(n+1)[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)]}$, and we assume that (i) $2\gamma+5\nu > 1-\kappa$, (ii) $4(1-\kappa-\mu)+(n+1)[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)] > 0$, and (iii) $2(1-\kappa-\mu)+(n+1)[2\mu+\gamma-(1-\kappa-\nu)] > 0$.

Assume first $p_s = 0$. Then, no customer uses servicization (the net benefit will be zero, versus $\nu\theta$ from secondary equipment), so $\theta_1 = 0$. Moreover, if $2\gamma+5\nu > 1-\kappa$ and $\epsilon > 0$ is sufficiently small, then $\theta_2 > 1$. Hence, we will assume that ϵ is sufficiently small such that $p_s > 0$, which is always possible at the given prices. Then, the equilibrium is such that customers $\theta \in [0,\theta_1]$ follow $\tilde{R}$, customers $\theta \in (\theta_1,\theta_2)$ follow S, and customers $\theta \in [\theta_2, 1]$ follow M, where $\theta_1 = \frac{(n+1)(2\gamma+5\nu-(1-\kappa)}{4(1-\kappa-\mu)+(n+1)[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)]}$

and $\theta_2 = \frac{1+\theta_1}{2}$. Given the assumptions, it is easy to verify that $0 < \theta_1 < \theta_2 < 1$. Again, the equilibrium is consistent with expectations and no customer prefers to deviate. The manufacturer receives profit $\Pi^{\tilde{R}SM(\epsilon)} = \frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right] + \frac{(1-\kappa-\nu)\left(1-\theta_2^2\right)}{2} - \gamma(1-\theta_2) + \nu\theta_1(1-\theta_1) + f(\epsilon)$, where $f(\epsilon)$ is some function of ϵ with $f(0) = 0$. Some algebra shows that the term can indeed be positive.

Equilibrium $\tilde{R}M$. Let $m = 1-\nu-\epsilon$ for some $\epsilon \in (0, 1-\nu]$, $p = \frac{(n+1)\gamma\epsilon}{1-\kappa+(n+1)\gamma+n\mu}$, and $u = 1-\nu\frac{n+1}{n}$, and assume $\nu \leq \frac{n}{n+1}$. The definition of m ensures that M is preferred to O and it is higher-usage customers that prefer M to $\tilde{R}$. Moreover, $\tilde{R}$ is weakly preferred to S due to the definition of u. Consider the usage requirement with equal profits from $\tilde{R}$ and M: $\theta_1 = \frac{(n+1)\gamma}{1-\kappa+(n+1)\gamma+n\mu}$. This is strictly between 0 and 1 and the manufacturer's profit can be positive: $\Pi^{\tilde{R}M(\epsilon)} = \frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-(\gamma+\nu)\right] + \frac{(1-\kappa-\nu)\left(1-\theta_1^2\right)}{2} - \gamma(1-\theta_1) + f(\epsilon)$, where $f(\epsilon)$ is some function of ϵ with $f(0) = 0$. $\square$

We can now show the optimal strategies in each sub-business model, starting with $\tilde{R}$SM. We assume that (i) $2\gamma+5\nu > 1-\kappa$, (ii) $4(1-\kappa-\mu)+(n+1)\left[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)\right] > 0$, and (iii) $2(1-\kappa-\mu)+(n+1)\left[2\mu+\gamma-(1-\kappa-\nu)\right] > 0$. If any condition is not fulfilled, the model degenerates to one of the other models, so we assume all conditions hold without loss of generality.

Lemma 11. *The manufacturer maximizes its profit from the* $\tilde{R}$*SM business model by inducing customers* $\theta \in [0, \theta_1)$ *to access the equipment through servicization, customers* $\theta \in [\theta_1, \theta_2)$ *to buy used equipment, and customers* $\theta \in [\theta_2, 1]$ *to buy new equipment and sell it on the secondary market after one period. The thresholds and profit, respectively, are* $\theta_1^{\tilde{R}SM} = \frac{(n+1)[2\gamma+5\nu-(1-\kappa)]}{4(1-\kappa-\mu)+(n+1)[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)]}$, $\theta_2^{\tilde{R}SM} = \frac{1+\theta_1^{\tilde{R}SM}}{2}$, *and* $\Pi^{\tilde{R}SM} = \frac{\left(\theta_1^{\tilde{R}SM}\right)^2\left[\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right]}{2} + \frac{\left(1-\left(\theta_2^{\tilde{R}SM}\right)^2\right)[1-\kappa-\nu]}{2} - \left(1-\theta_2^{\tilde{R}SM}\right)\gamma + \theta_1^{\tilde{R}SM}\left(1-\theta_1^{\tilde{R}SM}\right)\nu$.

Proof. Consider the centralized problem. Buyer and secondary market revenues, as well as production costs, are as in ASM. In addition, servicization generates revenues $\frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right]$, so total surplus is $\mathcal{P} = (1-\kappa)\frac{1-\theta_2^2}{2} + \nu\frac{\theta_2^2-\theta_1^2}{2} - \gamma(1-\theta_2) + \frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right]$. To avoid deviation, customers of type θ following strategy S need to obtain profits greater $\nu(\theta-\theta_1)$, and customers following strategy M need to obtain a higher profit than if they were to follow strategy S. Customers following strategy $\tilde{R}$ may obtain 0, as long as deviation to strategies S and M leads to a negative profit. We thus upper-bound the manufacturer's profit by $\mathcal{P} - \nu\frac{(1-\theta_1)^2}{2}$. Rewrite $\theta_2 = \frac{1+\theta_1}{2}$ and optimize the upper bound over the latter. Consider also the three conditions (i) $2\gamma+5\nu > 1-\kappa$, (ii) $4(1-\kappa-\mu)+(n+1)\left[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)\right] > 0$, and (iii) $2(1-\kappa-\mu)+(n+1)\left[2\mu+\gamma-(1-\kappa-\nu)\right] > 0$.

The objective function is concave if and only if condition (ii) holds. Moreover, the solution fulfilling the first-order conditions is on the interior if and only if either all conditions (i)-(iii) hold, or none. Since (ii) is required for concavity, we know that an optimal interior solution can obtain if and only if (i)-(iii) are fulfilled. In particular, the optimum threshold is $\theta_1^{\tilde{R}SM} = \frac{(n+1)(2\gamma+5\nu-(1-\kappa))}{4(1-\kappa-\mu)+(n+1)[4(\gamma+\mu+\nu)-3(1-\kappa-\nu)]} \in (0,1)$, leading to the upper bound $\Pi^{\tilde{R}SM}$. Clearly, with the prices chosen above, and letting $\epsilon \to 0$, we have $\Pi^{\tilde{R}SM(\epsilon)} \to \Pi^{\tilde{R}SM}$, while $\tilde{R}SM$ is the only feasible equilibrium. We again simply write $\Pi = \Pi^{\tilde{R}SM}$, as ϵ can be arbitrarily close to zero. Assume that either of conditions (i)-(iii) is not fulfilled. Then, θ_1 must be at an extreme point. Hence, either $\theta_1 = 1$, in which case $\tilde{R}$ dominates, or $\theta_1 = 0$, which corresponds to the equilibrium SM. □

The business model R̃M is only relevant if $\nu \leq \frac{n}{n+1}$. Otherwise, frictions for accessing customers are so high that the manufacturer cannot lower the servicization price sufficiently for none of them to buy secondary equipment instead. Hence, we can assume this without loss of generality:

Lemma 12. *The manufacturer maximizes its profit from the $\tilde{R}M$ business model by inducing customers $\theta \in [0,\theta_1)$ to access the equipment through servicization, and customers $\theta \in [\theta_1, 1]$ to buy new equipment. The threshold and profit, respectively, are $\theta_1^{\tilde{R}M} = \frac{(n+1)\gamma}{1-\kappa+(n+1)\gamma+n\mu}$ and $\Pi^{\tilde{R}M} = \frac{\left(\theta_1^{\tilde{R}M}\right)^2\left[\frac{n}{n+1}(1-\kappa-\mu)-(\gamma+\nu)\right]}{2} + \frac{\left(1-\left(\theta_1^{\tilde{R}M}\right)^2\right)[1-\kappa-\nu]}{2} - \left(1-\theta_1^{\tilde{R}M}\right)\gamma$.*

Proof. Consider the centralized problem. Buyers of new equipment generate net-revenues per period of $(1-\kappa)\frac{1-\theta_1^2}{2}$, servicization customers generate $\frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-\gamma\right]$, while production costs are $(1-\theta_1)\gamma$. To avoid deviation, customers following strategy R need to obtain profits at least as high as if they were to follow S. Because there is no demand for secondary equipment under the assumed equilibrium, but there is supply from customers following M, a customer θ following S makes $\nu\theta$. For customers following M to avoid deviation, they need to obtain $\epsilon > 0$ more than if following R. Overall, we can upper-bound the manufacturer's profit by $\frac{\theta_1^2}{2}\left[\frac{n}{n+1}(1-\kappa-\mu)-(\gamma+\nu)\right] + (1-\kappa-\nu)\frac{1-\theta_1^2}{2} - \gamma(1-\theta_1)$. This is strictly concave in θ_1 and takes its optimum, $\Pi^{\tilde{R}M}$, at $\theta_1^{\tilde{R}M} = \frac{(n+1)\gamma}{1-\kappa+(n+1)\gamma+n\mu}$. With the prices as in the proof of Lemma 10, letting $\epsilon \to 0$, we have $\Pi^{\tilde{R}M(\epsilon)} \to \Pi^{\tilde{R}M}$, while $\tilde{R}M$ is the only feasible equilibrium. Again, we simply write $\Pi = \Pi^{\tilde{R}M}$. □

Finally, consider the business model R̃, which is always feasible (as long as $\frac{n}{n+1}(1-\kappa-\mu) > \gamma$):

Lemma 13. *The manufacturer maximizes its profit from the $\tilde{R}$ business model by inducing customers $\theta \in [0,1]$ to access the equipment through servicization. The profit is $\Pi^{\tilde{R}} = \frac{\frac{n}{n+1}(1-\kappa-\mu)-\gamma}{2}$.*

Proof. This follows directly from the proof of Lemma 10. □

D.3. The effect of a secondary market on sharing

Customers have the same six strategies available as in the base case or, alternatively, the following:

- $d_\theta = R$: access new equipment through the sharing platform.

We again assume that an indifferent customer prefers accessing to owning the equipment. In a period in which a customer θ owns equipment, they may choose to generate additional income by sharing the equipment for the percentage of time $y_\theta \in [0, 1-\theta]$. Lemma 6 continues to hold, so we exclude strategies M' and O'. Moreover, as in the case without secondary markets, $y_\theta \in \{0, 1-\theta\}$ with the same choice for all customers following M, and no sharing by customers following O.

In addition to revenues from sales and after-sales, the manufacturer earns a commission. Assuming customers following M share their equipment, it solves $\Pi^{SP} = \max_{p,m,c,\phi} \int_0^1 \mathbb{1}_{\{d_\theta=O\}}[p-\gamma] + \mathbb{1}_{\{d_\theta=M\}}[p-\gamma+(m-\kappa)\theta]\,d\theta + \mathbb{1}_{\{d_\theta=R\}}\phi(c+m-\kappa)\theta$, subject to an equilibrium on the sharing market (and, possibly, the secondary market), and customers making profit-maximizing decisions.

LEMMA 14. *The manufacturer will only induce the following equilibria, or business models:*

- *RM: Customers $\theta \in [0, \theta_1)$ follow strategy R, customers $\theta \in [\theta_1, 1]$ follow strategy M, for some $0 < \theta_1 < 1$.*
- *RSM: Customers $\theta \in [0, \theta_1]$ follow strategy R, customers $\theta \in (\theta_1, \theta_2)$ follow strategy S, customers $\theta \in [\,\theta_2, 1]$ follow strategy M, for some $0 \le \theta_1 < \theta_2 < 1$.*

Proof. As in the case without a secondary market, we can show that there cannot be a sharing-equilibrium with customers following strategy O, or one where customers with a higher usage follow R and those with a lower usage follow M. Moreover, as in the case of SA, we can exclude any equilibrium wherein customers with a higher usage follow S and those with a lower usage follow M. It follows that we need to consider the equilibria SRM, RSM, and RM.

Equilibrium SRM. Customers of type θ following S obtain $\pi_\theta^S = \nu\theta - p_s$ while if they follow strategy R, they obtain profits $\pi_\theta^R = \phi(1-r)\theta$. Hence, the equilibrium can only obtain if $p_s = 0$. In that case, however, either $\phi(1-r) \ge \nu$, and all customers prefer sharing, or $\phi(1-r) < \nu$ and all customers prefer buying used equipment from the secondary market, leading to a contradiction.

Equilibrium RSM. Following the previous discussion, $p_s > 0$ must hold for this equilibrium to obtain. Thus, secondary market demand and supply must be equal, or $\theta_2 - \theta_1 = 1 - \theta_2 \Leftrightarrow \theta_2 = \frac{1+\theta_1}{2}$. Moreover, we have $\phi = \frac{n}{n+1}\min\left\{1, \frac{(1-\theta_2)^2}{\theta_1^2}\right\} = \frac{n}{n+1}\min\left\{1, \frac{(1-\theta_1)^2}{4\theta_1^2}\right\}$. Hence, we have to differentiate $\theta_1 \ge \frac{1}{3}$ (in which case, the minimum is $\frac{(1-\theta_1)^2}{4\theta_1^2}$), and $\theta_1 < \frac{1}{3}$ (in which case, the minimum is 1).

Define $\theta_1^{RSM(a)} = \frac{\gamma+2\nu-(2n+1)(1-\kappa-\mu-\gamma-2\nu)}{1-\kappa+3\nu+(2n+1)(\mu+3\nu)}$ and assume $(n+1)(3\gamma+3\nu-\mu) > (3n+2)(1-\kappa-\mu) \Leftrightarrow (n+1)(2\gamma+4\nu) > (3n+2)(1-\kappa-\mu) + (n+1)(\mu+\nu-\gamma)$. Then, $\theta_1^{RSM(a)} \in [1/3, 1]$. Let $r = 1$, $m = 1-\mu$, $c = 0$, and $p = \frac{1+\theta^{RSM(a)}}{2}(\mu+3\nu) - 2\nu$. Owners will weakly prefer to share their equipment, while low-usage customers will weakly prefer to access on the sharing market rather than abstain. Moreover, there must be buyers on the secondary market, otherwise there would be left-over secondary supply, which means a secondary price of zero and low-usage buyers strictly preferring S over R. Assume now that the secondary market price $p_s = 0$. We will show that SM is not a feasible equilibrium and, as a result, only RSM is feasible. In particular, if SM were to obtain, the threshold between S and M would be $\hat{\theta} < 1/2$ such that $\nu\hat{\theta} = (1-m)\hat{\theta} - p$. However, plugging in m and p and solving the above equation, we see that $\hat{\theta} < 1/2 \Leftrightarrow (2n+1)(1-\kappa-\mu) > (n+1)(2\gamma+4\nu)$.

For this to be feasible, we need that $(2n+1)(1-\kappa-\mu) > (3n+2)(1-\kappa-\mu)+(n+1)(\mu+\nu-\gamma) \Leftrightarrow 0 > 1-\kappa-\gamma+\nu$, which is a contradiction. Hence, RSM is the only feasible equilibrium, and it is easy to see that $\theta_1 = \theta_1^{RSM(a)}$ and $\theta_2 = \frac{1+2\theta_1^{RSM(a)}}{2}$ are the only values under which there is an equilibrium in both sharing and secondary markets, given the prices above.

Equilibrium RM. In any such equilibrium, $p_s = 0$. Hence, following strategy R needs to lead to a profit of at least $\nu\theta$. Define $\theta_1^{RM(a)} = \frac{(n+1)(\gamma+\mu-\nu)-n(1-\kappa-\mu)}{(n+1)\left(2\mu+\frac{\nu}{n}\right)+(1-\kappa-\mu)}$ and assume (i) $\left(\sqrt{\frac{1-\mu}{\nu}\frac{n+1}{n}}+1\right) \geq \frac{(2n+1)\mu+\gamma}{n(1-\kappa-\gamma+\nu)+\nu}$, and (ii) $\gamma \geq (2n+1)\left[1-\kappa-\gamma-\mu+\nu\frac{n+1}{n}\right]$. (ii) implies that $\theta_1^{RM(a)} \geq 1/2$ and (i) implies that $\theta_1^{RM(a)} \leq \frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}$. Let $r = 1 - \frac{(n+1)\nu\left(\theta_1^{RM(a)}\right)^2}{n\left(1-\theta_1^{RM(a)}\right)^2}$, $m = r-\mu$, $c = 0$, and $p = (1-m-\nu)\theta_1^{RM(a)}$. Owners will (weakly) prefer to share their equipment by definition of m, which is larger than zero due to assumption (i). Assume now that a sharing market emerges in equilibrium. Then, $\frac{n}{n+1}\min\left\{1, \frac{(1-\theta_1)^2}{\theta_1^2}\right\}(1-r)\theta_1 = (1-m)\theta_1 - p$. Assume first that $\theta_1 < 1/2$. The only solution then is $\theta_1 = \theta_1^{RM(a)}\left(1+\frac{n\nu\left(2\theta_1^{RM(a)}-1\right)}{\nu\left(\theta_1^{RM(a)}\right)^2+n\mu\left(1-\theta_1^{RM(a)}\right)^2}\right)$. But $\theta_1^{RM(a)} \geq 1/2$, so $\theta_1 \geq 1/2$, contradicting the assumption. Assume next that $\theta_1 \geq 1/2$. The two possible solutions are $\theta_1 = \theta_1^{RM(a)}$ and $\theta_1 = -\frac{n\nu\theta_1^{RM(a)}}{\nu\left(\theta_1^{RM(a)}\right)^2+n\mu\left(1-\theta_1^{RM(a)}\right)^2}$. The latter is clearly infeasible, so the only feasible equilibrium is $\theta_1 = \theta_1^{RM(a)}$. Note also that at this solution, $\phi(1-r) = \nu$, as required to avoid a deviation to RSM. ☐

We can now show the optimal strategies in each of these sub-business models, starting with RSM. This model is relevant unless either $\max\left\{2\gamma+4\nu, \frac{(n+1)(3\gamma+3\nu-\mu)}{2}\right\} \leq 1-\kappa-\mu \leq \frac{2(n+1)(\mu+3\nu)}{3n-1}$ or $\max\left\{\frac{2(n+1)(\mu+3\nu)}{3n-1}, \frac{2(n+1)(6\gamma+9\nu-\mu)}{7+3n}, \frac{(n+1)(3\gamma+3\nu-\mu)}{3n+2}\right\} \leq 1-\kappa-\mu$. In these cases, the model would degenerate to a special case of SM, so it is necessarily dominated. We will thus assume otherwise:

Lemma 15. *The manufacturer maximizes its profit from the RSM business model by inducing customers $\theta \in [0, \theta_1)$ to access the equipment through the sharing platform, customers $\theta \in [\theta_1, \theta_2)$ to buy used equipment, and customers $\theta \in [\theta_2, 1]$ to buy and share new equipment and sell it on the secondary market after one period. The thresholds and profit, respectively, are*

$$\theta_1^{RSM} = \begin{cases} \frac{\gamma+2\nu-(2n+1)(1-\kappa-\mu-\gamma-2\nu)}{1-\kappa+3\nu+(2n+1)(\mu+3\nu)}, & \text{if } 1-\kappa-\mu < \frac{(n+1)(3\gamma+3\nu-\mu)}{3n+2}, \\ \frac{(n+1)(2\gamma+5\nu-(1-\kappa)+(\mu-\nu))}{2(n+1)(\mu+3\nu)-(3n-1)(1-\kappa-\mu)}, & \text{if } \frac{(n+1)(3\gamma+3\nu-\mu)}{2} < 1-\kappa-\mu < \max\left\{\frac{2(n+1)(\mu+3\nu)}{3n-1}, 2\gamma+4\nu\right\}, \\ \frac{1}{3}, & \text{otherwise}, \end{cases}$$

$\theta_2^{RSM} = \frac{1+\theta_1^{RSM}}{2}$, *and* $\Pi^{RSM} = \frac{n}{n+1}\left(\mathbb{1}_{\{\theta_1^{RSM}<1/3\}}\frac{\left(\theta_1^{RSM}\right)^2}{2} + \mathbb{1}_{\{\theta_1^{RSM}\geq 1/3\}}\frac{\left(1-\theta_1^{RSM}\right)^2}{8}\right)[1-\kappa-\mu] + \frac{\left(1-\left(\theta_2^{RSM}\right)^2\right)[1-\kappa-\nu]}{2} - \left(1-\theta_2^{RSM}\right)\gamma + \theta_1^{RSM}\left(1-\theta_1^{RSM}\right)\nu - \frac{\left(1-\theta_1^{RSM}\right)^2[\mu-\nu]}{8}$.

Proof. Assume that $\theta_1 \geq \frac{1}{3}$ (so, $\theta_2 = \frac{1+\theta_1}{2}$) and consider the centralized problem. Buyer and secondary market revenues, as well as production costs, are as in ASM. In addition, sharing customers generate revenues $\frac{n}{n+1}\frac{(1-\theta_1)^2}{8}[1-\kappa-\mu]$, so $\mathcal{P} = (1-\kappa)\frac{3-2\theta_1-\theta_1^2}{8} + \nu\frac{1+2\theta_1-3\theta_1^2}{8} - \gamma\frac{1-\theta_1}{2} +$

$\frac{n}{n+1}\frac{(1-\theta_1)^2}{8}[1-\kappa-\mu]$. To avoid deviation, a customer θ following S needs to obtain profits greater $\nu(\theta-\theta_1)$. A customer following M needs to be willing to share their equipment, so $r-m-c-\mu\geq 0$, which implies that $m\leq 1-\mu$. Thus, a customer θ following M will obtain profit greater or equal $\mu\left(\theta-\frac{1+\theta_1}{2}\right)$. Finally, customers following R may obtain 0, as long as deviation to S or M leads to a negative profit. Hence, upper-bound the profit by $\mathcal{P}-\nu\frac{(1-\theta_1)^2}{2}-(\mu-\nu)\frac{(1-\theta_1)^2}{8}$. This has its optimum at $\theta_1^{RSM(a)}=\frac{\gamma+2\nu-(2n+1)(1-\kappa-\mu-\gamma-2\nu)}{1-\kappa+3\nu+(2n+1)(\mu+3\nu)}$ and we denote the corresponding value with $\Pi^{RSM(a)}$. Threshold $\theta_1^{RSM(a)}$ is always smaller 1. It is greater $\frac{1}{3}$ if and only if $(n+1)(3\gamma+3\nu-\mu)>(3n+2)(1-\kappa-\mu)$. Say this is not the case—then, we need to consider either the optimum resulting under the assumption $\theta_1<\frac{1}{3}$, or $\theta^{RSM(b)}=\frac{1}{3}$ (with corresponding value $\Pi^{RSM(b)}$).

Consider the manufacturer's problem and assume $(n+1)(3\gamma+3\nu-\mu)>(3n+2)(1-\kappa-\mu)$. With the prices as in the proof of Lemma 14, there is no deviation, $\theta_1=\theta_1^{RSM(a)}$, and $\Pi=\Pi^{RSM(a)}$. Assume now that $(n+1)(3\gamma+3\nu-\mu)\leq(3n+2)(1-\kappa-\mu)$ and let the prices $r=1$, $m=1-\mu$, and $p=\frac{1+\theta^{RSM(b)}}{2}(\mu+3\nu)-2\nu=\frac{2\mu}{3}$. As with ASM, we only need to consider a deviation to the equilibrium SM with threshold $\hat{\theta}$. Solve $\nu\hat{\theta}=(1-m)\hat{\theta}-p$ with the given prices. Then, $\hat{\theta}<1/2\Leftrightarrow 4\mu<3(\mu-\nu)\Leftrightarrow\mu+3\nu<0$, which is a contradiction, meaning that RSM is the only feasible equilibrium. As before, it is easy to see that $\theta_1=\theta_1^{RSM(b)}$ and $\Pi=\Pi^{RSM(b)}$ with the chosen prices.

Return to the centralized problem and assume $\theta_1<\frac{1}{3}$. Only the final term of $\mathcal{P}$ changes, becoming $\frac{n}{n+1}\frac{\theta_1^2}{2}[1-\kappa-\mu]$. The conditions to avoid deviations are unchanged, so the upper bound on the manufacturer's profit remains $\mathcal{P}-\nu\frac{(1-\theta_1)^2}{2}-(\mu-\nu)\frac{(1-\theta_1)^2}{8}$. This is concave iff $2(n+1)(\mu+3\nu)>(3n-1)(1-\kappa-\mu)$, denoted (i), in which case the maximum value, $\Pi^{RSM(c)}$, is achieved at $\theta_1^{RSM(c)}=\frac{(n+1)(2\gamma+5\nu-(1-\kappa)+(\mu-\nu))}{2(n+1)(\mu+3\nu)-(3n-1)(1-\kappa-\mu)}$. Note that, assuming (i) holds, $\theta_1^{RSM(c)}<\frac{1}{3}\Leftrightarrow(n+1)(3\gamma+3\nu-\mu)<2(1-\kappa-\mu)$, denoted (ii), and $\theta_1^{RSM(c)}>0\Leftrightarrow 2\gamma+5\nu-(1-\kappa)+(\mu-\nu)>0$, denoted (iii).

Consider again the manufacturer's problem and let the prices $r=1$, $m=1-\mu$, and $p=\frac{1+\theta_1^*}{2}(\mu+3\nu)-2\nu$, where $\theta_1^*\in\left\{0,\theta_1^{RSM(c)}\right\}$. We again only need to consider a deviation to SM with threshold $\hat{\theta}$. Solving $\nu\hat{\theta}=(1-m)\hat{\theta}-p$, we have that $\hat{\theta}<1/2\Leftrightarrow-\theta_1^*(\mu+3\nu)>0$. Hence RSM is again the only feasible equilibrium. If (iii) does not hold, either the optimal choice, assuming $\theta_1<\frac{1}{3}$, is $\theta_1^*=0$, which means a deviation to an SM type model, or we can ignore the case because it is dominated by case $RSM(b)$. As before, $\theta_1=\theta_1^*$ with the chosen prices and the corresponding upper bound on profits is attained.

To compare the different options, first assume (i) holds. Then, if $RSM(a)$ is feasible, we also have that (ii) does not hold, so $RSM(a)$ constitutes the optimal choice. If $RSM(a)$ is not feasible, and (ii) still does not hold, $RSM(b)$ constitutes the optimal choice. Finally, if (ii) holds, then the optimal choice is either $RSM(c)$ if (iii) also holds, or the business model is dominated by SM.

Second, assume (i) does not hold, so there is no interior solution to $RSM(c)$. Either $RSM(a)$ is feasible, or it will be optimal to deviate to $RSM(b)$ or the business model is dominated by SM. When $RSM(a)$ is feasible, this is always preferred to $RSM(b)$, which completes the cases. □

The business model RM is only feasible if $\frac{1-\mu}{\nu} \geq \frac{n+1}{n}$. Otherwise, frictions for accessing customers are so high that the manufacturer cannot lower the servicization price sufficiently for none of them to buy secondary equipment instead. Hence, we can assume this without loss of generality:

LEMMA 16. *The manufacturer maximizes its profit from the RM business model by inducing customers $\theta \in [0, \theta_1)$ to access the equipment through the sharing platform and customers $\theta \in [\theta_1, 1]$ to buy and share new equipment. The threshold and profit, respectively, are*

$$\theta_1^{RM} = \begin{cases} \frac{1}{2}, & \text{if } \gamma \leq (2n+1)\left[1-\kappa-\gamma-\mu+\nu\frac{n+1}{n}\right], \\ \frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}, & \text{if } \sqrt{\frac{1-\mu}{\nu}\frac{n+1}{n}}+1 \leq \frac{(2n+1)\mu+\gamma}{n(1-\kappa-\gamma+\nu)+\nu}, \\ \frac{(n+1)(\gamma+\mu-\nu)-n(1-\kappa-\mu)}{(n+1)\left(2\mu+\frac{\nu}{n}\right)+(1-\kappa-\mu)}, & \text{otherwise,} \end{cases}$$

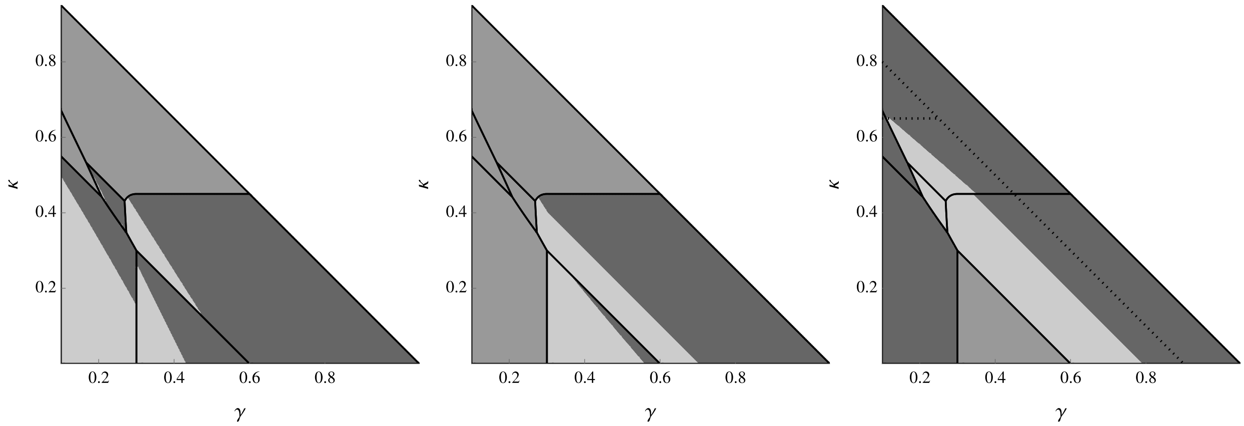
and $\Pi^{RM} = \frac{n}{n+1}\frac{\left(1-\theta_1^{RM}\right)^2[1-\kappa-\mu]}{2} + \frac{\left(1-\left(\theta_1^{RM}\right)^2\right)[1-\kappa-\nu]}{2} - (1-\theta_1^{RM})\gamma - \frac{2n+1}{n}\frac{\left(\theta_1^{RM}\right)^2\nu}{2} - \frac{\left(1-\theta_1^{RM}\right)^2[\mu-\nu]}{2}$.

Proof. Assume that $\theta_1 \geq 1/2$ and consider the centralized problem. Then, $\phi = \frac{n}{n+1}\frac{(1-\theta_1)^2}{\theta_1^2}$. We have $\mathcal{P} = (1-\kappa)\frac{1-\theta_1^2}{2} - \gamma(1-\theta_1) + \frac{n}{n+1}\frac{(1-\theta_1)^2}{2}(1-\kappa-\mu)$. At the same time, accessing customers need to obtain at least $\nu\theta$, which is only possible if $\phi(1-r) \geq \nu \Leftrightarrow \theta_1 \leq \frac{1}{1+\sqrt{\nu\frac{n+1}{n}}}$. Owners need to be induced to share, that is $r - m - c - \mu \geq 0$. We can upper-bound r using the previous inequality, that is $r \leq 1 - \nu\frac{n+1}{n}\frac{\theta_1^2}{(1-\theta_1)^2}$. Hence, we have that $0 \leq c + m \leq 1 - \mu - \nu\frac{n+1}{n}\frac{\theta_1^2}{(1-\theta_1)^2}$. Because $c, m \geq 0$ are required to avoid an infinite loss, this implies $\theta_1 \leq \frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}$. Note that $\frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}} \leq \frac{1}{1+\sqrt{\nu\frac{n+1}{n}}} \Leftrightarrow 1 \geq \sqrt{1-\mu}$, so only the second upper bound is relevant. Note also that $\frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}} \geq 1/2 \Leftrightarrow \frac{1-\mu}{\nu} \geq \frac{n+1}{n}$ which we will assume henceforth (otherwise the case is irrelevant).

Based on the accessing customers' minimum profits, and the fact that $m \leq r - \mu$, a buyer of type θ obtains at least $\nu\theta_1 + \left(\mu + \nu\frac{n+1}{n}\frac{\theta_1^2}{(1-\theta_1)^2}\right)(\theta - \theta_1)$. Hence, an upper bound on the profit is $\mathcal{P} - \frac{\nu}{2} - \left(\mu - \nu + \frac{n+1}{n}\frac{\theta_1^2}{(1-\theta_1)^2}\nu\right)\frac{(1-\theta_1)^2}{2}$. This upper bound is concave in θ_1 and has its maximum value, $\Pi^{RM(a)}$, at $\theta_1^{RM(a)} = \frac{(n+1)(\gamma+\mu-\nu)-n(1-\kappa-\mu)}{(n+1)\left(2\mu+\frac{\nu}{n}\right)+(1-\kappa-\mu)}$. The interior solution is feasible if and only if $1/2 \leq \frac{(n+1)(\gamma+\mu-\nu)-n(1-\kappa-\mu)}{(n+1)\left(2\mu+\frac{\nu}{n}\right)+(1-\kappa-\mu)} \leq \frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}$, that is (i) $\left(\sqrt{\frac{1-\mu}{\nu}\frac{n+1}{n}}+1\right) \geq \frac{(2n+1)\mu+\gamma}{n(1-\kappa-\gamma+\nu)+\nu}$, and (ii) $\gamma \geq (2n+1)\left[1-\kappa-\gamma-\mu+\nu\frac{n+1}{n}\right]$. If (ii) is not fulfilled, the optimal choice is $\theta_1^{RM(b)} = \frac{1}{2}$, and if (i) is not fulfilled, the optimal choice is $\theta_1^{RM(c)} = \frac{\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}{1+\sqrt{\frac{1-\mu}{\nu}\frac{n}{n+1}}}$. Assume the interior solution is feasible. With the prices chosen as in proof of Lemma 14, there is no deviation (as shown in that proof), $\theta_1 = \theta_1^{RM(a)}$, and $\Pi = \Pi^{RM(a)}$. The proof directly extends for any choice of θ_1 at the boundary.

Return to the centralized problem and assume $\theta_1 < \frac{1}{2}$. Then, $\phi = \frac{n}{n+1}$, so $\mathcal{P} = (1-\kappa)\frac{1-\theta_1^2}{2} - \gamma(1-\theta_1) + \frac{n}{n+1}\frac{\theta_1^2}{2}(1-\kappa-\mu)$. For accessing customers to obtain $\nu\theta$, we require $r \leq 1 - \frac{\nu}{\phi}$, necessitating $\nu \leq \frac{n}{n+1}$, which we assume henceforth. At the same time, for owners to share, we require $r - m - c - \mu \geq 0$ or $0 \leq m + c \leq 1 - \mu - \nu\frac{n+1}{n}$. Because $c, m \geq 0$, this implies $\nu \leq (1-\mu)\frac{n}{n+1}$. Note that this upper

Figure 8 Environmental impact of the optimal business model compared to:



(a) The SA business model. (b) The SA or SV business model. (c) The social planner's strategy.

Note. The environmental impact is lower/unchanged/higher under the optimal business model in the light/medium/dark gray region. Solid (resp. dotted) black lines indicate the boundaries between business model choices (resp. the social planner's strategies). Other parameters are $\nu = 0.05$, $\mu = 0.3$, $e_p = 0.05$, $e_u = 0.05$, and $n \to \infty$.

bound on ν is tighter, so we can ignore the first one. We will henceforth assume that the second upper bound is fulfilled, that is $\nu \leq (1-\mu)\frac{n}{n+1} \Leftrightarrow \frac{1-\mu}{\nu} \geq \frac{n+1}{n}$, as the case is irrelevant otherwise.

With accessing customers' minimum profits and $m \leq r - \mu$, we can upper-bound the manufacturer's profit by $\mathcal{P} - \frac{\nu}{2} - \left(\mu - \nu + \frac{n+1}{n}\nu\right)\frac{(1-\theta_1)^2}{2}$. This bound is concave in θ_1 and has its maximum value at $\theta_1^{RM(d)} = \frac{\gamma+\mu+\frac{\nu}{n}}{\frac{\nu}{n}+2\mu+\frac{1-\kappa-\mu}{n+1}}$. First, note that the denominator is always positive. This becomes clear when rewriting it as $\frac{\nu}{n} + \frac{1-k}{n+1} + \mu\frac{2n+1}{n+1}$. Hence, $\theta_1^{RM(d)} < \frac{1}{2} \Leftrightarrow \frac{\gamma n(2n+1)+\nu(n+1)}{\gamma n} < \frac{1-\kappa-\gamma-\mu}{\gamma}$. However, $\frac{\gamma n(2n+1)+\nu(n+1)}{\gamma n} > n \Leftrightarrow \gamma n^2 + \gamma n + \nu(n+1) > 0$, so we have a contradiction with the assumption that $n > \frac{1-\kappa-\gamma-\mu}{\gamma}$. □

D.4. The effect of a secondary market on the manufacturer's environmental impact

We verify robustness of results regarding the environmental impact through a numerical analysis. As displayed in Figure 8a, both servicization and sharing can reduce the environmental impact compared to an ownership-based model as long as κ and γ are sufficiently low. Importantly, this is the case for all the (sub-)business models.

When comparing sharing with SA/SV (Figure 8b), the picture also stays largely the same—when the SP-like model RM (resp. RSM) replaces the SV-like model $\tilde{\text{R}}$M (resp. $\tilde{\text{R}}$SM) sharing is environmentally more efficient, based on the logic outlined in Section 5.2. However, the SP-like RM may also replace the SV-like $\tilde{\text{R}}$SM. Omitting the secondary market in the new model means that equipment is used less efficiently, so the overall environmental impact may actually increase.

Figure 8c shows that the manufacturer's impact continues to be lower than the social planner's under broadly the same conditions. The regions tend to be larger, however, because the manufacturer is forced to reduce its sales to due to the secondary market (and, thus, it produces less).

Having complete control and considering customer surplus, the social planner will generally use the secondary market less and produce more equipment.

References for the Appendices

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