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DURABLE GOODS INNOVATION

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Consumer Guilt and Sustainable Choice: Environmental Impact of Durable Goods Innovation

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The paper develops a modeling framework to study how sustainability interventions impact consumer adoption of durable goods innovation, firm profit and environmental outcomes in equilibrium. Our two period model with forward looking consumers and a monopoly firm introducing an innovation in the second period accommodates three key features: (1) it builds on the psychology literature linking reactive and anticipatory guilt to consumers' environmental sensitivity on initial purchase and upgrade decisions; (2) it disentangles environmental harm over the product life into that arising from product use and dumping at replacement; and (3) it clarifies how a taxonomy of innovations (function, fashion and use-efficiency) differ in how they provide value and cause environmental harm during use and dumping. Given how guilt impacts environmental sensitivity, the model allows for owners upgrading a product to be more environmentally sensitive than first time buyers; this makes dumping harm and in-use harm from products not fungible. We find that with fashion and function innovations, increasing consumer sensitivity to environmental harm *can* surprisingly result in *increased* environmental harm. Further, when consumers are very sensitive to environmental harm, firms will not inform (pre-announce to) consumers about the impending arrival of use-efficiency innovation; to minimize environmental harm, a sustainability advocate needs to inform consumers. Thus, contrary to conventional wisdom, consumer environmental sensitivity does not always substitute for the role of sustainability advocates. Our results clarify how to design win-win policies for firms and the environment; and when advocates have complementary/adversarial roles relative to firms to achieve sustainability goals.

Key words: Durable goods, Planned Obsolescence, Sustainability, Innovation, Environmental Costs

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1. Introduction

Innovation and planned obsolescence have long been regarded as drivers of economic prosperity. Over the last century, as technological advances generated surplus production capacity relative to consumer demand, an emphasis on consumption-driven economic growth led to firms accelerating product obsolescence to induce consumers to replace goods even when the product is working. This idea of routinely obsoleting products through styling changes was symbolized by the “annual model changes” pioneered by General Motors in the 1920’s to induce customers to replace cars even when they were still working well. Planned obsolescence was justified as a means of job creation, growth and prosperity.¹ To be sure, innovation and obsolescence are not merely about styling and fashion changes, but also a means to improve product function and operational efficiency that reduces use cost. Planned obsolescence is now common across many industries including clothing, electronics and household appliances. In turn, consumer behavior has evolved to where accelerated replacement of goods in pursuit of fashion, function and use efficiency is the norm.

But planned obsolescence and frequent consumer upgrades have imposed a steep environmental cost in terms of trash generated, to the point where it is by now well beyond society’s capacity to absorb such trash. Early on, concerns that such consumption created unnecessary waste were brushed aside as a necessary cost of pursuing economic prosperity in a modern society.² By the end of the 20th century, however, the negative impact of runaway human production and consumption on the environment has become more visible and tangible, and concerns about the long-term

¹ J. Gordon Lippincott, the industrial designer who designed the Campbell soup label noted: “Any method that can motivate the flow of merchandise to new buyers will create jobs and work for industry and hence national prosperity... Our custom of trading in our automobiles every year, of having a new refrigerator, vacuum cleaner or electric iron every three or four years is economically sound” (Whiteley 1993).

² In a representative sentiment at the height of the Great Depression, Earnest Elmo Calkins, an advertising pioneer referred to as the “Dean of Advertising Men” justified changing consumer norms around thrift, reuse and recycling in a 1932 essay: “Does there seem to be a sad waste in the process? Not at all. Wearing things out does not produce prosperity, but buying things does. Thrift in the industrial society in which we now live consists of keeping all of the factories busy. Any plan which increases the consumption of goods is justifiable if we believe prosperity is a desirable thing.” See “What consumer engineering really is” as reprinted in (Gorman 2003), p.131.

sustainability of this production and consumption path have become more mainstream. The environmental impact of such waste is by now universally acknowledged as one of the fastest-growing pollution problems worldwide (e.g., Babu et al. 2007, Kang and Schoenung 2005, Wong et al. 2007, Cui and Zhang 2008, Kiddee et al. 2013). To put the problem in perspective, electronic waste (e-waste) alone generated 49.3 million tons in 2016, the equivalent in weight of 25 million cars. The potential value of raw materials in this e-waste is €55 billion, more than the GDP of many countries. Yet only 20% of this material was properly tracked and recycled.³ The clothing sector (especially fast fashion) is increasingly another major driver of environmental waste, increasing from 1.7 million tons of textiles dumped into landfills in 1960 to 11.2 million tons in 2017.⁴

In response, many sustainability interventions targeted towards consumers and firms have been proposed to mitigate environmental harm, while balancing consumer consumption needs and firm profitability. Demand side interventions targeted at consumers include consumer education and consumer taxes proportional to environmental harm. Similarly, supply side interventions include mandates to reduce environmental harm in production, use and disposal or firm-side taxes on products in proportion to environmental harm.

The purpose of this paper is to develop a modeling framework to study how sustainability interventions impact consumer adoption of innovation, firm profit, and overall environmental outcomes. We develop a two period model with forward-looking consumers and a monopolist firm that has one product in the market in the first period, and then introduces an innovation in the second period. Consumers buy not only based on price and value, but also environmental harm. We then solve for optimal firm strategies in subgame perfect equilibrium using backward induction, to assess the equilibrium outcomes in terms of firm profit and environmental harm.

³ E-waste includes discarded phones, computers, refrigerators, printers, televisions and any electronic device. E-waste has many toxic chemicals such as barium, lead and mercury, whose improper disposal creates serious health hazards. Estimates are from the Global E-waste Statistics Partnership. (<https://globalewaste.org/what-is-e-waste/>)

⁴ See EPA estimates at <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data>

We highlight three key features of our model: (i) modeling consumer sensitivity to environmental harm; (ii) disentangling environmental harm over the life cycle arising from product use and dumping the product at replacement; and (iii) a taxonomy of innovations (function, fashion and use-efficiency) that differ in how they provide incremental consumer value and cause environmental harm. First, we build on the behavioral literature linking consumer guilt to environmental sensitivity and sustainable choices. In the behavioral literature, guilt is widely considered as the primary mechanism driving sustainability behaviors (Antonetti and Maklan 2014, Schneider et al. 2017) and more broadly pro-social behaviors (e.g., Coulter et al. 1999). The psychology literature on guilt (e.g., Baumeister et al. 2007, Tangney et al. 2007) claims that guilt drives behaviors through an emotional feedback loop, where a past immoral, anti-social or unsustainable behavior evokes the guilty emotion (reactive guilt), which then serves to restrain such future behaviors through anticipatory guilt.⁵ In the context of our problem, this implies that first time consumers in the category, who have not yet experienced reactive guilt are not sensitive to environmental harm, but those considering upgrades who have experienced reactive guilt after their initial purchase experience anticipatory guilt and are sensitive to environmental harm. Accordingly, in the model, we assume that first time buyers do not consider environmental harm at time of purchase, but those who consider upgrading do. We later assess the importance of modeling this behavioral finding by comparing these results with a model when first time buyers also perceive some sensitivity to environmental harm at the time of purchase.

Second, in assessing environmental harm, we recognize the role of “life cycle analysis” to assess total environmental impact (Chang et al. 2014). For our purposes, we partition the total environmental impact of a product into an *in-use harm* component arising from usage during ownership

⁵ Baumeister et al. (2007) notes the sequence of guilt emotion feedback on choice that arises from a past immoral or anti-social action: “First came the act, then guilt, and the guilt in turn prompted a change in later behavior, which was chosen to avoid further guilt.” Tangney et al. (2007) also clarifies the role of history on anticipatory guilt and its effect on behavior thus: “In our view, people’s anticipatory emotional reactions are typically based on history—that is, based on their past consequential emotions in reactions to similar actual behaviors and events.”

of the product and *dumping harm* component when the product is replaced. As a shorthand, we label the ratio of per unit use harm to per unit dumping harm as “*use-dump harm ratio*” (λ). Examples of products with high use-dump harm ratio are cars, washing machines, air conditioners, where ongoing usage during the typical product’s life cycle requires significant fuel consumption and therefore creates large use cost related environmental harm, relative to the cost of dumping the item when it is replaced. Examples of products with small use-dump harm ratio are clothes, computers and televisions, as the ongoing energy consumption and environmental harm is relatively small during use. The use-dump harm ratio serves as a useful construct with explanatory power in how sustainability interventions impact equilibrium profit and environmental harm.⁶

Finally, we consider a taxonomy of three types of innovation—function, fashion and use efficiency. Each differs in terms of how they provide value to the customer and how they cause environmental harm. Specifically, function innovations improve the value of the new product by the addition of useful new features; fashion innovations incentivize replacement, by reducing the perceived value of the current product when a newer, more fashionable version is introduced; and use efficiency innovations reduce the operating cost relative to the existing product (e.g., an appliance with increased energy efficiency). All durable goods have an ongoing usage cost, and generate ongoing environmental harm while they are in use. Use-efficiency innovations save customers money in use (e.g., fuel/electricity savings), and also reduce in-use harm. All three types of innovations lead to dumping harm at replacement, when consumers upgrade.

Table 1 provides illustrative examples of different types of innovations with low and high use-dump harm ratios. It is important to note that use-dump ratio can be high or low for fashion, function and use-efficiency innovations. By fashion goods, we do not simply refer to clothes or accessories, but also to high-ticket durable goods like cars and refrigerators. Apart from their

⁶Weiss et al. (2000) notes that 75% of a car’s lifetime carbon emissions arise from the fuel it burns, not its production, which is only 6%. Even for a recent highly fuel efficient Volkswagen Golf, 68% of the car’s lifetime emissions came from driving it. See https://www.greencarreports.com/news/1093657_buying-a-new-car-is-greener-than-driving-an-old-one-really.

Innovation Type	Low λ	High λ
Fashion	Clothes, Handbags: Style Update	Cars, Refrigerators: Style Update
Function:	Rice Cooker, TV: Feature Update	Cars, Heaters, A/C: Feature Update
Use Efficiency	Rice Cooker, TV: Efficiency Update	Cars, Heaters, A/C: Efficiency Update

Table 1 Examples of innovation types with different use-dump harm ratios

intrinsic utility, these high ticket items also frequently serve as a fashion statement for their owners. Similarly functional innovations in categories like rice cookers and TVs with new features have low use-dump harm ratio, while energy hungry products like cars, air conditioners and home heating furnaces have high harm dump ratios. Finally, the above products could also improve on use efficiency. For example, newer flat screen TVs and hybrid/electric cars improve on energy efficiency.

We apply our dynamic modeling framework to study two types of consumer-targeted sustainability initiatives and their equilibrium impact on market outcomes: consumer choice/surplus, firm profit, environmental harm and social surplus. The first initiative involves increasing environmental sensitivity among consumers through education or other means so that consumers more fully account for the environmental harm of their choices. The second involves programs that inform and alert consumers about the arrival of new use-efficiency innovations required by time-targeted regulatory mandates.⁷ Such knowledge can help consumers who value use-efficiency and reduced environmental harm time their purchases around the introduction of the more efficient innovation, but usually consumer awareness tends to be limited. While in some cases, firms tend to support such mandates and embrace them, the industry often pushes back on such regulations (e.g., <https://cei.org/blog/safe-rule-examined-part-4-consumer-choice>). Our framework

⁷ Governments often mandate energy efficiency standards with target dates—thus often use-efficiency innovations are expected at certain periods. In the US, the federal government mandates and updates energy use standards on an ongoing basis. Various states also pass laws mandating such standards when they are not preempted by federal standards. California is often the leader in setting energy efficiency mandates. Other states may follow California, or legislate their own standards. For example, Connecticut enacted efficiency standards through their own legislative actions in 2004, 2007 and 2011.

of the use-efficiency innovation and when they would not, by comparing firm profits when consumers are informed/not informed in advance about the arrival of the use-efficiency innovation. This would allow sustainability education focused organizations (either governmental or NGOs) to decide when they can rely on businesses to voluntarily inform consumers in advance of the arrival of use-efficiency innovations, and when they need to step in to inform and educate the market in advance to obtain the maximum reduction in environmental harm from the mandate.

Our key findings are as follows. First, and surprisingly, we find conditions in which an increase in consumers' environmental sensitivity leads to *increased* environmental harm for function and fashion innovations. Specifically, we find that for function and fashion innovations that have high use-dump harm ratio, increasing green sensitivity among consumers can lead to greater environmental harm in equilibrium. The mechanism is as follows: Consumers' higher environmental sensitivity reduces their willingness to upgrade, which in turn leads the firm to reduce the new innovation's price. This reduction in price increases purchases of the good by lower valuation first-time buyers who would not have purchased otherwise, which in turn increases in-use environmental harm. The total environmental harm (reduced dumping harm, but greater in-use harm) increases (decreases) with consumers' green sensitivity, when the use-dump harm ratio is high (low). Further, despite these purchases by low valuation consumers, overall firm profit decreases as increased environmental sensitivity leads to lower prices and quantity of upgrades. However, unlike with function and fashion innovations, with use efficiency innovations, environmental harm *always decreases* with increasing consumer green sensitivity. The effect on firm profit with use efficiency innovations is however nuanced. In categories where the use-dump harm ratio is high (low), firm profit increases (decreases) with increasing consumer environmental sensitivity.

We find that these results are related to the behavioral assumption based on the role of guilt on environmental sensitivity that first time buyers are less sensitive than upgraders. The result that increasing environmental sensitivity leads to greater environmental harm for function and fashion innovations (for high levels of λ) remains robust up to a threshold level of environmental

sensitivity even among first time buyers, but once beyond the threshold, greater environmental sensitivity does reduce environmental harm. Overall, this highlights the importance of accounting for behavioral theories and its impacts on sustainable behaviors in analytical models to draw equilibrium implications.

The differences in the sign of the impact of consumer environmental sensitivity on profit and environmental harm for function, fashion and use efficiency innovations give insight into whether firms or environmental advocates should take the initiative with educating consumers about environmental harm: when increased consumer sensitivity leads to higher firm profit, firms have a natural incentive to educate consumers and increase environmental sensitivity, but otherwise, environmental advocates have to step in. It also provides the insight that increasing consumer environmental sensitivity could lead to a greater movement by firms towards use efficiency innovations (relative to function or fashion innovations) in categories where in-use harm dominates dumping harm.

Second, we find that the firm's incentive to inform consumers in advance about use efficiency innovations given equilibrium profit outcomes is often (but not always) misaligned with environmental outcomes. Interestingly alignment occurs only when consumer environmental sensitivity is low, and the use-dump harm ratio is high; and regulators/NGOs can follow a laissez faire policy on informing consumers about such innovations. Surprisingly, when use-dump harm ratio is high and there is high environmental sensitivity, firms will not alert consumers about the use efficiency innovation but the environment is better off if consumers are alerted in advance. This suggests that environmental advocates (or regulators themselves) need to step in to alert consumers in such high λ categories. This leads to the surprising finding that environmental advocacy groups (and regulators) may need to play an active role in helping the environment precisely when consumers are highly environmentally sensitive.⁸ The finding goes against the conventional wisdom that increas-

⁸ Environmental groups are often involved in push and pull advocacy towards environmental goals. Examples of push advocacy include building support among stakeholders for new and updated standards at the national and state levels. Examples of pull advocacy include consumer outreach and education. Often they also organize and coordinate collective efforts across consumer and environmental groups, utility companies and state government agencies across multiple states. An example of an advocacy group is the "Appliance Standards Awareness Project" (ASAP).

ing consumer sensitivity about the environment can be a substitute for environmental advocacy or regulator actions.

Overall, our work provides qualitative guidance on the role of firms, regulators and environmental advocates in sustainability debates. In recent years, there have been intense discussions of whether it pays to be green, i.e., whether environmentally beneficial actions are also profitable for firms—with vigorous arguments on both sides (e.g., [Hart and Ahuja 1996](#), [Orsato 2006](#), [Ambec and Lanoie 2008](#), [Orsato 2009](#), [Esty and Simmons 2011](#)). Our work provides structure within an economic modeling framework in one context—durable goods innovation—to assess when environmental and firm profit will be aligned and it pays to be green. When there is such win-win alignment, we can expect firms to automatically choose environmentally aligned policies; regulators can use a *laissez faire* approach with firms to obtain environmentally aligned outcomes. It also gives qualitative guidance of when such alignment will not occur and regulators and environmental advocates may need to step in and be adversarial with firms to obtain desirable environmental outcomes.

In summary, the paper makes the following contributions to the literature on sustainability marketing of durable goods. Overall, we develop a two-period modeling framework of consumer product replacement for new innovations that account for environmental sensitivity endogenized within a model of firm pricing, where both consumers and firms are forward looking. The model incorporates three key features useful for analysis of sustainable markets. First, building on the psychology literature on the role of “guilt” in sustainability choices, the model accounts for differential levels of environmental sensitivity among upgraders versus first-time buyers. Second, we distinguish between the environmental harm over the product life in terms of in-use harm and dumping harm; and show that the use-dump harm ratio is an important construct in characterizing equilibrium outcomes. Finally, conceptually, we introduce a taxonomy of innovations—fashion, function, and use efficiency with different consumer value propositions and environmental harm. We use this modeling framework to evaluate the equilibrium outcomes of sustainability initiatives. Specifically, we study how consumer environmental sensitivity and use efficiency innovation pre-announcements

affect equilibrium outcomes; the results provide insights on designing win-win policies for firms, consumers and the environment, and on when advocates/regulators need to be adversarial with firms to achieve desired sustainability goals.

The rest of the paper is organized as follows. §2 describes the related literature. §3 lays out the model. We introduce our two-period model of innovation and product obsolescence, where we model a forward looking consumer's innovation adoption and replacement, and the forward looking firm's model of pricing. We then first characterize innovation taxonomy within the modeling framework. §4 discusses the analysis of increasing consumer green sensitivity on equilibrium outcomes. §5 discusses the analysis of how pre-announcements of use efficiency innovations impact the equilibrium by impacting consumer expectations about the arrival of the innovation. §6 concludes.

2. Literature Review

We relate our work to several streams of the literature. The first is the consumer behavior literature on consumption of sustainable goods, with a specific focus on how guilt drives sustainable (and more generally prosocial) behaviors. The second stream involves economic models of how sustainability in manufacturing and product development impact market outcomes and is related in spirit to our approach. In terms of modeling, our paper is closely related to the industrial organization literature on product obsolescence in durable goods.

2.1. Consumer Behavior and Sustainability Choices

A rich consumer behavior literature has studied the growing segment of “green” consumers, who are generally oriented toward buying and consuming environmentally friendly products (e.g., [Haws et al. 2014, 2012](#), [White et al. 2019](#)). They find that such “green” consumers not only consider environmental harm during purchase, but are also willing to retain products longer and recycle them more to reduce environmental harm ([Haws et al. 2012](#)). The literature however notes an attitude-behavior gap in consumer's stated intentions and sustainability behaviors; according to recent survey 65% of respondents said they want to buy purpose-driven brands that advocate sustainability, yet only about 26% actually did. [White et al. \(2019\)](#) catalog a variety of tactics dubbed

“SHIFT” framework, by which to reduce the attitude-behavior gap. Tactics include information provision (e.g., eco-efficiency labels), educating consumers about environmental harm (e.g., Barth et al. 2012), social, emotional and financial nudges (price, taxes) (e.g. Winterich et al. 2019).

Guilt is widely considered in the literature as the key driver of sustainable behavior in its ability to motivate “reparative and preventative action” (Schneider et al. 2017). Following Rawlings (1970), a large literature has distinguished how three forms of guilt (reactive, anticipatory and existential guilt) impact prosocial behaviors in general (Coulter and Pinto 1995, Coulter et al. 1999) and sustainable behaviors in particular (Antonetti and Maklan 2014, Onwezen et al. 2013, Bamberg and Möser 2007).⁹ In our context, reactive guilt from past consumption fuels anticipatory guilt regarding future consumption, which in turn influences consumers’ utility and decision choices, because “anticipatory guilt occurs before buying and reactive guilt occurs after buying” (Bei et al. 2007, Rawlings 1970). As discussed earlier in the introduction, since reactive guilt is a response to past violations, it does not directly impact choice, but it induces anticipatory guilt when making future choices involving similar guilt inducing behaviors (Baumeister et al. 2007, Tangney et al. 2007). We operationalize this idea of how guilt impacts sustainable choice by allowing environmental harm to be accounted for only by upgraders, but not by first time buyers.

2.2. Economic Models of Sustainability Initiatives

Our work is in the tradition of a small, but growing literature that uses economic models to assess the environmental impact of “sustainability initiatives” by firms and regulators. The approach is to model how consumers and firm choices change in response to the sustainability initiative of interest and then assess the overall environmental impact in equilibrium. We begin with models focused on potentially “environmentally friendly” firm actions. For example, Chen (2001) studies product line decisions of a monopolist in markets with heterogeneous preferences among consumers for environmentally desirable features. The paper argues that “distortion” at the low end to prevent

⁹ Existential guilt, based on guilt induced due to one’s better fortune relative to others (favorable inequality) is of limited relevance for sustainable consumption; so we focus on reactive and anticipatory guilt here.

environmentally conscious consumers from buying the less environmentally friendly product can lead to more harmful environmental outcomes than would have been if the monopolist was restricted to just one product. Similarly, [Agrawal and Ülkü \(2013\)](#) show that modular manufacturing, often seen as an eco-friendly form of production may lead to greater environmental harm because of its heterogeneous impacts on production by firms and the use and replacement choices of consumers. [Agrawal et al. \(2012\)](#) and [Mutha et al. \(2021\)](#) show how a firm's decision to lease may on the surface reduce dumping harm by greater reuse the product over its full life, but can worsen environmental harm due to other strategic choices by firms such as product life. Finally, others have studied how firm efforts to signal environmental quality through external versus self-certification in competitive markets impact overall environmental outcomes (e.g., [Murali et al. 2019](#)).

In terms of regulatory actions, research has studied the environmental impact of various taxes. For example, [Sevigny \(1998\)](#) and [Fullerton and West \(2002\)](#) study emissions taxes (or taxes based on engine sizes and mileage) targeted to consumers or firms. [Fullerton \(1997\)](#) and [Williams \(2002\)](#) study the effect of taxes for environmental harm during production. Others have considered the effects of extended producer responsibility (EPR) in legislation by making the seller financially responsible for the recovery and environmentally friendly disposal of products they sell ([Lifset et al. 2013](#)) and its implications for product design ([Gui et al. 2018](#), [Alev et al. 2020](#), [Huang et al. 2019](#)).

2.3. Durable goods obsolescence and new product preannouncements

The paper is related to the literature on durable goods obsolescence and innovation preannouncements. In terms of the model, the paper is closest to the literature on product obsolescence. New product introductions in durable goods make the extant stock of products with consumers obsolete to varying degree, encouraging consumers to upgrade to new products. This has led to a number of fundamental questions related to product obsolescence ([Bulow 1986](#), [Waldman 1996](#)) and the resulting pricing dynamics across time ([Levinthal and Purohit 1989](#), [Dhebar 1994](#), [Fudenberg and Tirole 1998](#), [Kornish 2001](#)).

Our model structure is most closely related to [Levinthal and Purohit \(1989\)](#) and [Fudenberg and Tirole \(1998\)](#); like them, we use a two-period model where a firm sells a product to a unit mass

of consumers with heterogeneous valuations in the first period. The firm then introduces a new product in the second period, and then endogenously sets prices in the first and second period allowing for both consumers and firms to be forward looking. Consumers take into account not only first period prices, but also expectations of second period prices and the extent of improvement in the product in the second period as they decide whether to buy in the first period. Durability creates competition in period two between the older version and the newer version. In the second period firms have to consider both those who are upgrading and those who are buying newly in the second period. Thus like [Fudenberg and Tirole \(1998\)](#), our model involves both *static price discrimination* across high and low valuation customers as well as *inter-temporal price discrimination* across early and late purchasers.

We contribute to this literature in two ways. First, we introduce a taxonomy of durable goods innovation—fashion, function and use efficiency innovation—based on (a) structural differences in how they provide incremental value to consumers/obsolete existing products, and (b) separate sources of environmental harm. Second, in modeling sensitivity to environmental harm in consumer choice, based on the behavioral literature linking “guilt” to environmental choices, we allow consumers choosing to upgrade to display greater sensitivity to environmental harm relative to first time buyers.

The research question of whether sustainability advocates need to intervene to inform consumers about the arrival of a new “green” use-efficiency innovation required by time targeted efficiency mandates is related to the literature on “pre-announcements” (e.g., [Eliashberg and Robertson 1988](#), [Bayus et al. 2001](#)). Much of the literature on pre-announcements discuss its competitive advantages (e.g., [Farrell and Saloner 1986](#); see [Choi et al. \(2005\)](#) for a review) and signaling roles (e.g., [Eliashberg and Robertson 1988](#), see [Su and Rao \(2010\)](#) for a review). Also, pre-announcements of green products to signal sustainability credentials (“potential greenwashing”) have been studied (e.g., [Truong and Pinkse 2019](#)). This paper is more closely related to the literature on pre-announcements that focuses on changing consumer expectations about product arrival and its impact on timing of consumer purchases ([Ishihara and Kim 2018](#)).

3. The Model

We describe a two period monopoly market of forward looking consumers and firms, in which an innovation is introduced in the second period. We also characterize the three types of innovations: function, fashion and use efficiency.

3.1. The Market

We consider a two period market with first and second periods denoted by $t = 1, 2$, where a monopolist initially offers a product $j = 1$ in period 1 and then introduces an innovation, a new product $j = 2$ in period 2. Forward looking consumers decide whether to buy in the first period or postpone purchases to the second period. Those who have bought in the first period have to decide whether to continue using the product bought in the first period, or buy the second period product. Note that in the second period, only the new product $j = 2$ is available for purchase, though past buyers of product 1 can continue to use it. Figure 1 shows the timeline of the model.

Consumers perceive the vertical quality of the initial product (i.e., the product offered in period 1) to be q_{11} during period 1, and the perceived vertical quality of the innovation offered in period 2 to be q_{22} . To the extent that innovations cannot reduce quality, we expect $q_{22} \geq q_{11}$. q_{12} is the perceived quality of the initial product during period 2; since consumers may perceive a depreciation regarding the quality of the initial product in period 2, we assume $q_{12} \leq q_{11}$. Let e_j indicate a measure of use efficiency of the product in period j and impacts consumer utility by impacting product usage cost. To the extent that innovations do not worsen products, we expect $e_2 \geq e_1$. While an increase in product quality increases flow utility, an in-use efficiency impacts not only flow utility due to the reduced costs of use, but it also impacts choice through reduced environmental harm.

For model parsimony, we combine the benefits from product quality q_j and use efficiency e_j into an effective quality function $g(q_j, e_j)$, where g is weakly increasing in q_j and e_j . Let the consumer type θ be uniformly distributed in the interval $[0, 1]$. Therefore the flow utility from consumption obtained by a consumer of type θ from a product of effective quality $g(q_j, e_j)$ in period

j is $\theta g(q_j, e_j)$.¹⁰ In the period of purchase/upgrade, the consumer utility is reduced from the above flow utility by price p_j .

Further, the utility is impacted by environmental harm. We consider two types of environmental harm from the product: harm from ongoing use and harm from dumping. We specify the pollution generated by the product in use as $1 - e_j$, a decreasing function of use efficiency. Let λ_u be the harm per unit of pollution generated by the product; therefore the environmental harm from product use in any period is given by $\lambda_u(1 - e_j)$.¹¹ The harm from dumping the used product at replacement is denoted by λ_d per unit product discarded. We denote the use-dump harm ratio as $\lambda = \frac{\lambda_u}{\lambda_d}$, the ratio of the in-use environmental harm, to the dumping environmental harm. As discussed in the introduction (p.3 of §1), based on the behavioral literature linking guilt and sustainability behaviors, we assume that only upgraders consider environmental harm when making choices, and that first time buyers do not at the time of purchase. The unit cost of production of both the initial and new product is constant and fixed at c (which we later normalize to 1 without loss of generality).

Consumers are forward looking with respect to flow utilities (current and future), prices and disutility from environmental harm. For example, a consumer who considers purchasing in period 1 will consider (i) flow utility from consumption in period 1 and the price; (ii) flow utility from continuing to use the old product in period 2, versus the flow utility and price to be paid for an upgrade; and (iii) the environmental harm from use (either old or upgrade) in period 2 (due to reactive guilt for past behavior) and environmental harm from potential dumping (due to anticipatory guilt) in case of upgrade.

¹⁰ While it is possible to have different marginal impact of utility from q_j and e_j , by combining vertical quality and use efficiency allows us to parsimoniously account for consumer valuation of quality with a single parameter θ . In our main analysis, we consider the functional form $g(q_j, e_j) = q_j/(1 - e_j)$ as it leads to analytically tractable solutions. Our results are robust to other functional forms (e.g., additive $g(q_j, e_j) = q_j - (1 - e_j)$) and multiplicative (e.g., $g(q_j, e_j) = q_j(1 + e_j)$), but these require numerical solutions.

¹¹ Note that e_j impacts separates two aspects of utility: a more efficient product (e.g. car with greater fuel efficiency) provides greater utility in-use (e.g. lower fuel bill) that is captured through the $g(q_j, e_j)$ term and a lower disutility from lower environmental harm captured through the $\lambda_u(1 - e_j)$ term.

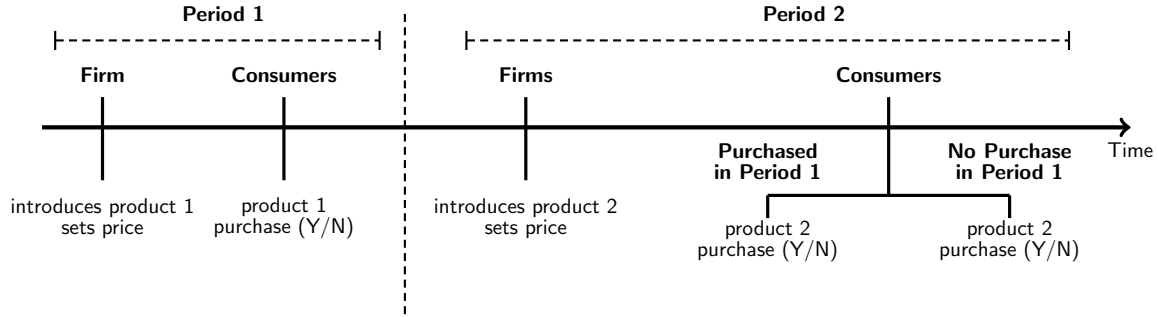


Figure 1 Timeline of Game

If the consumer's marginal disutility from environmental harm is a constant $\kappa \in [0, 1]$, the disutility from in-use harm is $\kappa\lambda_u(1 - e_j)$ and the disutility from dumping harm is $\kappa\lambda_d$.

Since first time buyers do not consider environmental harm, the flow utility U_{jt} for a first time user (denoted by superscript f) using product $j \in 1, 2$ in the corresponding periods $t \in 1, 2$ can be denoted as

$$U_{11}^f = \theta q_1 \frac{1}{1 - e_1} - p_1 \quad \text{and} \quad U_{22}^f = \theta q_2 \frac{1}{1 - e_2} - p_2 \quad (1)$$

where p_j is the price of product j .

Since current owners (denoted by subscript o) consider environmental harm from in-use and dumping in their flow utilities, their flow utilities are:

$$U_{12}^o = \theta \delta q_1 \frac{1}{1 - e_1} - \kappa\lambda_u(1 - e_1) \quad \text{and} \quad U_{22}^o = \theta q_2 \frac{1}{1 - e_2} - p_2 - \kappa(\lambda_u(1 - e_2) + \lambda_d) \quad (2)$$

In the above expressions, $\kappa\lambda_u(1 - e_j)$ reflects the consumer's environmental disutility from product usage for a product whose use efficiency is indexed by e_j , and $\kappa\lambda_d$ represents the disutility from dumping the older version.

In general, the modeling framework above can accommodate a variety of innovations as well as sustainability initiatives, as we discuss next.

3.2. Innovation Taxonomy

We classify innovation in durable goods along three types: function, fashion and use efficiency.

Within the two period framework of innovations described above, we model the three types of

	Period 1	Period 2	
	Product 1	Product 1	Product 2
Function Innovation:	$q_{22} > q_{11}, \delta = 1, e_1 = e_2 = 0$		
Effective Quality	q_{11}	$q_{12} = q_{11}$	$q_{22} > q_{11}$
Environmental Harm			
In-Use	λ_u	λ_u	λ_u
Dumping	NA	λ_d	NA
Fashion Innovation:	$q_{22} > q_{11}, 0 \leq \delta < 1, e_1 = e_2 = 0$		
Effective Quality	q_{11}	$q_{12} = \delta q_{11}$	$q_{22} = q_{11}$
Environmental Harm			
In-Use	λ_u	λ_u	λ_u
Dumping	NA	λ_d	NA
Use Efficiency Innovation:	$q_{22} = q_{11}, \delta = 1, e_2 = e > e_1 = 0$		
Effective Quality	q_{11}	$q_{12} = q_{11}$	$q_{22} = \frac{q_{11}}{(1-e)}$
Environmental Harm			
In-Use	λ_u	λ_u	$\lambda_u(1-e)$
Dumping	NA	λ_d	NA

Table 2 Innovation Taxonomy

innovation in terms of their initial quality, quality depreciation, use cost and environmental harm.

Table 2 summarizes the innovation taxonomy.

1. *Function innovation*: The innovation sold in period 2 is superior in perceived quality than the initial product sold in period 1, i.e., $q_{22} > q_{11}$. (For example, consider anti-lock braking systems in cars.) Further, there is no depreciation of perceived quality of period-1 product in period 2, i.e., $q_{12} = q_{11}$. The use efficiency of products sold in period 1 and period 2 are equal, i.e., $e_2 = e_1$.
2. *Fashion innovation*: When the fashion innovation is introduced with perceived quality q_{22} , it has the same perceived quality as the original product introduced in period 1, i.e., $q_{22} = q_{11}$, but the product bought in period 1 has depreciated in perceived quality, i.e., $q_{12} = \delta q_{11}$, where $0 < \delta < 1$ is the depreciation factor. (For instance, consider style changes in successive generations of car models.) The use efficiency of the products sold in period 1 and period 2 are equal, i.e., $e_2 = e_1$.
3. *Use efficiency innovation*: The perceived quality of the use efficiency innovation in period 2 is the same as that of the product introduced in period 1, i.e., $q_{22} = q_{11}$. There is also no depreciation in quality of product bought in period 1, $q_{12} = q_{11}$. But the use efficiency for period 2 product

is higher i.e., $e_2 > e_1$. (For example, consider newer versions of cars with higher fuel efficiency.) Without loss of generality, we normalize e_1 to 0 and e_2 to e for the use efficiency innovation case. For function and fashion innovation cases, we normalize e to be 0. The higher the e , the more use-efficient the product.

3.3. Equilibrium Analysis and Outcomes

We solve the model by backward induction. To solve for the equilibrium, we assume the threshold structure of purchases and upgrades in equilibrium as presented in Figure 2 and then verify that it holds in the solution.¹² In period 1, buyers with types in the range $[\theta_1, 1]$ buy the initial version q_1 . The threshold buyer θ_1 is indifferent between buying q_1 in period 1, and waiting and buying q_2 in period 2. In period 2, buyers in the range $[\theta_2, \theta_1]$ buy the newer version q_2 for the first time. The threshold buyer θ_2 is indifferent between buying q_2 , and buying nothing. In period 2, buyers in the range $[\theta_{12}, 1]$ upgrade to the newer version. The threshold buyer θ_{12} is indifferent between upgrading to q_2 , and continuing to use q_1 . Given the flow utilities per period discussed in §3.1, we can characterize the total utility across both periods for the three different segments of consumers who purchase in at least one of the two periods.

1. Purchase q_1 in period 1, upgrade to q_2 in period 2: Consumers in range $(\theta_{12}, 1)$ have total utility $U_{12} = U_{11}^f + U_{22}^o$.

2. Purchase q_1 in period 1, do not upgrade in period 2: Consumers in range (θ_1, θ_{12}) have total utility $U_1 = U_{11}^f + U_{12}^o$.

3. Don't purchase in period 1, wait and purchase q_2 in period 2: Consumers in range (θ_2, θ_1) have total utility: $U_2 = U_{22}^f$.

Second Period. In period 2, the firm sets price p_2 to optimally choose θ_2 and θ_{12} to maximize second period profit across those who upgrade as well as those who buy for the first time:

$$\pi_2 = (p_2 - c)(1 - \theta_{12}) + (p_2 - c)(\theta_1 - \theta_2)$$

¹² A more detailed outline of the analysis is provided in Appendix A.1; the indifference conditions at the thresholds are specified in Appendix A.1.1.

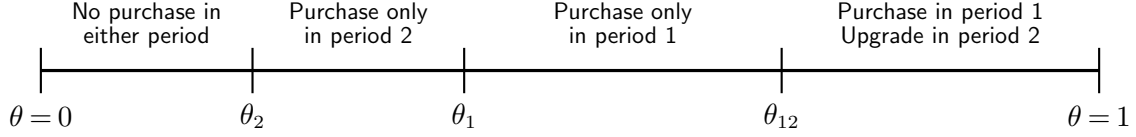


Figure 2 Equilibrium segmentation

where $1 - \theta_{12}$ is the fraction of consumers who upgrade, and $\theta_1 - \theta_2$ is the fraction of consumers who are first time buyers. Period 2 profit simplifies to:

$$\pi_2 = (p_2 - c)(1 - \theta_{12} + \theta_1 - \theta_2)$$

First Period. In period 1, the firm sets price p_1 to optimally choose θ_1 so as to maximize profits over both periods.

The total firm profit over both periods is given by

$$\text{Profit} = \pi = \pi_1 + \pi_2 = (p_1 - c)(1 - \theta_1) + \pi_2$$

Without loss of generality, we assume that the marginal cost of the product is 1, and so the margin per unit sales is $p_2 - 1$. Based on the optimal values of $\{\theta_1, \theta_2, \theta_{12}\}$, we derive the optimal firm profit.¹³

Given the consumer and firm choices in equilibrium, we can compute the total environmental harm, consumer surplus and social surplus as follows.

$$\begin{aligned} \text{Environmental Harm} &= \lambda_d(1 - \theta_{12}) + \lambda_u[(1 - \theta_1)(1 - e_1) \\ &\quad + (\theta_{12} - \theta_1)(1 - e_1) + (1 - \theta_{12})(1 - e_2) + (\theta_1 - \theta_2)(1 - e_2)] \end{aligned}$$

where $1 - \theta_{12}$ is the number of discards (units dumped). The unit environmental harm from operating a product (i.e. use cost related harm, or in-use harm) is $1 - e_i$, which is multiplied by the number of units using them in periods 1 and 2.

The consumer surplus is given by the following expression:

$$\begin{aligned} \text{Consumer Surplus} &= \int_{\theta_1}^1 \left(\theta q_1 \frac{1}{1 - e_1} - p_1 \right) d\theta + \int_{\theta_1}^{\theta_{12}} \left(\theta \delta q_1 \frac{1}{1 - e_1} - \kappa \lambda_u (1 - e_1) \right) d\theta \\ &\quad + \int_{\theta_{12}}^1 \left(\theta q_2 \frac{1}{1 - e_2} - p_2 - \kappa (\lambda_u (1 - e_2) + \lambda_d) \right) d\theta + \int_{\theta_2}^{\theta_1} \left(\theta q_2 \frac{1}{1 - e_2} - p_2 \right) d\theta \end{aligned}$$

¹³ The full expressions of optimal prices, quantities, and profits are available in the Appendix A.1.

The four terms capture (i) first period surplus for consumers who buy in period 1; (ii) second period surplus for those who do not upgrade; (iii) second period surplus for those who upgrade; and (iv) second period surplus for those who buy only in the second period.

The social surplus is given by the following expression:

$$\begin{aligned} \text{Social Surplus} = & \text{Firm Profit} + \text{Consumer Surplus} - \text{Environmental Harm} \\ & + \kappa[\lambda_d(1 - \theta_{12}) + \lambda_u(\theta_{12} - \theta_1)(1 - e_1) + \lambda_u(1 - \theta_{12})(1 - e_2)] \end{aligned}$$

For social surplus, we sum up the firm profit, the consumer surplus and subtract out the environmental harm. Finally, we add back the consumers' internalized environmental harm that was deducted in the consumer surplus expression.

We next use our modeling framework to study the effect of (i) increasing consumers' environmental sensitivity (κ) (§4); and (ii) informing consumers about arrival of use efficiency innovations on equilibrium outcomes (§5).

4. Consumers' Environmental Sensitivity

As described in §3.1, consumer's environmental sensitivity is modeled as $\kappa \in [0, 1]$ where 0 indicates that the consumer perceives no disutility from environmental harm and 1 indicates that the consumer fully internalizes environmental harm. We now present comparative statics around environmental sensitivity (κ) on the various market outcomes.

4.1. Demand Effects

We begin with demand effects—how a change in κ impacts prices and quantities over the two periods. We summarize the results of the comparative statics in Lemma 1.

Lemma 1. *Demand Effects*

a. Function and fashion innovation: As κ increases,

Period 1: price (p_1) decreases; quantity ($Q_1 = 1 - \theta_1$) does not change.

Period 2: price (p_2) decreases; new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; upgrade quantity ($Q_{12} = 1 - \theta_{12}$) decreases.

b. Use efficiency innovation: As κ increases,

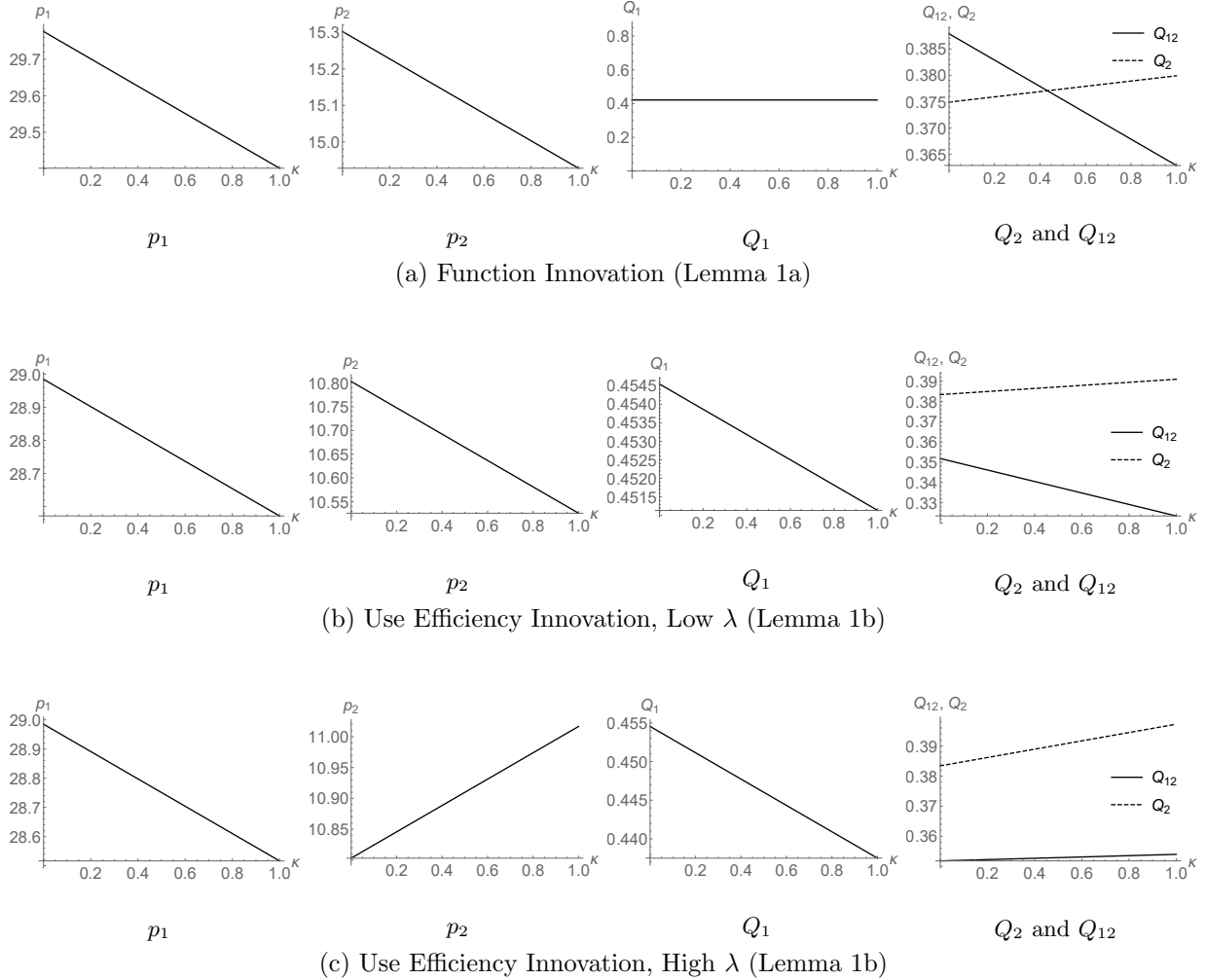


Figure 3 Impact of environmental sensitivity on prices & quantities

Period 1: Both price (p_1) and quantity ($Q_1 = 1 - \theta_1$) decrease.

Period 2:

At lower values of λ : price (p_2) decreases (when $\lambda < \lambda_{p_2}^$); new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; and upgrade quantity ($Q_{12} = 1 - \theta_{12}$) decreases (when $\lambda < \lambda_{Q_{12}}^*$).*

At higher values of λ : price (p_2) increases (when $\lambda > \lambda_{p_2}^$); new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; and upgrade quantity ($Q_{12} = 1 - \theta_{12}$) increases (when $\lambda > \lambda_{Q_{12}}^*$).*

The proof for Lemma 1 and the expressions for the λ thresholds are in Appendix A.2.

In Lemma 1, the results for function and fashion innovation as well as use efficiency innovation when λ values are small are qualitatively similar. So we will discuss these together (graphs for function innovation and use efficiency innovation are presented in Figure 3). We begin with the

discussion of the results in period 2. In all of these cases as environmental sensitivity increases, consumers who bought earlier do not wish to upgrade as they now are concerned more about dumping cost. With fashion and function innovation, dumping is the main concern. For use efficiency innovation, though the new version has less in-use environmental harm, at lower values of λ , dumping has greater impact than in-use environmental harm and reduces willingness to upgrade. This leads to lower upgrade quantity, but also induces firms to lower period-2 price. The lower period-2 price draws more new customers to purchase in period 2.

The falling price in period 2 for the innovation also depresses the price in period 1. But this falling price does not increase demand, as this is merely to account for the greater cross-substitution between the two periods due to the consumer sensitivity for product dumping. Period 1 demand stays flat for fashion and function innovation, and actually falls for use efficiency innovation, because customers anticipate a better product in period 2.

Interestingly, however the results are qualitatively different for higher values of λ , where the in-use environmental harm dominates dumping harm. Here the use efficiency innovation becomes more valuable as environmental sensitivity increases, leading to more interest in and higher price for upgrades, but also more purchases in period 2 – both by new buyers as well as those upgrading from the prior version. Thus increasing environmental sensitivity expands the market only for use efficiency innovation and that too only when λ is high. As before, in period 1, the price still is lower and the quantity decreases. This is because in period 1 consumers wait for the period-2 product, and this induces price reduction.

4.2. Firm Profit

We next report the comparative statics on firm profit in the following proposition.

Proposition 1. *Firm Profit*

- a. *Function and fashion innovation: As κ increases, firm profit decreases.*
- b. *Use efficiency innovation: As κ increases, (i) when $\lambda < \lambda_\pi^*$, firm profit decreases; and (ii) when $\lambda > \lambda_\pi^*$, firm profit increases.*

The expression for the λ threshold and the proof for Proposition 1 is in Appendix A.3.

As before in the discussion of demand effects in §4.1, we group the results in the function and fashion innovation with the use efficiency innovation result for $\lambda < \lambda_\pi^*$. For fashion and function, as expected, seller's profit falls with increasing environmental sensitivity κ of consumers. For use efficiency, as environmental sensitivity increases, firm profit falls when $\lambda < \lambda_\pi^*$. But in contrast, when $\lambda > \lambda_\pi^*$, the increasing consumer environmental sensitivity leads to greater demand and willingness to pay for the newer version, and firm profit rises. We illustrate in Figure 4 the divergent impact on profits as κ increases for λ above and below the threshold value λ_π^* as stated in Proposition 1b.

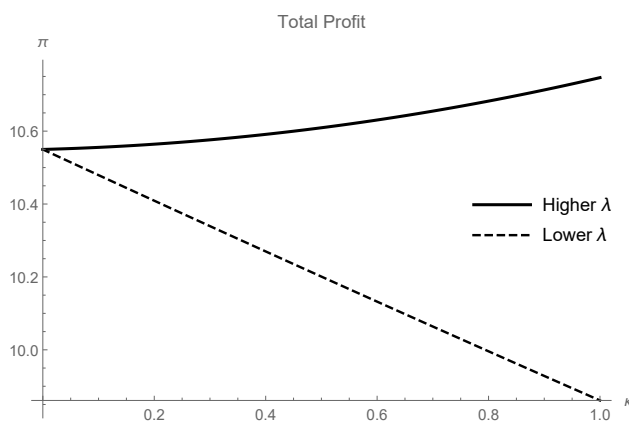


Figure 4 Use Efficiency Innovation: Impact of environmental sensitivity on firm profit
(when $\lambda < \lambda_\pi^*$ vs. when $\lambda > \lambda_\pi^*$) (Prop. 1b)

For use efficiency innovation, the basic intuition for the result when $\lambda < \lambda_\pi^*$ follows from the demand effects described earlier: increasing consumer sensitivity reduces the incremental value of the innovation as consumers become more sensitive to the dumping harm of upgrades, and this reduces prices and profitability overall, even though period-2 purchases by first-time buyers go up. However, when $\lambda > \lambda_\pi^*$, the incremental value of the innovation increases, encouraging upgrades, raising prices, and expanding the market.

4.3. Environmental Harm

We next consider the comparative statics of κ with respect to environmental harm.

Proposition 2. *Environmental Harm*

a. Function and fashion innovation: As κ increases, (i) dumping harm decreases; (ii) in-use harm increases; (iii) total harm decreases when $\lambda < \lambda_E^$; and increases when $\lambda > \lambda_E^*$.*

b. Use efficiency innovation: As κ increases,

At lower values of λ : (i) dumping harm decreases (when $\lambda < \lambda_D^$); (ii) in-use harm increases (when $\lambda < \lambda_U^*$); (iii) total harm decreases.*

At higher values of λ : (i) dumping harm increases (when $\lambda > \lambda_D^$); (ii) in-use harm decreases (when $\lambda > \lambda_U^*$); (iii) total harm decreases.*

The expressions of the λ thresholds and the proof of Proposition 2 are in Appendix A.3.

As before it is useful to group the results in function, fashion, and use efficiency innovation especially in the case of lower λ values. Figure 5 (a) (i) and (ii) show the changes in in-use, dumping and total environmental harm for low λ in the function innovation case. Qualitatively, the comparative statics of κ on environmental harm is similar for the fashion innovation case. Here as consumers become more environmentally sensitive, the total environmental harm decreases. It is useful to decompose the environmental harm; in all these cases rising environmental sensitivity reduces upgrades and therefore dumping harm, but as we noted in demand effects, the demand expands as second period demand from new buyers increases due to a reduction in prices, and this demand expansion leads to greater in-use harm. However since the in-use harm relative to dumping harm is low, the total harm decreases.

In contrast, at higher values of λ , the in-use harm is more significant relative to dumping harm, and therefore the total harm increases for function and fashion innovation as environmental sensitivity increases—again due to the expansion in the market. The proposition is illustrated in Figure 5 (a) (iii) and (iv). The key (and surprising) insight here is that for fashion and function innovation, there are conditions when increasing environmental sensitivity among consumers leads to greater total environmental harm, specifically, when in-use harm dominates. We later assess the sensitivity of the result to the assumption (motivated by the literature linking guilt and sustainable behaviors) and show that this result is due to the lower environmental harm sensitivity among first time

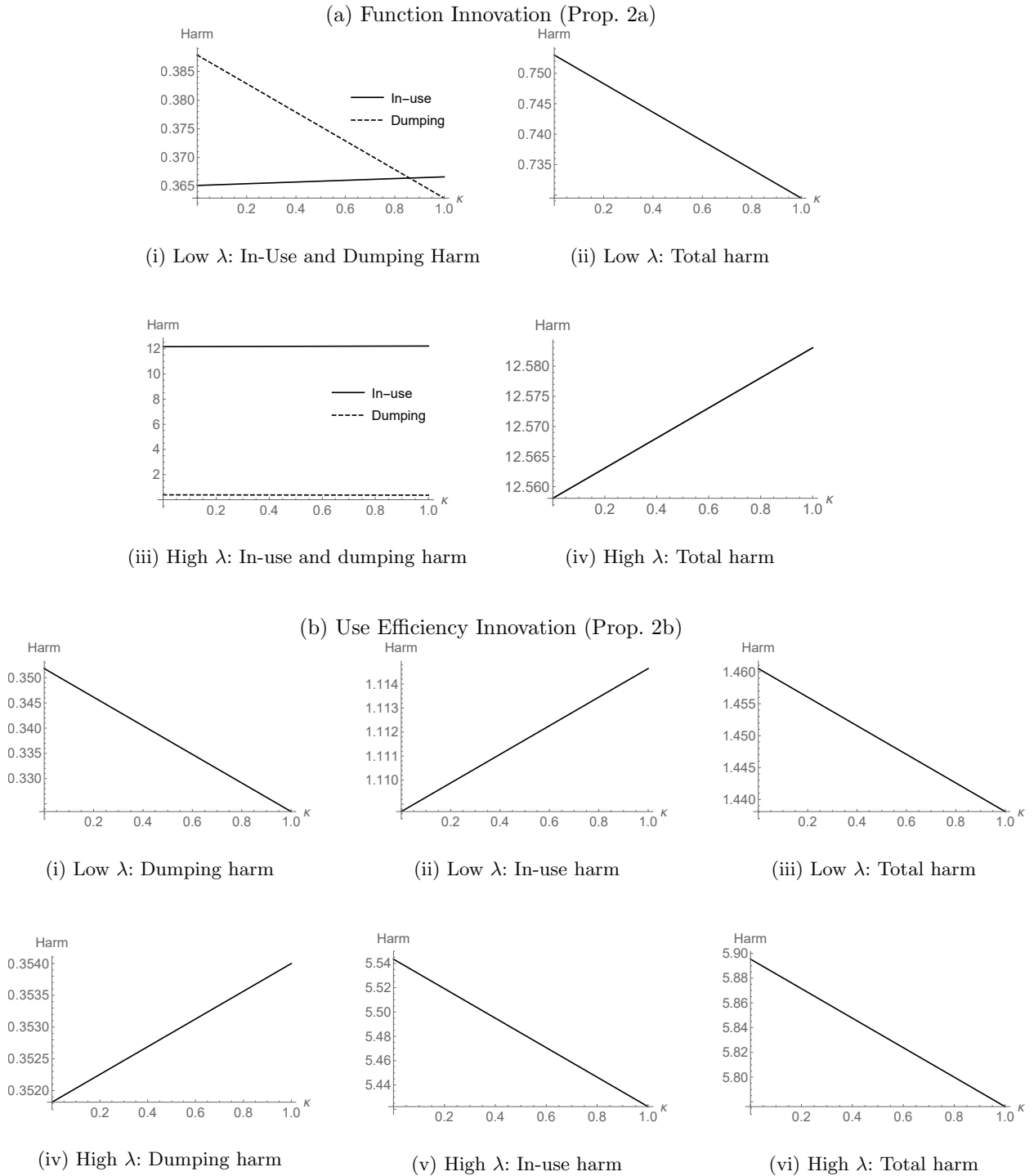


Figure 5 Impact of environmental sensitivity on environmental harm (Prop.2)

buyers, relative to upgraders at the time of purchase. This clarifies the importance of accounting for behavioral insights in sustainability choices within analytical models.

4.4. Consumer and Social Surplus

We next discuss the comparative statics of κ on consumer and social surplus.

Proposition 3. *Consumer and Social Surplus*

a. *Function and fashion innovation: As κ increases, (i) consumer surplus increases when $\lambda < \lambda_{CS}^*$; and decreases when $\lambda > \lambda_{CS}^*$; (ii) social surplus always decreases.*

b. *Use efficiency innovation: As κ increases, (i) consumer surplus increases when $\lambda < \lambda_{CS}^*$; and decreases when $\lambda > \lambda_{CS}^*$; (ii) social surplus decreases when $\lambda < \lambda_{SS}^*$; and increases when $\lambda > \lambda_{SS}^*$.*

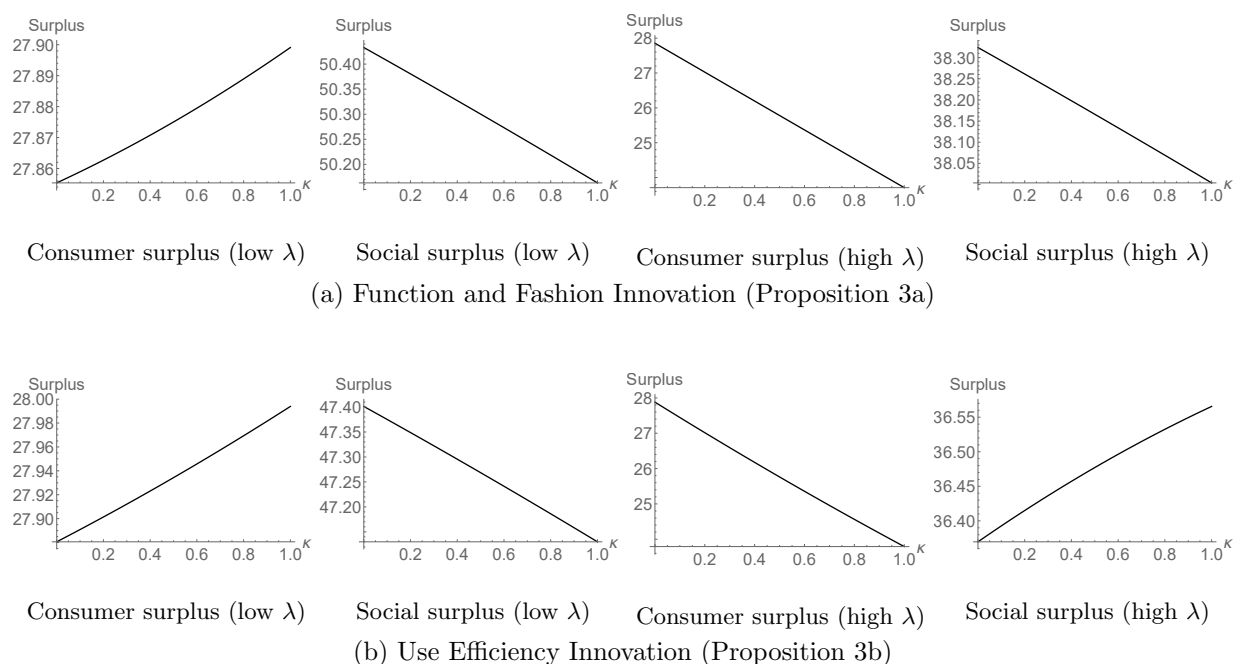


Figure 6 Impact of environmental sensitivity on consumer and social surplus

Note that unlike typical market settings where the differences in consumer surplus and social surplus arise primarily from how shares of surplus are allocated between firms and consumers (beyond the total expansion of surplus), here social surplus should account for environmental harm, and consumer surplus is also impacted by how much consumers internalize environmental harm through κ . It is therefore useful to consider an integrative discussion across the various metrics in discussing consumer and social surplus.

Figure 6 shows the basic results of Proposition 3. A companion figure of how environmental harm, firm profit, consumer surplus and social surplus change with κ as a function of λ is also provided

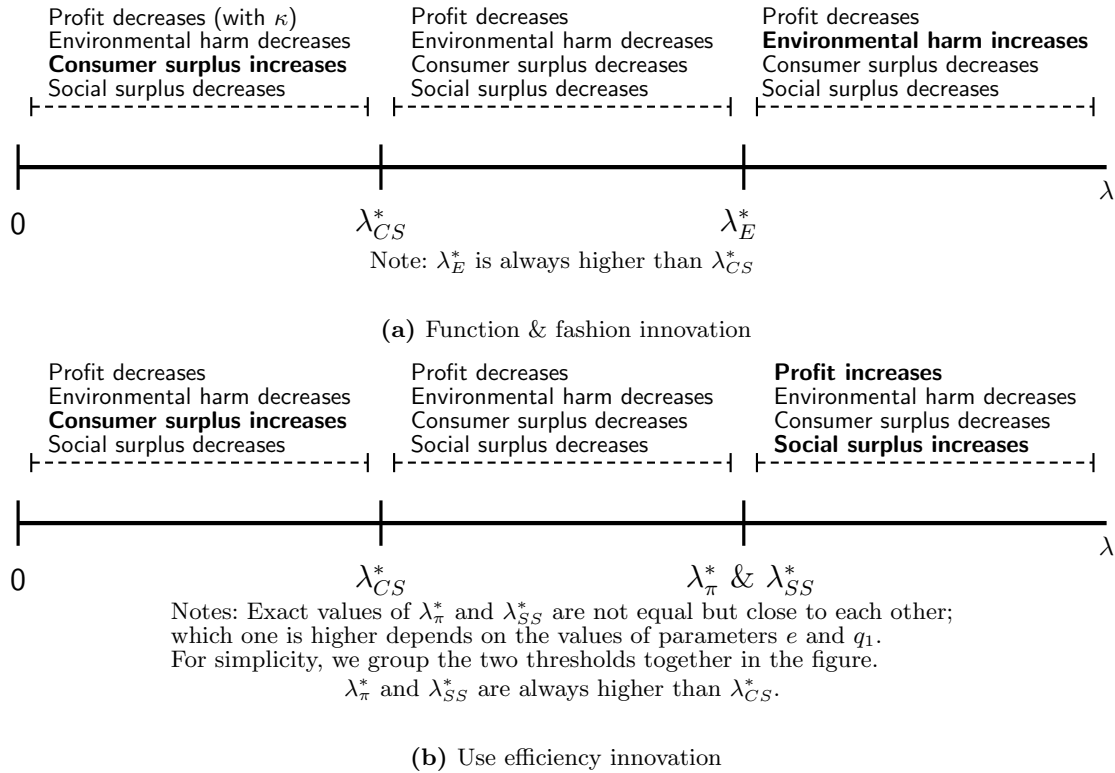


Figure 7 Comparing profit, environmental harm and surplus changes with environmental sensitivity

in Figure 7. A complete summary of the comparative statics across the lemmas and propositions are summarized in Table 3.

Overall, the following key takeaways stand out. For function and fashion innovation, social surplus always decreases with κ ; so the more consumers take into account environmental harm, the lower the social surplus. Note that there are three regions of λ to consider in Figure 7a. First, in the region where the use-dump harm ratio is low ($\lambda < \lambda_{CS}^*$), consumer surplus goes up and total environmental harm goes down. Note that the consumer surplus increases as a result of the market expansion in Q_2 , but fewer upgrades reduce dumping harm enough to reduce environmental harm. The fact that despite this the social surplus goes down means that the negative impact on profit for fashion and function innovations due to increase in κ overwhelms the decrease in environmental harm and increase in consumer surplus. In the middle range ($\lambda_{CS}^* < \lambda < \lambda_E^*$), environmental harm still decreases, but now consumer surplus also decreases. Now social surplus falls because the decrease in consumer surplus and profits more than overwhelms the decline in environmental harm.

	Innovation Type			
	Fashion/Function		Use Efficiency	
	Low λ	High λ	Low λ	High λ
p_1		–	–	–
Q_1		0	–	–
p_2		–	–	+
Q_2		+	+	+
Q_{12}		–	–	+
Total Dumping Harm		–	–	+
Total In-use Harm		+	+	–
Total Overall Harm	–	+	–	–
Profit		–	–	+
Consumer Surplus	+	–	+	–
Social Surplus	–	–	–	+

Table 3 Comparative statics with respect to κ

Note: The thresholds that separate “low and high λ ” vary across innovation types and metrics.

For exact λ thresholds, please see corresponding propositions.

Finally, in the high λ range ($\lambda > \lambda_E^*$), even the environmental harm increases, thus further increasing the downward slope of the social surplus.

Next we discuss the case of use-efficiency innovation. Again there are three regions of λ to consider in Figure 7b. First, in the region where the use-dump harm ratio is low ($\lambda < \lambda_{CS}^*$), the results are identical to the case of function and fashion innovation; social surplus goes down, consumer surplus goes up and total environmental harm goes down. Again the fact that despite the increase in consumer surplus and decrease in environmental harm, the social surplus goes down implies that the negative impact on profit for use efficiency innovations with low λ due to increase in κ overwhelms the decrease in environmental harm and increase in consumer surplus. In the middle range ($\lambda_{CS}^* < \lambda < \min(\lambda_{SS}^*, \lambda_{\pi}^*)$), environmental harm still decreases, but now consumer surplus also decreases. Now social surplus falls because the decrease in consumer surplus and profits more than overwhelms the decline in environmental harm. Finally, the key difference is in the high λ range ($\lambda > \max(\lambda_{SS}^*, \lambda_{\pi}^*)$), where not only the social surplus increases, but also profit, due to the

higher price p_2 that can be charged for the innovation with an increase in κ . Here consumer surplus decreases, but environmental harm also decreases.¹⁴

4.5. Who educates consumers on environmental sensitivity?

Our results on how profit and environmental harm changes in response to increasing κ can provide managerial insights on who would take responsibility for sensitizing and educating consumers about environmental harm. The results are summarized in Table 4. First, we find only one setting,

Innovation Type	Low λ	High λ
Fashion/Function	Profit: Decreases	Profit: Decreases
	Env Harm: Decreases	Env Harm: Increases
	Who Educates: Env Advocate	Who Educates: None
Use Efficiency	Profit: Decreases	Profit: Increases
	Env Harm: Decreases	Env Harm: Decreases
	Who Educates: Env Advocate	Who Educates: Firm

Table 4 Effect of increasing κ ; Who educates consumers on environmental sensitivity?

where there is an alignment between firm profit and environmental outcomes. When λ is high, use efficiency innovation increases firm profit and reduces environmental harm. This alignment implies that as consumer environmental sensitivity increases, firms will gravitate towards use efficiency innovations in categories where use-dump harm ratio is high. In these categories, firms may also choose to increase consumer environmental sensitivity as their profits will rise. Examples of innovations in this group are hybrid and electric cars, air conditioners, heating systems, washing machines, refrigerators with substantially higher fuel efficiency than prior generation machines. These categories are clearly high λ categories as they involve significant energy use (and environmental harm) in-use relative to dumping harm. Our analysis suggests that these are categories where there is high alignment between the producers of such innovation in terms of profits and environmental benefits, and that such innovators will lead with consumer education. Not surprisingly, manufacturers of hybrid and electric cars may not merely tout the usage efficiency of their products but be much more heavily embrace the sustainability movement among consumers.

¹⁴ For this qualitative discussion of the three regions of λ , we ignore the region $\lambda \in (\min(\lambda_{SS}^*, \lambda_\pi^*), \max(\lambda_{SS}^*, \lambda_\pi^*))$.

Second, when the use-dump harm ratio is low, increasing consumer environmental sensitivity reduces environmental harm and firm profits for all three types of innovations. Therefore in this setting, firms have little incentive to educate consumers about environmental harm, and environmental advocates have to take the leading in educating consumers to become more sensitive. As discussed earlier in Table 1, firms marketing fashion and function innovations rarely seek to increase consumer environmental sensitivity. Even with use-efficiency innovations, for product with low λ , firms rarely educate consumers directly about being sustainable; much of the advocacy is from environmental advocacy groups—consistent with our results.

When use-dump harm ratio is large, for fashion/function innovation, there is a lose-lose proposition for firms and the environment as profits fall, and environmental harm increases. In this condition, neither firms or environmental advocates would seek to increase consumer's environmental sensitivity. If consumers nevertheless became more environmentally sensitive, then firms have more incentive to shift away from fashion and function innovations towards use efficiency innovation. While in our current model, we have treated the innovations as exogenous, our results suggest that as sensitivity towards environmental harm increases, firms will be nudged to prioritize use efficiency improvements relative to pure fashion/function innovations. But given that it is often technically easier to produce fashion/function innovations compared to use-efficiency innovations, fashion/function innovations will still be introduced more frequently despite higher environmental sensitivity. Hence our results based on exogenous innovation types remain managerially valuable.

4.6. Robustness check: Environmental sensitivity among first time buyers

Based on the behavioral literature around guilt and its impact on environmental sensitivity and sustainable behaviors, we assumed in our main model that only upgraders are sensitive to environmental sensitivity. However, it is possible that even first time buyers may feel some anticipatory guilt, due to the reactive guilt they feel based on purchases outside the category that create environmental harm. In this section, we therefore relax the assumption of zero environmental sensitivity among first time buyers and assess the robustness of our result by allowing the sensitivity to environmental harm of first time buyers to be a fraction $\phi \in [0, 1]$ of the sensitivity of the upgraders.

Accordingly, we modify the flow utilities of first time buyers in period 1 and 2, from equation (1) as follows:

$$U_{11}^f = \theta q_1 \frac{1}{1 - e_1} - p_1 - \phi \kappa \lambda_u (1 - e_1) \quad \text{and} \quad U_{22}^f = \theta q_2 \frac{1}{1 - e_2} - p_2 - \phi \kappa \lambda_u (1 - e_2) \quad (3)$$

where p_j is the price of product j , and $\kappa \lambda_u (1 - e_j)$ reflects the consumer's environmental disutility from product usage for a product whose use efficiency is indexed by e_j . For owners who purchased in period 1, the period 2 utilities for those who upgrade (U_{22}^o) and continue with the same product (U_{12}^o) are the same as in equation (2).¹⁵

We focus our analysis on function and fashion innovations here to assess the robustness of our surprising result in Proposition 2(a), where we find that environmental harm increases as κ increases, when $\lambda > \lambda_E^*$. With first time buyers also having some environmental sensitivity, we obtain the following proposition.

Proposition 4. *For function and fashion innovation, as κ increases, there exists a cutoff $\phi_E^* \in (0, 1)$ such that for all $\phi < \phi_E^*$, total environmental harm increases for a sufficiently large $\lambda > \lambda_E^*$; for $\phi > \phi_E^*$, total environmental harm always decreases.*

The proof of Proposition 4 and expressions for the λ and ϕ thresholds for function and fashion innovations are in Appendix A.3. Proposition 4 shows that as the extent of environmental sensitivity among first time buyers increases, there exists a point at which environmental harm ceases to increase, and switches to always decreasing with increasing κ . The proposition clarifies the value of modeling the behavioral insight that first time buyers perceive less environmental harm on equilibrium outcomes. If we had not accounted for the behavioral theory based findings on sustainable choice, and simply assumed that both first time buyers and upgraders had equal environmental sensitivity, we would not have identified the insight that increasing environmental sensitivity can lead to greater environmental harm.

To understand the mechanism of how ϕ impacts environmental harm, it is useful to understand how equilibrium prices and quantities change as a function of κ and ϕ . Not surprisingly as κ

¹⁵ Please see Appendix A.1.4 for the relevant indifference equations with ϕ in the case of function innovation.

increases, the increase in ϕ among first time buyers always reduces not only Q_1 (the first time purchases in period 1); but also reduces Q_{12} (upgrades in period 2). But there is a range $\phi < \phi_E^*$, where as κ increases, this demand suppression leads to a decrease in p_2 and an increase in Q_2 such that total sales in the market is higher. At high levels of λ , this leads to higher-in use harm and higher total environmental harm.

5. Informing consumers about arrival of use efficiency innovation

Thus far, we have assumed rational expectations about the product launch in the second period; i.e., forward looking consumers and firms can correctly anticipate period 2 outcomes in period 1, in terms of firm pricing and innovation launch when they make choices. However, consumers usually do not know when an innovation will be launched unless there is some marketing effort by some entity (the firm, sustainability advocates or regulator) informing consumers about the future launch. To the extent that informing consumers in advance (we use “pre-announce” as a shorthand) about the arrival of time-targeted use-efficiency mandates can impact the timing of consumer purchases—whether to buy now or wait for the innovation, it will impact not only firm pricing and equilibrium profit, but also environmental harm. Thus both firms and regulators/sustainability advocates have an interest in pre-announcements depending on whether it increases profits or reduce environmental harm. In this section, we investigate how pre-announcements impact profit and environmental harm; specifically we focus on use efficiency innovations as they produce novel and useful qualitative insights.

For this analysis, we compare two situations: (a) the firm pre-announces the innovation in period 1, so consumers are aware in period 1 about its arrival in period 2 (as in our analysis thus far); and (b) there is no pre-announcement in period 1, so consumers are unaware in period 1, and they simply expect the same product as in period 1 to be available in period 2.¹⁶ We then compare the equilibrium outcomes (firm profit and environmental harm) in the two situations.

¹⁶ In their analysis of of product obsolescence of durable goods, [Levinthal and Purohit \(1989\)](#) study the question of whether a firm should inform consumers of their period 2 product introduction in advance. We follow their assumption that consumers assign zero probability of a new product arrival in period 2 when they are not informed. As

5.1. Demand Effects

We begin by comparing demand effects (prices and quantities) in the pre-announcement and no announcement cases. The results are summarized in Lemma 2.

Lemma 2. *For use efficiency innovation,*

When $\lambda < \lambda^{PA}$: Period 1 price (p_1) is lower, and period 1 quantity ($Q_1 = 1 - \theta_1$) is higher with pre-announcement. Though period 2 price (p_2) is lower with pre-announcement, new purchase quantity ($Q_2 = \theta_1 - \theta_2$) is lower, but upgrade quantity ($Q_{12} = 1 - \theta_{12}$) is higher with pre-announcement.*

When $\lambda > \lambda^{PA}$: Period 1 price (p_1) is lower, but period 1 quantity ($Q_1 = 1 - \theta_1$) is still lower with pre-announcement. Though period 2 price (p_2) is higher with pre-announcement, new purchase quantity ($Q_2 = \theta_1 - \theta_2$) is still higher, while upgrade quantity ($Q_{12} = 1 - \theta_{12}$) is lower with pre-announcement.*

5.2. Firm Profit

We next compare the firm profit in the pre-announcement and no announcement cases.

Proposition 5. *For use efficiency innovation,*

When $\lambda < \lambda_{\pi}^{PA}$: firm profit is higher with pre-announcement.*

When $\lambda > \lambda_{\pi}^{PA}$: (i) when $\kappa < \kappa_{\pi}^{PA*}(\lambda)$, firm profit is higher with pre-announcement; (ii) when $\kappa > \kappa_{\pi}^{PA*}(\lambda)$, firm profit is higher with no announcement. Further, the threshold $\kappa_{\pi}^{PA*}(\lambda)$ at which profits with and without pre-announcement intersects decreases in λ .*

The expressions for λ and κ thresholds and proof of Proposition 5 are in Appendix A.3.

Figures 8a and 8b illustrate Proposition 5. We denote profit under pre-announcement as π_a and under no announcement as π_u . Figure 8a shows that at low values of λ ($\lambda < \lambda_{\pi}^{PA*}$), the firm's profit is higher with pre-announcement. Figure 8b shows that at high values of λ ($\lambda > \lambda_{\pi}^{PA*}$), the firm's efficiency mandates are relatively uncommon in most appliance categories and consumers have little awareness of such mandates in the absence of advertising campaigns, this is a reasonable approximation. Going forward, we use "firm pre-announces" and "consumer is aware" interchangeably; and "firm does not pre-announce," "no-announcement" and "consumer is unaware" interchangeably.

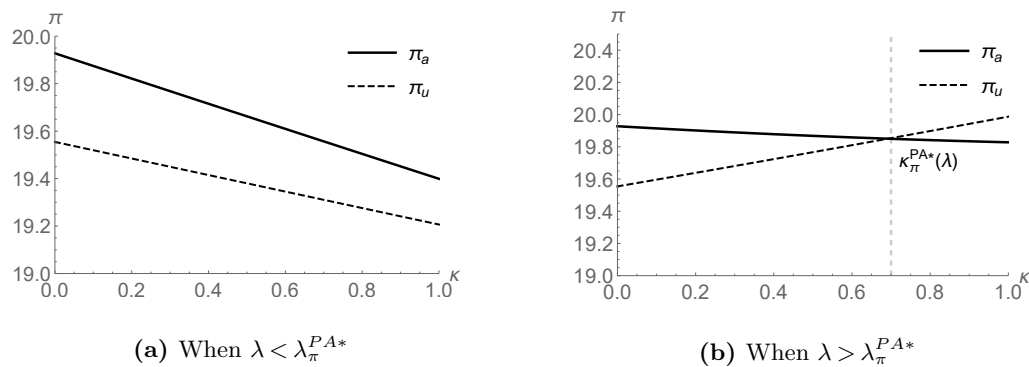


Figure 8 Profit under pre-announcement and no announcement for use efficiency innovation

profit under pre-announcement is lower when environmental sensitivity is above a threshold level of $\kappa_{\pi}^{PA*}(\lambda)$. This threshold point $\kappa_{\pi}^{PA*}(\lambda)$ shifts to the left with λ , i.e., decreases with λ .

To understand this result, note that with or without pre-announcement, in period 1, consumers have incentives to postpone buying to period 2, but for different reasons: (i) With pre-announcement, consumers wait to avail of the greater use efficiency in the innovation; especially when environmental sensitivity (κ) exceeds a threshold, they have a greater incentive to wait till period 2 for the use efficiency innovation. (ii) With no announcement, consumers expect the same product to be offered in period 2, but now expect a lower future price in period 2 as expected from the Coase conjecture (Coase 1972). Both of these reasons lead to lower demand (and lower prices) in period 1. When κ and use-dump harm ratio (λ) are high, consumers have more motivation to postpone purchase until period 2 when they are aware of the upcoming innovation. But without the announcement, the firm is able to generate more profit in period 1 compared with the pre-announcement case. Further, in period 2, the firm can charge a higher price for the use efficiency upgrade and still attract highly environmentally aware (high κ) consumers to upgrade, leading to higher profit without pre-announcement.

However, when the use-dump ratio λ is low, period 1 quantity increases due to the lower period 1 price, as in-use harm is less salient and a low price is effective to induce consumers to buy the product in period 1. The increase in period 1 purchases leads to a higher profit for the firm compared with no announcement, and hence the firm would find it optimal to pre-announce the innovation in period 1, instead of offering the use-efficiency innovation in period 2 as a “surprise.”

Our result that profit is higher with pre-announcement when λ is low mirrors the result in [Levinthal and Purohit \(1989\)](#), who do not consider environmental harm (so zero). The finding that profit is greater without pre-announcement when λ is high is novel.

It is also easy to see why there is an interaction effect between λ and κ in terms of the threshold at which pre-announcement or no-announcement is optimal. Clearly, use efficiency innovations are valued more at higher κ . Hence an increase in λ implies a lower κ threshold at which profit without announcement exceeds the profit with pre-announcement.

5.3. Environmental Harm

Next, we study the impact of pre-announcing the use efficiency innovation on environmental harm.

Proposition 6. *For use efficiency innovation, when $\lambda < \lambda^{PA*}$: dumping harm, in-use harm and total harm are higher when there is pre-announcement; when $\lambda > \lambda^{PA*}$: dumping harm, in-use harm and total harm are higher when there is no announcement.*

The expression for the λ threshold and proof for Proposition 6 are in Appendix A.3.

As discussed earlier, pre-announcements make consumers' intertemporal substitution elasticities greater. When the use-dump harm ratio λ is low, consumers are more focused on the dumping harm at replacement. The firm reduces prices to induce upgrades in period 2 (Q_{12} increases), which at the same time increases the overall quantities sold across the two periods, leading to greater overall environmental harm. But when in-use harm is large, the focus is not just on lower cost of use, but also on the reduced environmental harm; and getting consumers to focus on the benefits of the innovation (lower use cost and greater reduction in environmental harm) leads to overall better alignment with environmental outcomes when there is pre-announcement and consumers become aware of the future use efficiency innovation in period 1.

5.4. Consumer and Social Surplus

Proposition 7. *For use efficiency innovation, consumer surplus and social surplus are always higher with pre-announcement.*

The proof for Proposition 7 is provided in Appendix A.3.

	Low λ	High λ
Lower κ	Profit: Higher	Profit: Higher
	Env Harm: Higher	Env Harm: Lower
	Who Pre-announces: Firm	Who Pre-announces: Firm
Higher κ	Profit: Higher	Profit: Lower
	Env Harm: Higher	Env Harm: Lower
	Who Pre-announces: Firm	Who Pre-announces: Env Advocate

Table 5 Effect of pre-announcing use efficiency innovation; Who pre-announces?

As consumer and social surplus always increase with pre-announcements, consumer (not sustainability) advocates and regulators would always prefer to provide advance information about the arrival of use efficiency innovations through advertising and/or public relations in the media, even if firms are reluctant to do so given profit considerations.

5.5. Who pre-announces (educates) about arrival of use efficiency innovation?

We jointly consider the results in Propositions 5-7 to gain insight on who should educate consumers through pre-announcements of use-efficient innovation. Table 5 summarizes the effects of pre-announcements on profit and environmental harm. As consumer surplus and social surplus unambiguously favor pre-announcements, they are not included in the table.

We begin with the two low λ cases. Firm profit is higher with pre-announcement, but environmental harm is also higher. While environmental advocates will therefore prefer not to pre-announce, firms will pre-announce it due to higher profit. But consumer and social surplus are also greater with pre-announcement. Overall, however recall from the analysis reported in Table 4, that the use-efficiency innovation itself does reduce environmental harm even with pre-announcement.

But firms will not always pre-announce in the high λ cases. When κ is low, firm profit and environmental harm are aligned and the firm will indeed make pre-announcement and the environmental harm will be lower. But when κ is high, we have misalignment. The firm will not pre-announce as it reduces profit though there is an environmental benefit. But an environmental advocate can pre-announce and ensure the full benefit of reduced environmental harm is attained.

Overall our analysis sheds managerial insight on when firms or environmental advocates should take responsibility for consumer education about the arrival of time-mandated use efficiency innovations. Further, the set of results in the high λ case also go against conventional wisdom that

consumer environmental sensitivity through education is a substitute for regulatory intervention or environmental advocacy. Here, when consumer environmental sensitivity is low, firms make the environmentally aligned pre-announcement choice; but it is when the environmental sensitivity is high that the misalignment of profit incentives requires an environmental advocate to step in.

6. Conclusion

In this paper, we develop an economic modeling framework to understand how sustainability interventions impact firm profit and environmental harm in durable goods markets. We make three contributions in terms of modeling to the literature: First, we build on the behavioral literature on how reactive and anticipatory guilt impact sustainability choices; one implication of this literature for modeling is that consumers who own a product in the category already are more sensitive to environmental harm. Second, we disentangle environmental harm over the life cycle arising from product use and dumping the product at replacement; we clarify that the relative ratio of in-use and dumping harm play a crucial role in both understanding equilibrium outcomes and the effectiveness of different sustainability interventions. Finally, we introduce a taxonomy of innovations (function, fashion and use-efficiency) that differ in how they provide incremental consumer value and cause environmental harm; we show that use-efficiency innovations differ from fashion and function innovation in terms of many key results.

We capture the dynamics of market outcomes in a two period model where consumers and firms are forward looking. Consumers choose whether and when to buy accounting not only for flow utility and use cost but also environmental impact. Firms set prices in response to these consumer choices. We thus assess how equilibrium consumer choice, firm profit and environmental impact are affected in equilibrium for different innovation types.

We then consider the effect on firm profit and environmental harm from increasing consumer green sensitivity through education, first in the context of rational expectations for fashion, function and use-efficiency innovation, and then allowing for unexpected introduction of use efficiency innovation. We find conditions where counter-intuitively, (i) increasing green sensitivity can increase

environmental harm for fashion and function innovation, and (ii) pre-announcement of use efficiency innovations can hurt firm profits and increase environmental harm.

Overall, decomposing the environmental harm in terms of in-use harm and dumping harm turns out to be conceptually meaningful in the study of sustainable innovations, where consumers consider the tradeoff between dumping harm and in-use harm as they adopt and upgrade in durable goods markets. Further, with use efficiency innovation, there are situations when higher environmental awareness among consumers requires complementary regulatory support to protect the environment, which goes against the conventional wisdom that environmental awareness and regulatory action are substitutes. In general, our analysis provides insight on when there are win-win policies for both the firm and the environment, and when advocates/regulators need to be adversarial with firms to achieve desired sustainability goals.

6.1. Limitations and Future Research

We now discuss certain abstractions and limitations in our model that can be extended in future research. The analysis in the paper is based a two-period model with a static set of consumers; it would be useful to extend and assess the sensitivity to an infinite horizon model with overlapping generations of consumers.¹⁷ Further, we abstracted away from the potential presence of second-hand markets. In some categories, these can significantly impact for dumping harm, in-use harm, and market prices and quantities. Also, the paper considered a durable goods monopoly; it would be useful to extend the analysis to competitive settings to assess robustness and potential differences in insights. Further, we considered profit maximizing firms, whose choices are governed only by their effects on demand and profit. With firms increasingly incorporate sustainability goals into their own objectives, it would be promising to study the resulting equilibria in future research.

¹⁷ We note that the surprising result that environmental harm can be greater with rising κ will not be overturned by the presence of new consumers in period 2. This is because κ always suppresses period 2 prices (even if only a little if there are new consumers), and this price decrease will always increase Q_2 whether it is only from the residual demand of non-purchasers from the first period or includes new consumers from the second period. Thus the intuition for increase in environmental harm due to increase in Q_2 remains. We thank a reviewer for suggesting this discussion.

Our modeling framework is rich can be used and extended to study various demand and supply side sustainability interventions. As an example of demand side interventions, one could study how to structure sustainability taxes. For example, should it be a fixed fee per unit, percentage of price, or a multiple on estimated environmental harm? When should it be charged: at purchase or at disposal? On the supply side, one can evaluate the impact of sustainable design and manufacturing policies (e.g., modular upgrades, recyclable/biodegradable inputs) that impact market outcomes through their effect on environmental harm and thus consumer choices. One could study the effect of firm-side taxes based on environmental harm and its downstream pass-through effects not only on pricing, but also in the choice of production technology that minimizes environmental harm (e.g., modular production, firm recycling programs).

Finally, our analysis treated fashion, function and use efficiency innovations as distinct types of innovations, and product and upgrade characteristics as exogenous. This helped us isolate results associated with each type of innovation. We note however that typically, there are fewer technology constraints for fashion and function innovations than for use efficiency innovations; so fashion and function innovations tend to be more frequent than use efficiency innovations. The fact that our key insights are similar for fashion and function, but differ for use-efficiency innovations is therefore managerially useful.¹⁸ Nevertheless future work should consider innovations as a combination of these types, with characteristics that are endogenously chosen by firms. This would require adding a cost structure including marginal and fixed costs, and environmental harm arising from the use of different technologies to characterize the optimal choice of production/recycling methods. Overall, we hope our modeling framework accounting for consumer guilt in sustainable choice serves as a starting point for a rich agenda addressing sustainability issues in studying durable goods markets.

¹⁸ In the current paper, we did not focus on differences between fashion versus function innovations. This needs analysis on factors unique to fashion and function innovations—e.g., fashion depreciation or functional improvements. As an illustration, we report analysis of comparative statics on fashion depreciation δ in online appendix §[EC.2.1](#).

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Appendix A: Results and Proofs

In this appendix (including all solutions, proofs, and other discussions), for simplification, we use q_1 to uniformly represent the quality q_{11} in period 1 regarding all 3 innovation cases, and q_2 to represent the quality q_{22} in period 2 for function innovation. For use efficiency innovation, since $q_{22} = q_{11}$, in period 2, we still use q_1 to indicate the quality. For fashion innovation, the perceived quality of the product bought in period 1 has depreciated to δq_1 in period 2.

A.1. Main Model

A.1.1. Function innovation We proceed to solve period 2 optimal θ values first, and then period 1's by backward induction. In period 2, the threshold consumer θ_{12} is indifferent between (a) upgrading to q_2 at price p_2 , and experiencing environmental disutility from dumping (κ) and usage ($\kappa\lambda$), and (b) continuing to use q_1 at no extra expense, and incurring just the usage based environmental disutility ($\kappa\lambda$). This is captured in the following condition: $\theta_{12}q_2 - p_2 - \kappa(1 + \lambda) = \theta_{12}q_1 - \kappa\lambda$. Solving the condition for p_2 yields: $p_2 = \theta_{12}(q_2 - q_1) - \kappa$.

In period 2, the threshold consumer θ_2 is indifferent between (a) buying q_2 at price p_2 , and experiencing no environmental disutility (since guilt requires prior purchase and this consumer has not yet purchased the good), and (b) buying nothing, captured by the condition: $q_2\theta_2 - p_2 = 0$. Solving this condition, we obtain another expression for p_2 : $p_2 = q_2\theta_2$. Equating the two expressions for p_2 above, and solving for θ_{12} yields: $\theta_{12} = \frac{\kappa + \theta_2 q_2}{q_2 - q_1}$. We then substitute the above value for θ_{12} in the second period profit expressions: $\pi_2 = (\theta_1 - \theta_2)(p_2 - 1)$ and $\pi_{12} = (1 - \theta_{12})(p_2 - 1)$. And we solve the first order condition $\frac{\partial(\pi_2 + \pi_{12})}{\partial\theta_2} = 0$ for the optimal value of θ_1 in terms of θ_2 and other parameters, to obtain the following expression for θ_2 : $\theta_2 = \frac{\theta_1 q_2^2 - \theta_1 q_1 q_2 - \kappa q_2 + q_2^2 - q_1 q_2 + 2q_2 - q_1}{2q_2(2q_2 - q_1)}$.

We now turn to period 1, where the threshold consumer θ_1 is indifferent between (a) buying q_1 in period 1 at price p_1 , and using it for two periods, and (b) waiting and buying q_2 at period 2 at price p_2 , and using it for one period. In either alternative, this consumer feels no environmental disutility in period 1, because they have not yet consumed the product at the time of formulating this equation (and hence have not experienced guilt), and moreover, in period 2 the two product-alternatives q_1 and q_2 have identical usage efficiencies. This is captured in the following indifference condition: $2q_1\theta_1 - p_1 = q_2\theta_1 - p_2$. Substituting for p_2 and solving for p_1 , we have: $p_1 = \frac{4\theta_1 q_1^2 - 9\theta_1 q_2 q_1 + 3\theta_1 q_2^2 + \kappa q_2 + q_2 q_1 + q_1 - q_2^2 - 2q_2}{2(q_1 - 2q_2)}$.

Substituting for p_2 in the expression for period-1 profit $\pi_1 = (p_1 - 1)(1 - \theta_1)$, and solving the first order condition $\frac{\partial(\pi_1 + \pi_2 + \pi_{12})}{\partial \theta_1} = 0$, we obtain the optimal value for θ_1 : $\theta_1 = \frac{4q_1^2 - 9q_2q_1 + 3q_2^2}{8q_1^2 - 19q_2q_1 + 7q_2^2}$. Substituting for the above value for θ_1 into the expressions for θ_2 and θ_{12} , gives us the following segmentation boundaries:

$$\theta_2 = \frac{1}{14} \left(5 + \frac{7(\kappa + q_1)}{q_1 - 2q_2} + \frac{7}{q_2} + \frac{4q_1(-3q_1 + q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right)$$

$$\theta_{12} = \frac{1}{14} \left(5 - \frac{7(\kappa + q_1)}{q_1 - 2q_2} + \frac{7(1 + \kappa)}{-q_1 + q_2} + \frac{2q_1(8q_1 - 5q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right)$$

Substituting for these expressions in the profit and pricing expressions, gives the optimal solutions.

Endogenous segmentation boundaries are interior points:

It remains to be shown that $0 < \theta_2 < \theta_1 < \theta_{12} < 1$. The inequality translates to:

$$0 < \frac{1}{14} \left(5 + \frac{7(\kappa + q_1)}{q_1 - 2q_2} + \frac{7}{q_2} + \frac{4q_1(-3q_1 + q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right) < \frac{4q_1^2 - 9q_2q_1 + 3q_2^2}{8q_1^2 - 19q_1q_2 + 7q_2^2} < \frac{1}{14} \left(5 - \frac{7(\kappa + q_1)}{q_1 - 2q_2} + \frac{7(1 + \kappa)}{-q_1 + q_2} + \frac{2q_1(8q_1 - 5q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right) < 1$$

It can be verified algebraically that the above inequality is valid in the parameter range when $0 < q_1 < q_2 < \frac{3}{2}q_1$, $q_1 > 1$, and $q_1^2(35 + 62\kappa + 74q_1)q_2 + (14 + 21\kappa + 80q_1)q_2^3 > 8q_1^3(1 + 2\kappa + 2q_1) + q_1(45 + 71\kappa + 120q_1)q_2^2 + 18q_2^4$. The last condition can be interpreted as: the ratio q_2/q_1 (which measures the degree of innovation) should be above a threshold specified by q_1 . In other words, for a parameter range where we witness at least some meaningful innovation that has a floor (i.e. q_2/q_1 being above a threshold) and at most a realistically large extent of innovation that has a ceiling bound (i.e. $\frac{3}{2}q_1 > q_2$), we see that all the endogenously derived segmentation boundaries preserve their relative order and are bounded between 0 and 1.

The full expressions of the optimal solutions are:

$$\pi = \frac{1}{196}(-196 - 98\kappa + 51q_1 + \frac{49(\kappa + q_1)^2}{q_1 - 2q_2} + \frac{49}{q_2} + 42q_2 + \frac{49(1 + \kappa)^2}{-q_1 + q_2} - \frac{4q_1^2(4q_1 + q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2})$$

$$p_1 = \frac{16q_1^4 + q_1^3(8 - 64q_2) + q_1(45 - 19\kappa - 28q_2)q_2^2 + q_2^3(-14 + 7\kappa + 2q_2) + q_1^2q_2(-35 + 8\kappa + 78q_2)}{2(q_1 - 2q_2)(8q_1^2 - 19q_1q_2 + 7q_2^2)}$$

$$p_2 = \frac{q_1^2(-35 + 8\kappa - 40q_2)q_2 + (-14 + 7\kappa - 10q_2)q_2^3 + 4q_1^3(2 + 3q_2) + q_1q_2^2(45 - 19\kappa + 38q_2)}{2(q_1 - 2q_2)(8q_1^2 - 19q_1q_2 + 7q_2^2)}$$

$$Q_1 = \frac{4q_1^2 - 10q_1q_2 + 4q_2^2}{8q_1^2 - 19q_1q_2 + 7q_2^2}$$

$$Q_2 = \frac{(14 - 7\kappa - 2q_2)q_2^3 - 4q_1^3(2 + q_2) + q_1q_2^2(-45 + 19\kappa + 4q_2) + q_1^2q_2(35 - 8\kappa + 6q_2)}{2(q_1 - 2q_2)q_2(8q_1^2 - 19q_1q_2 + 7q_2^2)}$$

$$Q_{12} = \frac{16q_1^4 + 2q_1^3(4 + 8\kappa - 37q_2) + q_1(45 + 71\kappa - 80q_2)q_2^2 + q_2^3(-7(2 + 3\kappa) + 18q_2) + q_1^2q_2(-35 - 62\kappa + 120q_2)}{2(q_1 - 2q_2)(q_1 - q_2)(8q_1^2 - 19q_1q_2 + 7q_2^2)}$$

$$harm = \frac{1}{14} \left(9 + 17\lambda - \frac{7(-1 + \lambda)(\kappa + q_1)}{q_1 - 2q_2} + \frac{7(1 + \kappa)}{q_1 - q_2} - \frac{7\lambda}{q_2} + \frac{2q_1(2(-4 + \lambda)q_1 + (5 + 4\lambda)q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right)$$

A.1.2. Fashion innovation In this case, the analysis and results are essentially similar to the function case. The difference is that, while in the function case, the period-2 quality is q_2 as opposed to a period-1 quality of q_1 , in the case of fashion innovation, the period-2 quality remains q_1 , while the period-1 quality *in period 2* degenerates to δq_1 , where $0 < \delta < 1$.

The indifference equations are now: $\theta_{12}q_1 - p_2 - \kappa(\lambda + 1) = \delta\theta_{12}q_1 - \kappa\lambda$, $\theta_2q_1 - p_2 = 0$, and $(1 + \delta)q_1\theta_1 - p_1 = q_1\theta_1 - p_2$. To show that endogenous segmentation boundaries are interior points, it remains to be shown that $0 < \theta_2 < \theta_1 < \theta_{12} < 1$. The inequality translates to: $0 < \frac{2(\delta-2)\delta(3\delta-2)+2}{\delta(4\delta-7)-1} + \frac{\delta+\kappa-2}{q_1} < \frac{(3-2\delta)\delta+1}{(7-4\delta)\delta+1} < \frac{-2\delta\kappa-\delta+3\kappa+2}{q_1} - \frac{2((\delta-2)\delta(3\delta-2)+1)}{\delta(4\delta-7)-1} < 1$. It can be verified algebraically that this inequality is valid in the parameter range when $0.6 < \delta < 1$ and $q_1 > \frac{-2-13\delta+15\delta^2-4\delta^3-3\kappa-19\delta\kappa+26\delta^2\kappa-8\delta^3\kappa}{-2-14\delta+40\delta^2-32\delta^3+8\delta^4}$. Similar to the function innovation, the last condition can be interpreted as an upper bound for the value of δ determined by the value of q_1 , showing that the feasible parameter range requires at least some meaningful innovation. At the same time, $\delta > 0.6$ shows the lower bound for δ . In this specified parameter range, we see that all the endogenously derived segmentation boundaries preserve their relative order and are bounded between 0 and 1.

Using the same procedure as before, we derive the following optimal expressions:

$$\begin{aligned}\pi &= \frac{(-1-7\delta+4\delta^2)(2-\delta+\kappa)^2-4(1+6\delta-11\delta^2+4\delta^3)(-2+\delta-\kappa)q_1+4(-1-5\delta+13\delta^2-7\delta^3-\delta^4+\delta^5)q_1^2}{4(-2+\delta)(-1+\delta)(-1-7\delta+4\delta^2)q_1} \\ p_1 &= \frac{-2+\delta+\kappa+\frac{2(1+6\delta-3\delta^2-4\delta^3+2\delta^4)q_1}{-1-7\delta+4\delta^2}}{2(-2+\delta)} \\ p_2 &= \frac{-2+\delta+\kappa+\frac{2(1+4\delta-8\delta^2+3\delta^3)q_1}{-1-7\delta+4\delta^2}}{2(-2+\delta)} \\ Q_1 &= \frac{2(-2+\delta)\delta}{-1-7\delta+4\delta^2} \\ Q_2 &= \frac{\frac{2(1+\delta+\delta^2-\delta^3)}{-1-7\delta+4\delta^2} - \frac{-2+\delta+\kappa}{q_1}}{2(-2+\delta)} \\ Q_{12} &= \frac{\frac{2+14\delta-40\delta^2+32\delta^3-8\delta^4}{1+7\delta-4\delta^2} + \frac{-2+\delta-3\kappa+2\delta\kappa}{q_1}}{2(-2+\delta)(-1+\delta)} \\ harm &= \frac{\frac{2(1+\lambda+\delta^3(4+3\lambda)-3\delta^2(4+5\lambda)+\delta(8+17\lambda))}{-1-7\delta+4\delta^2} + \frac{\delta+\kappa(-3+\lambda)-\delta\kappa(-2+\lambda)+3\delta\lambda-\delta^2\lambda-2(1+\lambda)}{(-1+\delta)q_1}}{2(-2+\delta)}\end{aligned}$$

A.1.3. Use efficiency innovation In this case, we have the use efficiency term e_i , which is normalized to $e_1 = 0$ in period 1, and $e_2 = e$ in period 2. The intrinsic quality remains q_1 over both periods.

The indifference equations are now: $\theta_{12}\frac{q_1}{1-e} - p_2 - \kappa(\lambda(1-e) + 1) = \theta_{12}q_1 - \kappa\lambda$, $\theta_2\frac{q_1}{1-e} - p_2 = 0$, and $2q_1\theta_1 - p_1 = \frac{q_1}{1-e}\theta_1 - p_2 + \kappa\lambda e$. The reasoning for the indifference equations above is largely similar to that for function innovation in section A.1.1, with the exception that (i) in the first equation, on the left side, the usage based environmental disutility has a $(1-e)$ term (i.e. it is $\kappa\lambda(1-e)$) to account for the increased efficiency of the upgrade – which consequently leads to a lower environmental disutility for the consumer; (ii) the q_2 expression is replaced by $\frac{q_1}{1-e}$ to account for the increased intrinsic value of q_2 arising from increased use efficiency; and (iii) for the threshold period-1 buyer θ_1 , who may buy in period 1 and enjoy the product q_1 for two periods (hence $2q_1\theta_1 - p_1$ on the left side of the equation), on the right side of the equation we add $\kappa\lambda e$ ($= \kappa\lambda - \kappa\lambda(1-e)$), the net environmental utility from consuming a more energy efficient product if they choose to wait and buy in period 2. The obvious period-2 environmental benefit of consuming the

relatively more usage-efficient upgrade in period 2 with a lower disutility $\kappa\lambda(1-e)$ (compared to the higher disutility $\kappa\lambda$ of the original version available for purchase in period 1) causes the forward-looking consumer to factor in this benefit in their period-1 indifference equation.

Endogenous segmentation boundaries are interior points:

It remains to be shown that $0 < \theta_2 < \theta_1 < \theta_{12} < 1$. The inequality translates to:

$$\begin{aligned} 0 &< \frac{(e-1)((4-e(8e+3))(e-\kappa+1)-e(6e^2+e-4)\kappa\lambda)+2e(6e^2+2e-3)q_1}{2(e+1)(e(8e+3)-4)q_1} \\ &< \frac{2e(e^2-1)\kappa\lambda+(4e^2+e-2)q_1}{(e(8e+3)-4)q_1} \\ &< \frac{2e(6e^2+2e-3)q_1+(e-1)(e(e(16e(e+1)-3)-4)\kappa\lambda+(4-e(8e+3))(2e\kappa+e+\kappa+1))}{2e(e+1)(e(8e+3)-4)q_1} < 1 \end{aligned}$$

It can be verified algebraically that the above inequality is valid in the parameter range when $0 < e < 0.3$, $q_1 > \frac{-4+3e+12e^2-3e^3-8e^4-4\kappa-e\kappa+19e^2\kappa+2e^3\kappa-16e^4\kappa}{-2e-6e^2+10e^3+16e^4}$, and $0 < \lambda < \frac{4-3e-12e^2+3e^3+8e^4+4\kappa+e\kappa-19e^2\kappa-2e^3\kappa+16e^4\kappa+2e^5\kappa-6e^2q_1-2e^3q_1+8e^4q_1}{4e\kappa+3e^2\kappa-15e^3\kappa-4e^4\kappa+12e^5\kappa}$. Similar to the function and fashion innovation's boundary conditions, the conditions for the use efficiency innovation can also be interpreted as that we have both upper and lower bounds for the innovation degree (that is, e). Additionally, the value of λ cannot be very large. In the parameter range specified by the conditions above, all the endogenously derived segmentation boundaries preserve their relative order and are bounded between 0 and 1. We therefore derive the following optimal solutions:

$$\begin{aligned} \pi &= \frac{1}{4(-1+e)e(1+e)(-4+3e+8e^2)q_1} ((-1+e)^2(4(1+\kappa)^2+4e^5\kappa^2\lambda^2+8e^4(-1+2\kappa\lambda)-e(1+\kappa)(-5+\kappa(3+8\lambda))+ \\ &e^3(-19+\kappa^2\lambda(16+\lambda)+2\kappa(-8+11\lambda))+2e^2(-5-\kappa(11+\lambda)+\kappa^2(-4+3\lambda+2\lambda^2)))-4(-1+e)e(-4(1+\kappa)+ \\ &e^2(11+\kappa(8-3\lambda))+4e^4\kappa\lambda+e^3(8-2\kappa\lambda)+e(-1+\kappa(3+2\lambda)))q_1+4e(1+2e-6e^2-4e^3+4e^4)q_1^2) \\ p_1 &= \frac{-(-1+e)(4+e-4\kappa+3e\kappa+8e^4\kappa\lambda+e^2(-11+8\kappa-3\kappa\lambda)+4e^3(-2+\kappa\lambda))+2(2-9e^2+8e^4)q_1}{2(-1+e)(1+e)(-4+3e+8e^2)} \\ p_2 &= \frac{(-1+e)((-4+e(3+8e))(1+e-\kappa)+e(-4+e+6e^2)\kappa\lambda)-2e(-3+2e+6e^2)q_1}{2(-1+e)(1+e)(-4+3e+8e^2)} \\ Q_1 &= -\frac{2(1+e)((-1+e)e\kappa\lambda+(1-2e)q_1)}{(-4+3e+8e^2)q_1} \\ Q_2 &= \frac{(-1+e)((-4+e(3+8e))(1+e-\kappa)+e^2(9+10e)\kappa\lambda)+(-4+2e(2+(3-2e)e))q_1}{2(1+e)(-4+3e+8e^2)q_1} \\ Q_{12} &= \frac{(-1+e)((-4+e(3+8e))(1+e+\kappa+2e\kappa)+e(4+e(3-16e(1+e)))\kappa\lambda)+2e(-1+e(1+e)(-3+8e))q_1}{2e(1+e)(-4+3e+8e^2)q_1} \\ harm &= \frac{1}{2e(1+e)(-4+3e+8e^2)q_1} ((-1+e)(-4(1+\kappa)+2e^5\lambda(-4+3\kappa\lambda)+e^4\lambda(-11+3\kappa(-8+3\lambda))+e(-1+ \\ &\kappa(-5+12\lambda))+e^2(11+4\lambda+\kappa(14+\lambda-12\lambda^2))+e^3(8+\lambda+\kappa(16-35\lambda-10\lambda^2)))-2e(1+e(3-5\lambda))+2e^3(-4+ \\ &\lambda)+6\lambda+6e^4\lambda-e^2(5+16\lambda))q_1) \end{aligned}$$

A.1.4. Robustness check: Environmental sensitivity among first time buyers Since it is possible that even first time buyers may feel anticipatory guilt, we therefore relax the assumption of zero environmental sensitivity among first time buyers and assess the robustness of our result by allowing the sensitivity to environmental harm of first time buyers to be a fraction $\phi \in [0, 1]$ of the sensitivity of the upgraders. We now formulate the extent of anticipatory guilt as $\phi * \kappa$. Using function innovation as an example, we show the revised indifference equations as follows: $\theta_{12}q_2 - p_2 - \kappa(\lambda + 1) = \theta_{12}q_1 - \kappa\lambda$, $\theta_2q_2 - p_2 - \phi\kappa\lambda = 0$, and $2\theta_1q_1 - p_1 - 2\phi\kappa\lambda = \theta_1q_2 - p_2 - \phi\kappa\lambda$.

In the first equation above, in period 2 the θ_{12} buyer – if they upgrade (left side of equation) – feels environmental disutility due to guilt from dumping plus usage based harm: $\kappa(\lambda + 1)$; whereas if they don't upgrade (right side of equation), they feel the usage based harm alone ($\kappa\lambda$). The ϕ term is not involved here because the buyer does feel guilt from previous usage, and so feels the full environmental disutility. In the second equation, the new buyer θ_2 feels environmental disutility from usage ($\phi\kappa\lambda$) if they buy, and none if they don't. In the third equation, the buyer feels environmental disutility amounting to (a) $\phi\kappa\lambda$ for period 1 and another $\phi\kappa\lambda$ for period 2 on the left side of the equation, and (b) $\phi\kappa\lambda$ for only period 2 on the right side. The ϕ term is involved in environmental disutility when the buyer, when formulating the indifference equations, has not yet consumed the product and so feels anticipatory guilt (hence $\phi\kappa\lambda$). Setting $\phi = 1$ gives us the indifference equations of the case where anticipatory guilt is as strong as reactive guilt.

The optimal solutions in this robustness analysis (function and fashion innovation cases) and proof for Proposition 4 are provided in Appendix A.3.

A.2. Proofs of Lemmas

Proof of Lemma 1

In the function innovation case, we take partial derivatives of the optimal prices and quantities with respect to κ , and find that over the entire feasible range of parameter space of interest,¹⁹ all of the following hold:

$$\frac{\partial p_1}{\partial \kappa} = \frac{q_2}{2q_1 - 4q_2} < 0; \quad \frac{\partial p_2}{\partial \kappa} = \frac{q_2}{2q_1 - 4q_2} < 0; \quad \frac{\partial Q_1}{\partial \kappa} = 0; \quad \frac{\partial Q_2}{\partial \kappa} = \frac{1}{4q_2 - 2q_1} > 0; \quad \text{and} \quad \frac{\partial Q_{12}}{\partial \kappa} = \frac{1}{2q_1 - 4q_2} + \frac{1}{2q_1 - 2q_2} < 0.$$

Similarly, in the fashion innovation case, we take partial derivatives of the optimal prices and quantities with respect to κ , and find that over the entire feasible range of parameter space of interest, all of the following hold:

$$\text{hold: } \frac{\partial p_1}{\partial \kappa} = \frac{1}{2(-2+\delta)} < 0; \quad \frac{\partial p_2}{\partial \kappa} = \frac{1}{2(-2+\delta)} < 0; \quad \frac{\partial Q_1}{\partial \kappa} = 0; \quad \frac{\partial Q_2}{\partial \kappa} = \frac{1}{4q_1 - 2\delta q_1} > 0; \quad \text{and} \quad \frac{\partial Q_{12}}{\partial \kappa} = \frac{-3+2\delta}{2(2-3\delta+\delta^2)q_1} < 0.$$

¹⁹ Details of feasible range of parameters can be found in the proof for Proposition 1.

In the use efficiency innovation case, we take partial derivatives of the optimal prices and quantities with respect to κ . Over the entire feasible range of parameter space of interest, all of the following hold:

$$\frac{\partial p_1}{\partial \kappa} = \frac{4-e(3+8e+e(-3+4e+8e^2)\lambda)}{2(1+e)(-4+e(3+8e))} < 0; \quad \frac{\partial Q_1}{\partial \kappa} = -\frac{2e(-1+e^2)\lambda}{(-4+e(3+8e))q_1} < 0; \quad \frac{\partial Q_2}{\partial \kappa} = \frac{(-1+e)(4+e(-3-8e+e(9+10e)\lambda))}{2(1+e)(-4+e(3+8e))q_1} > 0.$$

If $\lambda > \lambda_{p_2}^* = \frac{-4+3e+8e^2}{-4e+e^2+6e^3}$, then $\frac{\partial p_2}{\partial \kappa} = \frac{4+e(-3-4\lambda+e(-8+\lambda+6e\lambda))}{2(1+e)(-4+e(3+8e))} > 0$; otherwise, if $\lambda < \lambda_{p_2}^*$, then $\frac{\partial p_2}{\partial \kappa} < 0$.

If $\lambda > \lambda_{Q_{12}}^* = \frac{-4-5e+14e^2+16e^3}{-4e-3e^2+16e^3+16e^4}$, then $\frac{\partial Q_{12}}{\partial \kappa} = \frac{4+e(1-4\lambda+e(-19+\lambda+e(-2+19\lambda-16e(-1+e\lambda))))}{2e(1+e)(-4+e(3+8e))q_1} > 0$; otherwise, if $\lambda < \lambda_{Q_{12}}^*$, then $\frac{\partial Q_{12}}{\partial \kappa} < 0$. \square

Proof of Lemma 2

The consumer type condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ holds in the use efficiency innovation case when $0 < e < 0.3$, $q_1 > \frac{-4+3e+12e^2-3e^3-8e^4-4\kappa-e\kappa+19e^2\kappa+2e^3\kappa-16e^4\kappa}{-2e-6e^2+10e^3+16e^4}$, and $0 < \lambda < \frac{4-3e-12e^2+3e^3+8e^4+4\kappa+e\kappa-19e^2\kappa-2e^3\kappa+16e^4\kappa+2eq_1-6e^2q_1-2e^3q_1+8e^4q_1}{4e\kappa+3e^2\kappa-15e^3\kappa-4e^4\kappa+12e^5\kappa}$.

Over the entire feasible range of parameter space of interest, $p_{1aware} < p_{2unaware}$ always holds.

Given that $\lambda < \lambda^{PA*} = \frac{4\kappa-7e\kappa-5e^2\kappa+8e^3\kappa+4q_1-4eq_1-10e^2q_1}{4\kappa+5e\kappa-11e^2\kappa-6e^3\kappa+8e^4\kappa}$, all of the following hold: $Q_{1aware} > Q_{1unaware}$, $p_{2aware} < p_{2unaware}$, $Q_{2aware} < Q_{2unaware}$, $Q_{12aware} > Q_{12unaware}$.

Given that $\lambda > \lambda^{PA*}$, all of the following hold: $Q_{1aware} < Q_{1unaware}$, $p_{2aware} > p_{2unaware}$, $Q_{2aware} > Q_{2unaware}$, $Q_{12aware} < Q_{12unaware}$. \square

A.3. Proofs of Propositions

Proof of Proposition 1

Function innovation: We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{1}{2}(-1 + \frac{\kappa+q_1}{q_1-2q_2} + \frac{1+\kappa}{-q_1+q_2}) < 0$ always holds over the entire feasible range of parameter space of interest. Based on our model, the consumer type condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ must hold to yield feasible market quantities. In the function innovation case, this condition holds when $0 < q_1 < q_2 < 1.5q_1$, $q_1 > 1$, and $q_1^2(35 + 62\kappa + 74q_1)q_2 + (14 + 21\kappa + 80q_1)q_2^3 > 8q_1^3(1 + 2\kappa + 2q_1) + q_1(45 + 71\kappa + 120q_1)q_2^2 + 18q_2^4$. The last condition can be interpreted as: the ratio q_2/q_1 (i.e., the innovation degree) should be above a threshold specified by the value of q_1 .

Fashion innovation: We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{2 + \frac{2-\delta+\kappa}{(-1+\delta)q_1}}{2(-2+\delta)} < 0$ always holds over the entire feasible range of parameter space of interest. The consumer type condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ holds in the fashion upgrade case when $0.6 < \delta < 1$ and $q_1 > \frac{-2-13\delta+15\delta^2-4\delta^3-3\kappa-19\delta\kappa+26\delta^2\kappa-8\delta^3\kappa}{-2-14\delta+40\delta^2-32\delta^3+8\delta^4}$.

Use efficiency innovation: $\frac{\partial \pi}{\partial \kappa} = ((-1+e)(-4+e(3+8e))(1+e+\kappa) + e(-4+e(3+8e))(1+e+2\kappa)\lambda + e^2(4+e+4e^3)\kappa\lambda^2) - 2e(-4+e(3+8e+(2+e(-3-2e+4e^2))\lambda))q_1 / (2e(1+e)(-4+e(3+8e))q_1) < 0$

holds over the feasible range of parameters when $\lambda < \lambda_\pi^* = \frac{1}{2(-4e^2\kappa + 3e^3\kappa + e^4\kappa - 4e^5\kappa + 4e^6\kappa)}(-4e + 3e^2 + 12e^3 - 3e^4 - 8e^5 - 8e\kappa + 14e^2\kappa + 10e^3\kappa - 16e^4\kappa + 4e^2q_1 - 6e^3q_1 - 4e^4q_1 + 8e^5q_1 - (-4(-4e^2\kappa + 3e^3\kappa + e^4\kappa - 4e^5\kappa + 4e^6\kappa)(-4 + 3e + 12e^2 - 3e^3 - 8e^4 - 4\kappa + 7e\kappa + 5e^2\kappa - 8e^3\kappa + 8eq_1 - 6e^2q_1 - 16e^3q_1) + (4e - 3e^2 - 12e^3 + 3e^4 + 8e^5 + 8e\kappa - 14e^2\kappa - 10e^3\kappa + 16e^4\kappa - 4e^2q_1 + 6e^3q_1 + 4e^4q_1 - 8e^5q_1)^2)^{1/2}$); and $\frac{\partial \pi}{\partial \kappa} > 0$ holds when $\lambda > \lambda_\pi^*$.

The consumer type condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ holds in the use efficiency innovation case when $0 < e < 0.3$, $q_1 > \frac{-4+3e+12e^2-3e^3-8e^4-4\kappa-e\kappa+19e^2\kappa+2e^3\kappa-16e^4\kappa}{-2e-6e^2+10e^3+16e^4}$, and $0 < \lambda < \frac{4-3e-12e^2+3e^3+8e^4+4\kappa+e\kappa-19e^2\kappa-2e^3\kappa+16e^4\kappa+2eq_1-6e^2q_1-2e^3q_1+8e^4q_1}{4e\kappa+3e^2\kappa-15e^3\kappa-4e^4\kappa+12e^5\kappa}$. \square

Proof of Proposition 2

We take partial derivatives of the total environmental harm *harm*, the dumping harm *dumping*, and the in-use harm *usage*, with respect to environmental sensitivity κ .

Function innovation: Over the entire feasible range of parameters of interest, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{1}{2}(\frac{1-\lambda}{q_1-2q_2} + \frac{1}{q_1-q_2}) < 0$ holds when $\lambda < \lambda_E^* = \frac{3q_2-2q_1}{q_2-q_1}$; and $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \lambda_E^*$. $\frac{\partial \text{dumping}}{\partial \kappa} = \frac{1}{2q_1-4q_2} + \frac{1}{2q_1-2q_2} < 0$ always holds. $\frac{\partial \text{usage}}{\partial \kappa} = \frac{\lambda}{4q_2-2q_1} > 0$ always holds.

Fashion innovation: Over the entire feasible range of parameters of interest, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{-3+2\delta+\lambda-\delta\lambda}{2(2-3\delta+\delta^2)q_1} < 0$ holds when $\lambda < \lambda_E^* = \frac{3-2\delta}{1-\delta}$; and $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \lambda_E^*$. $\frac{\partial \text{dumping}}{\partial \kappa} = \frac{-3+2\delta}{2(2-3\delta+\delta^2)q_1} < 0$ always holds. $\frac{\partial \text{usage}}{\partial \kappa} = \frac{\lambda}{4q_1-2\delta q_1} > 0$ always holds.

Use efficiency innovation: Over the entire feasible range of parameters of interest, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{(-1+e)(-4+e(-5+12\lambda+e(14+16e+\lambda-e(35+24e)\lambda+(-12+e(-10+9e+6e^2))\lambda^2)))}{2e(1+e)(-4+e(3+8e))q_1} < 0$ always holds. $\frac{\partial \text{dumping}}{\partial \kappa} = \frac{4+e(1-4\lambda+e(-19+\lambda+e(-2+19\lambda-16e(-1+e\lambda))))}{2e(1+e)(-4+e(3+8e))q_1} > 0$ holds when $\lambda > \lambda_D^* = \frac{-4-5e+14e^2+16e^3}{e(-4-3e+16e^2+16e^3)}$; and $\frac{\partial \text{dumping}}{\partial \kappa} < 0$ holds when $\lambda < \lambda_D^*$. $\frac{\partial \text{usage}}{\partial \kappa} = \frac{(-1+e)\lambda(8+e(-2(1+6\lambda)+e(-19-10\lambda+e(-8+(9+6e)\lambda))))}{2(1+e)(-4+e(3+8e))q_1} > 0$ holds when $\lambda < \lambda_U^* = \frac{-8+2e+19e^2+8e^3}{e(-12-10e+9e^2+6e^3)}$; and $\frac{\partial \text{usage}}{\partial \kappa} < 0$ holds when $\lambda > \lambda_U^*$. \square

Proof of Proposition 3

Consumer surplus: Taking the partial derivative of *Consumer Surplus* w.r.t. environmental sensitivity κ .

$$\text{Function innovation: } \frac{\partial \text{Consumer Surplus}}{\partial \kappa} = \frac{1}{28} \left(-16\lambda + \frac{7(\kappa+1)}{q_2-q_1} - \frac{21(\kappa+q_1)}{q_1-2q_2} + \frac{2q_1(8(\lambda+1)q_1-(12\lambda+5)q_2)}{8q_1^2-19q_2q_1+7q_2^2} - 9 \right)$$

$$\text{Fashion innovation: } \frac{\partial \text{Consumer Surplus}}{\partial \kappa} = \frac{-\delta(4\kappa+1)+5\kappa+2}{(\delta-1)q_1} - \frac{8\delta(\delta-2)^2\lambda+2\delta(\delta(8\delta-19)+7)+2}{4(\delta-2)}$$

Use efficiency innovation: $\frac{\partial \text{Consumer Surplus}}{\partial \kappa} = ((e-1)(e^2(e(29-4e(11e+8))+20)\kappa\lambda^2 + e\lambda(e(e(2e(32\kappa+5)+44\kappa+15)-22\kappa+1)-8\kappa-4) + (4-e(8e+3))(4e\kappa+e+\kappa+1)) + 2eq_1(e(4e(5(e^2-1)\lambda-4e)+\lambda+10) + 4\lambda-3))/(4e(e+1)(e(8e+3)-4)q_1)$

Over the feasible range of parameters of interest, we verify algebraically that $\frac{\partial \text{ConsumerSurplus}}{\partial \kappa} > 0$ holds when $\lambda < \lambda_{CS}^*$, and $\frac{\partial \text{ConsumerSurplus}}{\partial \kappa} < 0$ holds when $\lambda > \lambda_{CS}^*$.

$$\text{Function innovation: } \lambda_{CS}^* = \frac{(-32\kappa q_1^3 + 116\kappa q_2 q_1^2 - 123\kappa q_2^2 q_1 + 35\kappa q_2^3 - 32q_1^4 + 128q_2 q_1^3 - 8q_1^3 - 172q_2^2 q_1^2 + 35q_2 q_1^2 + 94q_2^3 q_1 - 45q_2^2 q_1 - q_2^4 + 14q_2^3)}{(16q_1^4 - 88q_2 q_1^3 + 168q_2^2 q_1^2 - 128q_2^3 q_1 + 32q_2^4)}$$

$$\text{Fashion innovation: } \lambda_{CS}^* = \frac{-16\delta^3 \kappa - 4\delta^3 + 48\delta^2 \kappa + 15\delta^2 - 31\delta \kappa - 13\delta - 5\kappa - 16\delta^4 q_1 + 54\delta^3 q_1 - 52\delta^2 q_1 + 12\delta q_1 + 2q_1 - 2}{8\delta^4 q_1 - 40\delta^3 q_1 + 64\delta^2 q_1 - 32\delta q_1}$$

$$\text{Use efficiency innovation: } \lambda_{CS}^* = \frac{16e^3 - 10e + 3}{20e^4 - 20e^2 + e + 4}$$

Social surplus: We take partial derivative of *SocialSurplus* w.r.t. environmental sensitivity κ .

$$\text{Function innovation: } \frac{\partial \text{SocialSurplus}}{\partial \kappa} = \frac{1}{28} \left(\frac{7(3\kappa + 2\lambda + q_1 - 2)}{q_1 - 2q_2} + \frac{7(\kappa - 3)}{q_1 - q_2} + \frac{2q_1(5q_2 - 8q_1)}{8q_1^2 - 19q_2 q_1 + 7q_2^2} - 5 \right)$$

$$\text{Fashion innovation: } \frac{\partial \text{SocialSurplus}}{\partial \kappa} = \frac{\frac{2(5-3\delta)\delta+2}{(7-4\delta)\delta+1} + \frac{\delta(4\kappa+2\lambda-5)-5\kappa-2\lambda+8}{(\delta-1)q_1}}{4(\delta-2)}$$

For function and fashion innovation, we verify algebraically that over the entire feasible range of parameters of interest, $\frac{\partial \text{SocialSurplus}}{\partial \kappa} < 0$ always holds.

$$\text{Use efficiency innovation: } \frac{\partial \text{SocialSurplus}}{\partial \kappa} = ((e-1)(e^2 \lambda^2 (e(2e(2e(7\kappa-3)+8\kappa-9)-13\kappa+20)-4(\kappa-6))-e(2e-1)\lambda(e(32\kappa-29)+38\kappa-57)+8\kappa-28)+(e(8e+3)-4)(e(4\kappa-5)+\kappa-3))-2eq_1(e(2e((e(2e-1)-2)\lambda+3)+\lambda+2)-3))/(4e(e+1)(e(8e+3)-4)q_1)$$

For use efficiency innovation, over the feasible range of parameters of interest, we verify algebraically that $\frac{\partial \text{SocialSurplus}}{\partial \kappa} < 0$ holds when $\lambda < \lambda_{SS}^*$, and $\frac{\partial \text{SocialSurplus}}{\partial \kappa} > 0$ holds when $\lambda > \lambda_{SS}^*$.

$$\begin{aligned} \lambda_{SS}^* = & (0.5(64e^4 \kappa + 8e^4 q_1 - 58e^4 - 20e^3 \kappa - 4e^3 q_1 - 27e^3 - 66e^2 \kappa - 8e^2 q_1 + 86e^2 + 14e\kappa \\ & + 2eq_1 + 27e + 8\kappa - 28))/((e^2 - e)(28e^3 \kappa - 12e^3 + 16e^2 \kappa - 18e^2 - 13e\kappa + 20e - 4\kappa + 24)) \\ & + 0.5((512e^8 \kappa^2 - 1408e^8 \kappa + 1024e^8 \kappa q_1 + 64e^8 q_1^2 - 928e^8 q_1 + 1444e^8 + 320e^7 \kappa^2 - 2976e^7 \kappa \\ & + 512e^7 \kappa q_1 - 64e^7 q_1^2 - 544e^7 q_1 + 2220e^7 - 1216e^6 \kappa^2 + 2816e^6 \kappa - 2048e^6 \kappa q_1 - 112e^6 q_1^2 + 2040e^6 q_1 \\ & - 743e^6 - 704e^5 \kappa^2 + 6752e^5 \kappa - 928e^5 \kappa q_1 + 96e^5 q_1^2 + 1960e^5 q_1 - 6040e^5 + 896e^4 \kappa^2 - 1216e^4 \kappa \\ & + 1248e^4 \kappa q_1 + 48e^4 q_1^2 - 1204e^4 q_1 - 2822e^4 + 448e^3 \kappa^2 - 4640e^3 \kappa + 480e^3 \kappa q_1 - 32e^3 q_1^2 - 1864e^3 q_1 \\ & + 5012e^3 - 192e^2 \kappa^2 - 320e^2 \kappa - 224e^2 \kappa q_1 + 4e^2 q_1^2 + 76e^2 q_1 + 2521e^2 - 64e\kappa^2 + 864e\kappa - 64e\kappa q_1 \\ & + 464eq_1 - 1224e + 128\kappa - 368)/((e-1)^2 e^2 (28e^3 \kappa - 12e^3 + 16e^2 \kappa - 18e^2 - 13e\kappa + 20e - 4\kappa + 24)^2))^{\frac{1}{2}} \end{aligned}$$

□

Proof of Proposition 4

Function innovation: Based on the optimal solutions given by equation (3), we take partial derivatives of prices, quantities, and the environmental impact *harm*, with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest,

$$\frac{\partial p_1}{\partial \kappa} = \frac{1}{28} \left(-23\lambda\phi + q_1 \left(\frac{7-7\lambda\phi}{q_1-2q_2} + \frac{8\lambda(2q_1-3q_2)\phi}{8q_1^2-19q_2q_1+7q_2^2} \right) - 7 \right) < 0 \text{ always holds.}$$

$$\frac{\partial p_2}{\partial \kappa} = \frac{1}{28} \left(-11\lambda\phi + q_1 \left(\frac{7-7\lambda\phi}{q_1-2q_2} + \frac{16\lambda(2q_1-3q_2)\phi}{8q_1^2-19q_2q_1+7q_2^2} \right) - 7 \right) < 0 \text{ always holds.}$$

$$\frac{\partial Q_1}{\partial \kappa} = -\frac{2\lambda(q_1-2q_2)\phi}{8q_1^2-19q_2q_1+7q_2^2} < 0 \text{ always holds.}$$

$$\frac{\partial Q_2}{\partial \kappa} = -\frac{\lambda\phi}{2q_2} + \frac{\lambda(q_1-3q_2)\phi}{8q_1^2-19q_2q_1+7q_2^2} + \frac{\lambda\phi-1}{2(q_1-2q_2)} < 0 \text{ holds when } \lambda > \frac{7q_2^3-19q_1q_2^2+8q_1^2q_2}{-8q_1^3\phi+45q_2q_1^2\phi-74q_2^2q_1\phi+33q_2^3\phi} \text{ and } \phi > \phi_Q^* = \frac{7q_2^3-19q_1q_2^2+8q_1^2q_2}{-80q_1^3+450q_2q_1^2-740q_2^2q_1+330q_2^3}; \text{ and } \frac{\partial Q_2}{\partial \kappa} > 0 \text{ holds when } \phi < \phi_Q^*, \text{ or when } \lambda < \frac{7q_2^3-19q_1q_2^2+8q_1^2q_2}{-8q_1^3\phi+45q_2q_1^2\phi-74q_2^2q_1\phi+33q_2^3\phi} \text{ and } \phi > \phi_Q^*.$$

$$\frac{\partial Q_{12}}{\partial \kappa} = \frac{1-\lambda\phi}{2q_1-4q_2} + \frac{\lambda q_2\phi}{8q_1^2-19q_2q_1+7q_2^2} + \frac{1}{2q_1-2q_2} < 0 \text{ always holds.}$$

$$\frac{\partial harm}{\partial \kappa} = \frac{1}{2} \left(-\frac{\lambda^2\phi}{q_2} + \frac{2\lambda\phi((5\lambda+1)q_2-3\lambda q_1)}{8q_1^2-19q_2q_1+7q_2^2} + \frac{(\lambda-1)(\lambda\phi-1)}{q_1-2q_2} + \frac{1}{q_1-q_2} \right) > 0 \text{ holds when } \lambda > \lambda_E^* = \frac{3q_2-2q_1}{q_2-q_1} \text{ and } \phi < \phi_E^* = \frac{7\lambda q_2^4-26\lambda q_1 q_2^3+27\lambda q_1^2 q_2^2-8\lambda q_1^3 q_2-21q_2^4+71q_1 q_2^3-62q_1^2 q_2^2+16q_1^3 q_2}{8\lambda^2 q_1^4-45\lambda^2 q_2 q_1^3+79\lambda^2 q_2^2 q_1^2-43\lambda^2 q_2^3 q_1+\lambda^2 q_2^4+8\lambda q_2 q_1^3-29\lambda q_2^2 q_1^2+32\lambda q_2^3 q_1-11\lambda q_2^4}; \text{ and } \frac{\partial harm}{\partial \kappa} < 0 \text{ holds when } \lambda < \lambda_E^* \text{ and } \phi < \phi_E^*, \text{ or when } \phi > \phi_E^*. \text{ We also find that } \phi_Q^* > \phi_E^* \text{ holds when } \lambda > \lambda_E^*.$$

Fashion innovation: Based on the optimal solutions given by equation (3), we take partial derivatives of prices, quantities, and the environmental impact *harm*, with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest,

$$\frac{\partial p_1}{\partial \kappa} = -\frac{\delta((\delta-2)(8\delta-11)\lambda\phi-4\delta+7)+\lambda\phi+1}{2(\delta-2)(\delta(4\delta-7)-1)} < 0 \text{ always holds.}$$

$$\frac{\partial p_2}{\partial \kappa} = -\frac{-4\delta^2+(\delta-1)(\delta(4\delta-9)+3)\lambda\phi+7\delta+1}{2(\delta-2)(\delta(4\delta-7)-1)} < 0 \text{ always holds.}$$

$$\frac{\partial Q_1}{\partial \kappa} = -\frac{2(\delta-2)\lambda\phi}{(\delta(4\delta-7)-1)q_1} < 0 \text{ always holds.}$$

$$\frac{\partial Q_2}{\partial \kappa} = \frac{-4\delta^2-(\delta-3)(\delta(4\delta-9)+3)\lambda\phi+7\delta+1}{2(\delta-2)(\delta(4\delta-7)-1)q_1} < 0 \text{ holds when } \lambda > \frac{-4\delta^2+7\delta+1}{4\delta^3-21\delta^2+30\delta-9} \text{ and } \phi > \phi_Q^* = \frac{(7-4\delta)\delta+1}{(\delta-3)(\delta(4\delta-9)+3)\lambda}; \text{ and}$$

$$\frac{\partial Q_2}{\partial \kappa} > 0 \text{ holds when } \phi < \phi_Q^*, \text{ or when } \lambda < \frac{-4\delta^2+7\delta+1}{4\delta^3-21\delta^2+30\delta-9} \text{ and } \phi > \phi_Q^*.$$

$$\frac{\partial Q_{12}}{\partial \kappa} = \frac{\delta(-\delta(4\delta-13)(\lambda\phi-2)-12\lambda\phi+19)+3\lambda\phi+3}{2(\delta-2)(\delta-1)(\delta(4\delta-7)-1)q_1} < 0 \text{ always holds.}$$

$$\frac{\partial harm}{\partial \kappa} = \frac{\lambda\phi(\delta(\delta((13-4\delta)\lambda-4)+2\lambda+9)-23\lambda-3)}{\delta(4\delta-7)-1} + \frac{1}{1-\delta} - \lambda + 2}{2(\delta-2)q_1} > 0 \text{ when } \lambda > \lambda_E^* = \frac{3-2\delta}{1-\delta} \text{ and } \phi < \phi_E^* =$$

$$\frac{-4\delta^3\lambda+8\delta^3+11\delta^2\lambda-26\delta^2-6\delta\lambda+19\delta-\lambda+3}{4\delta^4\lambda^2-17\delta^3\lambda^2+4\delta^3\lambda+11\delta^2\lambda^2-13\delta^2\lambda+25\delta\lambda^2+12\delta\lambda-23\lambda^2-3\lambda}; \text{ and } \frac{\partial harm}{\partial \kappa} < 0 \text{ holds when } \lambda < \lambda_E^* \text{ and } \phi < \phi_E^*, \text{ or when } \phi > \phi_E^*. \text{ We also find that } \phi_Q^* > \phi_E^* \text{ holds when } \lambda > \lambda_E^*. \square$$

Proof of Proposition 5

The profits under optimal conditions are:

$$\begin{aligned} \pi_{aware} &= \frac{1}{4(-1+e)e(1+e)(-4+3e+8e^2)q_1} ((-1+e)^2(4(1+\kappa)^2+4e^5\kappa^2\lambda^2+8e^4(-1+2\kappa\lambda)) \\ &\quad - e(1+\kappa)(-5+\kappa(3+8\lambda)) + e^3(-19+\kappa^2\lambda(16+\lambda)) + 2\kappa(-8+11\lambda)) + 2e^2(-5-\kappa(11+\lambda)) \\ &\quad + \kappa^2(-4+3\lambda+2\lambda^2)) - 4(-1+e)e(-4(1+\kappa)+e^2(11+\kappa(8-3\lambda))+4e^4\kappa\lambda \\ &\quad + e^3(8-2\kappa\lambda)+e(-1+\kappa(3+2\lambda)))q_1 + 4e(1+2e-6e^2-4e^3+4e^4)q_1^2) \end{aligned}$$

$$\begin{aligned} \pi_{unaware} = & \frac{1}{4e(-4+e+4e^2)q_1} ((-1+e)(4(1+\kappa)^2 - 4e^3(-1+\kappa\lambda)^2 \\ & - e(1+\kappa)(-3+\kappa(5+8\lambda)) + e^2(-5+\kappa(\kappa+2(-4+\lambda)+2\kappa\lambda(5+2\lambda)))) + 4eq_1(4(1+\kappa) \\ & + e(-1-4\kappa-e(4+\kappa)+3(-1+e)\kappa\lambda) + (-1+(-2+e)e)q_1)) \end{aligned}$$

The consumer type condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ holds in the use efficiency innovation case when $0 < e < 0.3$, $q_1 > \frac{-4+3e+12e^2-3e^3-8e^4-4\kappa-e\kappa+19e^2\kappa+2e^3\kappa-16e^4\kappa}{-2e-6e^2+10e^3+16e^4}$, and $0 < \lambda < \frac{4-3e-12e^2+3e^3+8e^4+4\kappa+e\kappa-19e^2\kappa-2e^3\kappa+16e^4\kappa+2eq_1-6e^2q_1-2e^3q_1+8e^4q_1}{4e\kappa+3e^2\kappa-15e^3\kappa-4e^4\kappa+12e^5\kappa}$.

(1) Given $e = 0.1$, the consumer type condition can be guaranteed if $\lambda < 40$.

Under this condition, $\pi_{aware} > \pi_{unaware}$ holds when $0 < \lambda < \lambda_{\pi_1}^{PA*} = 0.00003(8145 + 212558q_1) - 0.06066\sqrt{81 - 1764q_1 + 9604q_1^2}$; or when $\lambda_{\pi_1}^{PA*} < \lambda < 40$ and $0 < \kappa < \kappa_{\pi_1}^{PA*}(\lambda) = \frac{1.11111(-80545q_1+106279\lambda q_1)}{-4525-9050\lambda+18828\lambda^2} - 2284.37878\sqrt{\frac{1600q_1^2-3920\lambda q_1^2+2401\lambda^2 q_1^2}{(-4525-9050\lambda+18828\lambda^2)^2}}$.

$\pi_{aware} < \pi_{unaware}$ holds when $\lambda_{\pi_1}^{PA*} < \lambda < 40$ and $\kappa_{\pi_1}^{PA*}(\lambda) < \kappa < 1$.

(2) Given $e = 0.2$, the consumer type condition can be guaranteed if $\lambda < 20$.

Under this condition, $\pi_{aware} > \pi_{unaware}$ holds when $0 < \lambda < \lambda_{\pi_2}^{PA*} = 0.00157(110 + 1763q_1) - 0.11232\sqrt{16 - 184q_1 + 529q_1^2}$; or when $\lambda_{\pi_2}^{PA*} < \lambda < 20$ and $0 < \kappa < \kappa_{\pi_2}^{PA*}(\lambda) = \frac{2.5(-1045q_1+1763\lambda q_1)}{-275-550\lambda+11597\lambda^2} - 179.374\sqrt{\frac{225q_1^2-690\lambda q_1^2+529\lambda^2 q_1^2}{(-275-550\lambda+11597\lambda^2)^2}}$.

$\pi_{aware} < \pi_{unaware}$ holds when $\lambda_{\pi_2}^{PA*} < \lambda < 20$ and $\kappa_{\pi_2}^{PA*}(\lambda) < \kappa < 1$.

(3) Given $e = 0.3$, the consumer type condition can be guaranteed if $\lambda < 9$.

Under this condition, $\pi_{aware} > \pi_{unaware}$ holds when $0 < \lambda < \lambda_{\pi_3}^{PA*} = 0.00001(12495 + 153194q_1) - 0.01728\sqrt{441 - 3444q_1 + 6724q_1^2}$; or when $\lambda_{\pi_3}^{PA*} < \lambda < 9$ and $0 < \kappa < \kappa_{\pi_3}^{PA*}(\lambda) = \frac{0.47619(-36295q_1+76597\lambda q_1)}{-2975-5950\lambda+25248\lambda^2} - 872.682\sqrt{\frac{400q_1^2-1640\lambda q_1^2+1681\lambda^2 q_1^2}{(-2975-5950\lambda+25248\lambda^2)^2}}$.

$\pi_{aware} < \pi_{unaware}$ holds when $\lambda_{\pi_3}^{PA*} < \lambda < 9$ and $\kappa_{\pi_3}^{PA*}(\lambda) < \kappa < 1$.

We can verify algebraically that $\frac{\partial \kappa_{\pi}^{PA*}}{\partial \lambda} < 0$ holds for all the 3 cases $e = 0.1$, $e = 0.2$, and $e = 0.3$. Further, although the exact values of λ and κ thresholds change with the value of e and q_1 , there exists a pattern that for λ less than a threshold, the seller profit from aware consumers is higher than from unaware consumers at any value of κ ; while for λ above a threshold, the seller profit from unaware consumers is higher than from aware consumers κ above a threshold. Also, the κ threshold decreases with increasing λ . \square

Proof of Proposition 6

The environmental harms under optimal conditions are:

$$\begin{aligned}
harm_{aware} &= \frac{1}{2e(1+e)(-4+3e+8e^2)q_1} ((-1+e)(-4(1+\kappa)+2e^5\lambda(-4+3\kappa\lambda)) \\
&\quad + e^4\lambda(-11+3\kappa(-8+3\lambda))+e(-1+\kappa(-5+12\lambda))+e^2(11+4\lambda+\kappa(14+\lambda-12\lambda^2)) \\
&\quad + e^3(8+\lambda+\kappa(16-35\lambda-10\lambda^2))) - 2e(1+e(3-5\lambda))+2e^3(-4+\lambda)+6\lambda+6e^4\lambda-e^2(5+16\lambda))q_1 \\
usage_{aware} &= (\lambda((e-1)(e^4(6\kappa\lambda-8))+e^3(9\kappa\lambda-8\kappa-11))+e^2(-10\kappa\lambda-19\kappa+1) \\
&\quad -2e(6\kappa\lambda+\kappa-2)+8\kappa)-2(6e^4+2e^3-16e^2-5e+6)q_1)/(2(e+1)(8e^2+3e-4)q_1) \\
dumping_{aware} &= \frac{(-1+e)((-4+e(3+8e))(1+e+\kappa+2e\kappa)+e(4+e(3-16e(1+e))))\kappa\lambda+2e(-1+e(1+e)(-3+8e))q_1}{2e(1+e)(-4+3e+8e^2)q_1} \\
harm_{unaware} &= \frac{1}{2e(-4+e+4e^2)q_1} ((-1+e)(e-4(1+\kappa)+3e\kappa(-1+4\lambda)+4e^4\lambda(-1+\kappa\lambda)) \\
&\quad + e^3\lambda(-1+\kappa(-13+4\lambda))+e^2(4(1+\lambda)-2\kappa(-4+3\lambda+5\lambda^2))) \\
&\quad -2e(1+e(2-9\lambda))+6\lambda+3e^3\lambda-e^2(4+3\lambda))q_1 \\
usage_{unaware} &= \frac{\lambda((e-1)(4e^3(\kappa\lambda-1))+e^2(4\kappa\lambda-5\kappa-1)-2e(5\kappa\lambda+4\kappa-2)+8\kappa)-6(e^3-e^2-3e+2)q_1}{2(4e^2+e-4)q_1} \\
dumping_{unaware} &= \frac{-(-1+e)(4(1+\kappa)+e(-1+3\kappa-4\kappa\lambda+8e^2\kappa\lambda-2e(2+\kappa(4+\lambda))))+2e(-1-2e+4e^2)q_1}{2e(-4+e+4e^2)q_1}
\end{aligned}$$

Over the entire feasible range of parameters of interest:

When $\lambda < \lambda^{*[PA]} = \frac{4\kappa-7e\kappa-5e^2\kappa+8e^3\kappa+4q_1-4eq_1-10e^2q_1}{4\kappa+5e\kappa-11e^2\kappa-6e^3\kappa+8e^4\kappa}$, all of the following hold: $harm_{aware} > harm_{unaware}$,

$usage_{aware} > usage_{unaware}$, $dumping_{aware} > dumping_{unaware}$.

When $\lambda > \lambda^{*[PA]}$, all of the following hold: $harm_{aware} < harm_{unaware}$, $usage_{aware} < usage_{unaware}$,

$dumping_{aware} < dumping_{unaware}$. \square

Proof of Proposition 7

The consumer and social surpluses under optimal conditions are:

$$\begin{aligned}
ConsumerSurplus_{aware} &= ((e-1)^2(e^2(e(4e(11e+8))-29)-20)\kappa^2\lambda^2 \\
&\quad + (e(8e+3)-4)(e^2+2e(2\kappa^2+\kappa+1)+(\kappa+1)^2)-2e\kappa\lambda(e(e(2e(16\kappa+5) \\
&\quad +22\kappa+15)-11\kappa+1)-4(\kappa+1))) + 4eq_1((1-e)((20e^4-20e^2+e+4)\kappa\lambda \\
&\quad + e(-2e(e(8\kappa+5)+7)+10\kappa+1)-3\kappa+5) \\
&\quad + (e(e(4e-5)+6)+7)-5)q_1)/(8(e-1)e(e+1)(e(8e+3)-4)q_1)
\end{aligned}$$

$$\begin{aligned}
SocialSurplus_{aware} = & ((e-1)^2(e^2\kappa\lambda^2(e(4e(e(7\kappa-6)+4\kappa-9)-13\kappa+40)-4\kappa+48) \\
& + (e(8e+3)-4)(-3e^2+2e(\kappa(2\kappa-5)-5)+(\kappa-7)(\kappa+1)) \\
& + 2e\lambda(-(2e-1)(e(16e+19)+4)\kappa^2+(e+1)(2e-1)(29e+28)\kappa \\
& + 2e(e+1)(e(8e+3)-4))) - 4e(e-1)q_1(e(42e^2+\lambda(4e^3(\kappa-3)-2e^2(\kappa+2) \\
& - 4e(\kappa-8)+\kappa+10)+6e\kappa+46e+2\kappa-9)-3(\kappa+4\lambda+5)) \\
& + 4e(e(e(e(4e-3)-18)-3)+7)q_1^2)/(8(e-1)e(e+1)(e(8e+3)-4)q_1)
\end{aligned}$$

$$\begin{aligned}
ConsumerSurplus_{unaware} = & ((e-1)^2(-64e^6\kappa^2\lambda^2+16e^5(\kappa\lambda(\kappa(\lambda+8)+2)-1)+4e^4(\kappa^2(\lambda(27\lambda-10) \\
& - 20)+6\kappa(\lambda-1)-6)-e^3(\kappa(\kappa(12\lambda(\lambda+13)-35)+60\lambda+14)-23) \\
& + e^2(\kappa(\kappa(8(5-6\lambda)\lambda+95)-24\lambda+54)+39)+8e(\kappa(4(\kappa+1)\lambda-5\kappa+2)-1) \\
& - 16(\kappa+1)^2)+4eq_1((e-1)(4(e-1)(e+1)(e(e(8e-11)-3)+4)\kappa\lambda \\
& + e(e(-e(4e(8\kappa+5)-41\kappa+13)+24\kappa+38)-43\kappa+13)+4(3\kappa-5)) \\
& + (e(e(e(19e-40)-4)+43)-20)q_1))/(8(e-1)e(4e^2+e-4)^2q_1)
\end{aligned}$$

$$\begin{aligned}
SocialSurplus_{unaware} = & (4eq_1((e-1)(e(2(e(2e^2+e-6)+4)\kappa\lambda+e^2(-(e(8\kappa+84)+\kappa+21)) \\
& + 12e(\kappa+12)+6(e(e(4e-3)-17)+9)e\lambda+11\kappa+84\lambda+15)-12(\kappa+4\lambda+5)) \\
& + (e+1)(e(e(e(8e-11)-35)+65)-28)q_1)+(e-1)^2(64e^6\lambda((\kappa-1)\kappa\lambda+1) \\
& - 16e^5(\kappa(\kappa+5)\lambda^2+(\kappa-2)(8\kappa+1)\lambda+3)-4e^4(\kappa(\kappa(\lambda(25\lambda-6)-14) \\
& - \lambda(52\lambda+43)+38)+31\lambda+34)+e^3(\kappa(\kappa(4\lambda(9\lambda+49)-19)+4\lambda(26\lambda-109)+2) \\
& - 32\lambda+37)+e^2(\kappa(16(\kappa-10)\lambda^2-24(3\kappa+7)\lambda-95\kappa+258)+64\lambda+241) \\
& + 8e(\kappa(-4(\kappa-7)\lambda+5\kappa-2)+1)+16(\kappa-7)(\kappa+1)))/(8(e-1)e(4e^2+e-4)^2q_1)
\end{aligned}$$

Over the entire feasible range of parameter space of interest, $ConsumerSuplus_{aware} > ConsumerSuplus_{unaware}$ and $SocialSurplus_{aware} > SocialSurplus_{unaware}$ always hold. \square

Online Appendix

Appendix EC.1: Robustness Analyses

In this online appendix, we provide robustness checks of our analysis, with four alternative model specifications:

1. A model where the efficiency-adjusted quality of product j is $q_j(1 + e_j)$: that is, the usage-innovation term appears multiplicatively in the numerator with respect to the product quality (instead of multiplicative in the denominator as with the base model);
2. A model where the quality and use efficiency are additively separated (instead of being multiplicative) in the utility expression, i.e. $q_j - (1 - e_j)$;
3. A model with two types of consumers: those that feel environmental harm (proportion α), and those that don't (proportion $1 - \alpha$); and
4. Models with differentiated densities of low- and high-valuation consumers.

EC.1.1. Multiplicative use efficiency

We first consider the form of multiplicative efficiency in the utility expression: that is, the efficiency-adjusted quality of product j is $q_j(1 + e_j)$. As discussed below, the results are consistent with the main results in the paper.

For the **function** innovation case, where we set the use efficiency parameter e_j to 0, the indifference equations are given by:

$$\theta_{12}q_2 - p_2 - \kappa(1 + \lambda) = \theta_{12}q_1 - \kappa\lambda$$

$$q_2\theta_2 - p_2 = 0$$

$$2q_1\theta_1 - p_1 = q_2\theta_1 - p_2$$

The expression for seller profit is given by:

$$\pi = \frac{1}{196} \left(-196 - 98\kappa + 51q_1 + \frac{49(\kappa + q_1)^2}{q_1 - 2q_2} + \frac{49}{q_2} + 42q_2 + \frac{49(1 + \kappa)^2}{-q_1 + q_2} - \frac{4q_1^2(4q_1 + q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2} \right)$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{1}{2}(-1 + \frac{\kappa+q_1}{q_1-2q_2} + \frac{1+\kappa}{-q_1+q_2}) < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$harm = \frac{1}{14}(9 + 17\lambda - \frac{7(-1+\lambda)(\kappa+q_1)}{q_1-2q_2} + \frac{7(1+\kappa)}{q_1-q_2} - \frac{7\lambda}{q_2} + \frac{2q_1(2(-4+\lambda)q_1 + (5+4\lambda)q_2)}{8q_1^2 - 19q_1q_2 + 7q_2^2})$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} = \frac{1}{2}(\frac{1-\lambda}{q_1-2q_2} + \frac{1}{q_1-q_2}) < 0$ holds when $\lambda < \frac{3q_2-2q_1}{q_2-q_1}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{3q_2-2q_1}{q_2-q_1}$. \square

For the **fashion** innovation case, where we set the use efficiency parameter e_j to 0, the indifference equations are given by:

$$\theta_{12}q_1 - p_2 - \kappa(\lambda + 1) = \delta\theta_{12}q_1 - \kappa\lambda$$

$$\theta_2q_1 - p_2 = 0$$

$$(1 + \delta)q_1\theta_1 - p_1 = q_1\theta_1 - p_2$$

The expression for seller profit is given by:

$$\pi = \frac{(-1 - 7\delta + 4\delta^2)(2 - \delta + \kappa)^2 - 4(1 + 6\delta - 11\delta^2 + 4\delta^3)(-2 + \delta - \kappa)q_1 + 4(-1 - 5\delta + 13\delta^2 - 7\delta^3 - \delta^4 + \delta^5)q_1^2}{4(-2 + \delta)(-1 + \delta)(-1 - 7\delta + 4\delta^2)q_1}$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{2 + \frac{2-\delta+\kappa}{(-1+\delta)q_1}}{2(-2+\delta)} < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$harm = \left(\frac{2(1 + \lambda + \delta^3(4 + 3\lambda) - 3\delta^2(4 + 5\lambda) + \delta(8 + 17\lambda))}{-1 - 7\delta + 4\delta^2} + \frac{\delta + \kappa(-3 + \lambda) - \delta\kappa(-2 + \lambda) + 3\delta\lambda - \delta^2\lambda - 2(1 + \lambda)}{(-1 + \delta)q_1} \right) \frac{1}{2(-2 + \delta)}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

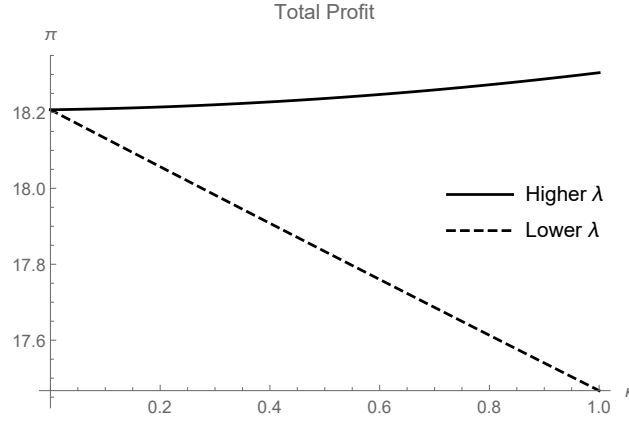


Figure EC.1 Robustness Analysis 1. Use Efficiency Innovation: Impact of κ on firm profit (Low λ vs. High λ)

Proof. We take partial derivative of environmental impact *harm* with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{-3+2\delta+\lambda-\delta\lambda}{2(2-3\delta+\delta^2)q_1} < 0$ holds when $\lambda < \frac{3-2\delta}{1-\delta}$; $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \frac{3-2\delta}{1-\delta}$. \square

For the **use efficiency** innovation case, where we set e_1 to 0, and $e_2 = e$, the indifference equations are given by:

$$\theta_{12}q_1(1+e) - p_2 - \kappa(\lambda(1-e) + 1) = \theta_{12}q_1 - \kappa\lambda$$

$$\theta_2q_1(1+e) - p_2 = 0$$

$$2q_1\theta_1 - p_1 = q_1(1+e)\theta_1 - p_2 + \kappa\lambda e$$

The expression for seller profit is given by:

$$\begin{aligned} \pi = & (-e^2(e+1)(e(e(9e+14)+13)+4)\kappa^2\lambda^2 - 2e(e+1)(e(7e-5)-4)\kappa\lambda(e(\kappa+2)+\kappa+1) \\ & + (e(7e-5)-4)(e(\kappa+2)+\kappa+1)^2 - 4e(e+1)q_1(e(e((e-2)e+3)+2)\kappa\lambda + (e(7e-5)-4)(e(\kappa+2) \\ & + \kappa+1)) + 4e(e(3(e-1)e(e+2)^2-7)-1)q_1^2)/(4e(e+1)(2e+1)(e(7e-5)-4)q_1) \end{aligned}$$

Consistent with Proposition 1b, as κ increases, seller profit decreases at lower values of λ , and increases at higher values of λ . Due to the intractability of the analytical proof, we show this result graphically. Seller profit changes with increasing κ as shown in Figure [EC.1](#).

The expression for overall environmental harm is given by:

$$\begin{aligned} harm = & (2e^2(e(e(31 - 3(e - 3)e) + 25) + 6)\kappa\lambda^2 + e\lambda((e + 1)(e(e(39e + 2) - 33) - 12)\kappa \\ & + 2e(2e + 1)(e(7e - 5) - 4)) + (-e - 1)(e(7e - 5) - 4)(e(3\kappa + 2) + \kappa + 1) \\ & - 2e(e + 1)q_1(e(e((10(e - 2)e - 11)\lambda - 9e + 4) \\ & + 13\lambda + 6) + 6\lambda + 1))/(2e(e + 1)(2e + 1)(e(7e - 5) - 4)q_1) \end{aligned}$$

Consistent with Proposition 2b, as κ increases, environmental harm decreases.

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . $\frac{\partial harm}{\partial \kappa} = \frac{e(e(2(e(19 - 3(e - 4)e) + 6)\lambda^2 + (e(39e + 2) - 33)\lambda - 21e + 8) - 12\lambda + 17) + 4}{2e(2e + 1)(e(7e - 5) - 4)q_1}$. Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} < 0$ holds. \square

EC.1.2. Additively separated use efficiency

We then consider a model where the quality and use efficiency are additively separated (instead of being multiplicative) in the utility expression, i.e. $q_j - (1 - e_j)$. As discussed below, the results are consistent with the main results in the paper.

For the **function** innovation case, where we set the use efficiency parameter e_j to 0, the indifference equations are given by:

$$\begin{aligned} \theta_{12}(q_2 - 1) - p_2 - \kappa(1 + \lambda) &= \theta_{12}(q_1 - 1) - \kappa\lambda \\ \theta_2(q_2 - 1) - p_2 &= 0 \\ 2(q_1 - 1)\theta_1 - p_1 &= \theta_1(q_2 - 1) - p_2 \end{aligned}$$

The expression for seller profit is given by:

$$\begin{aligned} \pi = & \frac{1}{196} \left(-98\kappa + \frac{49(\kappa + 1)^2}{q_2 - q_1} + \frac{49(\kappa + q_1 - 1)^2}{q_1 - 2q_2 + 1} + 51q_1 + 42q_2 \right. \\ & \left. + \frac{49}{q_2 - 1} - \frac{4(q_1 - 1)^2(4q_1 + q_2 - 5)}{8q_1^2 + (3 - 19q_2)q_1 + q_2(7q_2 + 5) - 4} - 289 \right) \end{aligned}$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{1}{2} \left(\frac{\kappa + 1}{q_2 - q_1} + \frac{\kappa + q_1 - 1}{q_1 - 2q_2 + 1} - 1 \right) < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$\begin{aligned} harm = & \frac{1}{14} \left(17\lambda - \frac{7(\lambda-1)(\kappa+q_1-1)}{q_1-2q_2+1} + \frac{7(\kappa+1)}{q_1-q_2} - \frac{7\lambda}{q_2-1} \right. \\ & \left. + \frac{2(q_1-1)(-6\lambda+2(\lambda-4)q_1+(4\lambda+5)q_2+3)}{8q_1^2+(3-19q_2)q_1+q_2(7q_2+5)-4} + 9 \right) \end{aligned}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} = \frac{1}{2} \left(\frac{1-\lambda}{q_1-2q_2+1} + \frac{1}{q_1-q_2} \right) < 0$ holds when $\lambda < \frac{3q_2-2q_1-1}{q_2-q_1}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{3q_2-2q_1-1}{q_2-q_1}$. \square

For the **fashion** innovation case, the indifference equations are given by:

$$\theta_{12}(q_1-1) - p_2 - \kappa(\lambda+1) = \delta\theta_{12}(q_1-1) - \kappa\lambda$$

$$\theta_2(q_1-1) - p_2 = 0$$

$$(1+\delta)(q_1-1)\theta_1 - p_1 = (q_1-1)\theta_1 - p_2$$

The expression for seller profit is given by:

$$\begin{aligned} \pi = & (-4(\kappa+1)^2 + q_1^2(2\delta^2(2\kappa^2 + \kappa - 19) + \delta(-5\kappa^2 + 90\kappa + 187) - 23\kappa^2 - 140\kappa - 173) \\ & + q_1^3(\delta^3(24\kappa + 23) + \delta^2(-8\kappa^2 - 72\kappa + 59) + \delta(13\kappa^2 - 54\kappa - 350) + 11\kappa^2 + 134\kappa + 284) \\ & + q_1^4(36\delta^4 - \delta^3(40\kappa + 187) + \delta^2(4\kappa^2 + 114\kappa + 187) + \delta(-7\kappa^2 - 34\kappa + 156) - \kappa^2 - 48\kappa - 196) \\ & - 4(\delta-1)q_1^5(\delta^4 + 8\delta^3 - 4\delta^2(\kappa+9) + \delta(7\kappa+23) + \kappa+13) + 4(\delta^5 - \delta^4 - 7\delta^3 + 13\delta^2 - 5\delta - 1)q_1^6 \\ & + q_1(-\delta(\kappa^2 + 26\kappa + 29) + 17\kappa^2 + 58\kappa + 45)/(4(\delta-1)(q_1-1)q_1((\delta-2)q_1+1)((4\delta^2-7\delta-1)q_1^2 - (\delta-9)q_1-4)) \end{aligned}$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = -\frac{\kappa-q_1(-3\delta+\kappa+2(\delta-1)q_1+4)+1}{2(\delta-1)q_1((\delta-2)q_1+1)} < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$\begin{aligned} harm = & (4(\kappa+1) + q_1^2(\delta^2(-\kappa(\lambda+2) + 13\lambda + 5) + \delta(\kappa(14\lambda - 23) - 86\lambda - 33) + \kappa(49 - 13\lambda) + 73\lambda + 52) \\ & + q_1^3(\delta^3(4\kappa(\lambda-2) - 15\lambda - 4) + \delta^2(\kappa(28 - 10\lambda) + 11\lambda - 6) + \delta(-\kappa(4\lambda + 5) + 107\lambda + 51) \\ & + \kappa(10\lambda - 31) - 103\lambda - 57) + 2(\delta-1)q_1^5(\delta^3(3\lambda+4) - 3\delta^2(5\lambda+4) + \delta(17\lambda+8) + \lambda+1) \\ & + q_1^4(-2\delta^4(5\lambda+4) + \delta^3(-4\kappa(\lambda-2) + 67\lambda + 36) + \delta^2(\kappa(11\lambda - 26) - 112\lambda - 39) \\ & + \delta(\kappa(19 - 6\lambda) + 11(\lambda - 1)) - \kappa(\lambda - 3) + 44\lambda + 26) + q_1(\delta(\kappa(9 - 4\lambda) + 16\lambda + 7) \\ & + \kappa(4\lambda - 25) - 16\lambda - 23)/(2(\delta-1)(q_1-1)q_1((\delta-2)q_1+1)((4\delta^2-7\delta-1)q_1^2 - (\delta-9)q_1-4)) \end{aligned}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact *harm* with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{q_1(-\delta(\lambda-2)+\lambda-3)+1}{2(\delta-1)q_1((\delta-2)q_1+1)} < 0$ holds when $\lambda < \frac{2\delta q_1-3q_1+1}{\delta q_1-q_1}$; $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \frac{2\delta q_1-3q_1+1}{\delta q_1-q_1}$. \square

For the **use efficiency** innovation case, where we set e_1 to 0, and $e_2 = e$, the indifference equations are given by:

$$\begin{aligned}\theta_{12}(q_1 - (1 - e)) - p_2 - \kappa(\lambda(1 - e) + 1) &= \theta_{12}(q_1 - 1) - \kappa\lambda \\ \theta_2(q_1 - (1 - e)) - p_2 &= 0 \\ 2(q_1 - 1)\theta_1 - p_1 &= (q_1 - (1 - e))\theta_1 - p_2 + \kappa\lambda e\end{aligned}$$

The expression for seller profit is given by:

$$\begin{aligned}\pi &= (e^6(12 - \kappa\lambda(9\kappa\lambda + 4)) + e^5(\kappa^2\lambda(23\lambda - 14) - 4\kappa(8\lambda + 7) - 92) + e^4(\kappa(\kappa(9(2 - 3\lambda)\lambda + 7) + 18\lambda + 64) \\ &+ 72) + e^3(\kappa(\kappa(\lambda(17\lambda + 14) - 9) + 52\lambda + 6) + 104) - e^2(\kappa^2(4\lambda^2 + 26\lambda + 7) + 42\kappa(\lambda + 2) + 125) \\ &+ q_1(e^5(\kappa\lambda(4 - 23\kappa\lambda) + 36) + 2e^4(\kappa(\lambda(9\kappa(3\lambda - 1) - 7) - 18) - 22) \\ &- e^3(\kappa(\kappa(\lambda(51\lambda + 28) - 9) + 124\lambda + 34) + 264) + 2e^2(\kappa(\kappa(\lambda(8\lambda + 39) + 7) + 67\lambda + 110) + 187) \\ &+ q_1(e^4(-\kappa)\lambda(27\kappa\lambda + 4) + e^3(\kappa(\kappa(\lambda(51\lambda + 14) + 92) + 28) + 208) - e^2(\kappa^2(6\lambda(4\lambda + 13) + 7) \\ &+ 2\kappa(75\lambda + 94) + 401) + q_1(e^3(-\kappa\lambda(17\kappa\lambda + 20) + 48)) + 2e^2(\kappa(\lambda(\kappa(8\lambda + 13) + 33) + 26) + 90) \\ &- 4q_1(e^2(\kappa\lambda(\kappa\lambda + 2) + 7) - e(2\kappa(\kappa\lambda + \lambda + 2) + 9) + e q_1 + (\kappa + 1)^2) - e(\kappa(32(\kappa + 1)\lambda + 13\kappa + 98) + 125) \\ &+ 16(\kappa + 1)^2) + e(3\kappa(16(\kappa + 1)\lambda + 13\kappa + 66) + 199) - 24(\kappa + 1)^2) - e(\kappa(32(\kappa + 1)\lambda \\ &+ 39\kappa + 166) + 147) + 16(\kappa + 1)^2) + e(\kappa(8(\kappa + 1)\lambda + 13\kappa + 50) + 41) \\ &- 4(\kappa + 1)^2)/(4e(e + q_1 - 1)(2e + q_1 - 1)(q_1(-5e - 4q_1 + 8) + e(7e + 5) - 4))\end{aligned}$$

Consistent with Proposition 1b, as κ increases, seller profit decreases at lower values of λ , and increases at higher values of λ . Due to the intractability of the analytical proof, we show this result graphically. Seller profit changes with increasing κ as shown in Figure [EC.2](#).

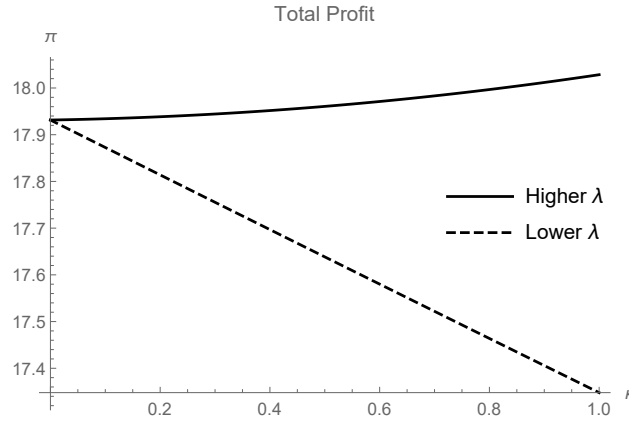


Figure EC.2 Robustness Analysis 2. Use Efficiency Innovation: Impact of κ on firm profit (Low λ vs. High λ)

The expression for overall environmental harm is given by:

$$\begin{aligned}
harm = & (2q_1^4(e^2\lambda(2\kappa\lambda + 3) - e(4(\kappa + 2)\lambda + 1) + 2(\kappa + 1)) + q_1^3(e^3\lambda(19\kappa\lambda + 26) \\
& - e^2(8\kappa\lambda^2 + (36\kappa + 89)\lambda + 14) + e(7\kappa(4\lambda + 3) + 68\lambda + 25) - 16(\kappa + 1)) + q_1^2(26e^4\lambda(\kappa\lambda + 1) \\
& - e^3(26\kappa\lambda^2 + 33\kappa\lambda + 137\lambda + 20) + e^2(99\kappa\lambda + 25\kappa + 244\lambda + 58) - 9e(4\kappa\lambda + 7\kappa + 12\lambda + 7) \\
& + 24(\kappa + 1)) + (1 - e)(2e^5\lambda(3\kappa\lambda + 10) - e^4(2\kappa\lambda^2 + (39\kappa + 56)\lambda + 18) + e^3(\kappa(8\lambda^2 - 12\lambda + 21) \\
& - 24\lambda + 6) + e^2(\kappa(-4\lambda^2 + 23\lambda + 8) + 64\lambda + 15) - e(4\kappa\lambda + 17\kappa + 20\lambda + 15) + 4(\kappa + 1)) + q_1(e^5\lambda(5\kappa\lambda - 14) \\
& - 2e^4(8\kappa\lambda^2 + (4 - 17\kappa)\lambda - 5) + e^3(\kappa(-5\lambda^2 + 68\lambda - 13) + 199\lambda + 29) + e^2(\kappa(8\lambda^2 - 90\lambda - 50) - 245\lambda - 74) \\
& + e(\kappa(20\lambda + 63) + 76\lambda + 59) - 16(\kappa + 1)))/(2e(e + q_1 - 1)(2e + q_1 - 1)(7e^2 + (8 - 5e)q_1 + 5e - 4q_1^2 - 4))
\end{aligned}$$

Consistent with Proposition 2b, as κ increases, environmental harm decreases.

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . $\frac{\partial harm}{\partial \kappa} = -\frac{(e\lambda-1)^2}{2e} - \frac{(\lambda-1)(e\lambda-1)}{2(2e+q_1-1)} + \frac{e\lambda(2(e(e+2)-1)\lambda+q_1((e+2)\lambda+1)+e-1)}{q_1(-5e-4q_1+8)+e(7e+5)-4}$. Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} < 0$ holds.²⁰ \square

²⁰ Since the model employs an additive form between q_1 and e to measure the effect of e , the boundary conditions for the feasible range are substantively different from the main model. In this robustness analysis, the feasible market quantity condition $1 > \theta_{12} > \theta_1 > \theta_2 > 0$ holds when $0.1q_1 < e < 0.3q_1$, $q_1 > 5$, $0 < \lambda < 0.2$, and $e((e(25e+2)-15)+4)\kappa\lambda + e(3e(6e-7\kappa-2)-8\kappa-15)+17\kappa+15) + q_1(-e(2((e-15)e+6)\kappa\lambda + e(8e-8\kappa-27)+34\kappa+32) + q_1(e(-3e(5\kappa\lambda+4)+12\kappa\lambda+17\kappa+19)-2q_1(2e\kappa\lambda+e-2(\kappa+1))-12(\kappa+1))+12(\kappa+1)) < 4(\kappa+1) < e((3e-1)(e(3e+7)-4)\kappa\lambda + e(e(2e-21\kappa-6)-8\kappa-3)+17\kappa+11) + q_1(-e(2(e(9e-19)+6)\kappa\lambda + e(8e-8\kappa-3)+34\kappa+20) + q_1(e(\kappa(-19e\lambda+12\lambda+17)+7)+2q_1(-2e\kappa\lambda+e+2\kappa+2)-12(\kappa+1))+12(\kappa+1)))$. The interpretation of the conditions remains the

EC.1.3. Two consumer types

Here, we generalize the previous model to have consumers who may or may not feel environmental harm. A fraction α of consumers feel environmental harm ($0 < \alpha < 1$), whereas the remaining consumers $(1 - \alpha)$ do not feel environmental harm. As discussed below, the results are consistent with the main results in the paper.

In this model, only the α fraction of consumers are sensitive to environmental harm and hence have the disutility related to environmental harm in their utility functions. The other consumers (i.e., the remaining fraction $(1 - \alpha)$) do not have environmental-related disutility in their decision making process. Hence all utility functions for α consumers remain the same as the main model; the utility functions for $(1 - \alpha)$ consumers are:

$$U_{11}^f = \theta q_1 \frac{1}{1 - e_1} - p_1 \quad \text{and} \quad U_{22}^f = \theta q_2 \frac{1}{1 - e_2} - p_2$$

$$U_{12}^o = \theta \delta q_1 \frac{1}{1 - e_1} \quad \text{and} \quad U_{22}^o = \theta q_2 \frac{1}{1 - e_2} - p_2$$

The entire market is hence divided into two segments α and $(1 - \alpha)$. The firm applies the same price for both segments in a period, and maximizes the total profit from the two segments over two periods. In this analysis, we use θ_α to denote the α -type consumers' valuation of the product, and θ to denote the $(1 - \alpha)$ -type consumers' valuation. The market quantities are hence given by: $Q_1 = \alpha(1 - \theta_{\alpha 1}) + (1 - \alpha)(1 - \theta_1)$, $Q_2 = \alpha(\theta_{\alpha 1} - \theta_{\alpha 2}) + (1 - \alpha)(\theta_1 - \theta_2)$, and $Q_{12} = \alpha(1 - \theta_{\alpha 12}) + (1 - \alpha)(1 - \theta_{12})$.

For the **function** innovation case, where we set the use efficiency parameter e_j to 0, the indifference equations for α consumers are given by:

$$\theta_{\alpha 12} q_2 - p_2 - \kappa(1 + \lambda) = \theta_{\alpha 12} q_1 - \kappa \lambda$$

$$q_2 \theta_{\alpha 2} - p_2 = 0$$

$$2q_1 \theta_{\alpha 1} - p_1 = q_2 \theta_{\alpha 1} - p_2$$

same with the main analysis, which says that the innovation degree (measured by e in the use efficiency case) has both lower and upper bounds, and the value of λ cannot exceed an upper bound.

And the indifference equations for $(1 - \alpha)$ consumers are given by:

$$\theta_{12}q_2 - p_2 = \theta_{12}q_1$$

$$q_2\theta_2 - p_2 = 0$$

$$2q_1\theta_1 - p_1 = q_2\theta_1 - p_2$$

The expression for seller profit is given by:

$$\pi = \frac{1}{196} \left(-98\alpha\kappa + \frac{49(\alpha\kappa + 1)^2}{q_2 - q_1} + \frac{49(\alpha\kappa + q_1)^2}{q_1 - 2q_2} + 51q_1 + 42q_2 + \frac{49}{q_2} - \frac{4q_1^2(4q_1 + q_2)}{8q_1^2 - 19q_2q_1 + 7q_2^2} - 196 \right)$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ .

We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{\alpha(q_2(\alpha\kappa - 2q_2 + 2) + q_1(2q_2 - 1))}{2(q_1 - 2q_2)(q_1 - q_2)} < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$harm = \frac{1}{14} \left(17\lambda - \frac{7(\lambda - 1)(\alpha\kappa + q_1)}{q_1 - 2q_2} + \frac{7\alpha\kappa + 7}{q_1 - q_2} - \frac{7\lambda}{q_2} + \frac{2q_1(2(\lambda - 4)q_1 + (4\lambda + 5)q_2)}{8q_1^2 - 19q_2q_1 + 7q_2^2} + 9 \right)$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} = \frac{1}{2}\alpha \left(\frac{1-\lambda}{q_1-2q_2} + \frac{1}{q_1-q_2} \right) < 0$ holds when $\lambda < \frac{3q_2-2q_1}{q_2-q_1}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{3q_2-2q_1}{q_2-q_1}$. \square

For the **fashion** innovation case, where we set the use efficiency parameter e_j to 0, the indifference equations for α consumers are given by:

$$\theta_{\alpha 12}q_1 - p_2 - \kappa(\lambda + 1) = \delta\theta_{\alpha 12}q_1 - \kappa\lambda$$

$$\theta_{\alpha 2}q_1 - p_2 = 0$$

$$(1 + \delta)q_1\theta_{\alpha 1} - p_1 = q_1\theta_{\alpha 1} - p_2$$

And the indifference equations for $(1 - \alpha)$ consumers are given by:

$$\theta_{12}q_1 - p_2 = \delta\theta_{12}q_1$$

$$\theta_2q_1 - p_2 = 0$$

$$(1 + \delta)q_1\theta_1 - p_1 = q_1\theta_1 - p_2$$

The expression for seller profit is given by:

$$\pi = \frac{4\alpha\kappa - 4\delta + \frac{(\alpha\kappa - \delta + 2)^2}{(\delta - 1)q_1} + \frac{4(\delta^3 - 7\delta + 6 + 1)q_1}{\delta(4\delta - 7) - 1}}{4(\delta - 2)} + 8$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ .

We verify algebraically that $\frac{\partial \pi}{\partial \kappa} = \frac{\alpha(\alpha\kappa - \delta + 2)(\delta - 1)q_1 + 2}{2(\delta - 2)(\delta - 1)q_1} < 0$ always holds over the entire feasible range of parameter space of interest. \square

The expression for overall environmental harm is given by:

$$harm = \frac{\frac{2((3(\delta - 5)\delta + 17)\delta\lambda + 4(\delta - 2)(\delta - 1)\delta + \lambda + 1)}{\delta(4\delta - 7) - 1} + \frac{-(\delta - 1)\lambda(\alpha\kappa + \delta - 2) + 2\alpha\delta\kappa - 3\alpha\kappa + \delta - 2}{(\delta - 1)q_1}}{2(\delta - 2)}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} = \frac{\alpha(-\delta(\lambda - 2) + \lambda - 3)}{2(\delta - 2)(\delta - 1)q_1} < 0$ holds when $\lambda < \frac{3 - 2\delta}{1 - \delta}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{3 - 2\delta}{1 - \delta}$. \square

For the **use efficiency** innovation case, where we set e_1 to 0, and $e_2 = e$, the indifference equations for α consumers are given by:

$$\begin{aligned} \theta_{\alpha 12} \frac{q_1}{1 - e} - p_2 - \kappa(\lambda(1 - e) + 1) &= \theta_{\alpha 12} q_1 - \kappa\lambda \\ \theta_{\alpha 2} \frac{q_1}{1 - e} - p_2 &= 0 \\ 2q_1\theta_{\alpha 1} - p_1 &= \frac{q_1}{1 - e}\theta_{\alpha 1} - p_2 + \kappa\lambda e \end{aligned}$$

And the indifference equations for $(1 - \alpha)$ consumers are given by:

$$\begin{aligned} \theta_{12} \frac{q_1}{1 - e} - p_2 &= \theta_{12} q_1 \\ \theta_2 \frac{q_1}{1 - e} - p_2 &= 0 \\ 2q_1\theta_1 - p_1 &= \frac{q_1}{1 - e}\theta_1 - p_2 \end{aligned}$$

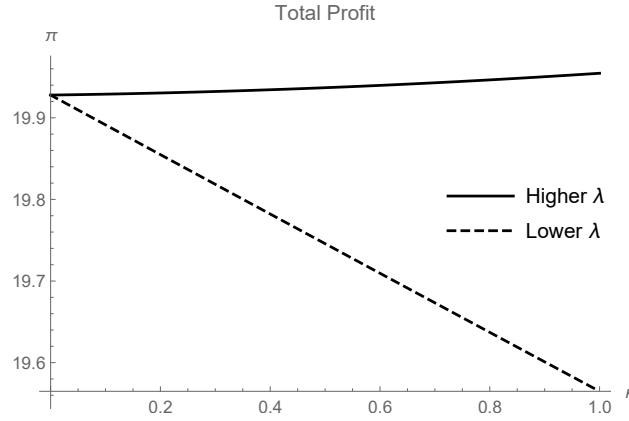


Figure EC.3 Robustness Analysis 3. Use Efficiency Innovation: Impact of κ on firm profit (Low λ vs. High λ)

The expression for seller profit is given by:

$$\begin{aligned} \pi = & (4eq_1((e-1)(\alpha e(-4e^2 + 2e + 3) - 2)\kappa\lambda \\ & + (4 - e(8e + 3))(\alpha\kappa + e + 1)) + (2e(e+1)(2(e-2)e+1) + 1)q_1) \\ & + (e-1)^2(\alpha^2 e^2(4e^3 + e + 4)\kappa^2\lambda^2 + 2\alpha e(e(8e+3) - 4)\kappa\lambda(\alpha\kappa + e + 1) \\ & + (4 - e(8e + 3))(\alpha\kappa + e + 1)^2)) / (4(e-1)e(e+1)(e(8e+3) - 4)q_1) \end{aligned}$$

Consistent with Proposition 1b, as κ increases, seller profit decreases at lower values of λ , and increases at higher values of λ . Due to the intractability of the analytical proof, we show this result graphically. Seller profit changes with increasing κ as shown in Figure EC.3.

The expression for overall environmental harm is given by:

$$\begin{aligned} harm = & ((e-1)(\alpha e^2(e(6e^2 + 9e - 10) - 12)\kappa\lambda^2 - e(e+1)\lambda(\alpha(e(24e+11) - 12)\kappa \\ & + e(e(8e+3) - 4)) + (e(8e+3) - 4)(\alpha\kappa + 2\alpha e\kappa + e + 1)) - 2eq_1(e(e(2(3e^2 + e - 8)\lambda - 8e - 5) \\ & - 5\lambda + 3) + 6\lambda + 1)) / (2e(e+1)(e(8e+3) - 4)q_1) \end{aligned}$$

Consistent with Proposition 2b, as κ increases, environmental harm decreases.

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ .

$$\begin{aligned} \frac{\partial harm}{\partial \kappa} = & (2\alpha(e-1)(e+1)^2(e(8e+3) - 4)(q_1(e(e(\lambda(6e^2\lambda - e(\lambda + 26) - 6\lambda - 8) + 20) + 12\lambda + 1) - 6) \\ & + (e-1)(e(e(\lambda((4e-3)\lambda - 16) - 6\lambda - 4) + 8) + 10\lambda + 3) - 4)) \\ & / ((e-1)(\alpha e(e(2e-7) - 8)\kappa\lambda + (e(8e+3) - 4)(-\alpha\kappa + e + 1)) + 2(e(3e(2e+5) + 2) - 6)q_1^2) \end{aligned}$$

Over the entire feasible range of parameter space of interest, $\frac{\partial harm}{\partial \kappa} < 0$ holds. \square

In addition, we also provide the results for how prices, quantities, profits and environmental harms change with α , which show that the market fraction parameter α affects the market in a way similar to κ :²¹

Price and quantities:

As α increases, Function and fashion innovation:

Period 1: price (p_1) decreases; quantity ($Q_1 = 1 - \theta_1$) does not change.

Period 2: price (p_2) decreases; new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; upgrade quantity ($Q_{12} = 1 - \theta_{12}$) decreases.

Use efficiency innovation:

Period 1: Both price (p_1) and quantity ($Q_1 = 1 - \theta_1$) decrease.

Period 2:

At lower values of λ : price (p_2) decreases; new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; and upgrade quantity ($Q_{12} = 1 - \theta_{12}$) decreases.

At higher values of λ : price (p_2) increases; new purchase quantity ($Q_2 = \theta_1 - \theta_2$) increases; and upgrade quantity ($Q_{12} = 1 - \theta_{12}$) increases.

Profit:

Function and fashion innovation: As α increases, firm profit decreases.

Use efficiency innovation: As α increases, (i) at lower values of λ , firm profit decreases; and (ii) at higher values of λ , firm profit increases.

Environmental harm:

Function and fashion innovation: As α increases, (i) dumping harm decreases; (ii) in-use harm increases; (iii) total harm decreases at lower values of λ , and increases at higher values of λ .

Use efficiency innovation: As α increases,

At lower values of λ : (i) dumping harm decreases; (ii) in-use harm increases; (iii) total harm decreases.

At higher values of λ : (i) dumping harm increases; (ii) in-use harm decreases; (iii) total harm decreases.

²¹ Proofs of these results are available upon request.

EC.1.4. Differentiated densities of low- and high-valuation consumers

In the main model, we assume that consumers are uniformly distributed through the lowest valuation 0 to the highest valuation 1 – that is, the density function of θ is $f(\theta) = 1$, for $\theta \in [0, 1]$. We also provide two other distributions to reflect differentiated densities of low- and high-valuation consumers. The first alternative distribution describes a high density of low-valuation consumers and a low density of high-valuation consumers, of which the density function of θ is as follows:

$$f(\theta) = \begin{cases} \frac{3}{2} & \text{if } \theta \in [0, \frac{1}{2}) \\ \frac{1}{2} & \text{if } \theta \in [\frac{1}{2}, 1] \end{cases}$$

Consumers' utility functions and the indifference equations remain the same with the main model, whereas the market quantities now reflect the differentiated densities: the fraction of consumers who purchase in period 1 is $\frac{1}{2}(1 - \theta_1)$, the fraction of consumers who upgrade is $\frac{1}{2}(1 - \theta_{12})$, and the fraction of consumers who are first time buyers in period 2 is $\frac{1}{2}(\theta_1 - \frac{1}{2}) + \frac{3}{2}(\frac{1}{2} - \theta_2)$.²²

The second alternative distribution describes a low density of low-valuation consumers and a high density of high-valuation consumers, of which the density function of θ is as follows:

$$f(\theta) = \begin{cases} \frac{1}{2} & \text{if } \theta \in [0, \frac{1}{2}) \\ \frac{3}{2} & \text{if } \theta \in [\frac{1}{2}, 1] \end{cases}$$

Consumers' utility functions and the indifference equations remain the same with the main model, whereas the market quantities now reflect the differentiated densities: the fraction of consumers who purchase in period 1 is $\frac{3}{2}(1 - \theta_1)$, the fraction of consumers who upgrade is $\frac{3}{2}(1 - \theta_{12})$, and the fraction of consumers who are first time buyers in period 2 is $\frac{3}{2}(\theta_1 - \frac{1}{2}) + \frac{1}{2}(\frac{1}{2} - \theta_2)$.

As discussed below, with the alternative distributions, all results are consistent with the main results in the paper.

For the **function** innovation case, we set the use efficiency parameter e_j to 0.

²² Based on the conditions of feasible market quantities, we prove that for both alternative distributions in this robustness analysis, θ_{12} and θ_1 are always in $[\frac{1}{2}, 1]$ and θ_2 is always in $[0, \frac{1}{2}]$.

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for seller profit is given by:

$$\begin{aligned} \pi = & \frac{1}{8(3q_1 - 4q_2)(q_1 - q_2)q_2(24q_1^2 - 43q_2q_1 + 15q_2^2)} (q_2^2q_1^2(3(8\kappa^2 + 150\kappa + 517) - 6(67\kappa + 442)q_2 + 97q_2^2) \\ & - q_2^3q_1(43\kappa^2 + 434\kappa - 6(58\kappa + 277)q_2 + 241q_2^2 + 1048) + q_2q_1^3(-9(16\kappa + 107) + 18(8\kappa + 99)q_2 + 385q_2^2) \\ & + q_2^4(15(\kappa + 4)^2 - 90(\kappa + 4)q_2 + 71q_2^2) + 144q_2q_1^5 - 24(19q_2^2 + 18q_2 - 9)q_1^4) \end{aligned}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for seller profit is given by:

$$\begin{aligned} \pi = & \frac{1}{8(q_1 - 4q_2)(q_1 - q_2)q_2(8q_1^2 - 33q_2q_1 + 13q_2^2)} (3q_2^2q_1^2(24\kappa^2 + 130\kappa - 10(41\kappa + 70)q_2 + 49q_2^2 + 135) \\ & - q_2^3q_1(297\kappa^2 + 870\kappa - 10(138\kappa + 197)q_2 + 419q_2^2 + 632) + q_2q_1^3(-48\kappa + 10(24\kappa + 73)q_2 + 371q_2^2 - 97) \\ & + q_2^4(13(3\kappa + 4)^2 - 130(3\kappa + 4)q_2 + 133q_2^2) + 48q_2q_1^5 - 8(35q_2^2 + 10q_2 - 1)q_1^4) \end{aligned}$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ .

We verify algebraically that for the distribution of high low-valuation consumer density and low high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = \frac{1}{16} \left(\frac{4(\kappa+1)}{q_2-q_1} + \frac{12\kappa+9q_1}{3q_1-4q_2} - 3 \right) < 0$ always holds over the entire feasible range of parameter space of interest. For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = \frac{3}{16} \left(\frac{4(\kappa+1)}{q_2-q_1} + \frac{4\kappa+5q_1}{q_1-4q_2} - 5 \right) < 0$ always holds over the entire feasible range of parameter space of interest. \square

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for overall environmental harm is given by:

$$\begin{aligned} harm = & \frac{1}{4(3q_1 - 4q_2)(q_1 - q_2)q_2(24q_1^2 - 43q_2q_1 + 15q_2^2)} (3q_2q_1^3(3(-8\kappa(\lambda - 2) + 99\lambda + 8) - (269\lambda + 178)q_2) \\ & + 3q_2^2q_1^2(67\kappa\lambda - 142\kappa - 442\lambda + (429\lambda + 239)q_2 - 75) + q_2^3q_1(-174\kappa\lambda + 391\kappa + 831\lambda \\ & - (853\lambda + 410)q_2 + 217) + q_2^4(15(3\kappa\lambda - 7\kappa - 12\lambda - 4) + (193\lambda + 83)q_2) + 36q_1^4((5\lambda + 4)q_2 - 6\lambda)) \end{aligned}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for overall environmental harm is given by:

$$\begin{aligned} harm = & \frac{1}{4(q_1 - 4q_2)(q_1 - q_2)q_2(8q_1^2 - 33q_2q_1 + 13q_2^2)} (q_2q_1^3(-24\kappa(\lambda - 2) + 73\lambda - (353\lambda + 354)q_2 + 24) \\ & + 3q_2^2q_1^2(\kappa(41\lambda - 106) - 70\lambda + (411\lambda + 281)q_2 - 65) + q_2^3q_1(\kappa(573 - 138\lambda) + 197\lambda \\ & - (1267\lambda + 726)q_2 + 435) + q_2^4(39\kappa(\lambda - 5) - 52(\lambda + 3) + (359\lambda + 189)q_2) + 4q_1^4((7\lambda + 12)q_2 - 2\lambda)) \end{aligned}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact *harm* with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, for the distribution of high low-valuation consumer density and low high-valuation consumer density, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{3(\lambda-1)}{4(4q_2-3q_1)} + \frac{1}{4q_1-4q_2} < 0$ holds when $\lambda < \frac{7q_2-6q_1}{3q_2-3q_1}$; $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \frac{7q_2-6q_1}{3q_2-3q_1}$. For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial \text{harm}}{\partial \kappa} = \frac{3}{4} \left(\frac{1-\lambda}{q_1-4q_2} + \frac{1}{q_1-q_2} \right) < 0$ holds when $\lambda < \frac{5q_2-2q_1}{q_2-q_1}$; $\frac{\partial \text{harm}}{\partial \kappa} > 0$ holds when $\lambda > \frac{5q_2-2q_1}{q_2-q_1}$. \square

For the **fashion** innovation case, we set the use efficiency parameter e_j to 0.

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for seller profit is given by:

$$\pi = \frac{6(-3\delta + \kappa + 4) + \frac{(-3\delta + \kappa + 4)^2}{(\delta-1)q_1} + \frac{(\delta(\delta(12\delta(3\delta+1)-179)+126)+9)q_1}{3\delta(4\delta-5)-1}}{8(3\delta-4)}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for seller profit is given by:

$$\pi = \frac{-10(\delta - 3\kappa - 4) + \frac{(\delta-3\kappa-4)^2}{(\delta-1)q_1} + \frac{(\delta+5)(2\delta-3)(\delta(6\delta-19)-5)q_1}{\delta(4\delta-13)-3}}{8(\delta-4)}$$

Consistent with Proposition 1a, as κ increases, seller profit decreases.

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . We verify algebraically that for the distribution of high low-valuation consumer density and low high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = \frac{-3\delta + \kappa + 3(\delta-1)q_1 + 4}{4(\delta-1)(3\delta-4)q_1} < 0$ always holds over the entire feasible range of parameter space of interest. For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = \frac{3(-\delta + 3\kappa + 5(\delta-1)q_1 + 4)}{4(\delta-4)(\delta-1)q_1} < 0$ always holds over the entire feasible range of parameter space of interest. \square

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for overall environmental harm is given by:

$$\text{harm} = \frac{\frac{\delta(3\delta(6\delta(5\lambda+4)-89\lambda-52)+190\lambda+77)+7\lambda+5}{3\delta(4\delta-5)-1} + \frac{-3(\delta-1)\lambda(3\delta+\kappa-4)+6\delta\kappa+3\delta-7\kappa-4}{(\delta-1)q_1}}{4(3\delta-4)}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for overall environmental harm is given by:

$$harm = \frac{\frac{(\delta(\delta(14\delta-157)+362)+33)\lambda+3(\delta-3)(4\delta(2\delta-5)-3)}{\delta(4\delta-13)-3} + \frac{3(2\delta\kappa+\delta-5\kappa-4)-(\delta-1)\lambda(\delta+3\kappa-4)}{(\delta-1)q_1}}{4(\delta-4)}$$

Consistent with Proposition 2a, as κ increases, environmental harm decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of environmental impact $harm$ with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, for the distribution of high low-valuation consumer density and low high-valuation consumer density,

$\frac{\partial harm}{\partial \kappa} = \frac{-3\delta\lambda+6\delta+3\lambda-7}{4(3\delta^2-7\delta+4)q_1} < 0$ holds when $\lambda < \frac{6\delta-7}{3\delta-3}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{6\delta-7}{3\delta-3}$. For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial harm}{\partial \kappa} = \frac{3(-\delta(\lambda-2)+\lambda-5)}{4(\delta-4)(\delta-1)q_1} < 0$ holds when $\lambda < \frac{2\delta-5}{\delta-1}$; $\frac{\partial harm}{\partial \kappa} > 0$ holds when $\lambda > \frac{2\delta-5}{\delta-1}$. \square

For the **use efficiency** innovation case, we set $e_1 = 0$ and $e_2 = e$.

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for seller profit is given by:

$$\begin{aligned} \pi = & \frac{1}{8(e-1)e(3e+1)(e(24e-5)-4)q_1} ((e-1)^2(e^2(36e^3+9e+4)\kappa^2\lambda^2 \\ & + 2e(e(24e-5)-4)\kappa\lambda(3e+\kappa+1) + (4-e(24e-5))(3e+\kappa+1)^2) \\ & + eq_1((e(24(6e-11)e^2+e+44)+4)q_1 + 2(e-1)(e(-72e^3+60e^2+e-8)\kappa\lambda \\ & - 3(e(24e-5)-4)(3e+\kappa+1)))) \end{aligned}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for seller profit is given by:

$$\begin{aligned} \pi = & \frac{1}{8(e-1)e(e+3)(e(8e+17)-12)q_1} (-2e(e-1)q_1(3e(e(8e^2+4e-37)+24)\kappa\lambda \\ & + 5(e(8e+17)-12)(e+3\kappa+3)) + (e-1)^2(3e^2(4e^3-15e+36)\kappa^2\lambda^2 \\ & + 6e(e(8e+17)-12)\kappa\lambda(e+3\kappa+3) + (12-e(8e+17))(e+3\kappa+3)^2) \\ & + (e-2)e(4e+3)(e(12e+25)-18)q_1^2) \end{aligned}$$

Consistent with Proposition 1b, as κ increases, seller profit decreases at lower values of λ , and increases at higher values of λ .

Proof. We take partial derivative of firm profit π with respect to environmental sensitivity κ . Over the entire feasible range of parameter space of interest, for the distribution of high low-valuation consumer density and low high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = ((e - 1)(e^2(36e^3 + 9e + 4)\kappa\lambda^2 + e(e(24e - 5) - 4)\lambda(3e + 2\kappa + 1) + (4 - e(24e - 5))(3e + \kappa + 1)) + eq_1(e(e(12(5 - 6e)e\lambda + \lambda - 72) - 8\lambda + 15) + 12))/(4e(3e + 1)(e(24e - 5) - 4)q_1) < 0$ holds when $\lambda < \frac{1}{2(36e^6\kappa - 36e^5\kappa + 9e^4\kappa - 5e^3\kappa - 4e^2\kappa)}(72e^5q_1 - 72e^5 - 48e^4\kappa - 60e^4q_1 + 63e^4 + 58e^3\kappa - e^3q_1 + 26e^3 - 2e^2\kappa + 8e^2q_1 - 13e^2 - ((-72e^5q_1 + 72e^5 + 48e^4\kappa + 60e^4q_1 - 63e^4 - 58e^3\kappa + e^3q_1 - 26e^3 + 2e^2\kappa - 8e^2q_1 + 13e^2 + 8e\kappa + 4e)^2 - 4(36e^6\kappa - 36e^5\kappa + 9e^4\kappa - 5e^3\kappa - 4e^2\kappa)(-72e^4 - 24e^3\kappa - 72e^3q_1 + 63e^3 + 29e^2\kappa + 15e^2q_1 + 26e^2 - e\kappa + 12eq_1 - 13e - 4\kappa - 4))^{\frac{1}{2}} - 8e\kappa - 4e)$; $\frac{\partial \pi}{\partial \kappa} > 0$ holds when λ is greater than this threshold.

For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial \pi}{\partial \kappa} = (3(e - 1)(e^2(4e^3 - 15e + 36)\kappa\lambda^2 + e(e(8e + 17) - 12)\lambda(e + 6\kappa + 3) + (12 - e(8e + 17))(e + 3\kappa + 3)) - 3eq_1(e(e((8e^2 + 4e - 37)\lambda + 40) + 24\lambda + 85) - 60))/(4e(e + 3)(e(8e + 17) - 12)q_1) < 0$ holds when $\lambda < \frac{1}{2(12e^6\kappa - 12e^5\kappa - 45e^4\kappa + 153e^3\kappa - 108e^2\kappa)}(24e^5q_1 - 24e^5 - 144e^4\kappa + 12e^4q_1 - 99e^4 - 162e^3\kappa - 111e^3q_1 + 6e^3 + 522e^2\kappa + 72e^2q_1 + 225e^2 - ((-24e^5q_1 + 24e^5 + 144e^4\kappa - 12e^4q_1 + 99e^4 + 162e^3\kappa + 111e^3q_1 - 6e^3 - 522e^2\kappa - 72e^2q_1 - 225e^2 + 216e\kappa + 108e)^2 - 4(12e^6\kappa - 12e^5\kappa - 45e^4\kappa + 153e^3\kappa - 108e^2\kappa)(-24e^4 - 72e^3\kappa - 120e^3q_1 - 99e^3 - 81e^2\kappa - 255e^2q_1 + 6e^2 + 261e\kappa + 180eq_1 + 225e - 108\kappa - 108))^{\frac{1}{2}} - 216e\kappa - 108e)$; $\frac{\partial \pi}{\partial \kappa} > 0$ holds when λ is greater than this threshold. \square

For the distribution of high low-valuation consumer density and low high-valuation consumer density, the expression for overall environmental harm is given by:

$$\begin{aligned} harm = & \frac{1}{4e(3e + 1)(e(24e - 5) - 4)q_1} ((e - 1)(e^2(e(3e(18e + 5) - 64) - 20)\kappa\lambda^2 \\ & + e\lambda(e(3e(-72e^2 - 9(8e + 3)\kappa + 39e + 23) + 59\kappa - 22) + 20\kappa - 8) \\ & + (e(24e - 5) - 4)(e(6\kappa + 3) + \kappa + 1)) \\ & + eq_1(e(e(3e((53 - 60e)\lambda + 48) + 130\lambda - 42) - 44\lambda - 21) - 20\lambda + 2)) \end{aligned}$$

For the distribution of low low-valuation consumer density and high high-valuation consumer density, the expression for overall environmental harm is given by:

$$\begin{aligned} harm = & \frac{1}{4e(e+3)(e(8e+17)-12)q_1} ((e-1)(3e^2(e(e(6e+31)+8)-84)\kappa\lambda^2 \\ & - e\lambda(e(e(e(8e+72\kappa+57)+339\kappa+121)+303\kappa+42)-36(7\kappa+2)) \\ & + 3(e(8e+17)-12)(2e\kappa+e+3\kappa+3)) + eq_1(e(e(e(48-(28e+111)\lambda) \\ & + 2(59\lambda+81))+468\lambda+69)-18(14\lambda+5))) \end{aligned}$$

Consistent with Proposition 2b, as κ increases, environmental harm decreases.

Proof. We take partial derivative of environmental harm $harm$ with respect to environmental sensitivity κ . We verify algebraically that for the distribution of high low-valuation consumer density and low high-valuation consumer density, $\frac{\partial harm}{\partial \kappa} = \frac{(e-1)(e(e((e(3e(18e+5)-64)-20)\lambda^2+(59-27e(8e+3))\lambda+144e-6)+20\lambda-29)-4)}{4e(3e+1)(e(24e-5)-4)q_1} < 0$ always holds over the entire feasible range of parameter space of interest. For the distribution of low low-valuation consumer density and high high-valuation consumer density, $\frac{\partial harm}{\partial \kappa} = \frac{3(e-1)(e((e(e(6e+31)+8)-84)\lambda^2-(e(24e+113)+101)\lambda+16e+58)+84\lambda+27)-36)}{4e(e+3)(e(8e+17)-12)q_1} < 0$ always holds over the entire feasible range of parameter space of interest. \square

Appendix EC.2: Additional Insights

EC.2.1. Fashion Depreciation

For the fashion innovation, the initial version of the product would decay in its perceived value when a new version is introduced in period 2, because of the depreciation in terms of fashion. In this section, we provide additional insights into the role of the fashion depreciation factor (δ) in affecting our main results.

The depreciation factor δ is between 0 and 1, and a lower value of δ indicates a higher degree of depreciation in the perceived quality. Our main results show that in the fashion innovation case, firm profit decreases with consumers' increasing environmental sensitivity (κ), and environmental harm decreases with κ when the use-dump harm ratio λ is low but increases with κ when λ is

high. We show the role of the depreciation factor δ regarding these two results in Figure EC.4 and Figure EC.5, in which we assign 3 different values (high, medium, and low) to δ and compare the corresponding profits and environmental harms.

As the depreciation factor becomes smaller; i.e., fashion depreciation of the old product becomes higher, the firm profit becomes larger. This result is intuitive since with a higher degree of fashion innovation (which leads to higher degree of depreciation), the firm should be able to set higher prices and make more profit.

For the environmental harm, we consider a low λ case and a high λ case. In our main model, at lower values of λ , environmental harm decreases with κ , and at higher values of λ , environmental harm increases with κ . In Figure EC.5a, lower values of the depreciation factor δ lead to more environmental harm. This is because in the low use-dump harm ratio case, dumping presents more harm than usage. High fashion depreciation would lead to more purchase of the upgraded product and hence more dumping, which brings about worse environmental impact. In contrast, Figure EC.5b shows that in the high λ case, high fashion depreciation is associated with less harm.

Our analysis shows that when fashion depreciation becomes higher (i.e., the value of depreciation factor becomes lower), prices in both period 1 and period 2 would rise. The high prices then reduce the first-time purchase in both periods, while the high depreciation induces more upgrades. In other words, only the upgrade quantity in period 2 would increase with the degree of depreciation. We find that the dumping harm increases and the in-use harm decreases with depreciation degree over the feasible range of parameters, because of the increasing upgrade quantity and the decreasing first-time purchase. Therefore, when λ is low and the dumping harm dominates the overall environmental harm, a high depreciation is associated with more overall harm. When λ is large and the in-use harm becomes dominant, a high depreciation is associated with less overall harm.

Additionally, we show the effects of δ on social surplus in Figure EC.6. Overall, lower values of δ (higher degree of fashion depreciation) are associated with both lower consumer and social surplus.

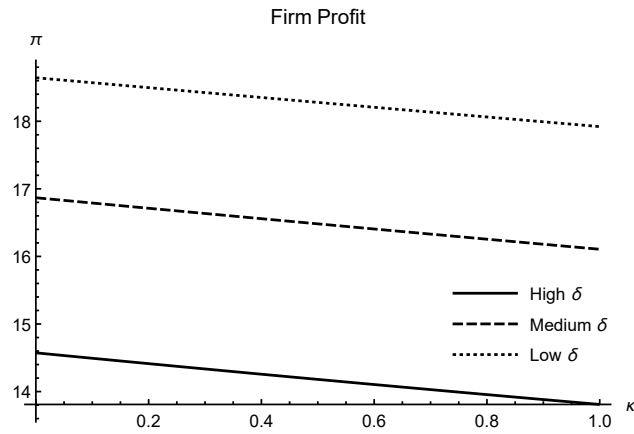
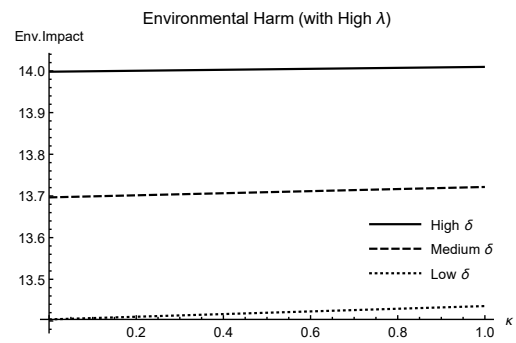
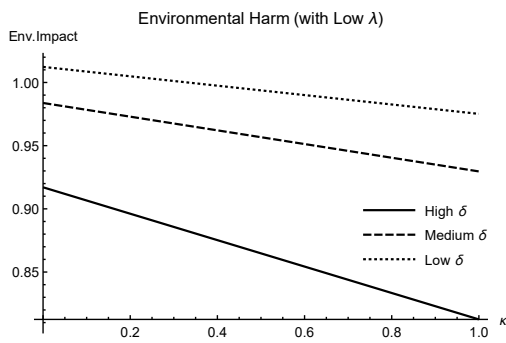
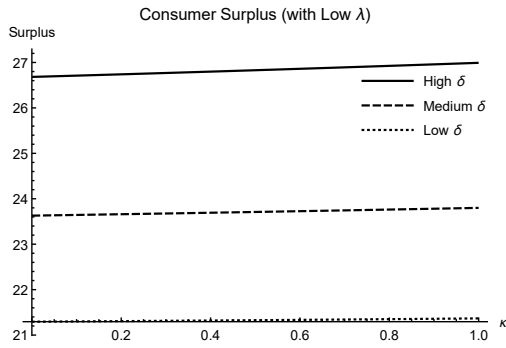


Figure EC.4 Fashion Innovation: Role of depreciation factor for firm profit

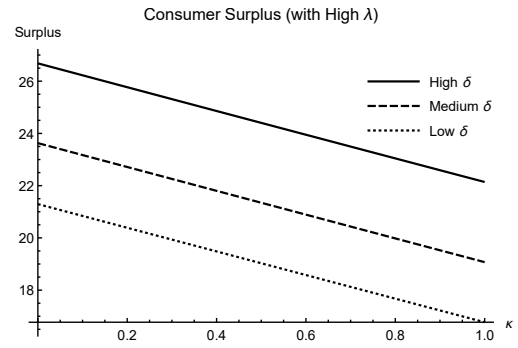


(a) Lower λ : Environmental harm decreases with κ (b) Higher λ : Environmental harm increases with κ

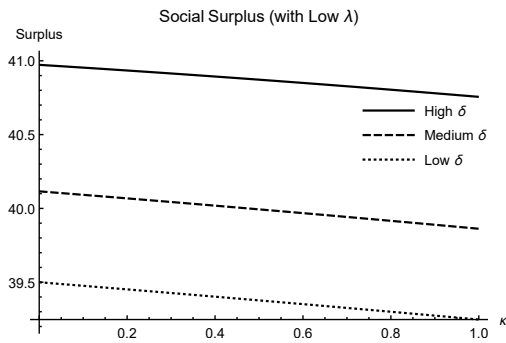
Figure EC.5 Fashion Innovation: Role of depreciation factor for environmental harm



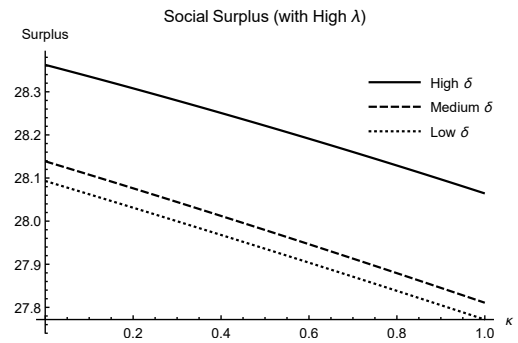
(a) Lower λ : Consumer surplus increases with κ



(b) Higher λ : Consumer surplus decreases with κ



(c) Lower λ : Social surplus decreases with κ



(d) Higher λ : Social surplus decreases with κ

Figure EC.6 Fashion Innovation: Role of depreciation factor for consumer and social surplus