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Many industries, including consumer electronics and telecommunications equipment, are characterized with short product life-cycles, constant technological innovations, rapid product introductions, and fast obsolescence. Firms in such industries need to make frequent design changes to incorporate innovations, and the effort to keep up with the rate of technological change often leaves little room for the consideration of product reuse. In this paper, we study the design for reusability and product reuse decisions in the presence of both a known rate of incremental innovations and a stochastic rate of radical innovations over time. We formulate this problem as a Markov Decision Process. Our steady-state results confirm the conventional wisdom that a higher probability of radical innovations would lead to reductions in the firm's investments in reusability as well as the amount of reuse the firm ends up doing. Interestingly, the design for reusability decreases much more slowly than the actual reuse. We identify some specific scenarios, however, where there is no tradeoff between the possibility of radical innovations and the firms reusability and reuse decisions. Based on over 425,000 problem instances generated over the entire range of model parameters, we also provide insights into the negative impact of radical innovations on firm profits, but show that the environmental impact of increased radical innovation is not necessarily negative. Our results also have several implications for policy makers seeking to encourage reuse.

Key words: reusability, reuse, innovation, Markov decision process

1. Introduction

Product reuse effectively "closes the loop" in a supply chain by routing used products from the end consumer back into the production/distribution process, thereby creating an additional useful life for used products. Over the last two decades, as firms have increasingly recognized product reuse as an important source of profits, the academic literature has devoted significant attention to the strategic, operational, and tactical issues regarding product reuse (see Dekker et al. (2004), Guide and Van Wassenhove (2009), and Souza (2013) for extensive reviews).

Product reuse is often viewed as an effective strategy for enhancing environmental sustainability given the potential environmental advantage of reuse over new production (since generally fewer new raw materials are needed when components of 'old' items are reused). Firms usually voluntarily engage in product reuse when there are clear economic benefits, and when this is not the case the regulators often intervene by enacting legislation or financial incentives to encourage reuse. To this end, the firms need to simultaneously (i) design products that are reusable and (ii) reuse products that are returned by (or collected from) the customer. The former involves strategic investments in materials and production technologies that result in reusable designs, while the latter requires investment in operation systems that facilitate acquisition or take-back of used products and their remanufacturing. In innovative industries with short product life-cycles, this has to be done taking into account the rapid technological advances over time, which force the firms to follow the technological trajectory by introducing new (and improved) products.

It is important to distinguish different types of innovations. One important distinction is made between disruptive and sustaining innovations. According to Christensen (1997): 'What all sustaining technologies have in common is that they improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued' (p. 11). This is contrasted with disruptive innovations, which 'bring to a market a very different value proposition than had been available previously' (p. 11). As disruptive innovations have the potential to completely change markets, we limit our focus to sustaining innovations in this paper. Sustaining innovations can be further broken down into *incremental* and *radical* innovations (Tushman and O'Reilly, 1996). Incremental innovations are (as the name suggests) of a relatively gradual and predictable nature, whereas a radical innovation is more stochastic in nature and can be viewed as a significant 'step change' in a particular technology. The electronics industry has experienced a well-known series of sustaining innovations, with a consistent stream of incremental improvements (e.g. Intel's progression through various iterations of the Pentium chip) interrupted by infrequent and generally unpredictable radical innovations (e.g. the vacuum tube being replaced by transistor technology, which in turn was replaced by the semiconductor) (Harvard Business School Press, 2013). The technological development of light-emitting Diodes (LEDs) since 1920s displays a similar trajectory of continuous incremental innovations improving the efficiency of the light that is punctuated by radical innovations involving the discovery of red, green and finally blue LEDs (Verganti 2009).

Intuitively, one would expect that both types of sustaining innovations would have have a negative effect on the degree of reusability built into the product as well as the extent of reuse undertaken by a firm. This is because innovation will occur while a customer is using a product. Thus, when the product becomes available for reuse, it does not contain the latest innovations and is thus less attractive to consumers compared to newly produced items. Such a possibility would also hinder the incentives of the firm to design its product to be more reusable. The primary aim of this research is to formally investigate the relationship between *innovation*, *product reusability* and *amount of reuse* using an analytical model that incorporates both incremental *and* radical sustaining innovations. We find that the interplay between these decisions is not always straightforward and intuitive, and our results have important implications for both firms and policy makers.

Although, as mentioned above, reuse and remanufacturing have been studied extensively in the literature, the interaction of reuse with product design has received much less attention. Most papers take a qualitative approach to assessing the value of considering remanufacturing during the design phase (see, for example, Kerr and Ryan 2001, Gray and Charter 2007). Analytical studies in this area are scant but have been increasing in recent years. Mukhopadhyay and Setoputro (2005) examine the modularity decision from the perspective of improving the salvage value of returned items, but product reuse is not modeled. Other papers have considered design decisions as they pertain to product recovery and e-waste disposal (Plambeck and Wang, 2009; Atasu and Subramanian, 2012). More recently, several analytical papers have begun to specifically address the intersection of design and reuse/remanufacturing. Wu (2012) models a manufacturer's decision regarding the 'disassemblability' of its products, with a focus on how disassemblability can be used as a competitive lever. Subramanian et al. (2013) examines how firm decisions regarding common components across products are affected when the impact of component commonality on remanufacturing is considered. Atasu and Souza (2013) examine how reuse interacts with a firm's optimal quality choice. These recently published models have expanded our understanding of the interaction of design and reuse, but do not offer how they are shaped by the rate of technological advances and innovations in the industry, which is the focus of our paper.

There is still very little analytical work addressing design and reuse in the presence of innovation. Extant closed-loop supply chain literature treats the impact of innovation at best *indirectly*, through the "marginal value of time" (Blackburn et al. 2004, Guide et al. 2006). This concept captures the idea that products become less appealing over time, but does not explicitly model innovation or successive iterations of products. A notable exception is Galbreth et al. (2013), who developed a (stationary) model for reuse, examining both profit and environmental impact (measured in terms of virgin material usage) in a context that included only incremental innovation. However, that paper did not incorporate two salient characteristics of innovative industries: i) the possibility of a radical innovation and ii) the strategic design investment firms can make in product reusability. Instead, their primary analysis assumes that the firm makes reusable only those parts that do not face incremental innovations, while in an extension they investigate the possibilities of making the product fully reusable or fully non-reusable (disposable). In reality, for any given market environment, the firm can choose the *optimal* level of reusability for its products and engage in collection and reuse operations when those products reach the end of their lives. In this paper, we explicitly consider the possibility of radical innovations and design for reusability as well. This enables us to comment on product reusability and reuse strategies for the common scenario in which both incremental innovation and the threat of radical innovation exist – insights that have not been possible using the models in the extant literature.

Our analysis provides insights into how incremental and radical innovations affect a firm's decision on whether to design its product for reuse and how many items to actually reuse after the uncertainties are resolved. We study how these decisions are influenced by different contextual factors such as the *rate* of incremental innovation, the *probability* of radical innovation, consumer perceptions of old vs. new technologies, as well as relative costs of manufacturing products with these technologies at different reusability levels. In order to represent our business context of interest, which includes a time-dependent stochastic radical innovation component, we employ a Markov Decision Process (MDP) model, which enables us to capture the dynamic nature of a firm's production decisions–these need not be constant over time, but instead depend on when radical innovations have taken place in the past as well as future expectations of innovations.

The remainder of this paper is organized as follows. Section 2 provides the modelling framework, while §3 discusses the MDP model and its solution. In §4, the results of an extensive numerical study over 425,000 problem instances are provided and discussed. Section 5 presents several extensions of this model, along with their robustness results. We conclude with a summary of key takeaways in §6. The Appendix presents an overview of the notation we use as well as the proofs of our two Propositions.

2. Modeling framework

We model a firm that manufactures a product that may be made reusable and subsequently reused, and is subject to both incremental and radical innovations. Table 4 in the Appendix summarizes our notation. Firm decisions take place at discrete points in time and are represented as an MDP. Before formally defining the MDP, we provide more details regarding how innovation and reuse are modeled, the different product variants that can be produced, consumer utilities and the demand model, and manufacturing costs.

Innovation: A conceptual representation of sustaining innovations based on Christensen (1997) is provided in Figure 1. We assume that the firm is committed to making the incremental product improvements that are necessary to keep up with the rate of incremental innovations and thus continue to appeal to consumers. Specifically, there is a known *rate* of incremental innovation, $\beta \in [0, 1]$, which means that in each period a fraction β of the product is subject to incremental innovations, and hence will be replaced with incrementally improved parts.

For radical innovations, we assume that the firm is an innovation 'follower,' in the sense that it reacts to radical innovations (i.e., technology breakthroughs) as they occur, by incorporating them into the new products. This enables us to abstract away from the firm's decisions to invest in R&D in pursing innovations and the uncertainties therein. As a result, in our model the radical innovations occur exogenously, but the firm does not exactly know when such breakthroughs will occur. We model this by assuming that there is known *probability* of radical innovation in each period, denoted as α.

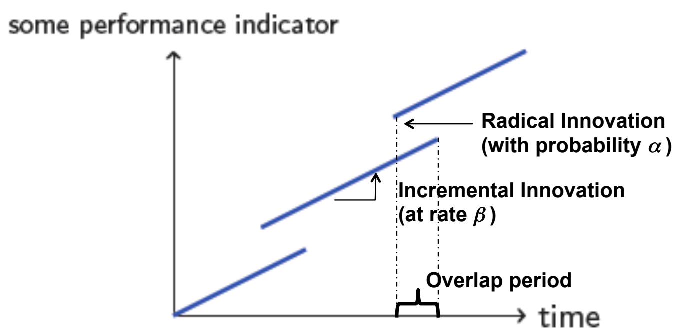


Figure 1 **Product/technology performance under sustaining innovations**

We refer to the current technology at any point in time as the incumbent technology, while the new technology if radical innovation occurs is the radical technology. We assume that the incumbent technology and the radical technology can be sold alongside each other in the period in which the radical technology is introduced. This single period of overlap can be seen as a transition period between technologies. One period *after* a radically innovative technology was introduced, we assume that the radical technology has been fully adopted by the market; the radical technology has become the (new) incumbent technology and there is no demand anymore for the 'old' incumbent technology in this period. This also means that we only refer to a certain technology as 'radical' in the period in which it is introduced. In the period(s) thereafter, it is the incumbent technology.

We remark that the one-period overlap assumption captures the essential dynamics of innovations and interplay between new and old technologies, while maintaining a manageable state space for the MDP. As we discuss in §5 our key results are valid with longer periods of overlap between the radical and incumbent technologies. Note also that whether a product does or does not contain incremental innovations, or whether it is of the incumbent or radical technology, both have effects on production costs and consumer valuations, as will be explained later in this section.

Reusability and Reuse: In our framework, we make a distinction between the reusability and reuse. We view the former as a strategic design-related decision that requires an investment (in more durable materials, etc.). Accordingly, we model it as a decision that the firm commits to at the beginning. Denote the fraction of the product that the firm decides to make reusable as $(1-\beta_u)$, where β_u is the fraction of the product that the firm must replace if remanufacturing occurs. As explained later in this section, we optimize the reusability decision $(1-\beta_u)$.

The reuse decisions are more tactical/operational, and are taken at each time period. After a product has been used by a consumer, it is collected by the firm. This collection takes at the end of the period in which the product was produced and sold (i.e. the length of a period equates to the usable life of the product). As it is often done in the literature, we take the collection rate as 100%, although an extension of the model to a lower rate is straightforward and does not yield additional structural results. Once collected, the firm can choose to remanufacture this product and sell it again. However, because the product was originally produced in the previous time period, it does not contain the current period's incremental innovations. Moreover, if there has been a radical innovation after the item was originally produced, then remanufacturing is based on the 'old', incumbent technology, which makes the remanufactured product even less appealing to consumers. As with most papers in the related literature, we assume that products can be remanufactured only once.

Products: The set of product variants that the manufacturer can produce depends on whether a radical innovation has been made in the current time period. If there is no radical innovation, then only products of the incumbent technology can be produced. If there is a radical innovation, then the incumbent and radical technology products can be produced alongside each other. In each time period, the firm decides upon the following production quantities. For ease of exposition we omit the time index. Nevertheless, production quantities need not be constant over time.

- q_n^{inc} : the number of new products of the incumbent technology, of which a part $(1-\beta_u)$ is made reusable;
- q_n^{rad} : the number of new products of the radically innovative technology, of which a part $(1-\beta_u)$ is made reusable (can only be produced if there is a radical innovation);
- q_r^{inc} : the number of used products of the incumbent technology that are reused.

Note that the reusability level $(1-\beta_u)$ is a strategic design decision by the firm which applies to all production in all periods (i.e. reusability level, unlike production quantity, is a long-term design decision that cannot be changed period-by-period, and instead is determined upfront).

Recall that in our model, in the event that there is a radical technology breakthrough, the firm has to adopt it in order to remain competitive in the market. We do, however, allow the firm to defer its adoption, i.e. it can choose to set $q_n^{rad}=0$. In this case, we still assume that consumers will be aware of the radical innovation and will thus value the incumbent technology lower. Note that the firm cannot choose to ignore the innovation indefinitely. Since consumer preferences completely shift to the new technology after one period, the firm can defer adoption for at most one period.

Denote by q^{ret} the number of products that are returned by consumers in a given period, which is equal to the number of new products of the latest technology that were produced in the previous period. That is, if there was no radical innovation in the previous period, then q^{ret} equals q_n^{inc} from the previous period, and if there was a radical innovation in the previous period, then q^{ret} equals q_n^{rad} from the previous period. Finally, $q_r^{inc} \leq q^{ret}$, i.e., the firm cannot reuse more products than are returned by the consumers. (Note that there is no inventory of returned items since the older returned items would miss too many incremental innovations to be reused in later periods.)

The production quantities of different variants depend on the prices set for each option and how customers value new and old technology as well as remanufactured products. We discuss these next.

Consumer Valuations and Market Demand: We consider a market with heterogenous customers. The total market size is normalized to 1 without loss of generality. Let V denote the consumer valuation of the 'best' product at that time, that is, a new (i.e., not reused) product of the latest technology. To express the heterogeneity of the consumer population, we let V follow a uniform distribution ($V \sim \text{uniform}[0,1]$). Furthermore, we assume that V is stationary; i.e. the valuation of the 'best' product in the current period does not change over time.

The product variants and hence the prices charged for each variant depend on the state of the world, i.e. whether or not there is a radical innovation in that period. For this reason, it is necessary to consider each case separately.

Suppose that there is no radical innovation in the current period. Let the subscript "0" represent this state. Then, the firm can produce a new product of the incumbent technology with a price p_n^{inc}. That product is the 'best' product at the current state of technology and therefore provides the consumer with a utility of:

$$U_{n,0}^{inc} := V - p_n^{inc}.$$

The firm can also remanufacture used products from the previous period. These reused products have a lower valuation for two reasons. First, just because the product contains reused material/components and is not entirely new, the valuation V is multiplied by a discount factor $\delta \in [0,1]$ (see Souza (2013)). Second, the reused product does not contain the β fraction of incrementally improved components, so the valuation is multiplied by $(1-\beta)$. This means that a reused product (of the incumbent technology) with a price p_r^{inc} has consumer utility

$$U_{r,0}^{inc} := (1-\beta)\delta V - p_r^{inc}.$$

Next, suppose that there is a radical innovation in a time period, which will be denoted by a subscript "1" in the notation for utilities. Then, for a new product of the radical technology sold at a price p_n^{rad} the consumer utility is:

$$U_{n,1}^{rad} := V - p_n^{rad}.$$

Furthermore, in this scenario the firm can still produce items of the incumbent technology. However, these items now have a lower valuation; because there is a radical technology, the incumbent technology is perceived as being 'outdated' to a certain degree. Therefore, the valuation V is multiplied by a factor $\gamma \in [0,1]$, indicating how the consumers perceive the incumbent technology relative to the radical technology. Hence, the consumer utility of a new item of the incumbent technology, given its price p_n^{inc}, is defined as:

$$U_{n,1}^{inc} := \gamma V - p_n^{inc}.$$

In a period with a radical innovation, a used item of the *incumbent* technology can also be remanufactured. Now these reused products have a lower valuation for three reasons: they contain used components, they are based on the outdated incumbent technology, and they do not even contain the incremental innovations of the incumbent technology. Hence, its consumer utility, given its price p_r^{inc}, is defined as:

$$U_{r,1}^{inc} := (1-\beta)\gamma\delta V - p_r^{inc}.$$

Recall that, starting one period *after* a radical innovation was introduced, there is no demand anymore for the incumbent technology.

Consumers choose the product that provides them with the highest utility, provided this is positive. In other words, we include the no-purchase option with a consumer utility of zero. A rather straightforward derivation yields the demand and inverse-demand functions presented in Table 2.

Costs: Each product variant has its own unit production and disposal related costs, which are assumed to be stationary. There are four components of the units costs which pametrized as:

- c_o: costs to produce an item that consists of only 'unimproved' components;
- c_n: costs to produce an item that consists of only 'improved' components;
- K: costs to make an item fully reusable;
- $d\tau$: end-of-life costs per item.

	Demand	Inverse Demand
No Radical	$q_n^{inc} = 1 - \frac{p_n^{inc} - p_r^{inc}}{1-(1-\beta)\delta}$	$p_n^{inc} = 1 - q_n^{inc} - (1-\beta)\,\delta q_r^{inc}$
Innovation	$q_r^{inc} = \frac{p_n^{inc} - p_r^{inc}}{1-(1-\beta)\delta} - \frac{p_r^{inc}}{(1-\beta)\delta}$	$p_r^{inc} = (1-\beta)\,\delta\,(1 - q_n^{inc} - q_r^{inc})$
With	$q_n^{rad} = 1 - \frac{p_n^{rad} - p_n^{inc}}{1-\gamma}$	$p_n^{rad} = 1 - q_n^{rad} - \gamma q_n^{inc} - \gamma\delta\,(1-\beta)\,q_r^{inc}$
Radical	$q_n^{inc} = \frac{p_n^{rad} - p_n^{inc}}{1-\gamma} - \frac{p_n^{inc} - p_r^{inc}}{\gamma(1-(1-\beta)\delta)}$	$p_n^{inc} = \gamma\,(1 - q_n^{rad} - q_n^{inc} - \delta\,(1-\beta)\,q_r^{inc})$
Innovation	$q_r^{inc} = \frac{p_n^{inc} - p_r^{inc}}{\gamma(1-(1-\beta)\delta)} - \frac{p_r^{inc}}{\gamma(1-\beta)\delta}$	$p_r^{inc} = \gamma\delta\,(1-\beta)\,(1 - q_n^{rad} - q_n^{inc} - q_r^{inc})$

Table 1 **Demand and Inverse Demand for all Product Variants**

We assume that the per-item end-of-life costs $d\tau$ that the firm incurs consist of a fraction τ of the products for which the firm has to pay some recycling or disposal costs, equal to d, with d and τ acting as a single parameter $d\tau$.

Consider now a new item of the incumbent technology. This product has a fraction β of incrementally improved components, which have production costs βc_n. The other part of components, $(1-\beta)$, has not experienced improvement, and has production costs $(1-\beta)c_o$. Furthermore, if the fraction $(1-\beta_u)$ is made reusable, we assume that reusability costs are linear, $K(1-\beta_u)$. Finally, the end-of-life costs $d\tau$ need to be added. Putting these together, the production costs of a new item of the incumbent technology becomes:

$$C_n^{inc} := (1-\beta)c_o + \beta c_n + K(1-\beta_u) + d\tau = c_o + \beta\,(c_n - c_o) + K(1-\beta_u) + d\tau.$$

For a remanufactured product, the costs depend critically on β_u, since this is the part that was not made reusable, and hence it needs to be produced from scratch. Remanufacturing brings the product to its original condition, which does not contain the incremental innovations, so the production costs are based on c_o rather than c_n. End-of-life costs are only incurred for the part β_u, as the end-of-life costs for the reused part $(1-\beta_u)$ have already been incurred when it was originally produced. This leads to unit cost:

$$C_r^{inc} := \beta_u\,(c_o + d\tau)\,.$$

Finally, consider a new item that is produced with the latest radical innovations. We define the costs to produce such an item as:

$$C_n^{rad} := c_n + K(1-\beta_u) + d\tau$$

For simplicity, we represent the production cost of the radical technology as c_n, i.e. we view the radical technology to consist entirely of improved components. (Our framework could also be used with production costs other than c_n, and we allow this radical production cost to be stochastic as a robustness check in Section 5.) The interpretation of the second and third terms of the above expression are the same as before.

Note that in the period after this radical innovation, the radically innovated technology becomes the incumbent technology. Hence the unit production cost of a new product goes down from C_n^{rad} to C_n^{inc}, which captures the effect of learning/economies of scale[1].

Timeline and Sequence of Events: As discussed above, we consider a discrete time model, where the firm first decides on the reusability level $(1-\beta_u)$, which will apply to all new product introductions in subsequent periods. As mentioned above, this reusability level is a long term design decision that cannot be changed between periods. Thus, even if a radical innovation occurs, this level of reusability is still included in any subsequent production of the incumbent product (despite the fact that it will not be reused anymore). This setup reflects the idea that design changes (even to eliminate reusability) will not be made on a soon-to-be-obsolete product. In each period, the firm decides on how much to produce (equivalently how much to charge) of each variant. In doing so, the firm first observes q^{ret} the number of products that are used in the previous period and returned by the consumers. Then, incremental innovations and (random) radical innovations are realized. Based on these, the firm decides on the production quantities q_n^{inc}, q_n^{rad}, and q_r^{inc}. Accordingly, the market demand is determined, revenues are collected and costs are incurred (including the

[1] We test the robustness of our model to these assumptions by considering a stochastic post-learning production cost and longer overlap durations in Section 5.

end-of-life costs). Subsequently, the firm moves into the next period. Alternatively, one could view as innovations taking place at the end of the previous period, without changing the results. Next, we describe the details of this model and its solution.

3. Markov decision process model and its solution

For any reusability level $(1-\beta_u)$, the firm determines the production quantities of different variants based on an average-reward Markov decision process. We adopt average-reward criterion since we are interested in the overall, average behavior of the firm, regardless of the initial state it is in (as there is no obvious choice for which state a firm would be in initially). The stationary cost and customer utilities facilitate calculation of steady-state average decisions and associated rewards. Nevertheless, dynamics play an important role in the firm's decisions. As noted before, the decisions will depend on whether there has been a radical innovation in a period or not, but the number of items of the latest technology that were produced in the previous period is also important, since this limits the number of products that can be reused. The extent of reuse, in turn, affects the number of new products that are produced in the current period, which affects the number of returns in the next period, etc.

As in any average-reward MDP, we need to specify four key components: states, actions, transition probabilities and immediate rewards.

States: In our MDP, the state is defined by the pair (q^{ret}, i), where q^{ret} is the number of returned items in the state (the firm can decide to reuse these in the current state) and i indicates whether there is a radical innovation in the state (1) or not (0).

Note that the time period is not part of the definition of a state. Since neither costs nor consumer utilities depend on time, (q^{ret}, i) gives sufficient information to determine the immediate reward (maximum profit in the current period) of taking a certain action in a state.

Actions: After observing the state, the firm needs to decide upon the production quantities q_n^{rad}, q_n^{inc} and q_r^{inc}. However, in an MDP, not every decision is also an *action*. Only those decisions that affect the probability of transitioning to a certain state are actions. This leads to the following definitions of actions:

- in a state with a radical innovation ($i=1$), the action is: q_n^{rad}, the production of new items of the radical technology, as this will be equal to the number of returns (q^{ret}) in the next state;
- in a state without a radical innovation ($i=0$), the action is: q_n^{inc}, the production of new items of the incumbent technology, as this will be equal to the number of returns (q^{ret}) in the next state.

The remaining decisions are *optimized* in each given period to determine the immediate reward.

Transition probabilities Let $p\left(\left(q_1^{ret}, i\right), \left(q_2^{ret}, j\right), a\right)$ denote the probability of transitioning from state (q_1^{ret}, i) to state (q_2^{ret}, j), given that action a is taken. The probability of a radical innovation in any period is given by α. Furthermore, we know that the number of new items of the latest technology in one state equals the number of returns in the next state. This leads to the following definition of the transition probabilities of the MDP:

$$p\left(\left(q_1^{ret}, i\right), \left(q_2^{ret}, j\right), a\right) = \begin{cases} \alpha & \text{if } a = q_2^{ret} \text{ and } j = 1 \\ 1-\alpha & \text{if } a = q_2^{ret} \text{ and } j = 0 \\ 0 & \text{otherwise} \end{cases} .$$

If the firm takes an action in which q_2^{ret} items of the latest technology are produced, then in the next state exactly q_2^{ret} items will be returned from consumers. Furthermore, there is a probability α that there is a radical innovation in the next state and a probability $1-\alpha$ that there is not.

Notice that the transition probabilities are independent of the current state, (q_1^{ret}, i). Of course, the optimal action will depend on the current state.

Immediate Rewards: In our MDP, the immediate reward $r\left(\left(q^{ret}, i\right), a\right)$ is the optimal profit that is associated with taking action a in state (q^{ret}, i) in a given period. This involves determining the remaining quantity decisions. These optimal decisions can be determined analytically, as we now show.

In states without a radical innovation: Given the action $a = q_n^{inc}$ in state $(q^{ret}, 0)$, the firm determines q_r^{inc} to maximize the profit in the period:

$$r\left(\left(q^{ret}, 0\right), q_n^{inc}\right) = \max_{0 \le q_r^{inc} \le q^{ret}} \left\{ q_n^{inc}\left(p_n^{inc} - C_n^{inc}\right) + q_r^{inc}\left(p_r^{inc} - C_r^{inc}\right) \right\}$$

The profit $r\left(\left(q^{ret}, 0\right), q_n^{inc}\right)$ is concave and the optimal choice of q_r^{inc} can be described by the following proposition.

PROPOSITION 1. In states without a radical innovation, the optimal quantity of remanufactured products with the incumbent technology q_r^{inc} is given as:

(i) $q_r^{inc*} = q^{ret}$ for low β_u $[\beta_u < \underline{\beta}]$

(ii) $q_r^{inc*} = \frac{1}{2} - q_n^{inc} - \dfrac{\beta_u (c_o + d\tau)}{2(1-\beta)\delta}$ for intermediate β_u $[\underline{\beta} < \beta_u < \overline{\beta}]$

(iii) $q_r^{inc*} = 0$ for high β_u $[\beta_u > \overline{\beta}]$

where $\overline{\beta} = \frac{(\beta-1)\delta(1-2q_n^{inc})}{c_o+d\tau}$; $\underline{\beta} = \frac{(\beta-1)\delta(1-2q_n^{inc}-2q^{ret})}{c_o+d\tau}$.

□

Note that Proposition 1 confirms intuition in that, as the fraction of the product that is *not* made reusable (β_u) increases (that is, reusability decreases), the quantity of the incumbent technology that is actually reused (q_r^{inc}) decreases as well.

In states with a radical innovation: Given the action $a = q_n^{rad}$ in state $(q^{ret}, 1)$, the firm determines q_n^{inc} and q_r^{inc} to maximize its profit in the period:

$$r\left((q^{ret},1), q_n^{rad}\right) = \max_{q_n^{inc}\geq 0,\, 0\leq q_r^{inc}\leq q^{ret}} \left\{ q_n^{rad}\left(p_n^{rad} - C_n^{rad}\right) + q_n^{inc}\left(p_n^{inc} - C_n^{inc}\right) + q_r^{inc}\left(p_r^{inc} - C_r^{inc}\right)\right\}.$$

This is constrained optimization of a concave, quadratic function with two variables under a linear constraint. The solution is formalized in the next proposition.

PROPOSITION 2. In states with a radical innovation, the six potential (q_n^{inc}, q_r^{inc}) solutions to the problem, along with the ranges in which they are defined, are given as below (refer to the proof for detailed expressions).

Sol.#	Valid Range	Name		Sol. #	Valid Range	Name
①	$q_n^{inc} > 0, 0 < q_r^{inc} < q^{ret}$	NEW, REM		④	$q_n^{inc} = 0, 0 < q_r^{inc} < q^{ret}$	NO NEW, REM
②	$q_n^{inc} > 0, q_r^{inc} = q^{ret}$	NEW, LIM REM		⑤	$q_n^{inc} = 0, q_r^{inc} = q^{ret}$	NO NEW, LIM REM
③	$q_n^{inc} > 0, q_r^{inc} = 0$	NEW, NO REM		⑥	$q_n^{inc} = 0, q_r^{inc} = 0$	NO NEW, NO REM

□

The optimal quantity of new products q_n^{inc*} and remanufactured products with the incumbent technology q_r^{inc*} depend on the action (quantity of radically new products q_n^{rad}), the state (quantity of returned products q^{ret}) and the reusability level β_u. The ordering of these solutions is presented in Figure 2 below (refer to the proof for exact specifications of the ranges).

Rad. New Prod. (q^{rad}) - **High**		NO NEW LIM REM 5	NO NEW REM 4	NO NEW NO REM 6	NEW NO REM 3
Rad. New Prod (q^{rad}) - **Low**	Returned Prod (q^{ret}) - **Low**	NO NEW LIM REM 5	NEW LIM REM 2	NEW REM 1	NEW NO REM 3
	Returned Prod. (q^{ret}) -**High**	NO NEW LIM REM 5	NO NEW REM 4	NEW REM 1	NEW NO REM 3

$\rightarrow \beta_u$

Figure 2 **Solution Space in States with a Radical Innovation**

As in the previous case, we see from Figure 2 that as reusability decreases, the quantity of the incumbent technology that is actually reused (q_r^{inc}) generally decreases, albeit in a more complicated fashion.

3.1. Solving the MDP

For a given β_u and other demand and cost parameters $(\alpha, \beta, \gamma, \delta, c_o, c_n, K, d\tau)$, the above described average-reward MDP can be solved after discretizing the state variable q^{ret} and actions q_n^{rad} (in states with a radical innovation) and q_n^{inc} (in states without a radical innovation). We solve MDP as a linear program using CPLEX 12.4. For details regarding how to solve MDPs as linear programs, we refer the reader to Tijms (2003, p. 252) or Kallenberg (2009, p. 148–156). From this solution we obtain an optimal policy, which specifies, for each state, those actions that maximize the firm's average profit. That is, given the number of returns in a state and given whether there is a radical innovation or not, we know the quantity of new items of the latest technology the firm should produce to maximize its average profit. Together with the solution obtained from the immediate reward functions, we then have the firm's optimal quantities (and prices) for all product variants under all circumstances.

The solution of the MDP also yields the steady-state probabilities of being in each of the states. Averaging over these steady state probabilities, we compute the key performance measures:

- *Profit;*
- *Rate of reuse* (for a given state it calculated as $\frac{(1-\beta_u)\, q_r^{inc}}{q_n^{rad}+q_n^{inc}}$);
- *Virgin material usage* (for a given state it is calculated as $q_n^{rad}+q_n^{inc}+\beta_u q_r^{inc}$).

3.2. Optimization of the reusability rate $(1-\beta_u)$

In order to determine the strategic design decision regarding how much of the products to make reusable we solve the above average-reward iteratively. We adopt Golden section search approach to find the optimal value of β_u.

4. Numerical Study and Results

The MDP defined in the previous section captures the key elements of reusability and reuse decisions in the presence of innovations, but this approach does not lend itself to an analytical solution. Instead, numerical studies are typically used to garner insights from an MDP (see, for example, Ferrer and Ketzenberg (2004)). In this section, we carry out an extensive numerical study that covers the entire feasible parameter space for our problem. We compute the performance metrics and investigate the effects of key market and operating factors accordingly.

In order to cover a broad range of the feasible parameter space, the following values were used in the computational experiments: $\alpha \in \{0, 0.1, 0.2, \ldots, 0.9\}$; β, γ and $\delta \in \{0, 0.2, 0.4, 0.6, 0.8, 1\}$; $c_n \in \{0.1, 0.3, 0.5, 0.7, 0.9\}$; K and $d\tau \in \{0, 0.04, 0.08, 0.12, 0.16, 0.2\}$. For simplicity, the value of c_o was fixed at 0.1 since costs impact the solution through the relative cost differential [between c_o and c_n], which was varied by adjusting c_n as described above. The model was solved for each combination of these parameter values, leading to over 425 thousand computational experiments $(11 \cdot 5 \cdot 6^5 = 427680)$.

In what follows, we first validate the model looking at a special case and relating the results to those in the literature. We then report some general insights that can be gleaned from the fully specified model, examining the overall average results from the full experimental design. After that, we investigate some exceptions to these general insights by demonstrating several specific cases from which interesting additional insights can be gleaned.

4.1. Baseline: simplified model

Consider a special case with no radical innovations $\alpha = 0$ but only incremental innovations at rate β. Furthermore, suppose that the firm does not determine the optimal reusability level, and designs only the part of the product that will not be subject to incremental innovations as reusable, i.e. $\beta_u = \beta$. This is the main scenario considered in the steady-state model of Galbreth et al. (2013), and analyzing helps validate our MDP. Figure 3 illustrates the optimal reuse strategy of the firm for an exemplary case (full reuse means $q_r^{inc} = q_n^{inc}$, partial reuse means $q_r^{inc} < q_n^{inc}$ and no reuse means $q_r^{inc} = 0$ in optimality).

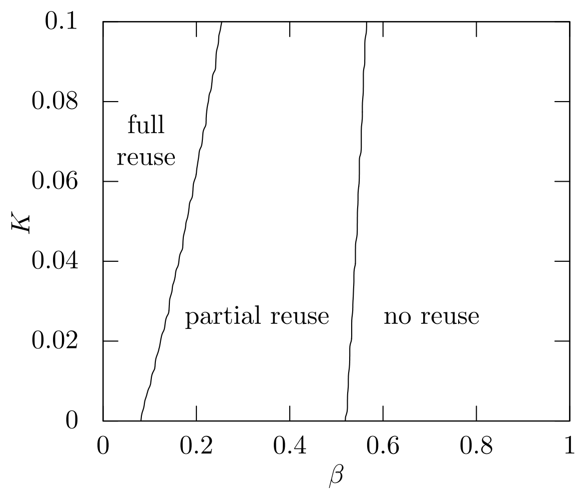


Figure 3 **Reuse with** $\beta_u = \beta$**. Parameters:** $\alpha = 0, \delta = 0.7, c_o = 0.1, c_n = 0.3, d\tau = 0.08$

As can be seen from Figure 3 the key conclusions in Galbreth et al. (2013) persist in our baseline model (Figure 3 is identical to Figure 1(b) in that paper). Specifically, higher rates of incremental innovations decrease the amount of reuse conducted by the firm. More interestingly, increasing the cost K of making products reusable may *encourage* reuse.

The baseline model serves a second purpose of illustrating the interactions between reusability in design and reuse operations. When design is fixed like above, as the cost to make products reusable increases, it becomes more costly to produce new products (that contain incremental innovations), so the firm might prefer to satisfy more demand with reused products. However, as conjectured in Galbreth et al. (2013), there is a potential counter effect that can limit reuse. As the cost to produce a product increases due to reusability cost, the firm might choose to reduce the part that is made reusable, and effectively limit the extent of reuse that can be achieved subsequently. Using our baseline model, we can formalize this conjecture by optimizing the reusability level $(1-\beta_u)$. The resulting rates of reuse are depicted in Figure 4 for the same example. Indeed, as seen in Figure 4, increasing K can still lead to more reuse by shifting the firm from partial to full reuse, but this is restricted to intermediate levels of β and lower levels of K.

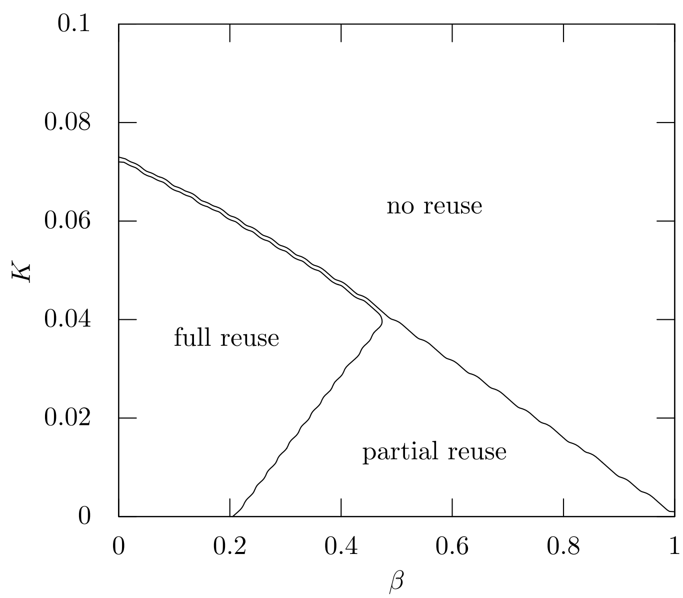


Figure 4 **Reuse with optimal β_u. Parameters:** $\alpha = 0, \delta = 0.7, c_o = 0.1, c_n = 0.3, d\tau = 0.08$

4.2. General Results of the Numerical Analysis

In this section we present the summary results from our fully specified model. Since our primary construct of interest is the effect of radical innovations, we first report in Table 2 *averages* of the firm's optimal decisions and resulting performance metrics across all experiments in which α had the particular value shown the first column. The second column of the table gives the average optimal rate of reuse, the third column gives the average optimal percentage of the product that the firm decides to make reusable, the fourth column gives the average optimal profit, the fifth column gives the average virgin material usage, and the subsequent columns give all average production quantities. Note that the average quantity of new products of the incumbent technology is different based on whether a radical innovation has occurred or not. Recall that, if a radical innovation occurs, then these incumbent products can no longer be reused in a future period.

α	rate of reuse (%)	$(1-\beta_u^*)$ (%)	profit	material usage	q_r^{inc}	q_n^{rad}	q_n^{inc} (no rad. inn.)	q_n^{inc} (rad. inn.)
0.0	19	21	0.107	0.29	0.046	0	0.28	0
0.1	19	21	0.103	0.28	0.044	0.017	0.25	0.006
0.2	18	20	0.100	0.28	0.041	0.033	0.23	0.013
0.3	17	20	0.097	0.27	0.038	0.050	0.20	0.020
0.4	16	19	0.093	0.27	0.036	0.066	0.17	0.027
0.5	15	19	0.090	0.26	0.033	0.083	0.14	0.034
0.6	14	18	0.087	0.26	0.030	0.099	0.12	0.041
0.7	14	18	0.083	0.25	0.027	0.12	0.087	0.048
0.8	13	18	0.080	0.25	0.024	0.13	0.058	0.056
0.9	13	18	0.077	0.24	0.022	0.15	0.029	0.063

Table 2 Average effects of radical innovations

There are three main insights that can be taken from Table 2. First, both the rate of reuse and the reusability of the product decrease as the probability of a radical innovation α increases. This is intuitive since when a radical innovation occurs, the consumer valuation of reused products, which do not contain this innovation, decreases. What is interesting, however, is that the effect of α on the average optimal reusability $(1-\beta_u^*)$ in the third column is much weaker than α's effect on the actual rate of reuse in the second column. As α increases from 0 to 0.9, the optimal reusability level $(1-\beta_u^*)$ is only decreases from 21% to 18% whereas the rate of reuse decreases from 19% to 13%. To understand this, consider that in periods with a radical innovation, it is still optimal to produce a significant number of new items of the incumbent technology. Regardless of how much reusable content they actually contain, these items are essentially disposable – they can never be reused since they are based on an old technology for which demand will disappear in the period following the radical innovation. This causes the rate of reuse to drop. However, as α increases, in most cases the firm does not change its decision to make a certain part of the product reusable. This is because there is still a chance that a radical innovation will *not* occur in the next period. In such a period, reused items still have a relatively high consumer valuation (compared to periods with a radical innovation) and are so profitable for the firm that this justifies the investment to make the product reusable. In this sense, investing in reusability provides the firm with a '*real option*' to reuse in the future if radical innovation does not occur, and the existence of this real option makes the optimal level of reusability decrease much more slowly than the actual rate of reuse as α increases. Put differently, when products are not made reusable, there is no possibility to reuse them even if favorable conditions arise. When they are made reusable, at least to some extent, the firm can operationally decide to reuse or not after observing any technological innovations. As a result, the strategic design decisions concerning product reusability are more robust to radical innovations.

Secondly, the fourth column of Table 2 shows that the average profit decreases as the probability of a radical innovation increases. There are two main drivers of this. First, because the radical technology is more expensive to produce than the incumbent technology, more frequent radical innovations imply that the market is served more frequently with the more costly new technology. In other words, the 'learning' that takes place in terms of a drop in production cost as a product matures cannot be leveraged. High costs prompt higher prices which curb demand, too. In addition, radical innovations reduce the consumer valuations of the incumbent technology (including reused products), causing the firm to charge a lower price for these products. Both of these effects cause a decrease in the average profit as the probability of radical innovation increases. In other words, a faster rate of radical innovations hurts firm profits on average due to an inability to leverage production cost decreases and a more likely deterioration in the consumer valuations of incumbent products.

The final insight shown in Table 2 concerns the effect of radical innovation on virgin material usage (column 5). Intuitively, since we have found that a higher α leads to less reuse (column 2), we would expect that virgin material usage would increase in α. However, we find exactly the opposite – as the probability of radical innovation α increases, virgin material usage goes down. This means it is possible that more radical innovation can have a *positive* environmental impact in terms of virgin materials. The effect that is opposing, and in fact completely offsetting, the reduction in reuse is the market size impact of radical innovation. As described above, radical innovations cause the firm to produce new products with the more expensive radical technology and makes the incumbent technology less attractive to consumers. This reduced profitability drives the firm to decide to reduce total production (and thus material usage). Specifically, an increase in radical innovation has a *shrinking* effect on the buying market, with the firm increasingly focused on a relatively small segment of high-end consumers who will pay for the radical product, and at the same time the firm finds it more difficult to generate profits on incumbent products that are very likely to experience a steep drop in valuation due to a radical innovation. Overall, the net effect of an increase in α on virgin material usage is negative. This finding runs counter to the conventional wisdom that more frequent technological breakthroughs (higher α) hurt the environment through more virgin material usage.

We remark that the observed reduction in virgin material usage depends on the single-firm assumption. In such a market, as the firm increasingly focuses on the high end of the market and at the same time reduces reuse, the customers customers in the middle of the market will no longer make any purchase. This may or may not hold in a multi-firm, competitive market. On one hand, if the middle market is served by competitors offering inferior products when the focal firm abandons it, then virgin material use can increase. This is because the negative impact of less reuse would remain, but the market shrinking effect might diminish/reduce. On the other hand, competition from the lower-end manufacturer might actually entice the focal firm to increase reuse, since those remanufactured products would enter direct competition with the low-end producer in the middle market (leaving the high-end market continue to be served by the radically new products). The increase in reuse might curb virgin material usage.

There are other general observations that we can derive from our full-scope numerical study. Table 3 summarizes the effects in our model of the key cost parameters (K, $d\tau$, and c_o) that have been found to have impact in an incremental innovations environment in prior research (Galbreth et al., 2013).

	K	$d\tau$	c_n
Rate of Reuse	$\downarrow$	$\uparrow$	$\uparrow$
Reusability Level $(1-\beta_u^*)$	$\downarrow$	$\uparrow$	$\uparrow$

Table 3 Average effects of key cost parameters

The effects are generally intuitive. As reusability cost K increases, on average the firm makes the product less reusable and engages less in reuse. Nevertheless, the counter-intuitive results from the baseline model persist in the presence of radical innovations. That is, for some intermediate values of α and β, it is possible that reuse increases first as K increases, but then it decreases as the firm reduces the parts that are made reusable. A noteworthy observation holds for the end-of-life costs. We find that increasing $d\tau$ always leads to higher optimal reuse rate, confirming that end-of-life cost is an effective lever for policy makers in the presence of not only incremental innovations, but also radical innovations. Furthermore, we find that as $d\tau$ increases optimal reusability level also increases. This double-positive effect substantiates the effectiveness of end-of-life costs as a policy level. For products that face radical technological advances, making end-of-life processing more costly to producers (through take-back legislation, disposal costs etc) should lead to more reusable designs and reuse activities. We observe that the same effect can be achieved by policy makers by making the cost of improved, new components (c_n) higher, but this would be harder to implement in practice.

The discussion in this section was based on overall average results from our wide-ranging numerical study. While these averages are interesting for general insights, there are of course interesting exceptions. We now turn our attention to some of these specific settings.

4.3. Insights from Context-Specific Analyses

We have seen that, *on average*, an increase in the probability of a radical innovation (α) will reduce the rate of reuse. This is intuitively clear as more innovations, radical or incremental, will reduce the (expected) value of reused products, which do not contain these innovations. However, this observation begs the question as to whether this is a universal result, and if there are exceptions, what factors define such scenarios. Through detailed analysis of specific cases, we find that an increase in α can lead to an *increase* in the rate of reuse, if there is a combination of the following two factors:

1. Reused products are not very attractive in the absence of radical innovations to either consumers (i.e. the consumer valuation of reused products (δ) is low and/or the rate of incremental innovation (β) is high) or to the firm (end-of-life costs ($d\tau$) are low, making 'disposable' products cheaper and thus more attractive).

2. The cost of the radical technology is high but its increase in consumer valuation is relatively low (i.e. the radical technology is not particularly appealing in a cost/benefit sense – high c_n, high γ).

The case described above can be clearly seen in Figure 5. Figure 5(a) gives the average rates of reuse, material usage and reusability decisions (denoted as β_u rather than $(1-\beta_u)$ to avoid overlap with the rate of reuse line). Figure 5(b) shows average production quantities by product type, arranged in descending order of the value of the product (i.e. radical production quantity on top, then incumbent when there has not been a radical innovation, etc.). The size of each bar in that figure indicates the size of each market segment for a particular value of α (note that not all bars will exist in any given period, since they depend on whether or not a radical innovation has occurred).

Initially (for low α), neither radical innovations or remanufactured products are produced. As noted above, both of these products are relatively very unappealing, and thus these segments are ignored when radical innovations are infrequent – the firm produces only new, non-reusable

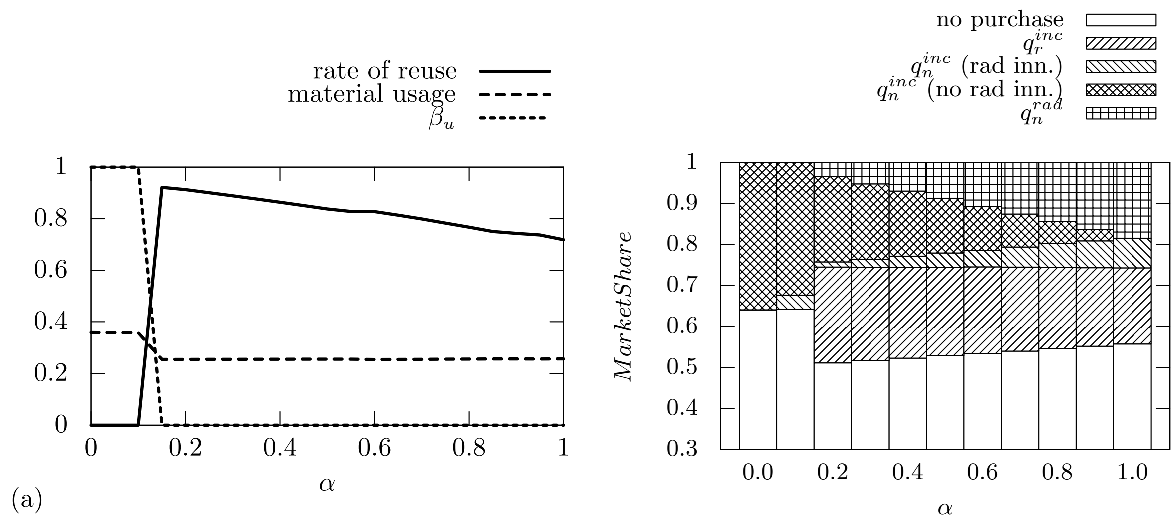
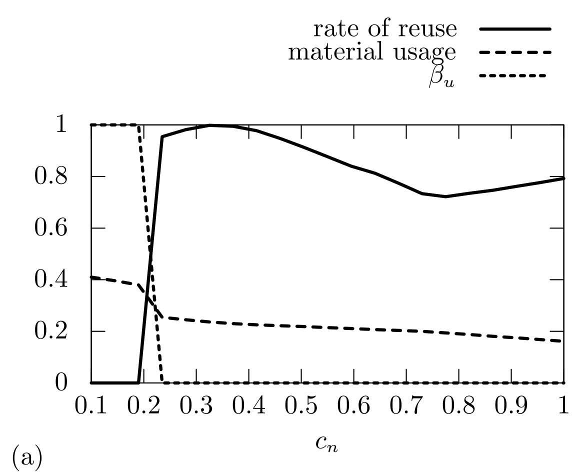


Figure 5 **The rate of reuse can increase and decrease in** α**.** **(**$\beta = 0.5, \gamma = 0.8, \delta = 0.7, c_o = 0.1, c_n = 0.3, K = 0.04, d\tau = 0.08$**)**

incumbent products. Essentially, in this case the firm is producing 'disposable' products. As α increases, periods in which a radical innovation occurs are more frequent, and it becomes optimal to produce the radical product. This is because, although the radical product is less appealing per point 2) above, there is still a high-end segment of the market that will buy it, and eventually α is sufficiently high such that the firm prefers to produce some radical items when a radical innovation occurs. This enables it to segment the market in two ways – by targeting the very high end with the radical product and, more importantly, since these radical items are certain to be reusable in the next period, to further segment the market by offering reused items at the lower end. Since consumers in the middle of the market will not buy the high-end radical product, and only some will be interested in the newly produced incumbent product, the guaranteed reuse option enabled by producing the radical product ensures that the firm can sell to a significant portion of the middle of the market, and this is the profit-maximizing strategy. Thus, an increase in reuse is observed (from zero to a positive amount, as can be seen by comparing $\alpha = 0.1$ and $\alpha = 0.2$ in Figure 5(a)). Observe that as α increases further, there are more periods with a radical innovation and in these periods, the middle market is served increasingly from new products of the incumbent technology. Since these cannot be reused, the rate of reuse gradually decreases again.

Two additional results also worth noting here. One concerns the the impact of c_n. As noted in the previous section, an increase in the cost of new, improved components c_n makes reuse more attractive. Likewise, one would expect an increase in the customer valuation γ of incumbent technology (with respect to the radically new one) to make reuse more attractive. We find that exceptions to this occur when the cost-to-consumer benefit ratio of the radical innovation is relatively high (high c_n and/or low γ). In such scenarios, when a radical innovation occurs, the firm may opt to not produce any new items with the latest technology but focus on the production of new products of the incumbent technology. These products cannot be reused in the subsequent periods as they are already based on the outdated technology. Consequently, the optimal reuse rate might decrease. We provide examples in terms of both c_n and γ in Figures 6 and 7.

First, consider Figure 6, which shows that when c_n is very low, then it makes sense for the firm to serve the market with new products only (hence no need to make them reusable). As c_n increases, a positive amount of reuse becomes optimal (radical products are becoming less appealing to the firm because of their high costs). However, as c_n continues to increase, reuse actually *decreases*, because the firm starts to phase out the production of radical products, instead producing more new incumbent products in periods with a radical innovation.



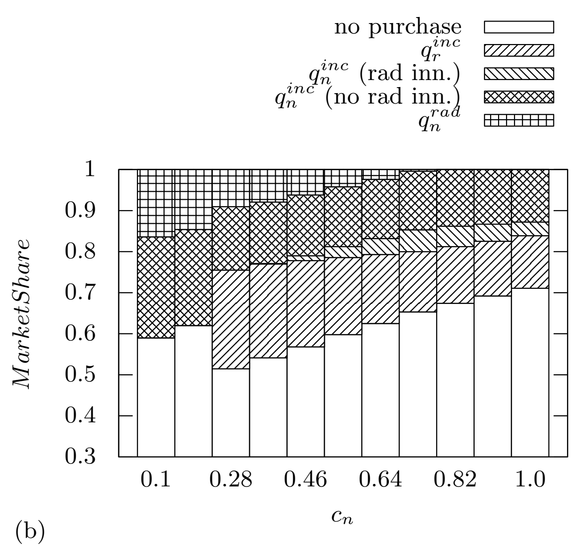


Figure 6 $\alpha = 0.4, \beta = 0.4, \gamma = 0.8, \delta = 0.7, c_o = 0.1, K = 0.04, d\tau = 0.08$

A similar effect can be seen as γ increases in Figure 7. At first, when γ is low, the firm does not make its product reusable, because the consumer valuation of the incumbent technology when there is a radical innovation is very low, so reuse is relatively unattractive. However, when γ increases, the firm eventually decides to make its products reusable, serving the higher end of the market with new products of the latest technology and the lower end with reused products. However, if γ increases even further, reuse again *decreases* since radical products enjoy less of an advantage with consumers, and the firm therefore concentrates on making items of the cheaper, incumbent technology instead, which cannot be reused.

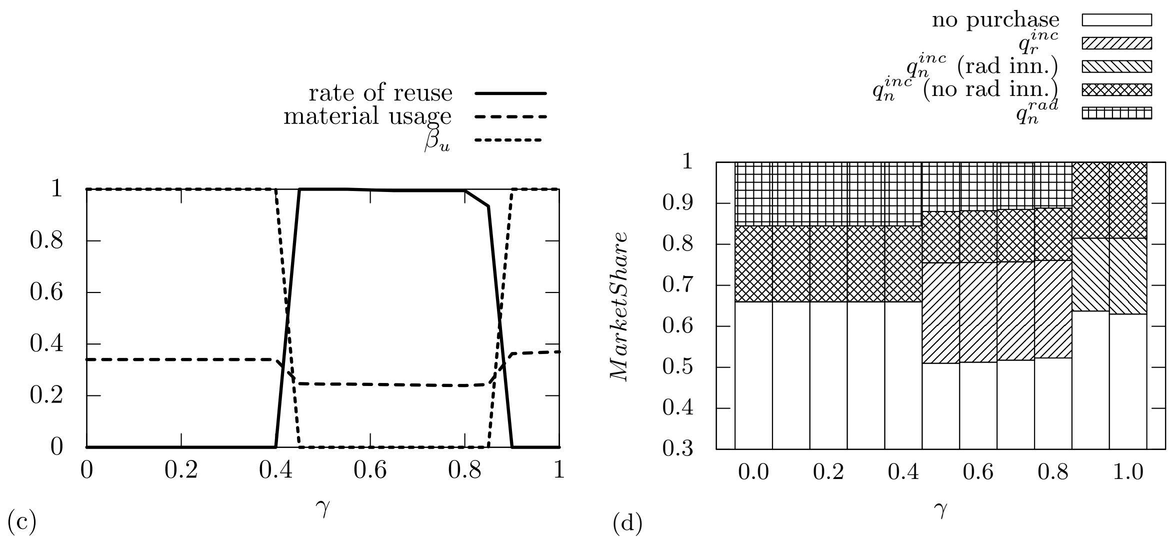


Figure 7 $\alpha = 0.5, \beta = 0.4, \delta = 0.7, c_o = 0.1, c_n = 0.3, K = 0.04, d\tau = 0.08$

These exceptions have important policy implications. In particular it cautions policy makers on the use of the levers c_n (e.g. taxing new generation products) and γ (i.e., consumer education campaigns), as there might be unintended consequences. This is perhaps more relevant for consumer valuations γ of older technologies. While conventional wisdom states improving the consumer's valuation of older technologies should make reuse more appealing, at very high levels of appreciation the effects could be the opposite. The firm actually increases the production of products of the older technology, but knowing that radical technology will soon takeover regardless, there is less incentive for reusable designs. A moderate discounting of older technologies is necessary since this enables the firm to segment the market and position different versions of the new and old technologies effectively.

5. Robustness

In this section we discuss several robustness checks that were conducted to test and extend the generality of our results. We have altered several assumptions of our framework and analyzed the resulting MDP numerically. In the interest of space, we provide here a brief account of the changes and the results. Full details are available upon request.

First, our main analysis assumes that a radical new product is produced at the cost rate c_n, after which the cost rate drops back to c_o one period later (at which point the radical technology is no longer expensive but is now the "old" technology). We investigated the extent to which this setup was driving our findings. Note that there are two implications of this assumption. First, it assumes that all radically new technologies are introduced at the same (high) cost. We addressed this by making c_n to take random values from a fixed set, allowing it go up and down each time a new radical technology is introduced. In effect, radical innovations are allowed to be cost-increasing, cost-neutral or cost-reducing. The second implication is that 'learning' takes effect rapidly and within one period and the cost rate drops to c_o. We addressed this by allowing this "floor" cost to vary with c_n stochastically (so that it is still lower than c_n) and by modelling the time it takes for the cost rate to fall to this level to be a parameter $\theta > 1$. With this generalized cost structure, the state space of the MDP grows significantly as it becomes necessary to track the costs associated with each technology introduced. In terms of insights, the results do not change qualitatively from our main model. The main impact of this stochastic cost structure is that the rate of reuse tends to be generally slightly lower than in our main model. This is driven by the uncertainty in costs, which might produce a case in which future production costs will be so low that reuse of old items is less appealing to the firm. In terms of a slower cost learning ($\theta > 1$), we find that this increases reuse relative to our main model. This is intuitive since a slower drop in costs makes producing new items less attractive, and thus the firm prefers to engage in more reuse.

In addition, we investigated the case in which the overlap between a radical innovation and the incumbent technology is more than one period. In our base model, the incumbent disappears from the market after one period, but in an extension we tested a model in which the overlap was $\zeta > 1$ periods. This might be more realistic in cases where the consumer learning regarding the radical innovation is relatively slow. Note that, since a radical innovation is possible in every time period, with this setup there might a case where a second (or more) radical innovation occurs while the incumbent is still for sale. In formulating the enhanced MDP, we assume in such cases that a second radical innovation within the ζ periods renders the original incumbent obsolete (and the first radical innovation within the ζ periods becomes the incumbent). Again, this results in an MDP that is significantly harder to solve due to increased state space. Nevertheless, we find that all of the main insights of our base model persist under this setup. The effect of a longer overlap between technologies is as expected: as older technologies can be sold for longer periods alongside the latest technology, reuse increases.

6. Conclusion

In this paper we have considered the effect of sustaining innovations – both a constant, known rate of incremental innovations as well as a stochastic rate of radical innovations – on optimal firm actions including design for reusability and product reuse. Since the effects of incremental innovations on the optimal reuse strategy of the firm have been explored in Galbreth et al. (2013), we focused our analysis on gaining insights regarding radical innovations and the firm's optimal design decisions. To our knowledge, our is the first study to provide insights into a firm's optimal design and reuse decisions in the face of radical innovations. Radical innovations render the incumbent technology obsolete after a limited period of overlap, and hence have a direct impact on how reusable the firm will make its products as well as how much it will actually reuse (remanufacture) previously sold items. Utilizing a Markov Decision Process model, we capture the salient characteristics of a rapidly evolving, innovative market environment for a firm engaged in both manufacturing and remanufacturing. We find that the firm's optimal reusability and reuse strategies are not always straightforward or intuitive. In fact, they are driven by how the firm chooses to segment the market, which itself is governed by the reusability, production, and end-of-life costs the firm has to bear as well as consumers' relative valuations of products of the latest and incumbent (old) technologies.

For managers, we provide three new insights regarding how innovation affects optimal reuse. We confirm the conventional wisdom that, on average across a range of business contexts, an increase in the probability of a radical innovation decreases both actual reuse and the optimal reusability of products. However, we add the new insight that optimal reusability decreases much more slowly than actual reuse. This is because reusability provides a real option for future reuse; by making the product reusable, the firm is able to decide later on whether to actually reuse returned products, depending on business conditions. For this reason, the reusability built in the design of the products is more robust to risks of radical innovations. Secondly, we find that a higher likelihood of radical innovations decreases average profits across all scenarios, since the firm has less opportunity to take advantage of learning effects in terms of lower production costs. Instead, it is more likely to be producing the relatively more expensive, radical products in each period. This curbs the overall size of the market served by the firm. An immediate consequence of this is the decrease in virgin material usage observed when radical innovation is more likely. Hence in a market that is served mainly by a dominant firm, radical innovation reduces reuse, but also shrinks the overall buying market, since high-end products that only appeal to high-end consumers are more frequently introduced. Thirdly, in addition to these general results, we also point out specific contexts in which the relationship between innovation and reuse is non-intuitive. In particular, we are able to pinpoint scenarios where an increase in the likelihood of radical innovations can actually prompt more reusable designs as well as more reuse activity.

For policy makers, we offer valuable insights as well. Galbreth et al. (2013) have previously shown that increasing end-of-life costs and, less intuitively, increasing reusability costs can increases reuse. We show that the latter strategy remains valid in the presence of radical innovations. However, by including the reusability in design as a decision for the firm, we go a step further and formalize that increasing reusability cost has a counter effect on the reusability level of the product, which itself limits how much reuse the firm can conduct. Hence, increasing reusability costs, for example by taxing reusable material, is effective only for intermediate reusability costs and intermediate rates of innovation. For end-of-life costs, we show that it remains as an effective strategy when there is the possibility of radical innovations. Furthermore, we establish that higher end-of-life costs also lead to more reusable designs. Therefore, increasing end-of-life costs, for example through take-back legislation or disposal bans, is a safe and effective policy lever. We also find that increasing the production costs of new generation products (e.g., via taxes) and increasing the consumers' valuations for older technologies (e.g., via consumer education campaigns) can also improve reusability and reuse. However, as policy levers these are not as safe as increasing end-of-life costs, since our results identify scenarios where they can fail to achieve the intended consequences.

One overarching insight of our study is that the firm invests more in reusability and engages in more reuse when it finds it profitable to segment the market and target the middle and low-end sections of the market with reused products. This is not purely driven by relative costs associated with producing with the radically new and incumbent technologies. It is also important that customers discount older technologies, but not very excessively. Likewise, some risk of radical innovations could be favourable as well. In light of these, it is important to distinguish how this middle market is served when the firm does not target it with reused products. In our single-firm market, this market ends up not being served. In reality, this may not be the case; there might be other firms targeting this segment with new or reused goods. Likewise, there could be competing firms in the primary markets. Including competition into our framework is not straightforward, and is left as a potential avenue of future research, with our single-firm model providing clean insights that can be further explored under competition. In addition, a complete picture of how innovation impacts reuse calls for consideration of disruptive innovations. This is a topic we are currently pursuing as well.

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Appendix

A. Glossary

Table 4 Notation

β	The fraction of a product that will require incremental improvement in each period
α	The probability of a radical innovation in each period
V	Consumer valuation of the best new product, V $U(0,1)$
δ	Valuation discount factor for used items
λ	Valuation discount factor for incumbent technology when a radical innovation has taken place
c_n	Unit cost of producing a product with 100% incrementally improved components
c_o	Unit cost of producing a product with 100% non-improved components
K	Additional unit to make a product entirely reusable
$d\tau$	End of life cost per item
q^{ret}	The number of products that are returned by consumers in a given period
β_u	The fraction of a product that will be made reusable (an initial firm decision)
q_n^{inc}, p_n^{inc}	The production quantity and price of new products of the incumbent technology (a firm decision in each period)
q_n^{rad}, p_n^{rad}	The production quantity and price of new products of the radically innovative technology (a firm decision in each period)
q_r^{inc}, p_r^{inc}	The quantity and price of used products of the incumbent technology that are reused (a firm decision in each period)

B. Proofs

Proof of Proposition 1:

The firm seeks to maximize the profit from taking action $a = q_n^{inc}$ in state $(q^{ret}, 0)$. Since q_n^{inc} is given by the action, only q_r^{inc} needs to be determined. Mathematically, $r\left(\left(q^{ret},0\right), q_n^{inc}\right) =$

$$
\begin{aligned}
&\max_{0\le q_r^{inc}\le q^{ret}} \left\{ q_n^{inc}\left(p_n^{inc} - C_n^{inc}\right) + q_r^{inc}\left(p_r^{inc} - C_r^{inc}\right)\right\} \\
=&\max_{0\le q_r^{inc}\le q^{ret}} \left\{ q_n^{inc}\left(1 - q_n^{inc} - (1-\beta)\,\delta q_r^{inc} - c_o - \beta\left(c_n - c_o\right) - K\left(1-\beta_u\right) - d\tau\right)\right. \\
&\qquad \left. + q_r^{inc}\left((1-\beta)\,\delta\left(1 - q_n^{inc} - q_r^{inc}\right) - \beta_u\left(c_o + d\tau\right)\right)\right\} \\
=&\max_{0\le q_r^{inc}\le q^{ret}} \left\{ -(1-\beta)\,\delta q_r^{inc2} + \left((1-\beta)\,\delta\left(1 - 2q_n^{inc}\right) - \beta_u\left(c_o + d\tau\right)\right) q_r^{inc}\right. \\
&\qquad \left. + \left(1 - q_n^{inc} - c_o - \beta\left(c_n - c_o\right) - K\left(1-\beta_u\right) - d\tau\right) q_n^{inc}\right\}
\end{aligned}
$$

which is a concave quadratic function of q_r^{inc}, resulting in a simple maximization of a quadratic function on an interval. It can be easily shown that the derivative of this profit function is negative at $q_r^{inc}=0$, and thus $q_r^{inc*}=0$, when $\beta_u>\overline{\beta}=\frac{(\beta-1)\delta(1-2q_n^{inc})}{c_o+d\tau}$. Similarly, the derivative of the profit function is positive at $q_r^{inc}=q^{ret}$, and thus $q_r^{inc*}=qret$, when $\beta_u<\underline{\beta}=\frac{(\beta-1)\delta(1-2q_n^{inc}-2q^{ret})}{c_o+d\tau}$. Otherwise (i.e. for intermediate levels of β_u), the function is maximized within the interval $[0,q^{ret}]$, and it can be easily show that the single inflection point is given by $\frac{1}{2}-q_n^{inc}-\dfrac{\beta_u\left(c_o+d\tau\right)}{2\left(1-\beta\right)\delta}$

Proof of Proposition 2:

Given the action $a=q_n^{rad}$ in state $(q^{ret},1)$, the decisions q_n^{inc} and q_r^{inc} are found by optimizing the immediate reward $\max_{0\leq q_r^{inc}\leq q^{ret}}\left\{q_n^{inc}\left(p_n^{inc}-C_n^{inc}\right)-q_r^{inc}\left(p_r^{inc}-C_r^{inc}\right)\right\}$ which in its explicit form can be expressed as:

$$\max_{0\leq q_r^{inc}\leq q^{ret}}\Big\{-\gamma q_n^{inc2}-\left(1-\beta\right)\gamma\delta q_r^{inc2}-2\left(1-\beta\right)\gamma\delta q_n^{inc}q_r^{inc}+\left(\gamma\left(1-2q_n^{rad}\right)-c_o-\beta\left(c_n-c_o\right)-K\left(1-\beta_u\right)-d\tau\right)q_n^{inc}$$
$$+\left(\left(1-\beta\right)\gamma\delta\left(1-2q_n^{rad}\right)-\beta_u\left(c_o+d\tau\right)\right)q_r^{inc}+\left(1-q_n^{rad}-c_n-K\left(1-\beta_u\right)-d\tau\right)q_n^{rad}\Big\}$$

This is a constrained maximization of a quadratic concave function in two variables, which can produce six potential solutions. These are:

- $0<q_r^{inc}<q^{ret},q_n^{inc}>0$: Unconstrained solution ①. By solving the first order conditions

$$\begin{aligned}
\frac{\partial r}{\partial q_n^{inc}} &= -2\gamma q_n^{inc}-2\left(1-\beta\right)\gamma\delta q_r^{inc}+\gamma\left(1-2q_n^{rad}\right)-c_o-\beta\left(c_n-c_o\right)-K\left(1-\beta_u\right)-d\tau=0\\
\frac{\partial r}{\partial q_r^{inc}} &= -2\left(1-\beta\right)\gamma\delta q_n^{inc}-2\left(1-\beta\right)\gamma\delta q_r^{inc}+\left(1-\beta\right)\gamma\delta\left(1-2q_n^{rad}\right)-\beta_u\left(c_o+d\tau\right)=0
\end{aligned}$$

we get

$$\begin{aligned}
q_n^{inc} &= \frac{\gamma\left(1-\delta\left(1-\beta\right)\right)\left(1-2q_n^{rad}\right)-\beta\left(c_n-c_o\right)-\left(1-\beta_u\right)\left(c_o+K+d\tau\right)}{2\gamma\left(1-\delta\left(1-\beta\right)\right)}\\
q_r^{inc} &= \frac{\left(1-\beta\right)^2\delta c_o+\beta\left(1-\beta\right)\delta c_n+\left(1-\beta\right)\delta\left(K\left(1-\beta_u\right)+d\tau\right)-\beta_u\left(c_o+d\tau\right)}{2\left(1-\beta\right)\gamma\delta\left(1-\delta\left(1-\beta\right)\right)}.
\end{aligned}$$

- $q_r^{inc}=q^{ret},q_n^{inc}>0$: Fixing $q_r^{inc}=q^{ret}$, we optimize over q_n^{inc} to get solution ②:

$$q_n^{inc}=\frac{1}{2}-q_n^{rad}-\left(1-\beta\right)\delta q^{ret}-\frac{c_o+\beta\left(c_n-c_o\right)+K\left(1-\beta_u\right)+d\tau}{2\gamma}.$$

- $q_r^{inc}=0,q_n^{inc}>0$: Fixing $q_r^{inc}=0$, we optimize over q_n^{inc} to get solution ③:

$$q_n^{inc}=\frac{1}{2}-q_n^{rad}-\frac{c_o+\beta\left(c_n-c_o\right)+K\left(1-\beta_u\right)+d\tau}{2\gamma}.$$

- $0 < q_r^{inc} < q^{ret}, q_n^{inc} = 0$: Fixing $q_n^{inc} = 0$, we optimize over q_r^{inc} to get solution ④: It follows that the optimal value for q_r^{inc} is:

$$q_r^{inc} = \frac{1}{2} - q_n^{rad} - \frac{\beta_u (c_o + d\tau)}{2(1-\beta)\gamma\delta}.$$

- The last two potential solutions are trivial: $q_r^{inc} = q^{ret}, q_n^{inc} = 0$ solution ⑤ and $q_r^{inc} = 0, q_n^{inc} = 0$ solution solution ⑥.

In order to find the ranges for which each solution is valid, we look at the non-negativity and the constraint $0 \leq q_r^{inc} \leq q^{ret}$. Take the interior solution ①. q_r^{inc} and $q_n^{inc} > 0$ are both monotone in β_u, and therefore we can easily find the following thresholds:

$$q_n^{inc} \geq 0 \rightarrow \beta_u \geq \beta_u^0,$$

$$q_r^{inc} \geq 0 \rightarrow \beta_u \leq \beta_u^1,$$

$$q_r^{inc} \leq q^{ret} \rightarrow \beta_u \geq \beta_u^2,$$

where $\beta_u^2 < \beta^1$. Furthermore, β_u^0 is increasing in q_n^{rad}, hence there exists another threshold $\hat{q}_n^{rad}$ such that for $q_n^{rad} > \hat{q}_n^{rad}$, the ordering of the thresholds are such that $\beta_u^2 < \beta_u^1 < \beta_u^0$. Mapping the solutions based on this ordering, we get the first row of the Table in Proposition 2.

In contrast, if $q_n^{rad} \leq \hat{q}_n^{rad}$, then $\beta_u^0 \leq \beta_u^1$. Then the ordering of the thresholds depend on β_u^2 which itself decreases in q^{ret}. Then, we can find another threshold $\hat{q}^{ret}$ such that if $q^{ret} < \hat{q}^{ret}$ then the thresholds are such that $\beta_u^0 < \beta_u^2 < \beta_u^1$, and otherwise they are $\beta_u^2 < \beta_u^0 < \beta_u^1$. Mapping the solutions based on these orderings, we get the second and last rows of the Table in Proposition 2 respectively.

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