

Design for the Environment: Life Cycle Approach Using a Newsvendor Model

Abstract

Introducing environmental innovations in product and process design can affect the product's cost and demand, as well as the environmental impact in different stages of its life cycle (such as manufacturing and use stages). In this paper, we advance understanding on where such design changes can be most effective economically to the firm and examine what their corresponding environmental consequences are. We consider a profit maximizing firm (newsvendor) deciding on the production quantity as well as its environmentally-focused design efforts. We focus our results along the two dimensions of demand characteristics and life cycle environmental impact levels, specifically functional versus innovative products, and higher manufacturing stage environmental impact versus higher use stage environmental impact. We also discuss the environmental impact of overproduction and how it relates to the different types of products and their salvage options. We find that although the environmental impact per unit always improves when firms use eco-efficient innovations, the total environmental impact can either increase or decrease due to increased production. We identify the conditions for such cases by looking at the environmentally-focused design efforts needed in order to compensate for the increase in production. We also show that the environmental impact of overproduction plays an important role in the overall environmental impact of the firm. We conclude by applying our model to different product categories.

Key words: newsvendor, life cycle assessment, design for the environment, overproduction, functional and innovative products

1 Introduction

Striving to increase the efficient use of resources, firms are seeking opportunities for “creating more goods and services with ever less use of resources, waste and pollution” (WBCSD 1992). While profitability remains the main goal, firms today also try to reduce the environmental impact of their operations and products due to increasing awareness of sustainability issues. To reduce their environmental impacts, firms apply product and process development concepts such as *Design for the Environment* (DfE) to incorporate changes into the design of products and their manufacturing processes (Graedel and Allenby 1995). For example, Hewlett-Packard (HP), one of the world’s largest IT companies, has been engaged in DfE efforts since 1992. Their efforts are focused around three main topics including: 1) materials innovation (reduce the quantity and environmental impact of the materials in HP products during the production stage); 2) product energy efficiency (improving the energy efficiency of their products in the use stage); and 3) Design for Recyclability (design products that are easier to upgrade/recycle). Each of the focus areas affects the environmental impact of the product in different stages of the life cycle and, according to HP, “customer demand increasingly influences environmental product design decisions” (HP 2011). This statement highlights the importance of investing in DfE efforts, since those not only affect product cost (Lenox et al. 2000), but can also increase product demand because (for example) reducing the cost that consumers incur during the use stage will likely increase consumer demand (Howarth et al. 2000).

Using *Life Cycle Assessment* (LCA) based tools (Hertwich et al. 1997), firms can evaluate the environmental impact of their processes and products, helping them to decide in which stages of the life cycle to invest effort in order to reduce the overall environmental impact. However, while LCA methodology is useful in understanding the multiple environmental

impacts of the firm's design decisions and their tradeoffs, and in some cases it even aids in understanding the associated cost differences, it does not take into account the full firm-level economic consequences such as potential changes in demand.

In this paper we develop a model that integrates both the environmental and economic implications of the firm's design decisions. We examine the case of a firm that pursues environmentally-friendly design strategies that will improve its economic bottom-line, either by decreasing the production cost through eco-efficiency gains in the manufacturing stage or by increasing demand through environmentally-focused product innovations that will be attractive to cost-conscious consumers through cost-of-use reduction or to environmentally-minded consumers through environmental performance enhancement. (We later consider the case of innovations that increase the cost of production.) A profit maximizing firm will choose the mix of design efforts that maximizes its profit (taking into account the reduction in cost and increase in demand), however, these design choices also have environmental consequences in each stage.

In general, a firm may choose to make improvements in the manufacturing and use life cycle stages that can either improve or worsen the environmental impacts of their products. However, our interest in this paper is in firm strategies that can reduce the total environmental impact, and since innovations that worsen the per-unit impact will never achieve this goal, we focus on innovations that improve the per-unit environmental impact. An investment in effort that reduces per-unit environmental impact and also decreases unit cost is termed eco-efficient and is anticipated to create competitive advantage (Porter and Van de Linde 1995). Although eco-efficiency choices seem rational and promising to be pursued even without environmental considerations, there is still evidence that firms miss eco-efficiency opportunities for reasons such as organizational and operational barriers, including lack of awareness to new technologies

or materials (Muthulingam et al. 2010). This phenomenon has been identified as the “energy efficiency gap” (Jaffe and Stavins 1994). Shedding light on the performance consequences of such design options may help to alleviate these barriers.

The overall profitability and environmental performance of a firm implementing product and process innovations depend on two main product characteristics: first, the type of demand pattern of the product, and second, the environmental impacts in the different life cycle stages. Fisher (1997) classifies products into two categories, *functional* and *innovative*, that are differentiated based on product lifecycle length, average demand, and level of demand predictability. Functional products have long product lifecycles (for example, food products such as bread and vegetables have been around for centuries), higher and more stable demand, and lower margins, which together imply smaller overproduction quantities and a low stock-out rate. Examples for such products include food items or basic consumer goods such as floor fans. On the other hand, innovative products have shorter product lifecycles, with lower demand and higher variability that usually results in higher overproduction quantities. Companies charge higher margins for them and often the stock-out rates at the end of the season are high. Examples include fashion items or fast-changing technology products such as smartphones.

Products can also be differentiated by the environmental impact during their life cycle stages. For example, some products (such as food) have higher impact from the manufacturing stage, while others (such as fashion goods) have higher impact during the use stage, mainly due to the laundry impact. Although the end-of-life (EoL) treatment stage is critical to improving environmental outcomes, LCA studies have found that the environmental impacts of the EoL stage are usually smaller than that of the manufacturing and use stages (e.g., computer monitors in Kim et al. 2001, and electronic toys in Muñoz et al. 2009). In addition, much of the earlier

sustainable operations literature has focused on the EoL stage (see Ferguson and Souza 2010). Therefore, in this paper we focus on the manufacturing and use stages.

Considering these two dimensions of product type and life cycle stage environmental impact, we formulate a newsvendor model that enables us to depict the characteristics of functional and innovative products with respect to their demand uncertainty in a way that cannot be captured in models with deterministic demand. We also model explicitly the effect of overproduction for the different products and cases considered in our model. Figure 1 illustrates the different cases and product examples.

Figure 1. Matrix of Cases with Example Product Categories.

		Product Type	
		Functional	Innovative
Environmental Impact	Higher env. impact during mfg. stage	Food	Smartphones
	Higher env. impact during use stage	Floor Fans	Fashion

Food products are typically classified as functional goods because demand is relatively stable and the products have long product lifecycles. Food products may be completely perishable, such as vegetables or bread, or have a relatively short shelf life (dairy). Generally, food products will have a higher environmental impact during manufacturing (i.e., growing and processing) than in the use stage (i.e., refrigerating or cooking). Fans are another example of a functional product, with a seasonal nature, making them well-suited for the newsvendor model. The use stage is expected to have a higher impact due to the electricity used (Meier et al 1992).

Smartphones are considered to be an innovative product because of their short product lifecycle and high margins. For example, for the newly released N9 model, Nokia reports its

manufacturing (raw materials and production) accounts for approximately 67% of the greenhouse gas emissions, while the use stage (3 year life assumed) accounts for only 17% (Nokia 2011). Due to the use of precious metals, the manufacturing stage has a high environmental impact. Finally, fashion serves as another example of an innovative product. Due to the use of washing machines for laundry, the use stage impact for clothing is typically higher than the impact of the manufacturing stage (Smith and Barker 1995).

As demand planning and overproduction play an important role in sustainability efforts of firms (Winston 2011), we also account for the environmental impacts of overproduction in our analysis. Overproduction units are manufactured but may not get used and thus may end up as unsold, leftover units. Consequently, in addition to the financial cost incurred for overproduction, the firm also incurs an environmental cost for those units in the form of excess use of raw materials and energy as well as more waste and emissions (EPA 2011). The overall environmental impact of overproduction mainly depends on the fate of these units; innovative products may have better chances of being sold in alternative markets. The environmental impact is also influenced by whether these units displace sales of other products or just increase the overall consumption, but capturing this effect is outside the scope of our paper.

We show that functional products in general will have higher effort investment in manufacturing stage innovations than in use stage ones, while the opposite holds for innovative products. The classification of products in Figure 1 allows us to compare analytically the change in environmental impact in the two stages. We find that for the quadrants with smartphones and fans, the relationship depends only on the overproduction environmental impact in each of the stages. Using a comprehensive (data based) numerical study, we demonstrate that while food products display an improved overall environmental impact, the overall impact worsens for the

other three categories. Furthermore, we show that regardless of the type of product, when the firm invests in DfE innovation, the quantity produced will be higher than the case of no innovation, and consequently the overproduction quantity is higher as well.

Overall, we offer the following contributions to the literature. First, we quantify the overall change in environmental impact over the two life cycle stages, considering the cost and demand effects, while differentiating between the units sold and the units overproduced. Second, we add to the literature on sustainable supply chains by examining the impact of demand uncertainty using a newsvendor setting with both functional and innovative products. Third, we assess the different possible environmental impacts of overproduction, a topic which very limited research previously touched upon.

The rest of the paper is organized as follows: In Section 2, we discuss the related literature. Section 3 describes the model and the optimal decisions for the firm. In Section 4, we define and examine the environmental impact resulting from the firm's decisions analytically. In Section 5 we apply our model to the four product categories described above using (data based) numerical analysis, and in Section 6, we extend our analysis in several directions including cases where the firm uses strategies that are not eco-efficient. Finally, in Section 7 we provide conclusions and avenues for future research.

2 Literature Review

Our paper builds on three streams of literature: the sustainable operations literature, the industrial ecology literature on DfE and LCA, and the literature on sustainability strategies. The first stream relates to sustainable operations which covers a wide range of research in the area of closed-loop supply chains, remanufacturing (e.g., Guide et al. 2003; Ferguson and Souza 2010),

sustainable supply chains (e.g., Linton et al. 2007; Srivastava 2007), and greener technology choices (e.g. Krass et al. 2010).

Overproduction is mainly studied in the inventory control and secondary markets literature (e.g., Lee and Whang 2002). The environmental impact of overproduction is only in the early stage of discussion in the academic literature. For example, Frey and Barrett (2007) and Schneider (2008) examine overproduction within a specific product category, namely the food industry. Most of the discussion, however, is initiated by NGOs and other organizations focused on promoting sustainable production and consumption patterns (mindfully.org web site). Topics such as just-in-time (JIT) and lean manufacturing methods touch on the subject of waste, but usually in the context of cost savings. The US Environmental Protection Agency now promotes JIT thinking to help eliminate overproduction and therefore reduce unwanted scrap, energy and materials use, waste, and emissions associated with production processes (EPA 2011).

The second stream of literature, industrial ecology and specifically DfE and LCA (Graedel and Allenby 1995), discusses concepts mainly used by industrial ecology and product design scholars (e.g., Camahan and Thurston 1998, Kurk and Eagan 2008). LCA is a well-established methodology for quantifying the environmental impacts of production and consumption systems across the life cycle stages of a product, from raw materials extraction all the way to product disposal and recycling. The method can account for multiple impact categories (e.g., energy consumption, global warming, waste, toxicity, etc.) but also granulates the analysis per life cycle stage. This systematic approach provides a tool to understand the impacts in each stage and overall and helps guide the choice to improve the performance where it is most effective environmentally (Finster et al. 2001, Guinée 2002, Gasafi et al. 2003). Based on the understanding gained from LCA, design efforts can be made in order to reduce the impact in

the relevant stage. However, the method and its concepts are just beginning to be used in the operations management field, such as in this paper.

Our work relates also to two other industrial ecology concepts; the first is decoupling, which is defined as the need to break the relationship between economic growth and environmental resource degradation (OECD 2001). It is usually referred to in two terms: absolute decoupling and relative decoupling (UNEP 2011); we refer to these terms later when we distinguish between environmental impact per unit produced versus the overall environmental impact of production. The other concept we later refer to relates to the notion of displacement. The environmental impact of new production, either the firm's or competitor's products, is avoided by displacing new production with refurbished or overproduction units (Geyer and Doctori Blass 2010). In our case this is relevant when assessing the impact of overproduction units and their sales in the alternative markets. We discuss this further in our analytical results, the examples, and the conclusion sections.

Prior research in the context of DfE and operations management has mainly focused on product EoL management aspects such as design for remanufacturing (Dekker et al. 2004, Subramanian et al. 2009, Bras 2010). Researchers have also examined product and process design efforts and their relation to environmental performance. For example, Stuart et al. (1999) developed a mixed integer programming tool for considering process and product design options and their impact on manufacturing environmental performance, using a deterministic approach. Our work focuses on the manufacturing and use life cycle stages and, using the newsvendor model, we are able to study the impact of both production and overproduction.

Lastly, our paper also touches on the subject of sustainability strategies, and more specifically, eco-efficiency as a strategy. Porter and Van de Linde (1995) argue that more cost-

efficient use of resources can create competitive advantage and therefore should be considered as a viable strategy. However, Orsato (2009) argues that eco-efficiency as a strategy might not be sufficient to establish true competitive advantage. The latter suggests that process-intense firms are simply expected to pursue eco-efficiency strategies and that should be reflected in their performance measurements. While eco-efficiency is a well-understood way of measuring economic and environmental performance in theory, the use of such methods is still limited in practice. Since expressing environmental impacts in monetary terms is a challenge, an eco-efficiency approach can help to examine tradeoffs and to identify cases when environmental improvements are not necessarily worth pursuing (Huppel and Ishikawa 2005).

3 The Model and Analysis

This section develops our model and presents analytical results. A summary of notation can be found in Appendix B.

3.1 Model Description

Consider a single firm supplying a product to end consumers in a newsvendor setting. The firm faces a fixed retail price per unit of p and each unit initially costs c_0 to manufacture. The firm needs to decide on the quantity to produce, q , as well as the DfE efforts that change the product's environmental impacts in each life cycle stage and therefore its overall environmental impact. The firm can invest in effort that improves the environmental performance of the manufacturing stage, e_1 , and the use stage, e_2 , at a cost of de_i^2 , for $i = 1, 2$, where the quadratic cost function implies diseconomies of scale for both types of effort. While in some cases changes in design affect more than one life cycle stage, for the sake of tractability and to focus on first order effects, we assume in our model that each e_i affects the environmental impact only in stage i . We assume that the innovations made do not alter performance or functionality of the product;

however, they improve the quality (e.g., through reduced usage cost or reduced product toxicity) of the product and therefore its demand. These innovations decrease the environmental impact per unit as described in §4.

The cost to produce the product is decreasing in the innovation effort for the manufacturing stage:

$$c(e_1) = c_0(1 - \gamma e_1) > 0, \quad (1)$$

where c_0 is the original cost of the product and γ is the cost reduction effectiveness for the manufacturing stage innovation, where $\gamma \in [0, 1]$. This cost structure implies that the firm chooses eco-efficient innovations (i.e., reducing environmental impact while reducing cost) when investing effort in the manufacturing stage. (In §6, we extend the model to the case where $\gamma < 0$, which means that the environmental innovations the firm chooses are actually costly.)

End-consumer demand is stochastic and depends on the use stage innovation effort such that $D(e_2, \varepsilon) = A - k(1 - \delta e_2)p + \varepsilon$, where $\varepsilon \sim F(\cdot)$ on $[\alpha_1, \alpha_2]$ with density $f(\varepsilon)$, and $E(\varepsilon) = 0$. The parameter A denotes the market size, k indicates the level of price sensitivity, and $\delta \in [0, 1]$ is the firm's effectiveness in reducing the price sensitivity (per unit of use stage innovation effort). The parameter k can also be seen as a measure of willingness-to-pay for quality (Atasu and Souza 2011), and thus, use stage innovation effort increases that willingness-to-pay due to improved product quality through reduced usage cost or improved environmental performance. In general, the environmental innovations in the manufacturing stage do not directly impact consumers (i.e., do not reduce their cost), and thus we assume they do not alter the value consumers place on the product. While there may be a small fraction of consumers (often referred to as the green segment) that will be positively influenced by manufacturing innovations (in process, product, and EoL) in addition to the use stage innovations, because this demand

impact will be much smaller than that of the use stage, we do not include it in our model to increase tractability, enabling us to focus on the tradeoff between cost and demand. The use stage innovation, however, has a direct bearing on the consumers through (for example) a reduction in the energy consumption during the use stage (e.g., cold water wash of clothes). Thus, the use stage innovation effort increases consumer utility from the product and results in higher demand.

With the newsvendor model, the demand uncertainty results in unsold leftover (overproduction) units. We assume that there are two possibilities for these units: They can either be sold to an alternative market at a net salvage value of s_A , or recovered (for example recycled) at a net salvage value of $s_R < s_A$ (where the net value includes costs such as transportation to the alternative market or to the recovery/disposal facility). We define $\theta \in [0,1]$ as the portion of leftover units that can be sold to an alternative market. When $\theta = 0$, there is no alternative market where they can be sold and thus they are recycled, have parts recovered, or are simply thrown away (for example, in the case of perishable food, where there is no recovery value, $s_R = 0$). We assume that this fraction of leftover units sold (θ) remains constant even after environmental innovation effort takes place. (In §6, we extend our analysis to the case where the product innovation efforts can impact this fraction). The average salvage value per unit for the leftover units is therefore:

$$s_T(\theta) = \theta s_A + (1 - \theta) s_R, \quad (2)$$

where $0 \leq s_T(\theta) < c(e_1)$ (otherwise the firm could have unbounded profits).

3.2 The Firm's Maximization Problem

Using the demand and cost description above, we can now define the firm's expected profit, which includes the firm's cost for producing the units, the revenues from selling in the primary

market and salvaging the leftover units, as well as the costs of the innovation efforts. The firm's expected profit given quantity, q , and effort levels, e_1 and e_2 , is therefore:

$$\Pi(e_1, e_2, q) = -c(e_1)q + pE[\min(q, D(e_2, q))] + s_T(\theta)E[q - D(e_2, q)]^+ - d(e_1^2 + e_2^2).$$

To facilitate our solution, we use a change of variable (similar to Petruzzi and Dada 1999), where we let $z = q - (A - k(1 - \delta e_2)p)$. Henceforth, we use z , the stocking factor, instead of q in our analysis and discussions. The expected profit equation for the firm can therefore be written:

$$\begin{aligned} \Pi(e_1, e_2, z) = & -c(e_1)(A - k(1 - \delta e_2)p + z) + p(A - k(1 - \delta e_2)p - g_1(z)) \\ & + s_T(\theta)g_2(z) - d(e_1^2 + e_2^2) \end{aligned} \quad (3)$$

where

$$g_1(z) = \int_z^{\alpha_2} (u - z)f(u)du, \quad g_2(z) = \int_{\alpha_1}^z (z - u)f(u)du \quad (4)$$

are the expected shortages and overproduction (leftovers), respectively, and (α_1, α_2) is the domain of the distribution.

The firm maximizes its profit by deciding on its order quantity (stocking factor) and the efforts that improve the environmental performance of the manufacturing stage, e_1 , and the use stage, e_2 . Using the fact that $z + g_1(z) = g_2(z)$ (because $E(\varepsilon) = 0$), we can rewrite (3) to obtain the following maximization problem:

$$\begin{aligned} \max_{e_1, e_2, z} \Pi(e_1, e_2, z) = & (p - c(e_1))(A - k(1 - \delta e_2)p - g_1(z)) + (s_T(\theta) - c(e_1))g_2(z) \\ & - d(e_1^2 + e_2^2) \\ \text{subject to} \quad & c(e_1) > s_T(\theta) \\ & e_1, e_2 \geq 0 \\ & \alpha_1 \leq z \leq \alpha_2 \end{aligned}$$

The first term in the objective function is the contribution from the expected sales, the second term is the loss on overproduction because $s_T(\theta) < c(e_1)$, and the last term is the cost of

innovation. Also note that even when the salvage value is 0, there are still extra units produced at cost $c(e_1)$, but not used. We discuss this further in the next section.

The following Theorem describes the solution to the firm's maximization problem. All proofs can be found in Appendix A.

Theorem 1: If

$$2d - kp\delta a > \max\left(\frac{a((kp\delta)^2(p - c_0) + 2d(A - kp + z^*))}{kp\delta(c_0 - s_T(\theta))}, \frac{2da}{kp\delta(p - s_T(\theta))f(z^*)}\right), \quad (5)$$

then

$$e_1^* = \frac{\gamma c_0}{2d(2d - kp\delta a)} ((kp\delta)^2(p - c_0) + 2d(A - kp + z^*)), \quad (6)$$

and

$$e_2^* = \frac{kp\delta(p - c_0) + a(A - kp + z^*)}{2d - kp\delta a}, \quad (7)$$

and z^* solves:

$$kp\delta(p - s_T(\theta))(2d - kp\delta a)F(z^*) = 2d[kp\delta(p - c_0) + a(A - kp + z^*)], \quad (8)$$

where $a = (\gamma c_0)^2 kp\delta / (2d)$, and $s_T(\theta)$ is given in (2).

This theorem defines the optimal efforts as functions of the stocking factor z^* and finds an equation to solve for z^* , which depends on the demand distribution assumed. The condition guarantees concavity (based on the Hessian) and satisfies the constraint on $c(e_1)$. Note that the optimal e_1 and e_2 will always be positive if $2d - kp\delta a > 0$, which is satisfied by condition (5) because both terms on the right hand side are positive. We next turn to examining the firm's optimal decisions.

3.3 The Firm's Optimal Decisions

We first describe the effect of the problem parameters γ , δ , p , and c_0 on the optimal innovation efforts of the two life cycle stages.

Lemma 1: For a given z ,

- a) The optimal effort levels e_1^* and e_2^* are increasing in γ and δ .
- b) e_2^* is increasing in p , while e_1^* is increasing in p if $e_2^* > \frac{1}{2\delta} - \frac{k\delta p^2}{4d}$.
- c) e_1^* is increasing in c_0 if $e_2^* > \frac{kp\delta c_0}{(2d+kp\delta a)} - (A - kp + z)$, and e_2^* is increasing in c_0 if $e_1^* > \frac{1}{2\gamma}$.

As the effectiveness of either manufacturing or use stage effort increases, the effort devoted to not only the corresponding stage, but the other stage as well, increases. As the price increases, the revenue per unit increases, making it worthwhile to sell more by investing more in e_2 . However, only when e_2^* is already large enough will it make sense to also invest more in e_1 . Conversely, as c_0 increases, margin is decreasing, thus only when e_1^* is large enough (decreasing cost), will it be worth the additional investment in e_2 to increase demand. Because γ is less than one, this condition will be difficult to satisfy. For the manufacturing stage effort, a larger unit cost provides more room for improvement, however only as long as e_2^* is large enough to justify the increased effort. Note that the right hand side of the constraint on e_2^* might actually be negative, in which case the constraint holds for every value of c_0 .

Next we compare the levels of the two efforts. As can be seen in the next theorem, depending on the characteristics of the products, e_1 may be higher or lower than e_2 .

Theorem 2: $e_1^* > e_2^*$ if and only if

$$\frac{(A - kp + z^*)}{(p - c_0)} > \frac{kp\delta}{\gamma c_0}. \quad (9)$$

The left hand side of the condition is the ratio of the demand and the firm's margin, while the right hand side is the ratio of the firm's effectiveness in increasing demand through use stage innovation (per unit of effort) and the firm's effectiveness in decreasing cost (per unit of effort). When demand is high and margin low (for example in the case of functional products), this

condition will be easier to satisfy, while when demand is low and margin high (such as in the case of innovative products), the condition will be harder to satisfy. Thus, in general, we would expect functional products to have higher investment in process innovation than in product innovation, while the opposite will hold for innovative products.

To measure the environmental impacts of the firm's environmental innovation efforts, we compare the results from our general model with the newsvendor outcomes without innovation. The comparison includes the changes in quantities produced, sold, and overproduced, as well as the associated LCA based environmental impacts. Without investment in innovation effort, the firm solves a standard newsvendor problem (N) and thus the objective function in (3) simplifies to:

$$\Pi_N(z) = -c_0(A - kp + z) - p(A - kp - g_1(z)) + s_T(\theta)g_2(z)$$

where $g_1(z)$ and $g_2(z)$ are given in (4). The solution to this problem is the critical fractile solution:

$$F(z_N) = \frac{p - c_0}{p - s_T(\theta)}. \quad (10)$$

The environmental innovation efforts not only affect environmental outcomes, but they also decrease cost and increase demand. Accordingly, the quantity produced and the overproduction quantity will increase from the newsvendor benchmark, as can be seen in the next lemma. This is important since the increased quantity can worsen the environmental impact, even though the innovation improves the environmental impact per unit.

Lemma 2:

- a) $z^* > z_N$
- b) $g_1(z_N) > g_1(z^*)$ and $g_2(z_N) < g_2(z^*)$
- c) z^* and z_N increase in θ .

Part a) says that the stocking factor (and hence production quantity) will always increase

compared to the standard newsvendor case. This is due to the fact that the product cost decreases with innovation, and the stocking factor decreases in the cost. Recall that $g_1(z)$ is (expected) shortages, while $g_2(z)$ is (expected) overproduction. In part b), we see that, in the innovation case, the shortages decrease, while overproduction increases, as compared to the standard newsvendor case. Part c) confirms that an increase in the fraction of overproduction units sold in an alternative market increases the salvage value, which in turn increases the stocking factor in both the newsvendor and the innovation case.

4 Environmental Impact

4.1 The Firm's Environmental Impact Measures

We begin by defining the environmental impact per unit for the manufacturing stage as b_1 and for the use stage as b_2 . A firm could use a variety of measures for different impact categories or an overall impact score, a combined measure of multiple impact categories, based on LCA methodology.

When the firm invests effort toward environmental innovation in one or both life cycle stages, the environmental impact per unit is decreased in each stage by βe_i , $i=1, 2$, where $\beta > 0$ is the environmental improvement effectiveness of each innovation effort e_i . We assume that the effectiveness, β , is the same for each stage, allowing us to isolate and assess the contribution of the environmental impact of each stage, b_i , to the overall environmental impact change. We make the assumption that β is positive because we are interested in improving environmental outcomes as discussed in the introduction. Given the impact factors, efforts and improvement effectiveness, the total environmental impact of the two life cycle stages modeled is equal to the sum of each stage's environmental impact:

$$E_T(e_1, e_2, z) = E_1(e_1, e_2, z) + E_2(e_1, e_2, z) \quad (11)$$

where

$$E_1(e_1, e_2, z) = (b_1 - \beta e_1) \underbrace{(A - k(1 - \delta e_2)p + z)}_{\text{Production Qty}} \quad (12)$$

and

$$E_2(e_1, e_2, z) = (b_2 - \beta e_2) \underbrace{(A - k(1 - \delta e_2)p - g_1(z))}_{\text{Expected Sales}} + (b_2 - \beta e_2) \underbrace{\theta g_2(z)}_{\text{Alt. Market Overproduction}}. \quad (13)$$

The environmental impact in the manufacturing stage is assessed on all units produced, whether or not they are sold, while the impact of the use stage is assessed on expected sales and the fraction of overproduction units sold to an alternative market (θ), as defined earlier in §3. Units not sold to either market are never used, thus do not incur any use stage impact. However, these units may then undergo recovery and we discuss their potential impact in §4.2.

Recall that to measure the environmental impact of the firm's DfE efforts, we use the newsvendor outcomes without DfE innovation as the basis for comparison. For this case without innovation, the overall environmental impact of the product across both life cycle stages is:

$$E_N = E_{N1} + E_{N2}, \quad (14)$$

where $E_{Ni} = E_i(e_1, e_2, z)$, $i = 1, 2$ from equations (12) and (13), with $e_1 = e_2 = 0$, and $z = z_N$.

While the per-unit environmental impact of each stage will decrease from b_i to $(b_i - \beta e_i)$, the overall change in environmental impact associated with the firm's decision to invest effort in environmental innovation may be either positive or negative, depending on the total quantity produced and used. We define this change as ΔE_i , which is the difference between the environmental impact with and without innovation effort e_i in stage i and thus:

$$\begin{aligned} \Delta E_1 &= E_{N1} - E_1(e_1^*, e_2^*, z^*) = b_1(A - kp + z_N) - (b_1 - \beta e_1^*)(A - k(1 - \delta e_2^*)p + z^*) \\ &= b_1((z_N - z^*) - kp\delta e_2^*) + \beta e_1^*(A - k(1 - \delta e_2^*)p + z^*), \end{aligned} \quad (15)$$

$$\begin{aligned} \Delta E_2 &= E_{N2} - E_2(e_1^*, e_2^*, z^*) = b_2(A - kp - g_1(z_N)) + b_2\theta g_2(z_N) - (b_2 - \beta e_2^*)(A - \\ &k(1 - \delta e_2^*)p - g_1(z^*)) - (b_2 - \beta e_2^*)\theta g_2(z^*) \end{aligned}$$

$$= b_2((g_1(z^*) - g_1(z_N)) - kp\delta e_2^*) + \beta e_2^*(A - k(1 - \delta e_2^*)p - g_1(z^*)) + \theta(b_2(g_2(z_N) - g_2(z^*)) + \beta e_2^*g_2(z^*)), \quad (16)$$

The overall change in environmental impact is equal to $\Delta E_T = \Delta E_1 + \Delta E_2$. Note that a positive delta value indicates an improvement (less environmental impact), while a negative value indicates the firm's expected impact has worsened.

4.2 The Environmental Impact of Overproduction

In this section we examine the environmental impact of overproduction. There are different considerations for assessing the environmental impact of overproduction: the type of the product and its fate in case it does not get used. For short shelf-life products (perishable products for example), most of the overproduction units will be wasted and disposed of. Long shelf-life products can many times be sold at a reduced price (salvage price) either as new products in less developed markets that do not demand the latest technology (θ), or as parts for repairs and recycling ($1 - \theta$). To further assess and granulate the environmental impact, we therefore separate $E_1(e_1, e_2, z)$ and $E_2(e_1, e_2, z)$ from (12) and (13) (using the fact that $z + g_1(z) = g_2(z)$) into three categories of environmental impact: 1) primary market expected sales (S), 2) overproduction sold in an alternative market (OPA), and 3) overproduction recovered through recycling or spare parts extraction (OPR):

$$E_i(e_1, e_2, z) = E_{Si}(e_1, e_2, z) + E_{OPAi}(e_1, e_2, z) + E_{OPRi}(e_1, e_2, z), \quad i = 1, 2 \quad (17)$$

where

$$E_{Si}(e_1, e_2, z) = (b_i - \beta e_i)(A - k(1 - \delta e_2)p - g_1(z)), \quad i = 1, 2 \quad (18)$$

and

$$E_{OPA1}(e_1, e_2, z) = (b_1 - \beta e_1)\theta g_2(z), \quad E_{OPA2}(e_1, e_2, z) = (b_2 - \beta e_2)\theta g_2(z), \quad (19)$$

$$E_{OPR1}(e_1, e_2, z) = (b_1 - \beta e_1)(1 - \theta)g_2(z), \quad E_{OPR2}(e_1, e_2, z) = 0.$$

In order to be consistent with our model set-up which does not include the impact of the EoL stage, we assume that $E_{OPR2}(e_1, e_2, z) = 0$, although in practice, the recovery of the unsold units also carries environmental impacts (from transportation and recycling processes). The differentiation between overproduction units sold in an alternative market and therefore still being used compared to overproduction recovered units which are not used is important for two reasons: first, units produced and not sold are a poor waste of resources, even if we recover some of those resources through recycling and reuse of parts. Second, from an environmental perspective, there is uncertainty about the impact of units sold in an alternative market; they may displace other new units that would have been sold (and then decrease the overall impact if they are more environmentally friendly than the other units), or they may contribute to growth in consumption (i.e., because they were sold inexpensively, people bought them as extra), leading to an overall increase in environmental impact.

We now define the change in environmental impact from sales and overproduction for each stage and overall using (17) – (19) (for ease of exposition, we don't formally define the environmental impact of sales and overproduction for the newsvendor case, however, they are the same as the general case with $e_1 = e_2 = 0$ and $z = z_N$), which are:

$$\Delta E_{Si} = [\beta e_i^*(A - k(1 - \delta e_2^*)p - g_1(z^*)) - b_i(kp\delta e_2^* + g_1(z_N) - g_1(z^*))], \quad i = 1, 2 \quad (20)$$

$$\Delta E_S = \Delta E_{S1} + \Delta E_{S2}$$

$$= \left[\underbrace{\beta(e_1^* + e_2^*) (A - k(1 - \delta e_2^*)p - g_1(z^*))}_{Exp\ Sales > 0} - \underbrace{(b_1 + b_2) (kp\delta e_2^* + g_1(z_N) - g_1(z^*))}_{\Delta Exp\ Sales > 0} \right] \quad (21)$$

$$\Delta E_{OPA1} = \theta(b_1 g_2(z_N) - (b_1 - \beta e_1^*) g_2(z^*)), \quad \Delta E_{OPA2} = \theta(b_2 g_2(z_N) - (b_2 - \beta e_2^*) g_2(z^*)) \quad (22)$$

$$\Delta E_{OPR1} = (1 - \theta)(b_1 g_2(z_N) - (b_1 - \beta e_1^*) g_2(z^*)), \quad (23)$$

and

$$\begin{aligned}\Delta E_{OP} &= \Delta E_{OP1} + \Delta E_{OP2} = (\Delta E_{OPA1} + \Delta E_{OPR1}) + \Delta E_{OPA2} \\ &= \left((b_1 + \theta b_2)g_2(z_N) - ((b_1 + \theta b_2) - \beta(e_1^* + e_2^*))g_2(z^*) \right).\end{aligned}\quad (24)$$

We use these various delta measures as different ways to analyze the environmental outcomes of the innovation efforts. Although the per-unit impact of each stage will improve, the potential increase in quantity produced, and the portion thrown away (or partially if not 100% recovered), represents an important aspect of the environmental impact. These measures help us to examine the decoupling impact of the innovation efforts discussed earlier.

4.3 Change in Overall Environmental Impact

We next provide insights regarding the change in the total environmental impact. First, using (21) and (24), we can write the change in total environmental impact as:

$$\begin{aligned}\Delta E_T &= \Delta E_S + \Delta E_{OP} \\ &= \left[\beta(e_1^* + e_2^*)(A - k(1 - \delta e_2^*)p - g_1(z^*)) - (b_1 + b_2)(kp\delta e_2^* + g_1(z_N) - g_1(z^*)) \right] \\ &\quad + \left((b_1 + \theta b_2)g_2(z_N) - ((b_1 + \theta b_2) - \beta(e_1^* + \theta e_2^*))g_2(z^*) \right)\end{aligned}\quad (25)$$

As expected, the change in total environmental impact is increasing in β and decreasing in b_1 and b_2 . Whether the impact has improved (positive) or worsened (negative), depends on both the quantity (through the optimal stocking factor, z^* , and the deterministic increase in quantity, $kp\delta e_2^*$) and the environmental impact factors β and $b_i, i = 1, 2$. The following definition helps to characterize the condition for when the overall environmental impact worsens, even while the per-unit impact improves.

Definition 1:

a) A product is *S-compensatory* if the characteristics of the products are such that $\Delta E_S > 0$, equivalently

$$\frac{(kp\delta e_2^* + g_1(z_N) - g_1(z^*))}{(A - k(1 - \delta e_2^*)p - g_1(z^*))} < \left(\frac{\beta(e_1^* + e_2^*)}{b_1 + b_2} \right).\quad (26)$$

b) A product is *OP-compensatory* if the characteristics of the products are such that $\Delta E_{OP} > 0$, equivalently

$$\frac{g_2(z^*) - g_2(z_N)}{g_2(z_N)} < \frac{\beta(e_1^* + \theta e_2^*)}{(b_1 - \beta e_1^*) + \theta(b_2 - \beta e_2^*)}. \quad (27)$$

We use *compensatory* to mean that the per-unit environmental innovation improvement compensates for the quantity increase. This corresponds to the UNEP argument (UNEP 2011, page 5) about achieving absolute decoupling only “*when the growth rate of resource productivity exceeds the growth rate of the economy*”. Thus, absolute decoupling implies that we have to decrease the per-unit environmental impact enough to compensate for increased production (for example reduce the impact per unit by half and grow the market of 30%). In our model, this compensation can happen in two ways: First, the decrease in environmental impact of the expected sales can *compensate* for the increase in the expected sales ($\Delta \text{Exp Sales} / \text{Exp Sales}$, see Equation (21)). Second, the decrease in the environmental impact of overproduction can compensate for the increase in the overproduction quantity. In other words, if the efforts and their effectiveness β are large enough to reduce the environmental impact per unit in a substantial way, then the efforts can compensate for the impact from increased sales and overproduction quantities, thus overall we still achieve a reduction in the total environmental impact. As the next theorem shows, the sign of the change in environmental impact depends on the compensatory nature of the product.

Theorem 3:

- a) If the product is both *S-compensatory* and *OP-compensatory*, then $\Delta E_T > 0$.
- b) If the product is neither *S-compensatory* nor *OP-compensatory*, then $\Delta E_T < 0$.
- c) Otherwise ΔE_T can be positive or negative.

If the product is both S- and OP-compensatory, then the environmental innovation efforts, combined with the effectiveness β , are large enough to overcome the increase in environmental impact due to the quantity increase. If neither holds, then neither the sales quantity increase nor the overproduction quantity increase can be overcome and the overall environmental impact will worsen. However, if one is positive and the other negative, the overall impact could improve or worsen depending on the size of the tradeoff between increased quantity and reduced impact per unit. Thus the *compensatory* concept captures the inherent tradeoff in decoupling and gives us the ability to distinguish between relative decoupling and absolute decoupling within the operation of the modeled firm.

4.4 Comparing the Environmental Impact for the Different Life Cycle Stages

Another interesting question is under what conditions will the environmental impact for the manufacturing stage be higher than that of the use stage and vice versa. The next theorem provides these conditions.

Theorem 4: $\Delta E_1 > \Delta E_2$ if and only if

$$\begin{aligned} & \beta(e_1^* - e_2^*) \underbrace{(A - k(1 - \delta e_2^*)p - g_1(z^*))}_{Exp\ Sales > 0} + (b_2 - b_1) \underbrace{(kp\delta e_2^* + g_1(z_N^*) - g_1(z^*))}_{\Delta Exp\ Sales > 0} \\ & + \underbrace{(b_1 g_2(z_N^*) - (b_1 - \beta e_1^*)g_2(z^*))}_{\Delta E_{OP1}} - \underbrace{(\theta(b_2 g_2(z_N^*) - (b_2 - \beta e_2^*)g_2(z^*)))}_{\Delta E_{OP2}} > 0. \quad (28) \end{aligned}$$

The expected sales and Δ expected sales are always positive. Whether the first two terms are positive is directly related to the type of product. For example, the first two terms will be positive if a product has higher investment in process innovation than product innovation ($e_1^* \geq e_2^*$) and higher environmental impact per unit in the use stage ($b_2 > b_1$). If the first two terms are positive, then the relationship between the change in environmental impact for the manufacturing stage and that of the use stage depends only on the environmental impact of

overproduction for the two stages. This can be seen in the next corollary.

Corollary 1:

- a) If $e_1^* > e_2^*$, and $b_2 > b_1$, then $\Delta E_1 > \Delta E_2$ if $\Delta E_{OP1} > \Delta E_{OP2}$.
- b) If $e_1^* < e_2^*$, and $b_2 < b_1$, then $\Delta E_1 < \Delta E_2$ if $\Delta E_{OP1} < \Delta E_{OP2}$.
- c) Otherwise ΔE_1 can be either higher or lower than ΔE_2 .

Recall that the optimal efforts e_1 and e_2 do not depend on b_i , $i = 1, 2$. Also by Theorem 2, in general, we expect innovative products to have lower investment in process innovation than in product innovation, and thus by Corollary 1(b), innovative products that have higher environmental impact per unit in the manufacturing stage will actually have higher total environmental impact in the use stage as long as the environmental impact of overproduction is higher in the use stage.

5 Discussion of Product Categories

In order to demonstrate our analytical results, we apply our model to each of the four product categories presented in Figure 1. We conduct a numerical study using realistic parameters including LCA data from the literature.

5.1 The Numerical Study

The four products we analyze are bread (for food products), fans, smartphones, and down sweaters (for fashion). The application of the model to each of the products includes innovations in the manufacturing and use stages. For example, La Boulangerie, a Swedish bakery, uses fair trade cotton bags for distribution instead of plastic and paper bags (La Boulangerie 2010). This use stage innovation reduces energy and other resources because the bags can be used multiple times, not immediately thrown away. Patagonia, a down sweater manufacturer, uses recycled polyester for the sweater shell, a manufacturing stage innovation (Patagonia 2011).

We ran a full-factorial numerical analysis with 6 parameters at 3 levels each, for a total of 729 runs per product. Full details of the parameters used are in Appendix C. We highlight some of the key ones here. The experimental parameters are p , c_0 , θ , β , γ , δ , while the other parameters remained fixed. As can be seen in Table 1, price affects the value of mean demand as well as the percent demand variability. Prices were chosen as representative of the product category, with realistic margins, while the manufacturing and use stage impact parameters b_1 and b_2 were taken from LCA studies in the literature and represent mega joules (MJ) of electricity usage. Although the impact can be measured using an LCA score that represents multiple impact categories, in this study we refer to a single category of measurement, the primary energy consumption.

Table 1: Range of Parameter Values.

	Bread	Fans	Smartphones	Down Sweaters
Price (p)	3, 5, 7	40, 50, 60	500, 550, 600	250, 300, 350
Mean Demand ($A-kp$)	72, 80, 88	40, 50, 60	10, 18, 25	9, 22, 35
% Demand Variability (($\alpha_2 - \alpha_1$)/Mean demand)	11.4, 12.5, 13.9	16.7, 20, 25	40, 57.1, 100	28.5, 45.5, 111
Cost (c_0/p)	0.7, 0.8, 0.9	0.7, 0.8, 0.9	0.4, 0.5, 0.6	0.5, 0.55, 0.6
θ	0, 0.05, 0.1	0.3, 0.5, 0.7	0.8, 0.9, 1	0.9, 0.95, 1
β	1, 3, 5			
γ	0.1, 0.2, 0.3			
δ	0.1, 0.2, 0.3			
b_1	10	25	200	35
b_2	1	50	115	60
s_A	0.5p	0.5p	0.25p	0.25p
s_R	0	5	10	5

5.2 Results

Table 2 shows the average results for the numerical study including the stocking factor z , the critical fractile, the efforts, profit, percent change in quantity and overproduction, and the average change in environmental impacts in each stage and overall. The fractile is above 50% for innovative products that have higher margins, but lower than 50% for the functional, low margin products.

Table 2: Summary Results (Averages over All Cases)

	Bread	Fans	Smartphones	Down Sweaters
z	-2.93	-1.94	1.98	1.09
Fractile	0.21	0.31	0.70	0.61
e_1	0.010	0.063	0.327	0.161
e_2	0.0007	0.018	0.829	0.375
Profit	74.4	468.5	6745.0	3073.2
% ΔQ	0.03%	0.88%	106.66%	50.95%
% ΔOP	2.53%	16.78%	18.28%	9.77%
$\Delta OP / \Delta Q$	15.7%	12.3%	2.0%	2.2%
ΔE_1 (% cases > 0)	2.02 (100%)	-0.76 (47.2%)	-3316.7 (0%)	-241.83 (0.3%)
ΔE_2 (% cases > 0)	0.14 (82.7%)	-15.99 (0%)	-1824.21 (0%)	-406.34 (0%)
ΔE_T (% cases > 0)	2.2 (100%)	-16.7 (14.8%)	-5140.9 (0%)	-648.2 (0%)

In general, the efforts for the functional products are lower than those for the innovative ones, due to the lower margin. Additionally, which type of effort is higher depends on the type of product as well, with functional products incurring more manufacturing stage innovation effort to reduce cost and increase margin, while innovative products have higher use stage innovation effort (as expected from Theorem 2). The quantity produced increases over the no innovation case (standard newsvendor) as does the overproduction, for all products as predicted by Lemma 2. Note however, that the percentage increase in quantity produced is much smaller for functional products than innovative ones. The percentage increase in overproduction, $\% \Delta OP$, (which is equivalent to the left hand side of equation (27)) depends on the margin, the fraction of overproduction that can be sold to an alternative market (θ), and the salvage values (s_A and s_R). We see that smartphones have a much higher $\% \Delta OP$ than down sweaters, even though they have similar values of margin and θ , due to the higher salvage values s_A and s_R for the smartphones.

Recall that the per-unit change in environmental impact is always positive since the innovations chosen are eco-efficient. However, it is possible to obtain a worse impact overall due to the increase in quantity. In our results, only the overall impact of bread is improved from the

efforts (which means that the increase in production was small enough so the per-unit improvement compensated for it), while the other three products (fans, smartphones and sweaters) have a negative change in overall environmental impact. Table 2 shows the average value for ΔE_i and the percentage of the 729 cases that are positive. We discuss these in more detail in Figure 2 below.

Next we provide evidence to how the product characteristics influence the environmental impact outcomes. Similarly to Figure 1, we group products by functional/innovative and whether they have higher manufacturing or use stage impact to summarize our findings. Figure 2 displays some directional results from the numerical analysis. The number in parentheses shows the percentage of cases for which the corresponding result was achieved.

Figure 2: Results Summary Per Product Type

		Product Type			
		Functional	Innovative		
Environmental Impact	Higher env. impact during mfg. stage $(b_1 > b_2)$	Bread			
		$z^* < 0$	(100%)	Smartphones	
		$e_1^* > e_2^*$	(100%)	$z^* > 0$	(100%)
		$\Delta E_T > 0$	(100%)	$e_2^* > e_1^*$	(95.5%)
		$\Delta E_1 > \Delta E_2$	(99.6%)	$\Delta E_T < 0$	(100%)
		$\Delta E_S > 0$	(100%)	$\Delta E_2 > \Delta E_1$	(100%)
		$\Delta E_{OP} < 0$	(96.3%)	$\Delta E_S < 0$	(100%)
		$\Delta E_{OP1} < \Delta E_{OP2}$	(96.3%)	$\Delta E_{OP} < 0$	(99.5%)
			$\Delta E_{OP1} < \Delta E_{OP2}$	(100%)	
	Higher env. impact during use stage $(b_2 > b_1)$	Fans		Down Sweaters	
		$z^* < 0$	(95.1%)	$z^* > 0$	(100%)
		$e_1^* > e_2^*$	(95.1%)	$e_2^* > e_1^*$	(87.7%)
		$\Delta E_T < 0$	(85.2%)	$\Delta E_T < 0$	(100%)
		$\Delta E_1 > \Delta E_2$	(100%)	$\Delta E_1 > \Delta E_2$	(100%)
$\Delta E_S < 0$		(80.5%)	$\Delta E_S < 0$	(100%)	
$\Delta E_{OP} < 0$		(100%)	$\Delta E_{OP} < 0$	(90.1%)	
	$\Delta E_{OP1} > \Delta E_{OP2}$	(66.7%)	$\Delta E_{OP1} > \Delta E_{OP2}$	(74.2%)	

It is clear that the type of product affects the choice of z . Functional products have lower margins, thus will have lower a stocking factor z . In fact, for functional products, z is almost always less than 0, meaning that production is less than the mean expected demand (margins are less than 50%). Fans have slightly higher z values due to their higher salvage value, which comes from the existence of alternative markets and the possibility of recycling/reusing unused parts such as motors. Conversely, the innovative products have positive z values, thus are producing more than the mean expected demand due to higher margins and higher salvage values.

For bread and fans, the functional products, we see as predicted by Theorem 2 and the discussion surrounding it that $e_1^* > e_2^*$ (100% for bread and 95.1% for fans), while for the innovative products the use stage innovation effort is higher (95.5% for smartphones and 87.7% for down sweaters). This can be attributed to the fact that functional products have low margins and high demand, and thus firms are motivated to decrease cost (impacting all units) through manufacturing stage innovations. On the other hand, the margin is already relatively high on innovative goods, but demand is not. Thus the motivation for innovative goods is to increase demand through use stage innovations.

Corollary 1 provides conditions under which $\Delta E_1 > \Delta E_2$. Fans represent part a) of the corollary while smartphones represent part b). For fans, $b_2 > b_1$, almost always $e_1^* > e_2^*$, and, in addition, 2/3 of the cases have $\Delta E_{OP1} > \Delta E_{OP2}$. In 100% of the cases, $\Delta E_1 > \Delta E_2$ for fans because the first two terms of (25) are large enough (even when ΔE_{OP1} is not greater than ΔE_{OP2}) to ensure that the change in manufacturing stage impact is larger. For smartphones, $b_1 > b_2$, almost always $e_2^* > e_1^*$, and $\Delta E_{OP1} < \Delta E_{OP2}$. Thus we expect from the corollary to find the change in use stage impact to be largest, and it is in 100% of the cases. For the other two products, the corollary does not specify what will happen. However, for the parameters we

consider, ΔE_1 is larger for both bread and down sweaters. The fans (smartphones) results show that even when the use (manufacturing) stage impact is higher, for functional (innovative) products it is worth investing more in the manufacturing (use) stage innovation, as shown in Theorem 2, and thus the change in environmental impact will be higher for the manufacturing (use) stage.

Using Figure 2 we can also examine when the change in the overall environmental impact is negative or positive. Recall that ΔE_T will be positive if the product is both S- and OP-compensatory. We see that only bread is S-compensatory ($\Delta E_S > 0$), which means that the per-unit environmental impact change compensates for the increase in quantity, which by Table 2 is quite small (due to a low margin and low θ). We find that none of the products are OP-compensatory in a majority of the cases. Thus the increase in overproduction is not compensated by the reduction in environmental impact per unit. Interestingly, smartphones are almost never OP-compensatory, and are so less frequently than down sweaters. This can be attributed to the size of the initial impacts, b_1 and b_2 . From (27), it can be seen that larger b_i values will make the condition harder to satisfy. For bread and fans, because the efforts are small, the change in per-unit impact is also small. However, because the initial impacts for fans are larger, there are fewer (in fact zero) cases where fans are OP-compensatory as compared to bread. These results show very well how hard it could be to achieve absolute decoupling with anticipated growth

Regardless of the fact that the per-unit change in environmental impact is positive, Table 2 and Figure 3 show that it is still possible to obtain overall worse environmental outcomes ($\Delta E_T < 0$). The majority of this impact change comes from the increase in sales in our numerical study. The values of ΔE_S are large (in absolute value) and close to the values of ΔE_T . Thus

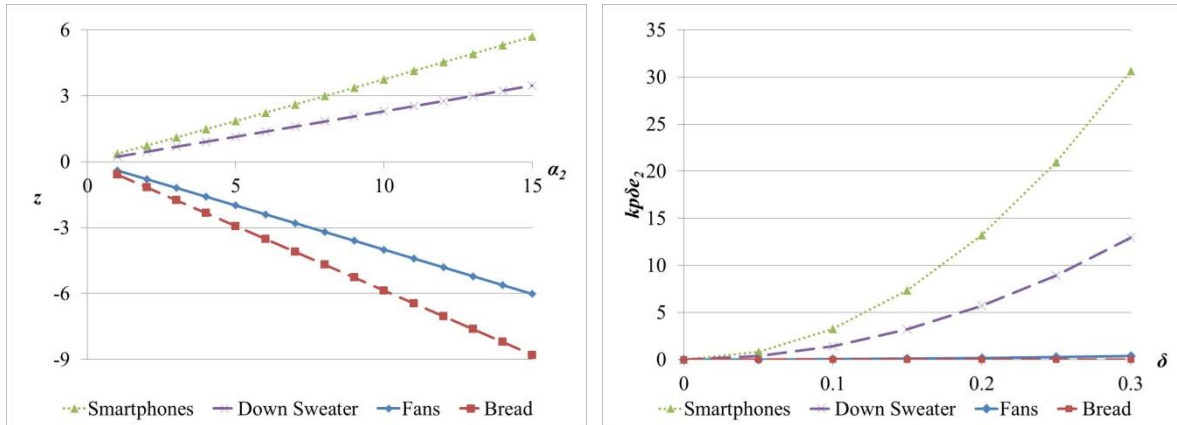
growth in production increases the environmental impact, although traditionally growth is typically considered a positive occurrence.

5.3 Comparative Statics

To gain more insight into how the parameters affect the solution, we examine how increased variability, use stage innovation effectiveness, price and cost affect outcomes. Figure 3 shows a) the stochastic portion of demand (the stocking factor z) as a function of α_2 (recall $\alpha_1 = -\alpha_2$.) and b) the deterministic portion of demand ($kp\delta e_2$) as a function of δ . First, consider part a). Interestingly, for the innovative goods, the stocking factor increases in variability and for functional goods, it decreases. This is because, for the uniform distribution, if z is above (below) the mean, increased variability increases (reduces) $F(z)$. From a practical standpoint, if margins are low as they are for functional goods, increased variability makes it riskier to produce more as there is a higher chance of not selling the additional item. Thus from the newsvendor model framework, we would expect increased variability to reduce the production amount when variability is high for low margin items. In essence, as uncertainty increases, the firm becomes more conservative for functional goods, but becomes more ‘optimistic’ for innovative goods.

Figure 3b) shows the change in deterministic demand as use stage innovation effort effectiveness increases. The functional goods have very little change as δ increases, while the innovative have more, with the change for smartphones fairly significant. Recall functional goods already have a fairly large average demand but low margins, thus as δ increases, there is little incentive to create additional demand. Note also that the relationship is nonlinear because e_2^* also increases in δ as shown in Lemma 1a).

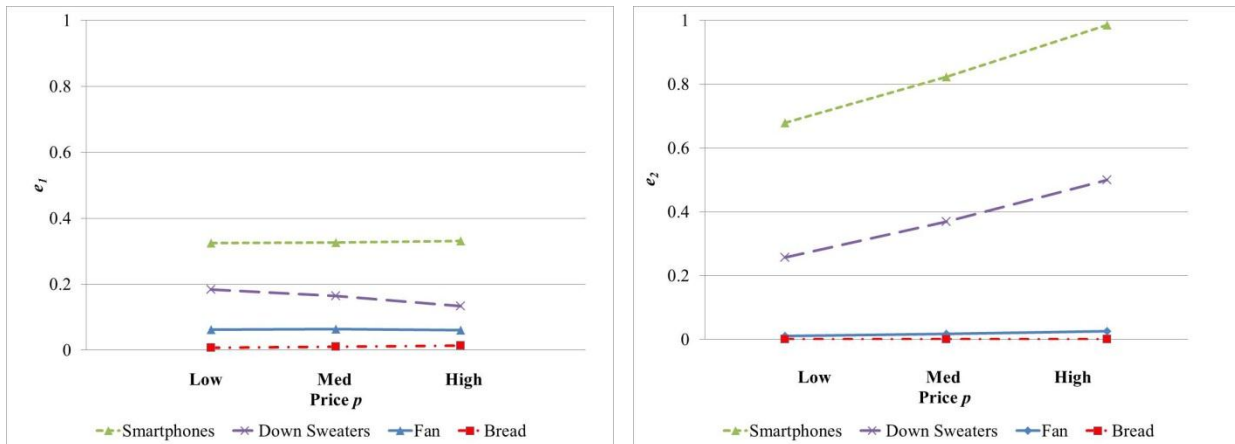
Figure 3. a) Stochastic and b) Deterministic Parts of Demand



Note: All parameters fixed at mean value from numerical study except a) α_2 ($= -\alpha_1$) and b) δ .

Figure 4 shows the effect of price on the manufacturing and use stage efforts. The numerical study data was averaged for all instances where price was high to obtain the reported results. First, note that the higher the price level (smartphones are priced higher than the other products), the higher both types of effort. The figure also demonstrates Lemma 1b): Use stage effort increases as price increases, but manufacturing stage effort only increases with price if the condition in the lemma is met.

Figure 4. Efforts a) e_1 and b) e_2 as Price Varies.

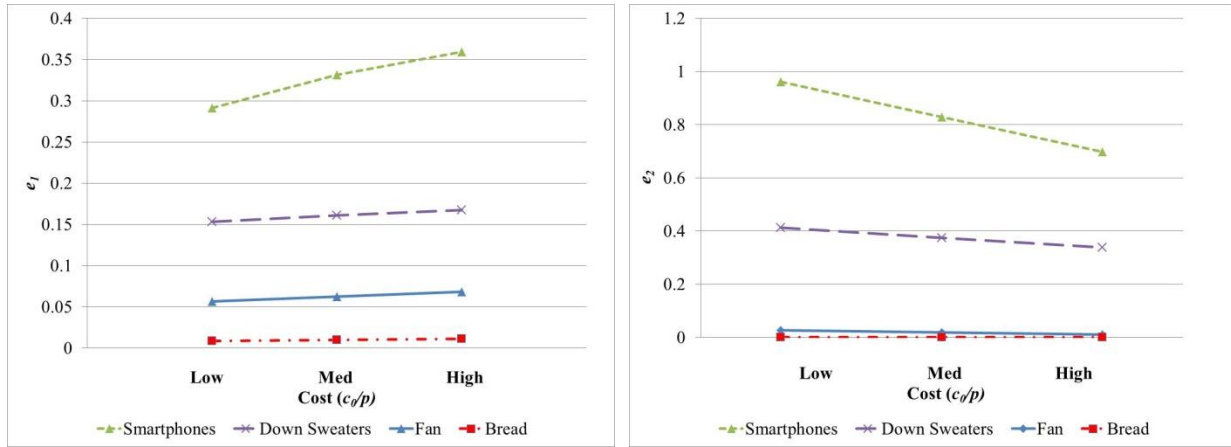


Note: All numerical study instances for price at a particular level averaged.

Figure 5 shows the efforts as the initial cost c_0 increases as a fraction of p . As described in Lemma 1c), the efforts are not linear in cost. For these parameters, manufacturing stage effort

increases in cost while use stage effort decreases. This is as expected: as the cost increases toward price, the firm will invest more manufacturing stage effort to improve its margin, but at the same time, it is less interested in selling more through use stage effort because each unit has a lower margin.

Figure 5. Efforts a) e_1 and b) e_2 as Cost c_0 Varies.



Note: All numerical study instances for cost at a particular level averaged.

6 Extensions

We next extend our model in two ways. First we incorporate the possibility of the firm investing in costly environmental innovations, and second, we examine the case where the product innovation effort affects the portion of overproduction units sold in the alternative market.

6.1 Costly Environmental Innovation

So far we assumed that the firm invests in environmental innovations that reduce the cost of the product or increase its demand. It is possible, however, that the environmental innovation is costly and thus would increase the product's unit cost. The next theorem describes the result of this on the optimal efforts and stocking factor as well as the change in environmental impact of the two stages and overall.

Theorem 5: When the cost reduction effectiveness, $\gamma < 0$,

a) $e_1^* = 0$, $e_2^* = kp\delta(p - c_0)/2d$, and $z^* = z_N$

b) $\Delta E_1 = -b_1 kp \delta e_2^*$, $\Delta E_2 = -b_2 kp \delta e_2^* + \beta e_2^* (A - k(1 - \delta e_2)p - g_1(z)) + \beta e_2^* \theta g_2(z)$, and

$$\Delta E_T = \left[\frac{\beta e_2^* (A - k(1 - \delta e_2)p - g_1(z)) - (b_1 + b_2) kp \delta e_2^*}{\Delta E_S} \right] + \frac{\beta e_2^* \theta g_2(z)}{\Delta E_{OP}}$$

c) If the product is S-compensatory, then $\Delta E_T > 0$, where equation (26) becomes:

$$\frac{(kp \delta e_2^*)}{(A - k(1 - \delta e_2^*)p - g_1(z^*))} < \left(\frac{\beta e_2^*}{b_1 + b_2} \right). \quad (29)$$

As can be seen in the theorem, if the manufacturing stage innovation is costly, the firm will not want to invest any effort in it (since the firm maximizes over profits). Thus, the stocking factor will be identical to the one of the newsvendor case and thus the only increase in quantity is due to the use stage innovation effort that increases the deterministic demand. By part b), $\Delta E_{OP} > 0$ and thus the change in total environmental impact will be positive if the product is S-compensatory.

6.2 Use Stage Innovation Increases Fraction Sold in Alternative Market

Thus far we assumed that the fraction of units sold to an alternative market is independent of the firm's action. It is possible, however, that when the firm improves the use stage environmental performance of the product through product innovation efforts, it will also increase the fraction of overproduction units that can be sold in an alternative market. In this case, the fraction is a function of the effort invested in use stage innovation and is equal to: $\theta(e_2) = \theta + \omega e_2 \leq 1$. This functional form assumes that effort always increases θ ($\omega > 0$). The next theorem describes the result of this dependency on the optimal efforts and stocking factor.

Theorem 6: When $\theta(e_2) = \theta + \omega e_2$, then,

$$\text{If } 2d - kp\delta a > \max \left(\frac{\left(a + \frac{h}{kp\delta} \right) (kp\delta^2(p - c_0) + hg_2(z)) + (2d + h)(A - kp + z^*)a}{(c_0 - s_T(\theta))kp\delta}, \right.$$

$$\frac{2da + \left(\frac{h}{kp\delta}\right) \left((2kp\delta a + hF(z_\theta^*))F(z_\theta^*) + (kp\delta^2(p - c_0) + 2kp\delta a(A - kp + z_\theta^*) + hg_2(z_\theta^*))f(z_\theta^*) \right)}{(p - s_T(\theta))f(z^*)kp\delta}$$

then

$$e_{1\theta}^* = \frac{\gamma c_0}{2d(2d - kp\delta a)} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z_\theta^*) + hg_2(z) \right), \quad (30)$$

and

$$e_{2\theta}^* = \frac{kp\delta(p - c_0) + a(A - kp + z_\theta^*) + hg_2(z)/kp\delta}{2d - kp\delta a}, \quad (31)$$

and z_θ^* solves:

$$kp\delta(p - s_T(\theta))(2d - kp\delta a)F(z_\theta^*) = (2d + hF(z_\theta^*)) [kp\delta(p - c_0) + a(A - kp + z_\theta^*)] \quad (32)$$

where $a = (\gamma c_0)^2 kp\delta / (2d)$, $h = \omega(s_A - s_R)kp\delta$, and $s_T(\theta)$ is given in (2).

As can be seen in the theorem, if the fraction of units sold in alternative markets increases in the use stage innovation effort (as formulated) then this will increase the manufacturing and use stage innovation efforts as well as the stocking factor. Comparing (30) and (31) with (6) and (7), allowing θ to increase with use stage effort simply adds a positive term to each expression, thus clearly both efforts increase over the fixed θ case. As can be seen in the next corollary, it is not clear if the total environmental impact will be higher or lower than the case with constant θ . Because the efforts increase, the change in per-unit environmental impact will be larger. However, the stocking factor also increases, thus the quantity will increase. Whether the change in overall environmental impact increases or decreases from ΔE_T depends on this tradeoff between quantity increase and per-unit impact improvement.

Corollary 2: When $\theta(e_2) = \theta + \omega e_2$, then,

- a) $e_{1\theta}^* > e_1^*$, $e_{2\theta}^* > e_2^*$
- b) $z_\theta^* > z^*$
- c) $\Delta E_{T\theta}$ can either be higher or lower than ΔE_T .

7 Conclusions

As firms recognize the need to reduce environmental impacts, there is an increasing demand for guidance on how and where to improve. Using a newsvendor setting with a life cycle perspective, we provide a framework capturing the differences between functional and innovative products and a product's environmental impact in different life cycle stages. We focus on eco-efficient innovations in the manufacturing stage and demand-enhancing innovations (through cost-of-use reduction or improved environmental performance) in the use stage. We provide analytical results for the optimal quantity and effort decisions as well as the environmental impacts of the firm's decisions. We also apply our model to different categories of products using environmental LCA data and show that while for some products (such as food) the overall environmental impact improves, for others (such as fans, smartphones and sweaters), the total impact worsens.

We show that functional products in general will have higher effort investment in manufacturing stage innovations than in the use stage, while the opposite holds for innovative products. Our findings that suggest that designers of innovative products should focus more on the use stage fits well with Fisher's (1997) framework which stresses using responsive supply chain practices to get product to market to satisfy uncertain demand for innovative products and with the general prescription that innovation efforts should focus on products when they are earlier in their product lifecycles but process innovation should be the focus for mature products (Utterback and Abernathy 1975). Thus, product designers should focus on the demand enhancement potential of eco-innovations, not necessarily eco-efficiency only. Demand expansion can come from both environmentally conscious consumers, but also those concerned with total cost of ownership even if environmental considerations are not their priority.

We find that while the firm improves environmental performance per unit produced, the demand for the product increases so the overall environmental impact can still be larger with the adoption of the design efforts. This directly relates to the concept of decoupling, which is currently on the agenda for many policy makers. In our case, the environmental improvement per unit is related to achieving relative decoupling, while the increase in overall production and the possible resulted increase of total environmental impact demonstrates well the barrier to achieving absolute decoupling. Consequently, the environmental progress measurement needs to be tested at two levels: resource use efficiency per unit and the overall use of the resource. For example, in order to achieve decoupling in energy, the efficiency per unit should improve (less energy consumed per unit), and the overall use should stay the same or decrease. That means that we can produce additional units (i.e., allow growth), while overall depleting fewer energy resources. We find that absolute decoupling does not occur in our case for innovative products, and is more likely to occur for functional products. Products that are either S- or OP-compensatory may achieve absolute decoupling, and products that are both do achieve it. Therefore, our S- and OP-compensatory conditions serve as an important contribution in turning absolute decoupling into a practical consideration for firms and for society. This phenomenon is also related to the concept of rebound effect (Berkhout et. al. 2000, Hertwich 2005), when efficiency gains are lost back in overuse of resources. This observation is especially relevant for innovative products due to the high demand uncertainty characteristic of innovative products.

We also find that environmentally-focused innovation effort increases the amount of overproduction units in our model. Our numerical study demonstrates that the firm's environmental impact from overproduction generally grew worse with innovation efforts. From a global perspective, factors specific to the product such as ability and cost to recycle, reuse, or

recover parts, size and existence of alternative markets, and how consumer purchase the items determine the global change in environmental impact. Whenever such units are sold in alternative markets, they have the potential to displace new production, which will be positive for the environment and also for the firm's competitiveness. However, many times these units expand consumption and the market size due to the low salvage price they command, and thus the result is worse global environmental impact, with partial economic losses to the firm. The scale of this issue is related to both the type of the product and its LCA use stage impact. As we show in our model, the amount of overproduction quantity is directly related to the type of product which affects the uncertainty in demand and therefore the production quantity and the salvage value. For functional products whose demand is more stable and predictable, the overproduction quantity is lower compared to innovative products where demand uncertainty is high. Thus the difference in product type will affect the change in environmental impact due to the difference in overproduction.

Our model assumes a single firm. A competitive environment might alter our results. For example, a "cleaner" firm that produces more and takes customers (displace new production) from a firm with higher environmental impact might be preferable from a social welfare perspective. Other considerations for future research also include the EoL impact considerations and the introduction of taxes on the two life cycle stages to incentivize the firm to reduce its environmental impact.

8 References

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Appendix A: Proofs

Proof of Theorem 1:

Taking the first order conditions with respect to e_1 we get:

$$\frac{\partial \Pi(e_1, e_2, z)}{\partial e_1} = \gamma c_0(A - k(1 - \delta e_2)p + z) - 2de_1 = 0$$

which implies that:

$$e_1 = \frac{\gamma c_0(A - k(1 - \delta e_2)p + z)}{2d}. \quad (\text{A1})$$

With respect to e_2 , taking the first order condition we get:

$$\frac{\partial \Pi(e_1, e_2, z)}{\partial e_2} = -c_0kp\delta(1 - \gamma e_1) + kp^2\delta - 2de_2 = 0$$

Simplifying and using (A1) and the definition of a in Theorem 1, we get (6) and (7).

Taking the first derivative with respect to z we get:

$$\frac{\partial \Pi(e_1, e_2, z)}{\partial z} = -c_0(1 - \gamma e_1) + p\bar{F}(z) - s_T(\theta)F(z) = 0.$$

Using (A1) and rearranging we get (8).

Note that because $c(e_1)$ must be larger than the salvage value, we simplify $c(e_1^*) > s_T$ to obtain the first term in the max in condition (5) from the theorem.

The solution for e_1^* , e_2^* , and z^* in (6) – (8) are optimal if the Hessian $\pi(e_1^*, e_2^*, z^*)$ is negative semi definite where the Hessian is given by:

$$\begin{pmatrix} -2d & kp\delta\gamma c_0 & \gamma c_0 \\ kp\delta\gamma c_0 & -2d & 0 \\ \gamma c_0 & 0 & -(p - s_T)f(z) \end{pmatrix} \quad (\text{A2})$$

H1 = $-2d$, which is always negative. H2 results in the condition $4d^2 > (kp\delta\gamma c_0)^2$, which simplifies to $2d - kp\delta a > 0$ and H3 results in the condition $4d^2 > (kp\delta\gamma c_0)^2 + \frac{2d(\gamma c_0)^2}{(p - s_T)f(z)}$ which simplifies to $2d - kp\delta a > \frac{2da}{kp\delta(p - s_T(\theta))f(z^*)}$. Thus condition H2 is satisfied if condition H3 is satisfied, and for optimality, combining with the condition on the cost, we have condition (5) from the theorem. \square

Proof of Lemma 1:

(a) First, we take the derivative of e_1^* and e_2^* with respect to γ :

$$\begin{aligned}\frac{\partial e_1^*}{\partial \gamma} &= \frac{2dc_0(2d - kp\delta a) + 2\gamma^2(kp\delta)^2c_0^3}{(2d)^2(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) \\ &= \frac{c_0(2d + kp\delta a)}{2d(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) > 0 \\ \frac{\partial e_2^*}{\partial \gamma} &= \frac{kp\delta\gamma c_0^2}{d(2d - kp\delta a)^2} \left((2d - kp\delta a)(A - kp + z) + kp\delta(kp\delta(p - c_0) + a(A - kp + z)) \right) \\ &= \frac{kp\delta\gamma c_0^2}{d(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) > 0\end{aligned}$$

and thus both e_1^* and e_2^* increase in γ . With respect to δ , we have the following:

$$\begin{aligned}\frac{\partial e_1^*}{\partial \delta} &= \frac{2\delta(kp)^2(\gamma c_0)^3}{(2d)^2(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) + \frac{2\delta\gamma c_0(kp)^2(p - c_0)}{2d(2d - kp\delta a)} \\ &= \frac{2kp\gamma c_0}{2d(2d - kp\delta a)^2} \left(a \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) + kp\delta(p - c_0)(2d - kp\delta a) \right) \\ &= \frac{2kp\gamma c_0}{(2d - kp\delta a)^2} \left(kp\delta(p - c_0) + a(A - kp + z) \right) > 0 \\ \frac{\partial e_2^*}{\partial \delta} &= \\ &= \frac{\left(\left(kp((p - c_0) + \frac{(\gamma c_0)^2}{2d}(A - kp + z)) \right) (2d - kp\delta a) + \left(\frac{\delta(kp)^2(\gamma c_0)^2}{d} \right) (kp\delta(p - c_0) + a(A - kp + z)) \right)}{(2d - kp\delta a)^2} \\ &= \frac{\left((kp\delta(p - c_0) + a(A - kp + z))(2d/\delta - kpa) + 2kpa(kp\delta(p - c_0) + a(A - kp + z)) \right)}{(2d - kp\delta a)^2} \\ &= \frac{\left((kp\delta(p - c_0) + a(A - kp + z))(2d + kp\delta a) \right)}{\delta(2d - kp\delta a)^2} > 0\end{aligned}$$

and thus both e_1^* and e_2^* increase in δ .

$$(b) \frac{\partial e_1^*}{\partial p} = \frac{2p(k\delta)^2(\gamma c_0)^3}{(2d)^2(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right)$$

$$\begin{aligned}
& + \frac{\gamma c_0(2p(k\delta)^2(p - c_0) + (kp\delta)^2 - 2dk)}{2d(2d - kp\delta a)} \\
& = \frac{2k\delta\gamma c_0}{2d(2d - kp\delta a)^2} \left(a((kp\delta)^2(p - c_0) + 2d(A - kp + z)) + kp\delta(p - c_0)(2d - kp\delta a) \right) \\
& + \frac{\gamma c_0((kp\delta)^2 - 2dk)}{2d(2d - kp\delta a)} \\
& = \frac{4dk\delta\gamma c_0}{2d(2d - kp\delta a)^2} (kp\delta(p - c_0) + a(A - kp + z)) + \frac{k\gamma c_0(k(p\delta)^2 - 2d)}{2d(2d - kp\delta a)} \\
& = \frac{k\gamma c_0}{2d(2d - kp\delta a)} (4d\delta e_2^* + k(p\delta)^2 - 2d)
\end{aligned}$$

Thus $\frac{\partial e_1^*}{\partial p} > 0$ if and only if $4d\delta e_2^* + k(p\delta)^2 > 2d$, which can be simplified to: $e_2^* > \frac{1}{2\delta} - \frac{k\delta p^2}{4d}$.

$$\frac{\partial e_2^*}{\partial p} =$$

$$\begin{aligned}
& \left[\frac{\left(k\delta(p - c_0) + kp\delta + \frac{k\delta(\gamma c_0)^2}{2d}(A - kp + z) - ka \right) (2d - kp\delta a) + 2k\delta a(kp\delta(p - c_0) + a(A - kp + z))}{(2d - kp\delta a)^2} \right] \\
& = \frac{\left((kp\delta(p - c_0) + a(A - kp + z) + kp(p\delta - a))(2d - kp\delta a) + 2kp\delta a(kp\delta(p - c_0) + a(A - kp + z)) \right)}{p(2d - kp\delta a)^2} \\
& = \frac{\left((kp\delta(p - c_0) + a(A - kp + z))(2d + kp\delta a) + kp(p\delta - a)(2d - kp\delta a) \right)}{p(2d - kp\delta a)^2}
\end{aligned}$$

Since the first part is always positive, $\frac{\partial e_2^*}{\partial p} > 0$ always if $p\delta > a$. Using the definition of a in

Theorem 1, the condition becomes $k(\gamma c_0)^2 < 2d$. Under most reasonable conditions this will hold because $d \gg \gamma c_0$ and thus e_2^* is increasing in p .

$$\begin{aligned}
\text{(c)} \quad \frac{\partial e_1^*}{\partial c_0} & = \frac{2d\gamma(2d - kp\delta a) + 2c_0^2(kp\delta)^2\gamma^3}{(2d)^2(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) \\
& - \frac{(kp\delta)^2\gamma c_0}{2d(2d - kp\delta a)}
\end{aligned}$$

$$\begin{aligned}
&= \frac{\gamma(2d + kp\delta a)}{2d(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) - \frac{(kp\delta)^2\gamma c_0}{2d(2d - kp\delta a)} \\
&= \frac{\gamma}{2d(2d - kp\delta a)} \left(\frac{(2d + kp\delta a)((kp\delta)^2(p - c_0) + 2d(A - kp + z))}{(2d - kp\delta a)} - (kp\delta)^2 c_0 \right) \\
&= \frac{\gamma}{2d(2d - kp\delta a)} \left(\frac{(2d + kp\delta a)((kp\delta)^2(p - c_0) + (2d - kp\delta a + kp\delta a)(A - kp + z))}{(2d - kp\delta a)} \right. \\
&\quad \left. - (kp\delta)^2 c_0 \right) \\
&= \frac{\gamma}{2d(2d - kp\delta a)} \left((2d + kp\delta a)kp\delta(e_2^* + (A - kp + z)) - (kp\delta)^2 c_0 \right)
\end{aligned}$$

Thus $\frac{\partial e_1^*}{\partial c_0} > 0$ if and only if $e_2^* > \frac{kp\delta c_0}{(2d + kp\delta a)} - (A - kp + z)$.

$$\begin{aligned}
\frac{\partial e_2^*}{\partial c_0} &= \frac{kp\delta\gamma^2 c_0}{d(2d - kp\delta a)^2} \left((2d - kp\delta a)(A - kp + z) + kp\delta(kp\delta(p - c_0) + a(A - kp + z)) \right) \\
&\quad - \frac{kp\delta}{(2d - kp\delta a)} \\
&= \frac{kp\delta\gamma^2 c_0}{d(2d - kp\delta a)^2} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z) \right) - \frac{kp\delta}{(2d - kp\delta a)} \\
&= \frac{2kp\delta\gamma e_1^*}{(2d - kp\delta a)} - \frac{kp\delta}{(2d - kp\delta a)}
\end{aligned}$$

Thus $\frac{\partial e_2^*}{\partial c_0} > 0$ if and only if $e_1^* > \frac{1}{2\gamma}$. \square

Proof of Theorem 2:

$e_1^* > e_2^*$ implies:

$$\frac{\gamma c_0}{2d(2d - kp\delta a)} \left((kp\delta)^2(p - c_0) + 2d(A - kp + z^*) \right) > \frac{kp\delta(p - c_0) + a(A - kp + z^*)}{2d - kp\delta a}$$

Rearranging and simplifying this condition becomes:

$$\left(\frac{\gamma c_0 kp\delta}{2d} - 1 \right) (kp\delta(p - c_0) - \gamma c_0(A - kp + z^*)) > 0. \quad (A3)$$

Note that $\frac{\gamma c_0 k p \delta}{2d} < 1$ is equivalent to the condition $2d - k p \delta a > 0$ which is guaranteed by (5) and thus for (A3) to be positive we need $k p \delta (p - c_0) < \gamma c_0 (A - k p + z^*)$. The result then follows. \square

Proof of Lemma 2:

(a) By (10), z_N is the solution to

$$(p - s_T(\theta))F(z_N) - (p - c_0) = 0. \quad (\text{A4})$$

By (8), the solution to z^* can be rearranged to:

$$(p - s_T(\theta))F(z^*) - (p - c_0) = \left(\frac{k p \delta a F(z^*)}{2} + \frac{a(A - k p + z^*)}{k p \delta} \right) > 0 \quad (\text{A5})$$

By (A4) and (A5), we get that $(p - s_T(\theta))F(z^*) - (p - c_0) > (p - s_T(\theta))F(z_N) - (p - c_0)$, which implies that $F(z^*) > F(z_N)$. The result then follows.

(b) Using part (a) and the fact that $g_1(z)$ is decreasing in z , while $g_2(z)$ is increasing in z , the result follows.

(c) By (8) and (10), both z^* and z_N are increasing in $s_T(\theta)$. The result then follows using the fact that by (2), $s_T(\theta)$ increases in θ . \square

Proof of Theorem 3:

Using (25) and the definition of S- and OP-compensatory in (26) and (27), respectively, the result follows. \square

Proof of Theorem 4:

Using the definition of $\Delta E_1, \Delta E_2, \Delta E_{OP1}$, and ΔE_{OP2} in (15), (16), and (24), the result follows. \square

Proof of Theorem 5:

(a) When $\gamma < 0$, the firm's objective function in (3) is decreasing in e_l , and thus it is optimal to have $e_1^* = 0$. The rest of the proof follows the proof of Theorem 1 with $e_1^* = 0$. The result then follows.

(b) The result follows the definition of $\Delta E_1, \Delta E_2$, and ΔE_T in (15), (16), and (25), and the fact that $e_1^* = 0$.

(c) Using part (b), equation (22) and the fact that $\Delta E_{OP} > 0$ in this case, the result follows. \square

Proof of Theorem 6:

Taking the first order conditions with respect to e_1 and rearranging we get (A1).

With respect to e_2 , taking the first order condition we get:

$$\frac{\partial \Pi(e_1, e_2, z)}{\partial e_2} = -c_0 k p \delta (1 - \gamma e_1) + k p^2 \delta + \omega(S_A - S_R) g_2(z) - 2d e_2 = 0$$

Simplifying and using (A1) and the definition of a and h in Theorem 6, we get (30) and (31).

Taking the first derivative with respect to z we get:

$$\frac{\partial \Pi(e_1, e_2, z)}{\partial z} = -c_0 (1 - \gamma e_1) + p \bar{F}(z) + s_T(\theta) F(z) + \omega(S_A - S_R) F(z) e_2 = 0$$

Using (A1) and the definition of h in Theorem 6 and rearranging we get (32).

Similar to Theorem 1, the first term in the max condition of the Theorem comes from simplifying and rearranging $c(e_1^*) > s_T$. The second term is based on the second order condition.

The solution for $e_{1\theta}^*$, $e_{2\theta}^*$, and z_θ^* in (30) – (32) are optimal if the Hessian $\pi(e_{1\theta}^*, e_{2\theta}^*, z_\theta^*)$ is negative semi definite where the Hessian is given by:

$$\begin{pmatrix} -2d & k p \delta \gamma c_0 & \gamma c_0 \\ k p \delta \gamma c_0 & -2d & \frac{hF(z_\theta^*)}{k p \delta} \\ \gamma c_0 & \frac{hF(z_\theta^*)}{k p \delta} & -\left(p - s_T(\theta) - \frac{h e_{2\theta}^*}{k p \delta}\right) f(z_\theta^*) \end{pmatrix} \quad (\text{A6})$$

H1 = $-2d$, which is always negative. H2 results in the condition $4d^2 > (k p \delta \gamma c_0)^2$, which simplifies to $2d - k p \delta a > 0$ and H3 results in the condition

$$(4d^2 - (k p \delta \gamma c_0)^2) \left(p - s_T(\theta) - \frac{h e_2^*}{k p \delta} \right) f(z) > 2h(\gamma c_0)^2 F(z) + 2d(\gamma c_0)^2 + \frac{2d(hF(z))^2}{(k p \delta \gamma)^2}$$

Using the solution for e_2^* in (31) and rearranging, we get the second term in the max condition.

Thus condition H2 is satisfied if condition H3 is satisfied, and the result follows. \square

Appendix B: Notation

Table B1: Parameters and Decision Variables Notation

Parameters and Decision Variables	Definition
i	$i = 1,2$, where 1 = manufacturing stage and 2 = use stage
z	Stocking factor (Decision Variable)
e_i	Effort level i , $i = 1,2$ (Decision Variables)
$\Pi(e_1, e_2, z)$	Profit expression
p	Price
c_0	Initial unit cost
$c(e_1)$	Cost after cost reduction effort incurred
q	Quantity
z	Stocking factor
A	Market size
k	Price sensitivity
ε	Demand distribution, where $\varepsilon \sim F(\cdot)$ on $[a_1, a_2]$ with density $f(\varepsilon)$, and $E(\varepsilon) = 0$
$[a_1, a_2]$	Domain of the distribution of $F(\cdot)$
$g_1(z)$	Expected shortages
$g_2(z)$	Expected leftovers
d	Cost per unit of effort
δ	firm's effectiveness in reducing the price sensitivity per unit of use stage innovation effort.
γ	Cost reduction (manufacturing stage) effectiveness
θ	Portion of leftover units that can be sold to an alternative market
s_A	Net salvage value when sold to an alternative market
s_R	Net salvage value when recovered
$s_T(\theta)$	Average salvage value per unit for leftover units
a	Parameter defined for convenience, $a = (\gamma c_0)^2 k p \delta / (2d)$
b_i	Life cycle stage environmental impact parameter $i = 1,2$
β	Environmental improvement effectiveness
N	Newsvendor problem, the no innovation case
$\theta(e_2)$	Fraction of overproduction units that can be sold in an alternative market and is affected by use stage effort
$e_{i\theta}^*$	Optimal effort when θ depends on use stage effort, $i = 1,2$
z_θ^*	Optimal stocking factor when θ depends on use stage effort
h	Parameter defined for convenience, $h = \omega(s_A - s_R) k p \delta$
ω	Per unit of effort improvement in $\theta(e_2)$

Table B2: Environmental Measures Notation.

Environmental Measures	Definition
$E_i(e_1, e_2, z)$	Environmental impact per stage i , $i = 1,2$
$E_T(e_1, e_2, z)$	Total environmental impact across both life cycle stages
E_{Ni}	Environmental impact per stage i , $i = 1,2$ in the standard newsvendor case (without innovation)
E_N	Total environmental impact across both life cycle stages in the standard newsvendor case (without innovation)
ΔE_i	Difference between the environmental impact with and without innovation effort e_i in stage i , $i = 1,2$
ΔE_T	Difference between the total environmental impact with and without innovation effort
$E_{si}(e_1, e_2, z)$	Primary market expected sales environmental impact per stage i , $i = 1,2$
$E_s(e_1, e_2, z)$	Primary market expected sales environmental impact in both stages
$E_{OPAi}(e_1, e_2, z)$	Environmental impact of overproduction sold in an alternative market in stage i , $i = 1,2$
$E_{OPRi}(e_1, e_2, z)$	Environmental impact of overproduction recovered through recycling or spare parts extraction
ΔE_{Si}	Difference between environmental impact from sales with and without innovation effort in stage i , $i = 1,2$
ΔE_S	Difference between environmental impact from sales with and without innovation effort overall
ΔE_{OPAi}	Difference between environmental impact from overproduction sold in an alternative market with and without innovation effort in stage i , $i = 1,2$
ΔE_{OPR1}	Difference between environmental impact from overproduction overproduction recovered through recycling or spare parts extraction with and without innovation effort in stage 1
ΔE_{OPi}	Difference between environmental impact from all overproduction with and without innovation effort in stage i , $i = 1,2$
ΔE_{OP}	Difference between environmental impact from all overproduction with and without innovation effort overall
$\Delta E_{T\theta}$	Difference between the total environmental impact with and without innovation effort with θ

Appendix C: Numerical Study

To develop further insights about the effects of DfE efforts on cost, quantity produced, and environmental impacts, we ran a full-factorial experimental design for six model parameters for the two product types and two levels of environmental impact, resulting in 4 products. The levels for each of the 6 parameters varied range from a low value to a high value, with intermediate levels in between the extremes. With a full-factorial setup, where the optimal solution is found for every combination of parameter values, our experimental design covers a wide range of possible scenarios ($3^6 = 729$) for each case of the four considered. Our numerical study is therefore extensive, and the resulting insights robust. The complete set of parameters used, both fixed and experimental, can be found in Table C.1. We used bread, fans, smartphones and down sweaters as the specific examples. The demand is assumed uniform on $[A - kp + \alpha_1, A - kp + \alpha_2]$ where $(\alpha_1, \alpha_2) = (-5, 5)$. (We keep this fixed in this numerical study, but explore the consequences of increasing the range separately as discussed in the paper.) Bread and fans are functional as they have lower prices and higher expected demand as shown in Table 1 in the paper. Specifically we assume $A = 100$ for all products and vary k and p to obtain the mean demand. Demands are chosen to be correct in relative terms, but we use a base of $A = 100$ to make comparisons more straightforward. The prices were chosen as representative of the product, using web prices as a guide. For example, the price for down sweaters was evaluated using Patagonia products. The innovative products have higher demand variability as a percent of the mean demand, as shown in Table 1 in the paper. For initial environmental impact, we use data from LCA studies and provide references for each in the table.

Table C.1: Experimental design parameter values.

	Bread	Fans	Smartphones	Down Sweaters
Fixed Parameters				
A	100			
$U[\alpha_1, \alpha_2]$	U[-5,5]			
d	3000			
k	4	1	0.15	0.26
b_1	10	25	200	35
b_2	1	50	115	60
Reference for LCA data	Andersson et al. 1999	Meier 1992	Doctori Blass et al 2006 Frey et al. 2006	Patagonia 2011 Smith and Barker 1995
s_A	.5p	.5p	0.25p	0.25p
s_R	0	5	10	5
Experimental Parameters				
p	3, 5, 7	40, 50, 60	500, 550, 600	250, 300, 350
δ	0.1, 0.2, 0.3			
c_0/p	0.7, 0.8, 0.9	0.7, 0.8, 0.9	0.4, 0.5, 0.6	0.5, 0.55, 0.6
γ	0.1, 0.2, 0.3			
β	1, 3, 5			
θ	0, 0.05, 0.1	0.3, 0.5, 0.7	0.8, 0.9, 1	0.8, 0.9, 1

The deterministic portion of demand is increased per unit of effort by the parameter δ , which is the effectiveness of the effort e_2 in demand generation. The parameter δ is chosen to be 0.1, 0.2, or 0.3. Thus a single unit of effort may increase demand by 0.1 unit, 0.2 units or 0.3 units. For the functional product, with a high level of expected demand, this represents small demand increases in the range of (0.1%,0.75%) per unit of effort, while for the innovative product with a smaller level of expected demand, this represents demand increases in the range of (0.3% , 3.33%).

For each product type, we consider three levels of c_0 , which are a function of price, allowing us to capture the differences in margins between functional and innovative products. These margins were based our estimates given the product for bread and fans, and on web data

(Perez 2011) for smartphones and Patagonia financial data (Reinhardt et al. 2010) for down sweaters. This initial cost is reduced by innovation efforts e_I based on its effectiveness for reducing cost, γ . We consider the same levels, 0.1, 0.2, and 0.3, for γ as used for δ . These can be interpreted as meaning one unit of effort would reduce cost by $(1-\gamma)$, equivalently, 10%, 20% or 30%.

The efforts also reduce the initial environmental impacts based on β , the environmental effectiveness of the innovation efforts. We keep the three levels of β (1, 3, 5) fixed across products to facilitate comparisons. As we are using MJ of energy as our impact category, we can interpret the values of β as reducing the initial level of MJ by 1, 3 or 5 MJ per unit of effort.

Due to our interest in overproduction in this paper, we vary θ , the fraction of product sold to an alternative market. Realistically, this will vary both by product type, functional or innovative, and also by the specific product. Because bread is perishable, the salvage value and fraction salvaged will be low. “Day old bread” is one possible alternative market, where the previous day’s leftovers, slightly stale, are marked down in price. Fashion, on the other hand, tends to be marked down, moved to outlets or discounters, and eventually sold. The value of the product when sold to an alternative market is s_A . We estimate this as a fraction of price, which is less than cost. The value of products not sold is s_R . We estimate this based on the materials in the product and their value if disassembled for parts or recycled. For example, bread, once stale, is essentially waste. Fans have a motor which could potentially be reused, and fashion has textiles which could be recycled. Smartphones are given the highest value as they contain parts that can be cannibalized and precious metals which are actively sought and recycled.

The cost per unit of innovation effort (d) is fixed at \$3000. We initially varied it, but found the effect on the results to be insignificant. These may be interpreted as the weekly rate of

effort, equating to an annual salary of \$156,000. Of course, the monetary unit of dollars is arbitrary as is the interpretation as a weekly rate. We could consider lower costs and interpret them as hourly rates, or raise and interpret them as monthly rates.

The optimal values, z^* , e_1^* , and e_2^* , are found for the case of a uniform distribution using Theorem 1. Corresponding profits and environmental impacts are computed. Details of the algorithm (implemented in Scilab 5.3.1) are available from the authors.