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

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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 article, we advance understanding on where such design changes can be most effective economically to the firm and examine their corresponding environmental consequences. 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 vs. innovative products, and higher manufacturing stage environmental impact vs. 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 or demand-enhancing innovations, the total environmental impact can either increase or decrease due to increased production quantities. We identify the conditions for such cases by looking at the environmentally focused design efforts needed 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; functional and innovative products; decoupling
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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" (Schmidheiny 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 do so, 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. Its efforts are focused around three main areas: (i) materials innovation (reduce materials usage and environmental impact during the manufacturing stage), (ii) product energy efficiency (improve the energy efficiency of HP products in the use stage), and (iii) 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, as these efforts 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 decide in which stages of the life cycle to invest effort in order to reduce their overall environmental impact. However, while LCA methodology is useful in understanding the multiple environmental impacts of the firm's design decisions and their trade-offs, and in some cases 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 article, 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 its product's environmental impacts. However, we focus on eco-efficient (demand-enhancing) innovations, those that improve the per-unit environmental impact while decreasing unit cost (increasing demand). Such an investment is anticipated to create competitive advantage (Porter and Van der Linde 1995). Although eco-efficiency choices seem rational and promising to pursue even without environmental considerations, there is still evidence that firms miss such opportunities for reasons such as organizational and operational barriers, including lack of awareness of new technologies or materials (Muthulingam et al. 2010). In the energy context, this has been identified as the "energy-efficiency gap" (Jaffe and Stavins 1994). Shedding light on the performance consequences of such design options may help alleviate these barriers.

The profitability and environmental performance of a firm implementing manufacturing and use stage innovations depend on two main product characteristics: first, the type of demand pattern 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 life-cycle length, average demand, and level of demand predictability. Functional products have relatively longer product life cycles, higher and more stable demand, and lower margins, which together imply relatively smaller overproduction quantities and lower stock-out rates. Examples for such products include perishable food items such as bread or vegetables and basic consumer goods such as floor fans. (Other examples could be used; however, we later use data from the industrial ecology literature focused on these.) On the other hand, innovative products have shorter product life cycles, with lower demand and higher variability that usually result in higher overproduction quantities. Companies charge higher margins for innovative products, and end of season mark-downs are often high. Examples include high-end fashion items such as women's suits or fast-changing technology products such as smartphones.

Products can also be differentiated by the environmental impact during their life-cycle stages. Some products have higher impact from the manufacturing stage, while others have higher impact during the use stage. In this article, our analysis focuses on the manufacturing and use stages. Although the end-of-life (EoL) stage is important from a resource-efficiency perspective and due to its ability to improve environmental outcomes, absent the incentive of take-back legislation, manufacturers still tend to invest relatively little in design for EoL.

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 explicitly model the effect of overproduction, including the likelihood these may be sold in an alternative market. Figure 1 illustrates the different categories and provides some product examples.

Categories 1 and 3 are functional goods. Perishable food products (completely perishable, such as vegetables or bread, or a relatively short shelf life, such as dairy) are typically classified as functional goods because demand is relatively stable and the products have long product life cycles. In general, perishable food products will have a higher environmental impact during the manufacturing stage (i.e., cultivat-

Figure 1 Matrix of Product Categories

Environmental Impact	Product Type: Functional	Product Type: Innovative
Higher env. impact during mfg. stage	Category 1: Perishable Food, Disposable Batteries	Category 2: Smartphones, Solar Panels
Higher env. impact during use stage	Category 3: Floor Fans, Basic Apparel	Category 4: High-end Fashion/ Computer Equipment

ing and processing) than in the use stage (i.e., refrigerating or cooking). Disposable batteries (e.g., AAAs) are another Category 1 example. They have a relatively short shelf life and have a higher impact during the manufacturing stage as the use stage impact is effectively zero (Olivetti et al. 2011). Fans, in Category 3, 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). Basic apparel is also functional, and due to the use of washing machines for laundering, the use stage impact is typically higher than that of the manufacturing stage (Smith and Barker 1995).

Categories 2 and 4 cover innovative products. Smartphones fall into Category 2 and are considered innovative products because of their short product life cycle and high margins. Their environmental impact tends to be higher during the manufacturing stage due to emissions and the use of precious metals. For example, for the Nokia N8, LCA data suggest that only 19% of the energy is consumed during use stage and about 68% is consumed during the manufacturing stage (Nokia 2011, 3 year life assumed). Solar panels are another example of innovative products (technology is rapidly improving and demand is growing), where the main environmental impact comes from the manufacturing stage (Kannan et al. 2006, SENSE Project Report 2008). Examples for Category 4 include high-end fashion and computer equipment. High-end fashion is considered an innovative product (Fisher 1997) due to its high-demand uncertainty and short product life cycle. Similar to basic apparel, its environmental impact is higher during the use stage due to the frequency of washing or the need for dry cleaning, where the environmental impact of dry cleaning is larger yet than washing (Keoleian et al. 1998). Finally, high-end computer equipment is also considered innovative due to the shorter product life cycles and higher margins. For example, Cisco Systems dominates the router market, making a reported 65% gross profit margin on these products (Vance 2009). Due to the high electricity draw during the use stage, the environmental impact during this stage is higher (Teehan and Kandlikar 2012). In section 5, we use four products from these categories and provide detailed insights from a numerical study using LCA data for each product's environmental impact.

As leftover units impact a firm's sustainability efforts (Winston 2011), our analysis accounts for the environmental impacts of overproduction. Overproduction units are manufactured, but are not sold or used in the firm's primary market; thus they become leftover units. Consequently, in addition to the financial cost of overproduction, the firm also incurs environmental costs in the form of excess raw material and energy use and 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 (e.g., a different geographic market). The environmental impact is also influenced by whether these units displace sales of other products or just increase overall consumption, but capturing this effect is outside the scope of our article.

We show that functional products will generally have higher effort invested in manufacturing stage innovations than in use stage ones, while the opposite holds for innovative products. Functional products tend to have lower margins and be in the mature phase of the product life cycle, which leads to higher investment in cost reduction (manufacturing stage innovation) to increase margin. For example, food products tend to have low margins and be fairly mature. Price cannot necessarily be increased, but formulations and manufacturing processes can be adjusted to try to reduce cost, increasing the margin (e.g., replacing equipment to be more energy efficient or changing inputs). On the other hand, the characteristics of innovative products, such as high-end fashion and smartphones, provide firms an incentive to innovate the product to increase demand. For fashion items, product innovations might include designing clothes from fabrics that can be washed effectively in cold water, and for smartphones, it might involve improving the use stage energy efficiency so phones need less frequent charging and less time per charge.

The classification of products into four categories in Figure 1 allows us to analytically compare the change in environmental impact between the two stages. We find that for products in Categories 2 and 3, the differential stage impact depends only on the relationship between the environmental impact of overproduction in each of the stages. In addition, we show that, regardless of category, when the firm invests in DfE innovation, the quantity produced will be higher than the case without innovation, and consequently the overproduction quantity is higher as well. Furthermore, using a comprehensive (data based) numerical study, we demonstrate that while bread (representative of perishable food products) displays an improved overall environmental impact with investment in DfE innovation, the overall impact worsens for the other three categories' representative examples.

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 previously addressed in a very limited manner.

The rest of this article 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 analytically define and examine the environmental impacts resulting from the firm's decisions. In section 5, we apply our model to the four product categories described above using (LCA data based) numerical analysis, and in section 6, we extend our analysis, 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 study 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, sustainable operations, covers a wide range of research in the areas of closed-loop supply chains, remanufacturing (e.g., Ferguson and Souza 2010, Guide et al. 2003), sustainable supply chains (e.g., Linton et al. 2007, Srivastava 2007), and greener technology choices (e.g., Krass et al. 2012).

Overproduction is mainly studied in the inventory control and secondary markets literature (e.g., Lee and Whang 2002). Discussion of the environmental impact of overproduction is only in its early stages 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 non-governmental organizations and other organizations focused on promoting sustainable production and consumption patterns (Mindfully.org 2011). 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, and toxicity) but also granulates the analysis by life-cycle stage. This systematic approach provides a tool to understand the impacts per stage and helps guide the choice of where to focus improvement efforts (Finster et al. 2001, Gasafi et al. 2003, Guinée 2002). However, the method and its concepts are just beginning to be used in the operations management field, such as in this article.

Our work also relates 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) and is usually referred to in two ways: relative decoupling and absolute decoupling (United Nations Environmental Programme [UNEP] 2011). Relative decoupling refers to "when the growth rate of the environmentally relevant variable is positive, but less than the growth rate of the economic variable" (OECD 2001, UNEP 2011). Absolute decoupling, on the other hand, refers to the situation when the "resource use declines, irrespective of the growth rate of the economic driver" (UNEP 2011). These definitions are at an economy level. In our case, at the firm level, relative decoupling can be achieved if the environmental impact per unit produced is reduced, while absolute decoupling can be interpreted to mean that the overall environmental impact decreases, despite any growth in production quantity. We refer to those two decoupling terms later in the article when we discuss the improved environmental performance per unit compared with the overall environmental performance, taking into account the changes in demand as well. The other industrial ecology concept we later refer to is the notion of displacement, where the additional environmental impact of new production, either the firm's or competitors', 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 alternative markets.

Prior research in the context of DfE and operations management has mainly focused on product EoL management aspects such as design for remanufacturing (Bras 2010, Dekker et al. 2004, Subramanian et al. 2009). 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.

Finally, our article also touches on the subject of sustainability strategies and, more specifically, eco-efficiency as a strategy. Porter and Van der Linde (1995) argue that more cost-efficient use of resources can create a competitive advantage and therefore should be considered a viable strategy. However, Orsato (2009) argues that eco-efficiency as a strategy might not be sufficient to establish a 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. As expressing environmental impacts in monetary terms is a challenge, an eco-efficiency approach can help to examine trade-offs and to identify cases when environmental improvements are not necessarily worth pursuing (Huppes 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 A.

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 costs c_0 to manufacture in the absence of effort investment. 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 product or process design can 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 the performance or functionality of the product; however, use stage innovations improve the product quality (e.g., through reduced usage cost or reduced product toxicity) and therefore its demand. These innovations decrease the environmental impact per unit as described in section 4.

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

$$c(e_1) = c_0(1 - \gamma e_1) > 0, \tag{1}$$

where c_0 is the cost of the product absent innovation effort and γ is the cost reduction effectiveness per unit of manufacturing stage innovation effort, where $\gamma \in [0, 1]$. This cost structure implies that the firm chooses only eco-efficient innovations (i.e., reducing environmental impact while reducing cost) when investing effort in the manufacturing stage. (In section 6, we study $\gamma < 0$, which means that the environmental innovations the firm chooses are 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 (i.e., increasing demand) 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 2012). Use stage innovation effort increases k, willingness to pay, due to improved product quality through reduced usage cost or improved environmental performance. For example, reducing use stage energy consumption (e.g., switching from dry cleaning to washing by changing fabric types) may increase consumer utility, resulting in higher demand. Not all firms may be equally effective at identifying and implementing use stage innovations (similar to manufacturing stage innovations), and δ captures this.

Demand uncertainty results in 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 (e.g., 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 likelihood that a leftover unit can be sold in 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 (e.g., in the case of perishable food, where there is no recovery value, $s_R = 0$). We assume that this likelihood (θ) of selling leftover units remains constant even after environmental innovation effort takes place. (In section 6, we extend our analysis to the case where the product innovation efforts can impact this fraction.) The expected salvage value per unit for the leftover units is therefore

$$s_T(\theta) = \theta s_A + (1 - \theta)s_R, \tag{2}$$

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

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

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 discussion. The expected profit equation for the firm can thus be written as follows:

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

where

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

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 Equation (3) to obtain the following maximization problem:

$$\max_{e_1,e_2,z} \Pi(e_1,e_2,z) = (p - c(e_1))(A - k(1-\delta e_2)p - g_1(z)) + (s_T(\theta) - c(e_1))g_2(z) - d(e_1^2 + e_2^2)$$

subject to

$$c(e_1) > s_T(\theta)$$

$$e_1, e_2 \geq 0$$

$$\alpha_1 \leq z \leq \alpha_2.$$

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 sold or used. We discuss this further in the next section.

Theorem 1 describes the solution to the firm's maximization problem. All proofs can be found in Online Appendix S1.

THEOREM 1. *If*

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

then

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

and

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

and z^* *solves*

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

where $a = (\gamma c_0)^2 kp\delta/(2d)$, *and* $s_T(\theta)$ *is given in Equation (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 $c(e_1) > s_T(\theta)$. 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 DfE innovation efforts of the two life-cycle stages.

LEMMA 1. *For a given z,*

(i) *The optimal effort levels* e_1^* *and* e_2^* *are both increasing in* γ *and* δ.

(ii) e_2^* *is increasing in* p*, while* e_1^* *is increasing in* p *if* $e_2^* > \frac{1}{2\delta} - \frac{k\delta p^2}{4d}$.

(iii) 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 part (i) of Lemma 1 shows, 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. By part (ii), 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, part (iii) illustrates that 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, and thus generally we would not expect to see e_2^* increasing in c_0. 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 be negative, in which case the constraint holds for every value of c_0, and therefore e_1^* increases in c_0.

Next, we compare the levels of the two efforts. As can be seen in Theorem 2, 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*

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

The left-hand side of condition (9) 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 (e.g., in the case of functional products such as basic apparel), this condition will be easier to satisfy, while when demand is low and margin high (such as in the case of innovative products such as high-end fashion), the condition will be harder to satisfy. Thus, in general, we would expect functional products to have higher investment in manufacturing stage innovation than in use stage innovation, while the opposite will hold for innovative products. Manufacturing stage innovations might include using more cost and energy efficient equipment for farming and/or spinning fabric, while use stage innovations might include using fabrics that can be washed instead of being dry-cleaned.

To measure the environmental impacts of the firm's environmental innovation efforts, we compare the results from the newsvendor models with and without innovation. The comparison includes the changes in quantities produced, sold, and overproduced as well as the associated LCA-based environmental impacts. Absent investment in innovation effort, the firm solves a standard newsvendor problem (N), and thus the objective function in Equation (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 Equation (4). The solution to this is the critical fractile solution:

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

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

LEMMA 2.

(i) $z^* > z_N$
(ii) $g_1(z_N) > g_1(z^*)$ *and* $g_2(z_N) < g_2(z^*)$
(iii) z^* *and* z_N *increase in* θ.

Part (i) says that the stocking factor (and hence production quantity) will always increase compared with the newsvendor case without innovation. This is due to the fact that the product cost decreases with manufacturing stage 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 (ii), we see that, in the innovation case, the shortages decrease, while overproduction increases, as compared with the newsvendor case without innovation. Part (iii) confirms that an increase in the likelihood of selling overproduction units to an alternative market increases the salvage value, which in turn increases the stocking factor in both the with and without innovation cases.

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 (e.g., mega joules (MJ) of electricity consumed, tons of carbon emitted, or liters of water consumed) or an overall impact score, a combined measure of multiple impact categories, based on LCA methodology.

When the firm invests effort toward DfE 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. 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 due to our focus on eco-efficiency. 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:

$$E_T(e_1, e_2, z) = E_1(e_1, e_2, z) + E_2(e_1, e_2, z), \tag{11}$$

where

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

and

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

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 likelihood (θ) of selling overproduction units to an alternative market, as defined in section 3. Units not sold to either market are never used, and thus do not incur any use stage impact. However, these units may then undergo recovery (collection/recycling), and we discuss their potential impact in section 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

$$E_N = E_{N1} + E_{N2}, \tag{14}$$

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,

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

$$\begin{aligned}\Delta E_2 &= E_{N2} - E_2(e_1^*, e_2^*, z^*) \\ &= b_2(A - kp - g_1(z_N)) + b_2\theta g_2(z_N) - (b_2 - \beta e_2^*) \\ &\quad \times (A - k(1 - \delta e_2^*)p - g_1(z^*)) - (b_2 - \beta e_2^*)\theta g_2(z^*) \\ &= b_2((g_1(z^*) - g_1(z_N)) - kp\delta e_2^*) \\ &\quad + \beta e_2^*(A - k(1 - \delta e_2^*)p - g_1(z^*)) \\ &\quad + \theta(b_2(g_2(z_N) - g_2(z^*)) + \beta e_2^* g_2(z^*)).\end{aligned} \tag{16}$$

The overall change in environmental impact is equal to $\Delta E_T = \Delta E_1 + \Delta E_2$. Note that a positive Δ 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

To assess the environmental impact of overproduction, we consider the product type and its fate if it is not sold in the primary market. For short shelf-life products (e.g., perishable food products), most of the overproduction units will be wasted and discarded. Long shelf-life products may be sold at a reduced price (salvage price) either as new products in less developed markets that do not demand the latest technology (fraction θ of products produced) or as parts for repairs and recycling (fraction $(1 - \theta)$ of products produced). 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 Equations (12) and (13) (using $z + g_1(z) = g_2(z)$) into three categories of environmental impact: (i) primary market expected sales (S), (ii) overproduction sold in an alternative market (OPA), and (iii) overproduction that is not resold and therefore recovered through recycling or spare parts extraction (OPR):

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

where

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

and

$$\begin{aligned} E_{OPA1}(e_1,e_2,z) &= (b_1-\beta e_1)\theta g_2(z),\\ E_{OPA2}(e_1,e_2,z) &= (b_2-\beta e_2)\theta g_2(z), \end{aligned} \tag{19}$$

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

To be consistent with our model that does not include the impact of the EoL stage and because these units are never used, we assume that $E_{OPR2}(e_1, e_2, z) = 0$. In practice, recovery of 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 with overproduction units recovered that are not used is important for two reasons: First, units produced and not sold waste resources such as materials and energy, even if some of those resources can be recovered 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 ΔE_{Si} as the change in environmental impact from sales in stage $i = 1, 2$, and ΔE_S as the overall change in environmental impact from sales using Equations (17)–(18). Similarly, we define the change in environmental impact from overproduction sold in an alternative market in each stage i as ΔE_{OPAi}, $i = 1, 2$, and the change in environmental impact from overproduction that is not resold for stage 1 as ΔE_{OPR1}. We define the overall change in environmental impact from overproduction as ΔE_{OP}. (For ease of exposition, we do not formally define the environmental impact of sales and overproduction for the case without innovation; however, they are the same as the general case with $e_1 = e_2 = 0$ and $z = z_N$.) Accordingly, we have

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

$$\begin{aligned} \Delta E_S &= \Delta E_{S1}+\Delta E_{S2}\\ &= [\beta(e_1^*+e_2^*)\underbrace{(A-k(1-\delta e_2^*)p-g_1(z^*))}_{Exp\ Sales\ >\ 0}\\ &\quad -(b_1+b_2)\underbrace{(kp\delta e^*+g_1(z_N)-g_1(z^*))}_{\Delta Exp\ Sales\ >\ 0}], \end{aligned} \tag{21}$$

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

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

and

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

We use these various Δ measures 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 important aspects of the environmental impact. These measures help us examine the impact of innovation on achieving absolute decoupling when relative decoupling exists.

4.3. Change in Total Environmental Impact

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

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

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 factors β and b_i, $i = 1, 2$. The following definition helps to characterize the condition for when the total environmental impact worsens.

Definition 1.

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

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

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

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

(iii) *A product is compensatory if the characteristics of the products are such that $\Delta E_T > 0$, where ΔE_T is defined in Equation (25).*

We use *compensatory* to mean that the per-unit environmental innovation improvement compensates for the quantity increase. This corresponds well to the UNEP argument (UNEP 2011, p. 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 because of demand growth (e.g., reduce the impact per unit by half and grow the market by 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 (Δ*Exp Sales*/*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 these efforts can compensate for the impact from increased sales and overproduction quantities, and thus, overall we still achieve a reduction in the total environmental impact. As Theorem 3 shows, the sign of the change in environmental impact depends on the compensatory nature of the product.

THEOREM 3.

(i) If the product is both S-compensatory and OP-compensatory, then the product is compensatory.
(ii) If the product is neither S-compensatory nor OP-compensatory, then the product is non-compensatory.
(iii) Otherwise the product could be either compensatory or non-compensatory.

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 trade-off between increased quantity and reduced impact per unit. Thus, the *compensatory* concept captures the inherent trade-off 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

While LCA helps firms evaluate the environmental impact of different stages in the life cycle, the question remains under what conditions will the environmental impact for the manufacturing stage be higher than that of the use stage and vice versa. The understanding of the impact across the different life stages is important for several reasons: First, when the main impact is from the manufacturing stage, the firm's cost could increase if a tax was imposed (such as a carbon tax) and the firm might choose to mitigate this impact. Second, if the impact is mainly at the use stage and the firm invests in reducing it by changing design or technology, it might be able to charge a premium or use it as an environmental marketing tool. Third, from a policy-making perspective, understanding the source of the main impact will help design the right incentives in the forms of taxes, cap, and trade systems, or efficiency indices as in the case of cars or electric white goods. Theorem 4 provides these conditions.

THEOREM 4. *$\Delta E_1 > \Delta E_2$ if and only if*

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

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. This is summarized in the next corollary.

COROLLARY 1.

(i) If $e_1^* > e_2^*$, and $b_2 > b_1$, then $\Delta E_1 > \Delta E_2$ if $\Delta E_{OP1} > \Delta E_{OP2}$.

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

As can be seen by part (i) of the corollary, if a product has higher investment in manufacturing stage innovation ($e_1^* \geq e_2^*$) and higher environmental impact per unit in the use stage ($b_2 > b_1$), then the relationship between the change in environmental impact for the manufacturing stage and that of the use stage depends only on the change in environmental impact of overproduction for the two stages. Recall that by Theorem 2, we expect functional products to have higher investment in manufacturing stage innovation. Thus part (i) of the corollary refers to products in Category 3 of the products matrix (Figure 1), such as basic apparel, which is functional and has higher per-unit environmental impact in the use stage. Because the firm does not optimize environmental outcomes, the optimal efforts e_i do not depend on the environmental impact per stage b_i, $i = 1, 2$. This leads to the result that even though the use stage has higher environmental impact per unit, the firm invests more in manufacturing stage innovation and thus will have a larger change in manufacturing stage environmental impact. Part (ii) refers to innovative products in Category 2 (e.g., smartphones) that, although the manufacturing stage has a higher per-unit environmental impact, will have a larger change in use stage environmental impact as long as the change in environmental impact of overproduction is higher in the use stage.

5. Numerical Analysis of Product Categories

To demonstrate our analytical results, we apply our model to one example from each of the four product categories presented in Figure 1. We use representative products for which LCA data are available and conduct a numerical study using that data as described below.

5.1. The Numerical Study

The four products we analyze are bread (for perishable food products), a fan, a smartphone, and a down sweater (for high-end fashion). For each product, we had more than one LCA reference (see below and Table B2); thus, we are not referring to a specific model or brand. The application of the model to each of the products includes innovations in the manufacturing and use stages. For example, The Bread Factory, a British bakery, installed new energy efficient ovens, reuses cardboard trays, and changed other production processes to reduce waste of raw materials (The Bread Factory 2012). Patagonia, a down sweater manufacturer, uses recycled polyester for the sweater shell, a manufacturing stage innovation (Patagonia 2012). In designing the iPhone, Apple improved the energy efficiency of the USB adaptor, a use stage innovation (Apple 2012). Similarly, fan manufacturers are urged by the US Department of Energy to redesign motors to be more energy efficient in the use stage (DOE 2003).

We ran a full-factorial numerical analysis with six parameters at three levels each, for a total of 729 runs per product. Full details of the parameters used are in Appendix A. We highlight some of the key ones here. The experimental parameters are p, c_0, θ, β, γ, δ, while the other parameters remain 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 measured in megajoules of electricity usage. Although the impact can be measured using a LCA score that represents multiple impact categories, in this study we refer to a single category of measurement, energy consumption.

Table 1 Numerical Analysis Parameter Ranges

	Bread	Fan	Smartphone	Down sweater
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 outcomes including stocking factor z, critical fractile, efforts, profit, percent change in quantity and overproduction, and average change in environmental impacts in each stage and overall. The fractile is above 50% for innovative products, which have higher margins, but lower than 50% for the functional, low margin products.

In general, the efforts for the functional products (i.e., bread and fan) are lower than those for the innovative ones (i.e., smartphone and down sweater) due to the lower margins. In addition, 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 case without innovation, as does the overproduction, for all four products as predicted by Lemma 2. Note, however, that the percentage increase in quantity produced is much smaller for functional products than for 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 likelihood (θ) of selling overproduction to an alternative market, and the salvage values (s_A and s_R). We see that a smartphone has a much higher $\%\Delta OP$ than a down sweater does, even though they have similar values of margin and θ, due to the higher salvage values s_A and s_R for a smartphone.

Recall that the per-unit change in environmental impact is always positive, as the innovations chosen are eco-efficient. However, it is possible to obtain a worse impact overall due to the increase in quantity (i.e., relative but not absolute decoupling is achieved). In our results, only the overall impact of bread is improved from the efforts ($\Delta E_T > 0$), which means that the increase in production was small enough so the per-unit improvement compensated for it, while the other three products (fan, smartphone, and down sweater) have a negative change in overall environmental impact. Table 2 shows the average value for ΔE_i and the percentage of the 729 cases for which it is positive. We discuss these in more detail in Figure 2.

Figure 2 provides evidence as to how the product characteristics influence the environmental impact outcomes. In the figure, we use the four categories from Figure 1 (i.e., functional/innovative and whether they have higher manufacturing or use stage impact) to summarize our findings and results from the numerical analysis. The number in parentheses shows the percentage of cases for which the corresponding result was achieved.

It is clear that the type of product affects the choice of z. Functional products have lower margins and, 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 (recall margins are less than 50%). A fan has a slightly higher z value due to its higher salvage value, which comes from the existence of alternative markets and the possibility of recycling/reusing parts such as motors. Conversely, the innovative products have positive z values; thus, the firm

Figure 2 Results Summary by Category

Product Type

Environmental Impact	Functional	Innovative
Higher env. impact during mfg. stage (b_1>b_2)	Bread (Category 1) $z^* < 0$ (100%) $e_1^* > e_2^*$ (100%) $\Delta E_T > 0$ (100%) $\Delta E_1 > \Delta E_2$ (99.6%) $\Delta E_S > 0$ (100%) $\Delta E_{OP} < 0$ (96.3%) $\Delta E_{OP1} < \Delta E_{OP2}$ (96.3%)	Smartphone (Category 2) $z^* > 0$ (100%) $e_2^* > e_1^*$ (95.5%) $\Delta E_T < 0$ (100%) $\Delta E_2 > \Delta E_1$ (100%) $\Delta E_S < 0$ (100%) $\Delta E_{OP} < 0$ (99.5%) $\Delta E_{OP1} < \Delta E_{OP2}$ (100%)
Higher env. impact during use stage (b_2>b_1)	Fan (Category 3) $z^* < 0$ (95.1%) $e_1^* > e_2^*$ (95.1%) $\Delta E_T < 0$ (85.2%) $\Delta E_1 > \Delta E_2$ (100%) $\Delta E_S < 0$ (80.5%) $\Delta E_{OP} < 0$ (100%) $\Delta E_{OP1} > \Delta E_{OP2}$ (66.7%)	Down Sweater (Category 4) $z^* > 0$ (100%) $e_2^* > e_1^*$ (87.7%) $\Delta E_T < 0$ (100%) $\Delta E_1 > \Delta E_2$ (100%) $\Delta E_S < 0$ (100%) $\Delta E_{OP} < 0$ (90.1%) $\Delta E_{OP1} > \Delta E_{OP2}$ (74.2%)

Table 2 Summary Results (Averages over All Cases)

	Bread	Fan	Smartphone	Down sweater
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	$74.44	$468.50	$6744.97	$3073.18
$\%\Delta Q$	0.03%	0.88%	106.66%	50.95%
$\%\Delta OP$	2.53%	16.78%	18.28%	9.77%
$\Delta OP/\Delta Q$	15.71%	12.30%	2.03%	2.19%
ΔE_1 (% cases > 0)	2.02 (100%)	−0.76 (47.2%)	−3316.70 (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)	2.16 (100%)	−16.75 (14.8%)	−5140.91 (0%)	−648.17 (0%)

produces more than the mean expected demand due to higher margins and higher salvage values.

For bread and the fan, 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 the fan), while for the innovative products, the use stage innovation effort is higher (95.5% for the smartphone and 87.7% for the down sweater). This can be attributed to the fact that functional products have lower margins and higher 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.

Recall that Corollary 1 provides conditions under which $\Delta E_1 > \Delta E_2$. The fan represents part (i) of the corollary, while the smartphone represents part (ii). For the fan, there is higher environmental impact per unit in the use stage ($b_2 > b_1$), almost always higher investment in manufacturing stage innovation ($e_1^* > e_2^*$), and, in addition, two-thirds of the cases have $\Delta E_{OP1} > \Delta E_{OP2}$. In 100% of the cases, $\Delta E_1 > \Delta E_2$ for the fan 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. On the other hand, for the smartphone, there is higher environmental impact per unit in the manufacturing stage ($b_1 > b_2$), almost always higher investment in use stage innovation ($e_2^* > e_1^*$), 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 the down sweater. The results for the fan (smartphone) show that even when the use (manufacturing) stage impact is higher, for functional (innovative) products it is worth investing more in 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 total 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 ($\Delta E_S > 0$), meaning 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, the smartphone is almost never OP-compensatory and is so less frequently than the down sweater. This is due to the size of the initial impacts, b_1 and b_2. From Equation (27), it can be seen that larger b_i values will make the condition harder to satisfy. For bread and the fan, because the efforts are small, the change in per-unit impact is also small. However, because the initial impacts for the fan are larger, there are fewer (in fact zero) cases where the fan is OP-compensatory as compared with bread. These results show very well how hard it can be to achieve absolute decoupling with anticipated growth.

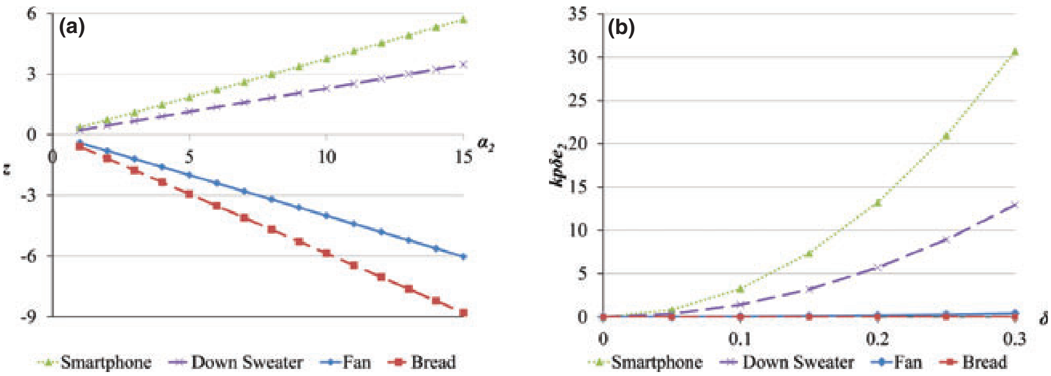
Regardless of the fact that the per-unit change in environmental impact is positive, Table 2 and Figure 2 show that it is still possible to obtain overall worse environmental outcomes ($\Delta E_T < 0$). The majority of this change in impact comes from the increase in sales in our numerical study. The 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 growth is typically considered a positive occurrence.

5.3. Comparative Statics

To gain more insight into the effects of the model parameters, we use the numerical results to examine how increased demand variability, use stage innovation effectiveness, 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 having leftover units for which the production cost is incurred. 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 aggressive for innovative goods.

Figure 3(b) shows the change in deterministic demand as use stage innovation effort effectiveness increases. The functional goods (fan and bread) have very little change as δ increases, while the innovative ones have more, with the change for the smartphone being fairly significant. Recall that 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 1(i).

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 the initial cost c_0 (as a fraction of p) on the manufacturing and use stage efforts. As described in Lemma 1(iii), the efforts are not linear in cost. For the example parameters, manufacturing stage effort increases in cost while use stage effort decreases. This is as expected: As the cost approaches 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.

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 use stage innovation effort affects the likelihood of an overproduction unit being sold in the alternative market.

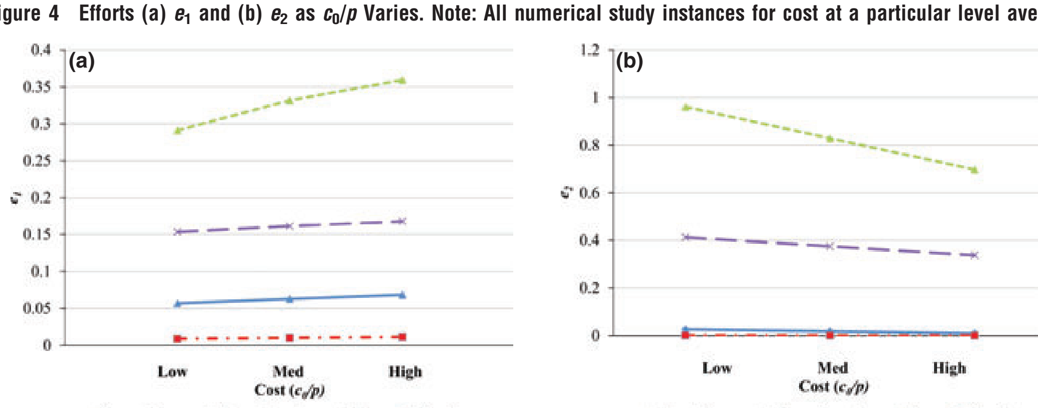
6.1. Costly Environmental Innovation

Thus far, we have assumed that the firm invests in DfE innovations that reduce the cost of the product or increase its demand. It is possible, however, that the innovation is costly and thus would increase the product's unit cost (i.e., $\gamma < 0$). As can be seen in Theorem A1 in the Online Appendix S1, if the manufacturing stage innovation is costly, the firm will not want to invest any effort in it (as the firm maximizes profits). Thus, the stocking factor will be identical to that in the case without innovation, and, consequently, the only increase in quantity is due to the use stage innovation effort, which increases the deterministic demand. It is also easy to show that $\Delta E_{OP} > 0$, and thus the change in total environmental impact (ΔE_T) will be positive if the product is S-compensatory.

6.2. Use Stage Innovation Increases the Likelihood of Selling Product in an Alternative Market

Thus far, we assumed that the likelihood a unit will be sold to an alternative market is independent of the firm's decisions. It is possible, however, that when the firm improves the use stage environmental performance of the product through use stage innovation efforts, it will also increase the likelihood an overproduction unit can be sold in an alternative market. In this case, the likelihood 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 ($\omega > 0$). Theorem 5

Figure 4 Efforts (a) e_1 and (b) e_2 as c_0/p Varies. Note: All numerical study instances for cost at a particular level averaged



describes the result of this dependency on the optimal efforts and stocking factor.

THEOREM 5. *When $\theta(e_2) = \theta + \omega e_2$,*

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

then

$$e^*_{1\theta} = \frac{\gamma c_0}{2d(2d - kp\delta a)}((kp\delta)^2(p - c_0) + 2d(A - kp + z^*_\theta) + hg_2(z)), \quad (29)$$

and

$$e^*_{2\theta} = \frac{kp\delta(p - c_0) + a(A - kp + z^*_\theta) + hg_2(z)/kp\delta}{2d - kp\delta a}, \quad (30)$$

and z^*_θ solves

$$kp\delta(p - s_T(\theta))(2d - kp\delta a)F(z^*_\theta) = (2d + hF(z^*_\theta))[kp\delta(p - c_0) + a(A - kp + z^*_\theta)], \quad (31)$$

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

As can be seen in the theorem, if the likelihood a unit is sold in an alternative market 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 Equations (29) and (30) with Equations (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 ($\Delta E_{T\theta}$) increases or decreases from ΔE_T depends on this trade-off between quantity increase and per-unit impact improvement.

COROLLARY 2. *When $\theta(e_2) = \theta + \omega e_2$, then*

(i) $e^*_{1\theta} > e^*_1, e^*_{2\theta} > e^*_2$
(ii) $z^*_\theta > z^*$
(iii) $\Delta E_{T\theta}$ 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 bread) the overall environmental impact improves, for others (such as a fan, a smartphone, and a down sweater), the total impact worsens.

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. Our findings suggesting 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 products to market to satisfy uncertain demand for innovative products and with the general prescription that innovation efforts should focus on products (use stage innovation) when they are earlier in their product life cycles, but process innovation (manufacturing stage 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 environmentally conscious consumers, but also from those concerned with total cost of ownership, even if environmental considerations are not their priority.

Firms should actively be engaged in design changes that affect the use stage environmental impact (such as designing clothes from fabrics that can be washed instead of dry-cleaned or washed in cold water instead of hot water) or improving the energy efficiency of smartphones so they need less charging time less frequently. 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 DfE 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 resulting increase in 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, 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 additional units can be produced (i.e., allow for growth), while overall depleting fewer energy resources. We find that absolute decoupling does not occur in our case for innovative products, but is more likely to occur for functional products. Products that have either improved overall environmental impact from sold quantities (S-compensatory) or from overproduced quantities (OP-compensatory) may achieve absolute decoupling, and products that are both S- and OP-compensatory do achieve it. Therefore, our S- and OP-compensatory definitions serve as an important contribution in turning absolute decoupling into a practical consideration at the firm level. This phenomenon is also related to the concept of the rebound effect (Berkhout et al. 2000, Hertwich 2005), where efficiency gains are lost back in overuse of resources. As we show, it is especially relevant for innovative products due to their inherently high-demand uncertainty.

We also find that environmentally focused innovation efforts increase the amount of overproduction units in our model. Our numerical study demonstrates that the firm's environmental impact from overproduction generally increases with innovation efforts. From a LCA 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 consumers purchase the items determine the overall 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 increased 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 (functional or innovative), 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 with 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 (displacing new production) from a firm with a higher environmental impact might be preferable from a social welfare perspective. For the sake of tractability, we focus on a limited setting where the use stage efforts have no impact on the unit cost, while the manufacturing stage efforts do not impact demand. Future research can look into the possibility of a stage's effort impacting both cost and demand. Other issues for future research 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.

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Appendix A: Notation

Table A1 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), where $z = q - (A - k(1 - \delta e_2)p)$
e_i	Effort level i, $i = 1, 2$ (decision variables)
$\Pi(e_1, e_2, z)$	Profit expression
p	Price
c_0	Manufacturing cost in the absence of investment
$c(e_1)$	Cost after manufacturing stage innovation effort incurred
q	Order quantity
A	Market size
k	Price sensitivity
ε	Variable portion of demand, where $\varepsilon \sim F(\cdot)$ on $[\alpha_1, \alpha_2]$ with density $f(\varepsilon)$, and $E(\varepsilon) = 0$

(continued)

Table A1 ***(continued)***

Parameters and decision variables	Definition
$D(e_2, \varepsilon)$	Demand distribution, where $D(e_2, \varepsilon) = A - k(1 - \delta e_2)p + \varepsilon$
$g_1(z)$	Expected shortage units
$g_2(z)$	Expected leftover units
d	Cost per unit of effort
γ	Effectiveness in decreasing cost through manufacturing stage innovation (per unit of effort), where $\gamma \in [0, 1]$.
δ	Effectiveness in increasing demand through use stage innovation (per unit of effort), where $\delta \in [0, 1]$.
θ	Likelihood that a leftover unit can be sold in an alternative market, where $\theta\ \varepsilon\ [0, 1]$
s_A	Net salvage value per unit when sold to an alternative market
s_R	Net salvage value per unit when recovered, $s_R < s_A$
$s_T(\theta)$	Expected salvage value per unit for leftover units
a	Parameter defined, $a = (\gamma c_0)^2 kp\delta/(2d)$
b_i	Environmental impact per unit for stage i, $i = 1, 2$
β	Environmental improvement effectiveness per unit of innovation effort

Table A2 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 newsvendor case without innovation
E_N	Total environmental impact across both life-cycle stages in the 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 expected sales with and without innovation effort in stage i, $i = 1, 2$
ΔE_S	Difference between environmental impact from expected 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 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

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1: Proofs.
Appendix S2: Numerical Study.