Manufacturing & Service Operations Management

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

The Role of Modular Upgradability as a Green Design Strategy

Vishal V. Agrawal, Sezer Ülkü

MANUFACTURING & SERVICE OPERATIONS MANAGEMENT
Vol. 15, No. 4, Fall 2013, pp. 640–648
ISSN 1523-4614 (print) | ISSN 1526-5498 (online)
http://dx.doi.org/10.1287/msom.1120.0396

The Role of Modular Upgradability as a Green Design Strategy

Vishal V. Agrawal, Sezer Ülkü
McDonough School of Business, Georgetown University, Washington, DC 20057
{va64@georgetown.edu, su8@msb.edu}

Modular upgradability has been suggested as a strategy for improving environmental performance: as technology improves, it allows for independent replacement of improving subsystems, instead of replacing the entire product. This may extend the useful life of stable subsystems, reducing production and disposal impact. However, this argument ignores the effect of modular upgradability on a firm's development and introduction decisions and the environmental impact during the use phase. In this paper, we investigate when modular upgradability leads to lower environmental impact and higher profits. We do so by endogenizing a firm's development and introduction decisions and considering the product's environmental impact during its entire life cycle. Our results show that although modular upgradability may accelerate the replacement of some subsystems, it delays the replacement of others. We find that modular upgradability can increase the environmental impact for some product categories due to accelerated obsolescence arising from more frequent introduction and replacement. However, we also find that accelerated obsolescence, under some conditions, can actually make modular upgradability greener.

Key words: modularity; green product design; sustainability; new product development; sustainable operations
History: Received: May 12, 2011; accepted: March 17, 2012. Published online in *Articles in Advance* October 5, 2012.

1. Introduction

Rapid technological progress, especially for electronic products (e.g., cell phones, PCs, printers), provides customers with an opportunity to use better and improved products. However, this also leads to shorter product life cycles, resulting in new production and disposal of obsolete products. This has a detrimental effect on the environment due to increased consumption of raw materials and energy, and pollution. For example, 315 million PCs (90% of which were still functioning) were scrapped in 2004, and in 2005, 100 million cell phones were discarded (Slade 2006).

A potential solution to address this negative environmental consequence of technological change is the use of a modular upgradable architecture: it enables the independent replacement of subsystems, which allows customers to only replace the improved subsystems while retaining the rest of the product. For example, Cisco networking products and Dell computers are designed so that subsystems such as processors, drives, and memory chips can be upgraded (Cisco 2009, Dell 2003). This is in contrast to integral designs, which do not allow for subsystem upgradability. For example, most Apple products (e.g., desktop computers) require the replacement of the entire product to upgrade memory or graphics capabilities (Greenpeace 2011). Because only some subsystems become obsolete and are discarded for modular upgradable products, the total quantity of production and disposal can be reduced. Hence, modular upgradability can be environmentally beneficial by extending the useful life of subsystems (Newcomb et al. 1996, Bras 2009, *Economist* 2011).

The use of modular upgradable architecture as an environmentally superior strategy has been promoted by several environmental groups (U.S. Office of Technology Assessment 1992, Keoleian and Menerey 1993, Minnesota Pollution Control Agency 2010, U.S. Environmental Protection Agency 2010). The Electronic Product Environmental Assessment Tool (EPEAT) environmental rating for electronic products (EPEAT 2006) and Walmart's ratings for its consumer electronics suppliers (Plambeck and Denend 2008) include modular upgradability as a criterion. Several consumer electronics and information technology firms have also included modular upgradable architectures as a part of their design-for-environment strategies: Cisco, Dell, Hewlett-Packard (HP), IBM, and Xerox design products for upgradability, which allows them to "breathe new life into old equipment" (Cisco 2009, Dell 2003, Hewlett-Packard 2011, IBM 2010, Xerox 2010).

Despite the popularity of modular upgradability with environmental groups and industry, the overall effect of modular upgradability on the environment is not well understood. In particular, the ability to decouple the introduction of subsystems may reduce the development time (Ulrich 1995, Baldwin and

Clark 1997, Ramachandran and Krishnan 2008). This leads to accelerated introduction and replacement under modular upgradability, resulting in an increase in the environmental burden as a result of greater production and disposal. Moreover, whereas the arguments for the environmental benefits of modular upgradability focus on the production and disposal impact of products, they ignore use impact, which may constitute most of the environmental impact for products such as manufacturing machinery, networking equipment, washers, and dryers.

In this paper, we investigate the role of modular upgradability as a green design strategy by endogenizing the firm's development and introduction decisions and customers' replacement decisions. We consider the environmental impact of the product in each phase of its life cycle (namely, production, use, and disposal). This enables us to explicitly investigate when modular upgradability leads to lower *total* environmental impact. Our research offers insights for firms that adopt modular upgradability as a green design strategy by identifying when it is more profitable and greener.

Our work builds on and contributes to the previous literature on sustainable operations, new product development, and engineering design. In the sustainable operations literature, an emerging stream of research examines the design decisions related to product recovery and reuse (Debo et al. 2005, Agrawal et al. 2012, Subramanian et al. 2012) and the effect of regulation on product design (Plambeck and Wang 2009, Atasu and Subramanian 2012; see Agrawal and Toktay 2009 for an overview). We complement this stream of literature by investigating the impact of product architecture on the environment. We build on the model of Plambeck and Wang (2009) to analyze the relationship between the rate of obsolescence and environmental impact. However, we model product architecture by considering the product to be composed of different subsystems and model both decoupled and coupled introduction of subsystems by the firm. In addition to the production and disposal impact, we also consider the environmental impact during the use phase of the product.

A stream of literature in engineering and industrial ecology studies the efficacy of different design-for-environment strategies (Graedel and Allenby 1995, Lenox et al. 2000). Newcomb et al. (1996) and Bras (2009) discuss the potential environmental benefits of modularity as a design-for-environment strategy because it allows customers to replace only the improved subsystem instead of the entire product. However, they ignore the effect of a modular upgradable architecture on the firm's development and introduction decisions. Moreover, they only focus on the production and disposal impact and do not consider the effect of modular upgradability on use impact.

The literature in new product development has studied the effect of modularity on the firm's development and introduction decisions (see Fixson 2007 for an overview). For example, modularity can accelerate the introduction of innovations both at the subsystem level and at the product level (Ulrich 1995, Baldwin and Clark 1997, Ramachandran and Krishnan 2008). This stream of literature does not consider the effect of modular upgradability on the firm's environmental performance. However, based on this literature, one may infer that it is environmentally detrimental due to the accelerated introduction of improvements. This insight conflicts with the arguments about the environmental superiority of modular upgradability in the engineering and industrial ecology literature.

In this paper, we investigate the overall effect of modular upgradability on the environment. To do so, we endogenize the firm's development and introduction decisions and also consider the product's environmental impact in its entire life cycle. We show that although modular upgradability may accelerate the introduction of a subsystem, it delays the introduction of others. We find that it can increase the environmental impact due to accelerated obsolescence arising from more frequent introduction and replacement. However, we find that under some conditions, accelerated obsolescence can actually make modular upgradability greener.

2. The Model

We consider a profit-maximizing monopolist that periodically introduces and sells a perfectly durable product over an infinite time horizon (Fishman and Rob 2000, Plambeck and Wang 2009). The performance of a product is the sum of the performance of its subsystems (Krishnan and Ramachandran 2011, Ülkü and Schmidt 2011). Without loss of generality, we assume that the product is composed of two subsystems. Product performance is cumulative, and every improvement builds on the previous generation. We denote the per-unit production cost for each subsystem $k \in \{1, 2\}$ by $c_k \geq 0$.[1] A summary of our notation is provided in Appendix B.

The sequence of events is as follows: First, the firm makes its strategic choice between a modular upgradable or an integral architecture. We denote the parameters for the modular upgradable architecture case by the subscript M and those for integral architecture case by the subscript I. Subsequently, by engaging in development, it can introduce successive generations of improvements. When an improved product or subsystem is introduced, customers decide whether to purchase it.

We assume that the business is profitable for the firm under both architectures; i.e., the costs are not

[1] Note that the presence of a disposal fee can be easily captured in our model by an increase in the production cost.

prohibitively high. For brevity and ease of exposition, we assume that $c_1 = c_2 = c$, but all our results hold for $c_1 \neq c_2$ (see the online supplement for details, available at http://dx.doi.org/10.1287/msom.1120.0396).

2.1. Architecture Choice

At time $t = 0$, the firm chooses either a modular upgradable or an integral architecture. For example, in the computer industry, some firms such as Dell choose a modular upgradable architecture, which allows for independent replacement of improved subsystems such as memory, processors, and drives (Dell 2003). However, other firms such as Apple utilize an integral architecture, which does not allow for hardware upgrades. This requires customers to replace the entire product to gain access to improvements.

The performance of a modular upgradable product may be lower than that of an integral one for several reasons: To enable future upgradability, a modular upgradable product may have additional interfaces, which may make it bulkier (Whitney 2004). Even when there is no such technical performance difference, customers may perceive a product with an upgraded subsystem to be of lower performance than an entirely new product (MacDonald 2011). We model such a performance loss due to modularization by a fraction $\delta \in [0, 1]$, which depends on the nature of the product (Whitney 2004). For example, δ is higher for mechanical systems such as washers and dryers, and it is lower for products such as computers, routers, and servers.

2.2. Development and Introduction of Subsystems

As commonly practiced in several industries such as computers, electronics, and networking equipment (Baldwin and Clark 1997), we assume that the firm develops the subsystems independently. For each subsystem k, the firm chooses how much time and money to spend on developing an improvement. For a development time T and an investment x, the resulting improvement in the performance of the subsystem is given by $g_k(x, T)$ and $(1-\delta)g_k(x, T)$ under the integral and modular upgradable architectures, respectively.

We assume that $g_k(x, T) = n_k x^\alpha T^{1-\alpha}$, where $n_k \geq 0$ captures the improvement potential for subsystem k and $\alpha \in (0, 1)$. This standard Cobb–Douglas specification for $g_k(x, T)$ is commonly used and supported by empirical evidence (Cohen et al. 1996). It also guarantees the existence of a unique equilibrium in our model (see the online supplement for details). The improvement in the performance $g_k(x, T)$ is increasing with marginal decreasing returns in both x and T, and x and T are complementary. The improvement potential depends on the underlying technology and the customers' valuation for an improvement in the performance of that subsystem, and it typically differs across subsystems. For example, the potential improvement and the customer's valuation for an improvement in input/output devices, such as a keyboard, is far smaller than for a processor. Without loss of generality, we assume that $n_1 > n_2$; i.e., the improvement potential for the first subsystem is higher. Let x_{kI} and x_{kM} denote the development investment for a subsystem k under the integral and modular upgradable architectures, respectively.

If the firm chooses an integral architecture, its introduction decision for the two subsystems is coupled; i.e., the time between introductions is the same for both subsystems. However, under a modular upgradable architecture, the firm can introduce the two subsystems independently. Because the improvement is increasing in the development time, the firm will continue developing the product or subsystem until its introduction. Therefore, under both architectures, the development time for a subsystem will be the same as the time between introductions (see the online supplement for details). Let the development time under the integral architecture be denoted by T_I and that for a subsystem k under the modular upgradable architecture be denoted by T_{kM}.

2.3. Customers

We assume that the firm faces a homogeneous and forward-looking customer population, the size of which is normalized to one. We assume that both the firm and customers have the same discount rate ρ, and all information regarding cost structures and preferences is common knowledge. The customers already own an existing product at time $t = 0$, and they have use for only one product at a time.

When a new product (or a subsystem) is introduced, the maximum price that customers are willing to pay depends on the improvement in the performance over their existing unit (Kornish 2001) and the expected duration of use from the new unit. Because the customers are homogeneous, the firm will find it optimal to charge this maximum price. Under the integral architecture, the customers' expected duration of use from a new generation product, T_I^e, is equal to the expected development time of the next generation. If the discount rate is ρ, the price the firm will charge for an improved product is given by $(g_1(x_{1I}, T_I) + g_2(x_{2I}, T_I)) \int_0^{T_I^e} e^{-\rho t}\, dt$. Under modular upgradability, if the expected duration of use from a new generation of subsystem k is T_{kM}^e, then the price that the firm will charge for an improved subsystem k is given by $(1-\delta)g_k(x_{kM}, T_{kM}) \int_0^{T_{kM}^e} e^{-\rho t}\, dt$.

2.4. Environmental Impact

When an existing product or subsystem is replaced by an improved version, new units are produced and existing units are disposed of, resulting in additional consumption of raw materials and energy, as well as increased waste and pollution. The use of the product also leads to environmental impact as a result of the consumption of energy and pollution. For example, the production and disposal of an Apple laptop results in approximately 300 kg of CO_2e emissions, and its use leads to 125 kg of CO_2e over an average lifetime (Apple 2011).

The environmental impact as a result of production, use, and disposal may decrease over time. For example, the imposition of energy-efficiency standards caused the efficiency of refrigerators to improve by more than 150% during 1980–2002 (Kim et al. 2006), and regulations like the Restriction of Hazardous Substances Directive (RoHS) and the regulation on Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) in the European Union (EU) are progressively causing manufacturers to eliminate hazardous materials and thus reduce production and disposal impact. The rate of use impact of an improved subsystem k introduced at time $t > 0$ is given by $i_k^u e^{-r^u t}$, where $r^u \geq 0$ is the exogenous rate of improvement in use impact. We assume that the rate of use impact for each unit is constant during its lifetime. When an improved version of subsystem k is introduced at time $t > 0$, the environmental impact due to the production of a new unit and the disposal of an old unit is given by $i_k^{pd} e^{-r^{pd} t}$, where $r^{pd} \geq 0$ is the exogenous rate of improvement in the production and disposal impact.

Let $\omega \doteq (i_1^{pd} + i_2^{pd})/(i_1^u + i_2^u)$ represent the magnitude of production and disposal impact relative to the use impact. Products such as computers, cell phones, and e-readers have higher values of ω, and products such as routers, servers, dryers, and washers have lower values of ω (Kuehr and Williams 2003, Fishbein et al. 2000).

3. Analysis and Results

We now formulate and solve the firm's problem and compare the total environmental impact under integral and modular upgradable architectures.

3.1. Formulation of the Firm's Problem

We restrict our attention to pure-strategy, stationary, and rational expectations equilibria, which implies that all customers have the same expectation regarding the introduction time of the next improvement, and this expectation is correct in equilibrium; i.e., $T_I = T_I^e$ and $T_{kM} = T_{kM}^e$. The firm's problem under the integral and modular upgradable architectures is then given by

$$\begin{aligned}\Pi_I^* &= \max_{T_I, x_{1I}, x_{2I} \geq 0} e^{-\rho T_I}[(g_1(x_{1I}, T_I) + g_2(x_{2I}, T_I)) f(T_I^e) \\ &\qquad - (x_{1I} + x_{2I}) - (c + c) + \Pi_I^*] \\ &= \max_{T_I, x_{1I}, x_{2I} \geq 0} \frac{e^{-\rho T_I}}{1 - e^{-\rho T_I}}[(g_1(x_{1I}, T_I) + g_2(x_{2I}, T_I)) f(T_I^e) \\ &\qquad - x_{1I} - x_{2I} - 2c] \quad \text{and} \end{aligned} \tag{1}$$

$$\begin{aligned}\Pi_M^* &= \sum_{k=1}^{2} \Pi_{kM}^* \\ &= \max_{T_{1M}, T_{2M}, x_{1M}, x_{2M} \geq 0} \sum_{k=1}^{2} (e^{-\rho T_{kM}}[(1-\delta) g_k(x_{kM}, T_{kM}) \\ &\qquad \cdot f(T_{kM}^e) - x_{kM} - c + \Pi_{kM}^*]) \\ &= \max_{T_{1M}, T_{2M}, x_{1M}, x_{2M} \geq 0} \sum_{k=1}^{2} \left(\frac{e^{-\rho T_{kM}}}{1 - e^{-\rho T_{kM}}}[(1-\delta) g_k(x_{kM}, T_{kM}) \right. \\ &\qquad \left. \cdot f(T_{kM}^e) - x_{kM} - c] \right), \end{aligned} \tag{2}$$

where the prices charged for an improvement are given by $(g_1(x_{1I}, T_I) + g_2(x_{2I}, T_I)) f(T_I^e)$ and $(1-\delta) \cdot g_k(x_{kM}, T_{kM}) f(T_{kM}^e)$ under the integral and modular upgradable architectures, respectively, and $f(T) = (1 - e^{-\rho T})/\rho$. There exists a unique equilibrium given by $(T_{1M}^*, T_{2M}^*, x_{1M}^*, x_{2M}^*)$ for the modular upgradable architecture and $(T_I^*, x_{1I}^*, x_{2I}^*)$ for the integral architecture (see Lemma A1 in the online supplement for details).

3.2. Equilibrium Environmental Impact

When the firm introduces an improved subsystem or product, new units are produced, and existing units are disposed of. When subsystem k is introduced at $t = jT$, for $j \in \mathbb{Z}_+$, the resulting production and disposal impact is given by $i_k^{pd} e^{-r^{pd} jT}$, which, discounted back to time $t = 0$, is $i_k^{pd} e^{-(r^{pd} + \rho) jT}$. Because an improved version of the unit is introduced periodically at $t = jT$, the production and disposal impact under the integral and modular upgradable architectures is given by

$$E_I^{pd} = \sum_{j=1}^{\infty} (i_1^{pd} + i_2^{pd}) e^{-(\rho + r^{pd}) j T_I^*} \quad \text{and}$$

$$E_M^{pd} = \sum_{k=1}^{2} \sum_{j=1}^{\infty} i_k^{pd} e^{-(\rho + r^{pd}) j T_{kM}^*}. \tag{3}$$

The rate of use impact for a subsystem k introduced at time $t = jT$ for $j \in \mathbb{Z}_+$ is given by $i_k^u e^{-r^u jT}$. Therefore, when discounted back to time $t = 0$, the use impact due to this unit is given by $\int_{jT}^{(j+1)T} i_k^u e^{-r^u jT} e^{-\rho t}\, dt$. Because an improved version of this unit is introduced periodically at $t = jT$, the use impact under the integral and modular upgradable architectures is given by

$$E_I^u = \sum_{j=0}^{\infty} \int_{jT_I^*}^{(j+1)T_I^*} (i_1^u + i_2^u) e^{-r^u j T_I^*} e^{-\rho t}\, dt \quad \text{and}$$

$$E_M^u = \sum_{k=1}^{2} \sum_{j=0}^{\infty} \int_{jT_{kM}^*}^{(j+1)T_{kM}^*} i_k^u e^{-r^u j T_{kM}^*} e^{-\rho t}\, dt. \tag{4}$$

The total environmental impact is then given by $E_I = E_I^{pd} + E_I^u$ and $E_M = E_M^{pd} + E_M^u$, respectively.

3.3. Comparing Modular Upgradable and Integral Architectures

We next compare the introduction decisions and the total environmental impact under the modular upgradable and integral architectures. We restrict our attention to the region where the firm is willing to adopt modular upgradability. When modularization loss is sufficiently low, modular upgradability is more profitable because the advantage from decoupled introduction of subsystems dominates the negative effect of modularization loss (see Proposition A1 in the online supplement for details). Therefore, modular upgradability is adopted by manufacturers selling products with low modularization losses, such as computers and networking equipment (Cisco 2009, Dell 2003, IBM 2010), and it is typically not used by manufacturers selling products such as washers, dryers, refrigerators, and e-readers.

3.3.1. Introduction Decisions. We first compare the development times between the integral and modular upgradable architectures. For brevity and ease of exposition, we relegate the expressions for the thresholds to Appendix A and suppress functional arguments.

PROPOSITION 1. *If modularization loss is sufficiently low, i.e., $\delta < \Delta_T$, then the development time for the faster-improving subsystem decreases and that for the slower-improving subsystem increases as a result of modular upgradability ($T^*_{1M} < T^*_I < T^*_{2M}$). Otherwise, the development times for both subsystems increase as a result of modular upgradability ($T^*_I \leq T^*_{1M} < T^*_{2M}$).*

Because the first subsystem has a higher improvement potential than the second one, a larger improvement can be achieved in it with the same development time. Therefore, under modular upgradability, the firm always chooses a shorter development time for the first subsystem.

Under the integral architecture, the firm is constrained to choose the same development time for both subsystems. When the modularization loss is sufficiently small, the firm chooses a development time longer than that for the first subsystem under the modular upgradable architecture, but shorter than that for the second subsystem under the modular upgradable architecture. When the modularization loss is large, a larger improvement is required to induce replacement of both subsystems under modular upgradability, leading to longer development times for both subsystems. Therefore, modular upgradability may delay obsolescence for both subsystems in products that have high modularization losses such as manufacturing equipment, e-readers, and appliances, but it may accelerate obsolescence only for one of the subsystems for products that have low modularization losses such as computers, routers, and servers.

3.3.2. Environmental Impact. We next investigate the effect of modular upgradability on the environmental performance of the firm. For brevity and clarity of exposition, we hereafter refer to the subsystem with higher improvement potential as the faster-improving one and the other subsystem as the slower-improving one.

PROPOSITION 2. *If modularization loss is sufficiently low ($\delta < \Delta_T$), then modular upgradable architecture leads to lower total environmental impact than the integral architecture if and only if*

(i) *the production and disposal impact is sufficiently large ($\omega \doteq (i_1^{pd} + i_2^{pd})/(i_1^u + i_2^u) \geq \Omega$), and the slower-improving subsystem is responsible for most of it ($\epsilon^{pd} \doteq i_1^{pd}/i_2^{pd} < Y^{pd}$), or*

(ii) *the use impact is sufficiently large ($\omega < \Omega$), and the faster-improving subsystem is responsible for most of it ($\epsilon^u \doteq i_1^u/i_2^u > Y^u$).*

If modularization loss is high ($\delta \geq \Delta_T$), then modular upgradable architecture leads to lower total environmental impact than the integral architecture if and only if the production and disposal impact is sufficiently large ($\omega > \Omega$).

When modular upgradability accelerates obsolescence ($\delta < \Delta_T$): For products such as computers and networking equipment, which have small modularization losses, new generations of the faster-improving subsystem are introduced more frequently, and those of the slower-improving subsystem are introduced less frequently under the modular upgradable architecture than under the integral architecture. Recall that the use impact per unit time for a unit is lower across generations. Therefore, modular upgradability increases the production and disposal impact and decreases the use impact due to the faster-improving subsystem. However, it decreases the production and disposal impact and increases the use impact due to the slower-improving subsystem.

Consider a product that has low modularization loss and most of its impact in the production and disposal phases ($\omega \geq \Omega$). Modular upgradability reduces the total environmental impact if and only if the faster-improving subsystem has sufficiently low production and disposal impact compared with the slower-improving subsystem. As a result, modular upgradability can increase the environmental impact for products such as computers for which the more frequently upgraded subsystem (i.e., processor) is also responsible for most of the production and disposal impact (Williams 2004). For such products, modular upgradability may be more profitable but environmentally worse. Now consider a product that has low modularization loss but most of its impact occurring in the use phase. Modular upgradability reduces the total environmental impact if and only if the faster-improving subsystem has sufficiently high use impact compared with the slower-improving subsystem. Hence, for products such as servers, where the faster-improving subsystem (i.e., the motherboard) drives the product's use impact (Intel 2011), modular upgradability is greener and more profitable.

When modular upgradability delays obsolescence ($\delta \geq \Delta_T$): For products such as e-readers, washers, and dryers, which have sufficiently high modularization loss, modular upgradability is less profitable and delays both subsystems. This results in lower production and disposal impact but higher use impact under modular upgradability. As a result, the total environmental impact is reduced if and only if the production and disposal impact of the product is sufficiently lower than its use impact. Therefore, modular upgradability is greener but less profitable for products such as e-readers; it is less profitable and environmentally worse for products such as washers and dryers.

4. Robustness and Discussion of Assumptions

We made some assumptions in our analysis to draw sharp and clean insights. We now discuss the implications of relaxing some of these assumptions for our results.

4.1. Product Recovery and Reuse

In practice, firms may recover, reuse, and recycle obsolete products because of legislation such as the European Waste Electrical and Electronic Equipment (WEEE) Directive, or because of the residual value in these products. Because it is easier to separate subsystems under modular upgradability (Newcomb et al. 1996, Bras 2009), the cost of recovery and reuse may be lower, and a larger fraction of the obsolete units may be recovered and reused.[2]

Incorporating a cost of recovery and reuse in our model is equivalent to a higher production cost, which results in longer development times and, consequently, lower production and disposal impact under both architectures. However, the reduction in production and disposal impact will be lower under modular upgradability because of the lower recovery and reuse cost. Thus, for products that have most of their impact in production and disposal phases (for which recovery and reuse is purported to be more beneficial), the presence of recovery and reuse may worsen the relative environmental performance of modular upgradability. However, recovery and reuse may also result in a lower per-unit production and disposal impact under modular upgradability because a larger fraction of units are recovered, improving the relative environmental performance of modular upgradability.

4.2. Effect of Heterogeneous Customers

In the presence of heterogeneous customers, if some customers do not own the current generation product, the firm faces a market segmented by different generations owned by customers. Following arguments analogous to those of Plambeck and Wang (2009), we can consider heterogenous customers, where, for a given generation product, the firm has an incentive to reduce the price over time to sell it to customers with lower valuations (Coase 1972). Because customers expect such price reductions, they will be less willing to purchase an improvement, and the price that the firm can charge is lower. As a result, the development time is higher and investment is lower than in the setting with homogeneous customers under both architectures.

4.3. The Effect of Customer Sensitivity to the Environment

We now consider the presence of customers that experience a disutility proportional to the environmental impact associated with their decisions, assuming that the environmental parameters remain constant across generations. In the presence of such customers, a larger improvement is required to induce replacement to compensate for the environmental impact as a result of new production and disposal. As a result, the development times are longer under both architectures.

5. Conclusions

Modular upgradability has been promoted by environmental groups and adopted by several firms as a green design strategy. However, its overall effect on the environment is not well understood. In this paper, we investigate this by endogenizing a firm's development and introduction decisions and by considering the entire product life cycle. Figure 1 summarizes our results by characterizing the relative profitability and environmental performance of modular upgradability for different product categories. We discuss our key insights for manufacturers and environmental groups below.

Modular upgradability can increase environmental impact: Contrary to conventional wisdom, we find that for certain product categories such as computers, modular upgradability can be detrimental to the environment, and yet firms may adopt it because of higher profitability. Therefore, the promotion of modular upgradable architectures by Walmart and the

[2] An integral product design may be more efficient in terms of energy and material use, resulting in lower per-unit environmental impact. In this setting, our qualitative and structural results hold, and the relative environmental performance of modular upgradability worsens.

Figure 1 **Relative Profitability and Environmental Performance of Modular Upgradability for Different Product Categories**

	Environmentally superior	Environmentally worse
More profitable	*Servers, routers*	*Computers*
Less profitable	*E-readers*	*Washers, dryers*

EPEAT certification may backfire by increasing the environmental impact, and the promotion of modular upgradability as environmentally beneficial by firms such as Dell and HP may be misleading and, consequently, criticized for greenwashing. Hence, a more nuanced approach is required to identify when modular upgradability should be adopted or promoted as a green design strategy.

What makes modular upgradability environmentally superior? Our analysis identifies two different mechanisms through which modular upgradability can reduce environmental impact. First, it can reduce the rate of obsolescence for subsystems with high environmental impact. Second, it can lower the environmental impact by accelerating the adoption of new units with lower use impact. Therefore, for products such as servers and routers, accelerating obsolescence can lower environmental impact. Hence, firms such as Cisco may benefit from emphasizing this mechanism while promoting their modular upgradability strategies as environmentally beneficial.

The effect of accelerated obsolescence on the environment: We find that modular upgradability may increase environmental impact because of accelerated obsolescence. However, we also find that accelerated obsolescence can actually make modular upgradability environmentally superior for certain product categories. Thus, whether or not modular upgradability accelerates obsolescence is not a good proxy for its effect on the environment.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.1120.0396.

Appendix A. Proofs

Proof of Proposition 1. There exists a unique equilibrium under both architectures under the Cobb–Douglas specification (similar to Plambeck and Wang 2009, see Lemma A1 in the online supplement). The first-order conditions are given by $G_{T_I}(T_I) \doteq \sum_{k=1}^{2}(f(T_I)g_{kT}(x_{kI}, T_I) - g_k(x_{kI}, T_I) + (x_{kI}(T_I) + c_k)/f(T_I)) = 0$ and $G_{x_{kI}}(x_{kI}) \doteq g_{kx}(x_{kI}(T_I), T_I)f(T_I) = 1$ under the integral architecture, and by $G_{T_{kM}}(T_{kM}) \doteq (1-\delta)(f(T_{kM})g_{kT}(x_{kM}, T_{kM}) - g_k(x_{kM}, T_{kM})) + (x_{kM}(T_{kM}) + c_k)/f(T_{kM}) = 0$ and $G_{x_{kM}}(x_{kM}) \doteq (1-\delta)g_{kx}(x_{kM}(T_{kM}), T_{kM})f(T_{kM}) = 1$ under the modular upgradable architecture, where $f(T) = (1 - e^{-\rho T})/\rho$. For the proofs, we do not assume $c_1 = c_2$, but we assume that $c_1 < X(c_2)$ holds (which always holds for $c_1 = c_2$). Our structural results and qualitative insights hold for $c_1 \geq X(c_2)$ (see the online supplement for details).

Comparison of T_{1M}^* and T_I^*: The value of T_I^* must satisfy $G_{T_I}(T_I) = 0$, which, evaluated at $x_{kI} = x_{kM}^*$ and $T_I = T_{1M}^*$, is given by $G_{T_I}(T_{1M}^*) = \sum_{k=1}^{2}(f(T_{1M}^*)g_{kT}(x_{kM}^*, T_{1M}^*) - g_k(x_{kM}^*, T_{1M}^*) + (x_{kM}^* + c_k)/f(T_{1M}^*)) = 0$. Since T_{kM}^* must satisfy $G_{T_{kM}}(T_{kM}^*) = 0$, we have that

$$\frac{x_{1M}^* + c_1}{f(T_{1M}^*)} = -(1-\delta)g_{1T}(x_{1M}^*, T_{1M}^*)f(T_{1M}^*) + (1-\delta)g_1(x_{1M}^*, T_{1M}^*) \quad \text{and}$$

$$\frac{x_{2M}^* + c_2}{f(T_{1M}^*)} = \frac{f(T_{2M}^*)}{f(T_{1M}^*)}\big((1-\delta)\big(g_2(x_{2M}^*, T_{2M}^*) - g_{2T}(x_{2M}^*, T_{2M}^*)f(T_{2M}^*)\big)\big).$$

Substituting these into the above, $G_{T_I}(T_{1M}^*) = (1/f(T_{1M}^*)) \cdot (\delta n_1(x_{1M}^*)^\alpha V_1(T_{1M}^*)) + (n_2(x_{2M}^*)^\alpha / f(T_{1M}^*))(V_1(T_{1M}^*) - (1-\delta) \cdot V_1(T_{2M}^*))$, where $V_1(T) \doteq f(T)T^{-\alpha}((1-\alpha)f(T) - T)$ is negative and decreasing in T. At $\delta = 0$, since $\alpha \in (0,1)$, $\rho > 0$, and $T_{2M}^* > T_{1M}^*$, $G_{T_I}(T_{1M}^*) = (n_2(x_{2M}^*)^\alpha / f(T_{1M}^*))(V_1(T_{1M}^*) - (1-\delta)V_1(T_{2M}^*)) > 0$. Since $G_{T_I}(T_I)$ is decreasing in T_I (from the proof of Lemma A1 in the online supplement), we have that $T_{1M}^* < T_I^*$ at $\delta = 0$. Note that as T_I^* is independent of δ, $dT_{1M}/d\delta = -(\partial G_{T_{1M}}/\partial\delta)/(\partial G_{T_{1M}}/\partial T_{1M})$, where $\partial G_{T_{1M}}/\partial T_{1M} < 0$ and $\partial G_{T_{1M}}/\partial\delta = -f(T_{1M}^*)g_{1T}(x_{1M}^*, T_{1M}^*) + g_1(x_{1M}^*, T_{1M}^*) > 0$. Therefore, $dT_{1M}^*/d\delta > 0$. Since $T_{1M}^* < T_I^*$ for $\delta = 0$ and $T_{1M}^* - T_I^*$ is increasing in δ, there exists a threshold Δ_T such that $T_{1M}^* < T_I^*$ if and only if $\delta < \Delta_T$.

Comparison of T_{2M}^* and T_I^*: The value of T_I^* must satisfy $G_{T_I}(T_I) = 0$. The function $G_{T_I}(T_I)$ evaluated at $x_{kI} = x_{kM}^*$ and $T_I = T_{2M}^*$ is given by $G_{T_I}(T_{2M}^*) = \sum_{k=1}^{2}(f(T_{2M}^*)g_{kT}(x_{kM}^*, T_{2M}^*) - g_k(x_{kM}^*, T_{2M}^*) + (x_{kM}^* + c_k)/f(T_{2M}^*)) = 0$. Similar to the comparison between T_{1M}^* and T_I^*, this simplifies to

$$G_{T_I}(T_{2M}^*) = -\frac{1}{f(T_{2M}^*)}(-\delta n_2(x_{2M}^*)^\alpha V_1(T_{2M}^*)) + \frac{n_1(x_{1M}^*)^\alpha}{f(T_{2M}^*)}(V_1(T_{2M}^*) - (1-\delta)V_1(T_{1M}^*)).$$

Since $\alpha \in (0,1)$, $\delta \in [0,1]$, $\rho > 0$, $T_{2M}^* > T_{1M}^* > 0$, and $V_1(T)$ is negative and decreasing in T, we have $G_{T_I}(T_{2M}^*) < 0$. We know that $G_{T_I}(T_I)$ is decreasing in T_I, which implies that $T_I^* < T_{2M}^*$ always holds. $\square$

Proof of Proposition 2. The production and disposal impact is given by

$$E_I^{pd} = \sum_{j=1}^{\infty}(i_1^{pd} + i_2^{pd})e^{-(\rho + r^{pd})jT_I^*} = \frac{i_1^{pd} + i_2^{pd}}{e^{(\rho + r^{pd}T_I^*)} - 1} \quad \text{and}$$

$$E_M^{pd} = \sum_{j=1}^{\infty}\big(i_1^{pd}e^{-(\rho + r^{pd})jT_{1M}^*} + i_2^{pd}e^{-(\rho + r^{pd})jT_{2M}^*}\big) = \sum_{k=1}^{2}\frac{i_k^{pd}}{e^{(\rho + r^{pd})T_{kM}^*} - 1}.$$

The use impact is given by

$$E_I^u = \sum_{j=0}^{\infty} \int_{jT_I^*}^{(j+1)T_I^*} (i_1^u + i_2^u) e^{-r^u jT_I^*} e^{-\rho t}\, dt$$
$$= \frac{i_1^u + i_2^u}{\rho} \frac{1 - e^{-\rho T_I^*}}{1 - e^{-(r^u+\rho)T_I^*}} \quad \text{and}$$
$$E_M^u = \sum_{k=1}^{2} \sum_{j=0}^{\infty} \int_{jT_{kM}^*}^{(j+1)T_{kM}^*} i_k^u e^{-r^u jT_{kM}^*} e^{-\rho t}\, dt$$
$$= \sum_{k=1}^{2} \frac{i_k^u}{\rho} \frac{1 - e^{-\rho T_{kM}^*}}{1 - e^{-(r^u+\rho)T_{kM}^*}}.$$

The difference between the total environmental impact is given by

$$E_M - E_I = (i_1^{pd} + i_2^{pd})\big(\gamma_{pd}(Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*)) + (1-\gamma_{pd})(Z_{pd}(T_{2M}^*) - Z_{pd}(T_I^*))\big) + \frac{i_1^u + i_2^u}{\rho}\big(\gamma_u(Z_u(T_{1M}^*) - Z_u(T_I^*)) + (1-\gamma_u)(Z_u(T_{2M}^*) - Z_u(T_I^*))\big),$$

where γ_{pd} and γ_u are constants defined as $\gamma_{pd} \doteq i_1^{pd}/(i_1^{pd} + i_2^{pd})$ and $\gamma_u \doteq i_1^u/(i_1^u + i_2^u)$, $Z_{pd}(T) \doteq 1/(e^{(r^{pd}+\rho)T} - 1)$, and $Z_u(T) \doteq (1 - e^{-\rho T})/(1 - e^{-(r^u+\rho)T})$. The function $Z_{pd}(T)$ is decreasing in T, and $Z_u(T)$ is increasing in T for all ρ, r^{pd}, r^u, and $T > 0$. Dividing throughout by $i_1^u + i_2^u$ and denoting $\omega = (i_1^{pd} + i_2^{pd})/(i_1^u + i_2^u)$, we get

$$\frac{E_M - E_I}{i_1^u + i_2^u} = \omega(\gamma_{pd}(Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*)) + (1-\gamma_{pd})(Z_{pd}(T_{2M}^*) - Z_{pd}(T_I^*))) + (\gamma_u(Z_u(T_{1M}^*) - Z_u(T_I^*)) + (1-\gamma_u)(Z_u(T_{2M}^*) - Z_u(T_I^*)))/\rho.$$

If $T_I^* \le T_{1M}^* < T_{2M}^*$, we have that $Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*) \le 0$, $Z_{pd}(T_{2M}^*) - Z_{pd}(T_I^*) < 0$, $Z_u(T_{1M}^*) - Z_u(T_I^*) \ge 0$ and $Z_u(T_{2M}^*) - Z_u(T_I^*) > 0$. Therefore, $E_M - E_I$ is decreasing in ω, positive at $\omega = 0$, and negative as $\omega \to \infty$. Therefore, there exists a threshold $\Omega \doteq (\gamma_u(Z_u(T_{1M}^*) - Z_u(T_I^*)) + (1-\gamma_u)(Z_u(T_{2M}^*) - Z_u(T_I^*)))/(\rho(\gamma_{pd}(Z_{pd}(T_I^*) - Z_{pd}(T_{1M}^*)) + (1-\gamma_{pd})(Z_{pd}(T_I^*) - Z_{pd}(T_{2M}^*))))$ such that if $\omega > \Omega$, then $E_M < E_I$. If $T_{1M}^* < T_I^* < T_{2M}^*$, we have that $Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*) > 0$, $Z_{pd}(T_{2M}^*) - Z_{pd}(T_I^*) < 0$, $Z_u(T_{1M}^*) - Z_u(T_I^*) < 0$, and $Z_u(T_{2M}^*) - Z_u(T_I^*) > 0$. Therefore, $E_M - E_I$ can be increasing or decreasing in ω. The derivative of $E_m - E_I$ with respect to ω is given by $d(E_M - E_I)/d\omega = (i_2^{pd}/(i_1^{pd} + i_2^{pd}))(\epsilon^{pd}(Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*)) + Z_{pd}(T_{2M}^*) - Z_{pd}(T_I^*))$, where $\epsilon^{pd} \doteq i_1^{pd}/i_2^{pd}$. The derivative $d(E_M - E_I)/d\omega$ is increasing in ϵ^{pd}, negative at $\epsilon^{pd} = 0$, and positive as $\epsilon^{pd} \to \infty$. Therefore, there exists a threshold $\Upsilon^{pd} \doteq (Z_{pd}(T_I^*) - Z_{pd}(T_{2M}^*))/(Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*))$ such that $d(E_M - E_I)/d\omega < 0$ if and only if $\epsilon^{pd} < \Upsilon^{pd}$. Also, at $\omega = 0$, $E_M - E_I = [i_2^u/(\rho(i_1^u + i_2^u))](\epsilon^u(Z_u(T_{1M}^*) - Z_u(T_I^*)) + Z_u(T_{2M}^*) - Z_u(T_I^*))$, where $\epsilon^u \doteq i_1^u/i_2^u$. $E_M - E_I$ is decreasing in ϵ^u, positive at $\epsilon^u = 0$, and negative as $\epsilon^u \to \infty$. Therefore, there exists a threshold $\Upsilon^u \doteq (Z_u(T_{2M}^*) - Z_u(T_I^*))/(Z_u(T_I^*) - Z_u(T_{1M}^*))$ such that if $\epsilon^u > \Upsilon^u$, then $E_M < E_I$ at $\omega = 0$. Since $E_M - E_I = 0$ for $\omega = \Omega$, $d(E_M - E_I)/d\omega < 0$ if and only if $\epsilon^{pd} < \Upsilon^{pd}$, and for $\omega = 0$, $E_M < E_I$ if and only if $\epsilon^u > \Upsilon^u$. Therefore, there are three cases where $E_M < E_I$ for a general value of ω: (a) $\epsilon^u > \Upsilon^u$ and $\epsilon^{pd} < \Upsilon^{pd}$; (b) $\epsilon^u > \Upsilon^u$, $\epsilon^{pd} > \Upsilon^{pd}$; and $\omega < \Omega$, and (c) $\epsilon^u < \Upsilon^u$, $\epsilon^{pd} < \Upsilon^{pd}$, and $\omega \ge \Omega$. Thus, $E_M < E_I$ holds only if $\omega \ge \Omega$ and $\epsilon^{pd} < \Upsilon^{pd}$, or if $\omega < \Omega$ and $\epsilon^u > \Upsilon^u$. □

Appendix B. Notation

I, M	Subscripts denoting integral and modular upgradable architectures, respectively
t	Time index
c_k	Production cost for subsystem k
ρ	Common discount factor for customers, firm, and environmental impact
δ	Performance loss due to modularization
n_k	Improvement potential for subsystem k
α	Standard Cobb–Douglas output elasticity for development investment
T_I^e and T_I	Customer expected and equilibrium development times for the product
T_{kM}^e and T_{kM}	Customer expected and equilibrium development times for subsystem k
x_{kI}, x_{kM}	Development investments for subsystem k under each architecture
$g_k(x, T)$	Subsystem k's performance improvement for investment x and time T
Π_I, Π_M	Infinite-horizon total discounted profits under each architecture
i_k^{pd}	Per-unit production and disposal impact of subsystem k
i_k^u	Per-unit use impact per unit time of the product (at $t = 0$)
r^{pd}, r^u	Exogenous rate of improvement in the production and disposal, and exogenous rate of improvement in the use impact
$\epsilon^{pd} = i_1^{pd}/i_2^{pd}$	Relative per-unit production and disposal impact of the first subsystem
$\epsilon^u = i_1^u/i_2^u$	Relative per-unit use impact of the first subsystem (at $t = 0$)
$\omega = (i_1^{pd} + i_2^{pd})/(i_1^u + i_2^u)$	Ratio of per-unit production and disposal impact to the per-unit use impact (at $t = 0$)
E_I^{pd}, E_M^{pd}	Total production and disposal impact under each architecture
E_I^u, E_M^u	Total use impact under each architecture
E_I, E_M	Total environmental impact under each architecture

$$Z_{pd}(T) \doteq \frac{1}{e^{(r^{pd}+\rho)T} - 1}, \quad Z_u(T) \doteq \frac{1 - e^{-\rho T}}{1 - e^{-(r^u+\rho)T}},$$
$$\Upsilon^{pd} \doteq \frac{Z_{pd}(T_I^*) - Z_{pd}(T_{2M}^*)}{Z_{pd}(T_{1M}^*) - Z_{pd}(T_I^*)}, \quad \Upsilon^u \doteq \frac{Z_u(T_{2M}^*) - Z_u(T_I^*)}{Z_u(T_I^*) - Z_u(T_{1M}^*)}$$
$$\Omega \doteq \frac{\gamma_u(Z_u(T_{1M}^*) - Z_u(T_I^*)) + (1-\gamma_u)(Z_u(T_{2M}^*) - Z_u(T_I^*))}{\rho(\gamma_{pd}(Z_{pd}(T_I^*) - Z_{pd}(T_{1M}^*)) + (1-\gamma_{pd})(Z_{pd}(T_I^*) - Z_{pd}(T_{2M}^*)))}$$

References

Agrawal V, Toktay LB (2009) Interdisciplinarity in closed-loop supply chain research. Ferguson ME, Souza GC, eds. *Closed-Loop Supply Chains: New Developments to Improve the Sustainability of Business Practices* (Taylor & Francis Publishing, Boca Raton, FL), 197–214.

Agrawal V, Ferguson M, Toktay LB, Thomas V (2012) Is leasing greener than selling? *Management Sci.* 58(3):523–533.

Apple (2011) 15-Inch MacBook Pro: Environmental report. Report, Apple Inc., Cupertino, CA. Accessed March 13, 2011, http://images.apple.com/environment/reports/docs/MacBookPro_15-inch_Product_Environmental_Report_Oct2011.pdf.

Atasu A, Subramanian R (2012) Extended producer responsibility for e-waste: Individual or collective producer responsibility? *Production Oper. Management* 21(6):1042–1059.

Baldwin C, Clark B (1997) Managing in the age of modularity. *Harvard Bus. Rev.* 75(5):84–93.

Bras B (2009) Product design issues. Ferguson ME, Souza GC, eds. *Closed-Loop Supply Chains: New Developments to Improve the Sustainability of Business Practices* (Taylor & Francis Publishing, Boca Raton, FL), 39–66.

Cisco (2009) Cisco corporate citizenship report. Report, Cisco, San Jose, CA. Accessed October 6, 2011, http://www.cisco.com/web/about/ac227/csr2009/pdfs/CSR_09_Environment.pdf.

Coase RH (1972) Durability and monopoly. *J. Law Econom.* 15(1):143–149.

Cohen MA, Eliashberg J, Ho T-H (1996) New product development: The performance and time-to-market tradeoff. *Management Sci.* 42(2):173–186.

Debo LG, Toktay LB, Van Wassenhove LN (2005) Market segmentation and product technology selection for remanufacturable products. *Management Sci.* 51(8):1193–1205.

Dell (2003) Creating a model for sustainability: Dell environmental report. Report, Dell, Round Rock, TX. Accessed November 11, 2011, http://i.dell.com/sites/content/corporate/environment/en/Documents/cr-report-2003.pdf.

Economist, *The* (2011) Electronic waste: Garbage in, garbage out. *Babbage* (blog), April 24, http://www.economist.com/blogs/babbage/2011/04/electronic_waste.

EPEAT (2006) EPEAT criteria: Product longevity/life cycle extension. Accessed August 25, 2010, http://www.epeat.net/resources/criteria-discussion/pc-display-criteria/.

Fishbein B, McGarry L, Dillon P (2000) Leasing: A step towards producer responsibility. Technical report, INFORM Inc., New York.

Fishman A, Rob R (2000) Product innovation by a durable-good monopoly. *RAND J. Econom.* 31(2):237–252.

Fixson SK (2007) Modularity and commonality research: Past developments and future opportunities. *Concurrent Engrg.: Res. Appl.* 15(2):85–111.

Graedel TE, Allenby BR (1995) *Industrial Ecology* (Prentice Hall, Englewood Cliffs, NJ).

Greenpeace (2011) iPoison+iWaste. Accessed November 19, 2011, http://web.archive.org/web/20100826115725/http://www.greenpeace.org/apple/itox.html.

Hewlett-Packard (2011) Product design for the environment. Accessed March 19, 2011, http://www8.hp.com/us/en/hp-information/environment/design-for-environment.html.

IBM (2010) Product stewardship. Accessed March 19, 2011, http://www.ibm.com/ibm/environment/products.

Intel (2011) Intel server system product brief. Report, Intel, Santa Clara, CA. Accessed November 19, 2011, http://cache-www.intel.com/cd/00/00/41/40/414099_414099.pdf.

Keoleian G, Menerey D (1993) *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System* (U.S. Environmental Protection Agency, Washington, DC).

Kim H, Keoleian G, Horie Y (2006) Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. *Energy Policy* 34(15):2310–2323.

Kornish LJ (2001) Pricing for a durable-goods monopolist under rapid sequential innovation. *Management Sci.* 47(11):1552–1561.

Krishnan V, Ramachandran K (2011) Integrated product architecture and pricing for managing sequential innovation. *Management Sci.* 57(11):2040–2053.

Kuehr R, Williams E (2003) *Computers and the Environment: Understanding and Managing Their Impacts*, Eco-Efficiency in Industry and Science Series, Vol. 14 (Kluwer Academic Publishers, Dordrecht, The Netherlands).

Lenox M, King A, Ehrenfeld J (2000) An assessment of design-for-environment practices in leading US electronics firms. *Interfaces* 30(3):83–94.

MacDonald E (2011) Seven cognitive principles for the design of sustainable products. Working paper, Iowa State University, Ames.

Minnesota Pollution Control Agency (2010) Product design and the environment: Extending product life. Report, Minnesota Office of Environmental Assistance, St. Paul. Accessed January 4, 2011, http://www.pca.state.mn.us/index.php/view-document.html?gid=4678.

Newcomb PJ, Bras B, Rosen DW (1996) Implications of modularity on product design for the life cycle. *Proc. 1996 ASME Design Engrg. Tech. Conf. Comput. Engrg. Conf.* (ASME, New York), 1–12.

Plambeck EL, Denend L (2008) The greening of Wal-Mart. *Stanford Soc. Innovation Rev.* 6(2), http://www.ssireview.org/articles/entry/the_greening_of_wal_mart.

Plambeck E, Wang Q (2009) Effects of e-waste regulation on new product introduction. *Management Sci.* 55(3):333–347.

Ramachandran K, Krishnan V (2008) Design architecture and introduction timing for rapidly improving industrial products. *Manufacturing Service Oper. Management* 10(1):149–171.

Slade G (2006) *Made to Break: Technology and Obsolescence in America* (Harvard University Press, Cambridge, MA).

Subramanian R, Ferguson M, Toktay LB (2012) Remanufacturing and the component commonality decision. *Production Oper. Management*. Forthcoming.

Ülkü S, Schmidt G (2011) Matching product architecture and supply chain configuration. *Production Oper. Management* 20(1):16–31.

Ulrich K (1995) The role of product architecture in the manufacturing firm. *Res. Policy* 24(3):419–440.

U.S. Environmental Protection Agency (2010) Resource conservation and eCycling: Buying green. Accessed March 19, 2011, http://www.epa.gov/epawaste/conserve/materials/ecycling/basic.htm.

U.S. Office of Technology Assessment (1992) Green products by design: Choices for a cleaner environment. Technical report, U.S. Congress, Washington, DC.

Whitney DE (2004) *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development* (Oxford University Press, New York).

Williams E (2004) Environmental impacts in the production of personal computers. Kuehr R, Williams E, eds. *Computers and the Environment: Understanding and Managing Their Impacts*, Eco-Efficiency in Industry and Science Series, Vol. 14 (Kluwer Academic Publishers, Dordrecht, The Netherlands), 41–72.

Xerox (2010) Waste prevention and management: 2010 report on global citizenship. Report, Xerox Corporation, Norwalk, CT. Accessed March 19, 2011, http://www.xerox.com/corporate-citizenship-2010/sustainability/waste-prevention.html.