

Consumer Valuation of Modularly Upgradeable Products

Sezer Ülkü

McDonough School of Business, Georgetown University, Washington, DC 20057,
su8@georgetown.edu

Claudiu V. Dimofte

College of Business Administration, San Diego State University, San Diego, California 92182,
cdimofte@mail.sdsu.edu

Glen M. Schmidt

David Eccles School of Business, University of Utah, Salt Lake City, Utah 84112,
glen.schmidt@business.utah.edu

Although *product modularity* is often advocated as a design strategy in the operations management literature, little is known about how consumers respond to modular products. In this research we undertake several experiments to explore consumer response to modularly upgradeable products in settings featuring technological change. We consider both the initial product choice (between a modularly upgradeable product and an integral one) and the subsequent upgrade decision (replacement of a module versus full product replacement). First, we show that consumers tend to discount the cost savings associated with modular upgrades excessively (insufficiently) when the time between the initial purchase and the upgrade is short (long). This suggests that modular upgradability as a product feature has higher profit potential for slowly rather than rapidly improving products. Second, we observe a preference reversal between the initial purchase and the point of upgrade: At the point of initial purchase, people foresee making a full product replacement in the future, yet, when faced with the actual upgrade decision, they are more likely to revert to modular upgrades. Finally, we discuss and test several pricing and product design strategies that the firm can use to respond to these cognitive biases.

Key words: product architecture; modularity; product upgrades; product replacement; pricing; temporal construal; hyperbolic discounting; resource slack

History: Received August 31, 2009; accepted December 6, 2011, by Kamalini Ramdas, entrepreneurship and innovation. Published online in *Articles in Advance* April 27, 2012.

1. Introduction and Background

Accelerating technological progress, especially for consumer electronics products (e.g., cell phones, personal computers (PCs), cameras), presents consumers with the opportunity to use superior products. At the same time, shortening product life cycles pose new challenges for consumers, firms, and the environment. From the consumer perspective, it is costly to keep up with new technologies. From the firm's perspective, rapid change may lead to a reduction in firm profits; consumers may delay making a purchase foreseeing the introduction of a superior new product, at a lower price, soon after their purchase (Dhebar 1994, Kornish 2001). Finally, the higher production volumes associated with frequent product replacements have a detrimental effect on the environment. In addition to greater energy and raw material consumption, a higher production volume implies a larger volume of obsolete products that end up in landfills. By some accounts, 315 million PCs (90% of which were still

functioning) were scrapped in 2004, whereas the number of cell phones discarded in 2005 was 100 million (Slade 2006).

Modular product architectures offer the potential to address some of these challenges attributable to rapid technological change. Ramachandran and Krishnan (2008) proposed *modular upgradeability* as a way to reduce consumers' cost of keeping up with new technologies.¹ A modularly upgradeable design isolates improving components from stable ones and thereby enables an upgrade via replacement of only the improving module(s). For example, Ricoh's GXR photo camera comes with an upgradeable lens/sensor module that can be replaced as technology advances.

¹ Baldwin and Clark (2000) identify three types of modularity: *modularity in design* allows for independent development of product subsystems; *modularity in production* involves using common components across products; and *modularity in use* allows consumers to configure, upgrade, and maintain the product. In this research, we focus on modularity in use.

Because only a few components become obsolete and are discarded instead of the entire product, modular upgradeability also has the potential to reduce the total quantity of waste (McDonough and Braungart 2002).

Even though modular product architectures have been often advocated in operations management, marketing, strategy, and engineering literatures (e.g., Ulrich 1995; Langlois and Robertson 1992; Garud and Kumaraswamy 1995; Baldwin and Clark 2000; Fixson 2003, 2007), little is known about how consumers respond to modularly upgradeable products. In fact, whereas such products are more common in industrial markets (Ramachandran and Krishnan 2008), they are less prevalent in consumer markets, despite the potential benefits they present. In this research, we conduct a series of experiments to probe how consumers value modular products in marketplace settings featuring technological change. More specifically, we explore the role of relevant cognitive biases in shaping consumers' valuations of, and decisions regarding, modular upgradeability. To our best knowledge, this is the first article to empirically address product modularity from the consumer perspective.

In our work, we consider both the consumers' initial product choices (modular or integral) and their subsequent upgrade decisions (replace product or module), which occur after the product is used for a period of time. When costs and benefits are spread over time, consumers tend to exhibit certain temporal inconsistencies (Read 2004, Frederick et al. 2002). Because these decision biases may prevent consumers from appropriately assessing the benefits associated with modularity, a firm launching a modular product needs to understand how consumers actually value such products and integrate this understanding into its design and pricing decisions.

We conduct three empirical studies to establish the magnitude and drivers of the value of modularity for consumers, at the point of initial purchase and at the moment of upgrade. In Study 1, we focus on the initial purchase decision. Based on previous findings on hyperbolic discounting (Loewenstein and Prelec 1992), we hypothesize and find that discount rates decline with the upgrade interval; hence consumers might undervalue (overvalue) the savings from modularity for products with short (long) upgrade intervals relative to the firm. In Study 2, we investigate the pricing implications that stem from this result, asking respondents to choose between two pricing plans (high initial purchase price and low upgrade price versus low initial purchase price and high upgrade price) for a modular product. We find that if the product has a short upgrade interval, the firm can increase its profits by reducing the initial product price and increasing the upgrade price; conversely,

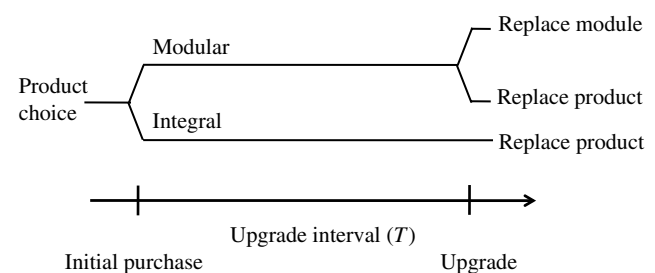
if the product has a long upgrade interval, the firm should increase the initial product price and lower the upgrade price. Study 2 also reinforces the results of Study 1, isolating the effect of time by keeping effort and quality constant across the alternatives.

Finally, in Study 3 we focus on the upgrade/replace decision faced by a consumer who already owns a modular product. Based on temporal construal (Liberman and Trope 1998) and resource slack (Zauberman and Lynch 2005) theories, we hypothesize and find that consumers prefer full product replacement when they are temporally distant from the moment of upgrade (as they focus on the quality differences between the two alternatives); however, when faced with an immediate replacement, they prefer to upgrade the module (because of increased sensitivity to cost considerations). Hence, at the point of initial purchase, consumers may overlook the value of modularity, even though they would benefit from it later on. In further pursuing ways to encourage the adoption of modular products, we explicitly manipulate the quality and effort associated with modularly upgrading the product. We hypothesize and find that by reducing the perceived quality differential between the two alternatives, it is possible to largely overcome this behavioral bias, thus increasing the value of modular upgrades for consumers not only at the moment of replacement, but also earlier, when they are making their initial purchase decision.

2. General Framework, Hypotheses, and Road Map

Our work is aimed at understanding how consumers value modular products in settings featuring technological progress. We consider both the initial choice between a modular and an integral product, and the upgrade decision that occurs after a length of time T , which we label *upgrade interval* (see Figure 1). A modularly upgradeable product allows the consumer to save money in the future when upgrading the product, as only a few improving components are replaced instead of the entire product. Hence, one would expect the consumer to be willing to pay a premium for a modular product. This premium depends

Figure 1 Two Stages of the Decision Process



on several factors. First, based on the temporal distance T , the consumer may value the savings more or less. Second, the consumer can perceive that when upgraded at time T , a modular product will have a lower level of quality relative to full product replacement. Finally, there may be a higher level of effort that must be exerted by the consumer in making the upgrade. Below we discuss the effect of each these factors and derive our hypotheses.

2.1. Consumers' Initial Valuation of Modularity

When choosing between a modular product and an integral product, consumers face a trade-off between a larger up-front investment for the modular alternative and cost savings in the future.² They need to pay a higher price for the modular product, but in the future, this allows them to upgrade the product to the latest technology at a lower cost. On the other hand, if they choose the integral alternative, they pay less in the present, but forego future savings opportunities. With the costs and benefits spread over time, an important aspect of this decision is its intertemporal nature, which is commonly represented using the discounted utility model (Samuelson 1937). At any time t , the future consumption utility (x_t, \dots, x_T) can be represented by $U^t(x_t, \dots, x_T) = \sum_{k=0}^{T-t} D(k)u(x_{t+k})$, where $D(k) = 1/(1+R)^k$. According to this model, rational decision makers equate their marginal rates of substitution between present and future money to the market interest rate; all disparate motives underlying the choice are captured by a single time-invariant parameter, the discount rate R (Frederick et al. 2002), which applies across different individuals and contexts (Read 2004). Nevertheless, behavioral research has identified many ways in which actual behavior deviates from this normative model. Among the best documented of these "anomalies" is hyperbolic discounting (Frederick et al. 2002, Soman et al. 2005): In both human and animal experiments, it is observed that rather than the exponential function assumed in the discounted utility model, the form of the discount function is better represented by a hyperbola (Ainslie 1974, Loewenstein and Prelec 1992, Ebert and Prelec 2007). A number of studies have confirmed that preferences follow a hyperbolic curve rather than the conventional, exponential curve that would produce consistent choice over time (for a review, see Frederick et al. 2002). Hyperbolic discount functions are thus "characterized by a relatively high discount rate over short horizons and a relatively low discount rate over long horizons" (Laibson 1997, p. 445).

² The modular product may be more expensive because of the need for a more robust design and a base module that will remain relevant for a longer time, larger production costs, and/or because of the manufacturer's pricing policy.

In line with both exponential and hyperbolic discounting, we expect consumer willingness to pay for modularity (i.e., the premium that consumers will pay when initially buying a modular product relative to a comparable integral product) to be lower for products with long time intervals between the initial purchase and the upgrade; as the upgrade interval increases, future cost savings from modularity should be discounted more heavily. However, in accordance with hyperbolic discounting, the imputed discount rate R should be higher for shorter upgrade intervals and lower for longer upgrade intervals (rather than remaining constant with the upgrade interval, as would be expected under exponential discounting).

HYPOTHESIS 1. *Consumers discount savings from modular products with shorter (longer) upgrade intervals at higher (lower) discount rates.*

Consider the firm selling the modular product. If, as hypothesized, the consumers' imputed discount rate is higher for short time intervals and lower for longer time intervals, one would expect the consumers' discount functions to cross that of a firm using exponential discounting. Said another way, one would expect that consumers value the benefits of modularity less than the firm for short time horizons, and more than the firm for long time horizons. By taking this consumer bias into account when making its pricing decisions, the firm can raise its total discounted profits. More specifically, with a short upgrade horizon, the firm can increase its total discounted profits by charging less for the product up front and more for the upgrade (as compared to what it would optimally charge in the absence of this consumer bias). On the other hand, with a longer upgrade horizon, the firm should charge more up front for the product and less for the upgrade.³ Formally stated:

HYPOTHESIS 2. *The firm's total discounted profits can be improved by charging a low (high) up-front price and a high (low) upgrade price for products with shorter (longer) upgrade intervals.*

2.2. Intertemporal Changes in Consumers' Valuation of Modularity

Although modular products allow low cost upgrades by enabling the replacement of specific components and retaining the rest, upgraded products may be perceived to be of inferior quality compared to full product replacement. Even if modular upgrades improve

³ Differently from consumers who often make ad hoc purchase decisions on the spot, firms determine pricing policies well in advance of a specific selling opportunity. Thus, although individual managers may be prone to the same types of biases, the firm can put in place certain decision rules (through decision support systems) that minimize biased decisions.

the performance of a critical component, consumers may feel that the remaining parts (even if less important to the product's overall performance) will underperform, will be less reliable, or simply look and feel obsolete. To the extent that the upgraded product is seen to have inferior quality (because of performance, reliability, or aesthetics), full product replacement will be more appealing. Conversely, modular upgrades will become more attractive if quality concerns are minimized, for example, by offering manufacturer warranties that cover the entire upgraded product.

We expect that when consumers are temporally distant from the moment of upgrade, they will focus on the *quality differences* between the two alternatives, and hence they will anticipate making a full product replacement in the future; however, when faced with an immediate replacement, they will be more sensitive to *cost differences*, and hence they will prefer a modular upgrade. This is supported by *temporal construal* (Liberman and Trope 1998; Trope and Liberman 2000, 2003) and *resource slack* (Zauberman and Lynch 2005) theories, which suggest that people may change their preferences over time because of changes in decision weights placed on different attributes of outcomes.

According to temporal construal theory, decision weights vary with time because of changes in mental representations.⁴ Specifically, individuals place a larger relative weight on the *desirability* of an outcome when temporally distant from the outcome, but focus on its *feasibility* when the outcome is in the immediate future.⁵ In our context, a brand new product acquired through full replacement offers superior overall quality, and hence is more desirable, but it is less feasible due to higher price. Meanwhile, because most existing components are retained, the modular upgrade is more cost effective, and hence feasible, but less desirable due to inferior perceived quality. Hence, temporal construal theory predicts that full replacement at a distant time is more appealing than a modular upgrade, because a larger weight is placed on desirability (i.e., quality) and a smaller weight on feasibility (i.e., cost). Meanwhile, a modular upgrade

becomes more appealing when the upgrade moment is near because of the larger relative weight of feasibility and a smaller relative weight of desirability.

According to resource slack theory, the rates at which resources such as money and time are discounted depend on their expected future availability; when individuals expect a resource to be more abundant in the future, they discount it more heavily.⁶ As expectations of availability of a resource change over time, so do the discount rates used for that resource. The prediction of resource slack theory is in the same direction as that of temporal construal: Given the expectation of higher future wealth (Arabsheibani et al. 2000, Zauberman and Lynch 2005, Zhang et al. 2008, Tam and Dholakia 2011), the weight of cost differences decreases with temporal distance; with a relatively small weight placed on cost, and hence a relatively large weight on quality, full product replacement is attractive when looking into the distant future. However, if the upgrade decision occurs in the immediate future, the salience of current budgetary constraints makes the low-cost modular upgrade more appealing. Hence, both temporal construal theory and resource slack theory predict the following:

HYPOTHESIS 3. *The attractiveness of a modularly upgraded product will be higher in the immediate future than in the distant future.*

Expectations of effort may also play a role in the upgrade/replace decision. Although upgrading a modular product should not require more than a reasonable amount of time investment, it may be perceived to be effortful, in particular if the product is not designed to be upgraded easily, or if consumers are not confident about their technical skills. To the extent that modular upgrades are seen as more effortful, we expect a higher consumer preference for replacing the entire product. Conversely, we expect modular upgrades to become more appealing if the associated effort is eliminated, for instance, through a modified design that allows old components to be unplugged and the new ones to be plugged in with little effort.⁷

Making clear predictions about the interaction of effort with time is not straightforward. First, effort is a multidimensional construct: In addition to the expenditure of time, successful task completion may

⁴ According to Trope and Liberman (2003, p. 409), "primary interests, compared with secondary interests, may carry more weight in distant-future than near-future decisions. Secondary advantages or disadvantages of distant-future activities are therefore unlikely to prevent one from making unequivocal decisions according to their primary, superordinate goals. However, as one gets closer in time to engaging in the activities, secondary considerations may become increasingly influential and capable of inducing conflict and hesitation."

⁵ According to Liberman and Trope (1998, p. 7), "desirability refers to the valence of an action's end state, whereas feasibility refers to the ease or difficulty of reaching the end state."

⁶ We thank an anonymous reviewer for suggesting this conceptual account.

⁷ It is possible that in certain contexts full product replacement requires more effort than modular replacement because of customer switching costs (e.g., learning to use a new product). In that case, both low cost and low effort would favor modular upgrade; hence, it would dominate the full replacement option in the absence of quality differences.

require different skills, and the effort itself may have positive utility (the “IKEA effect”; see Norton et al. 2011). Furthermore, time is perishable and is not readily exchangeable; the opportunity cost associated with time is ambiguous, and time constraints are relatively elastic (Okada and Hoch 2004). Hence, consumers cannot account for effort in a manner similar to how they account for money. Having no a priori expectations as to whether the modular upgrade alternative becomes more or less attractive with increasing temporal distance in the presence of effort (i.e., a specific time by effort interaction effect), we leave this question to be addressed empirically.

2.3. Road Map for the Studies

We conduct three studies to test the above hypotheses. Study 1 (see §3) focuses on the Stage 1 decision of choosing between modular and integral versions of a product and elicits the premiums respondents are willing to pay for a modular product through a series of choice tasks. We test whether consumers use higher discount rates for products with short upgrade intervals and lower discount rates for products with long upgrade intervals (Hypothesis 1). This is important, because in the presence of such a bias, the firm can adjust its prices to make a modular product more attractive, and thereby increase its profits. Because Study 1 involves choices between modular and integral products, which may be perceived to differ in quality and the effort entailed, we measure perceptions of relative quality and effort and control for their role in the consumers’ valuation of the modular product.

In Study 2 (see §4), we present a scenario wherein respondents choose between two pricing plans for a modular product, rather than choosing between modular and integral products. This experimental design fixes perceptions of quality and effort across two alternative pricing plans and thereby isolates the hyperbolic discounting effect (Hypothesis 1). Importantly, with this study we also test whether the firm can indeed increase its profits by adjusting prices, taking into account hyperbolic discounting by consumers (Hypothesis 2).

Finally, to further inform us as to how consumers perceive the value of modularity at different points in time, in Study 3 (see §5) we compare the eventual Stage 2 decision (of whether to upgrade a modular product or replace it with an entirely new one) with the decision that was anticipated at the point of initial purchase. In this study, we explore the effects of temporal distance, quality, and effort within a full factorial design and test Hypothesis 3. Collectively, these three studies complement each other in addressing consumers’ valuation of modular products.

3. Study 1: The Choice Between Integral and Modular Products

Study 1 examines whether consumers are willing to pay a premium for modular products when they make their initial purchase (i.e., Stage 1 in Figure 1), and how this premium varies with the upgrade interval. We elicited this premium by asking participants to make a series of choices between modular and integral versions of a product at different price points and estimating the discount rates for different lengths of the upgrade interval (manipulated between subjects). Because the estimated premium can also reflect potential concerns about perceived quality, effort, and uncertainty of the eventual modular upgrade, we employ these factors as covariates.

3.1. Participants and Design

Two hundred and seven undergraduate students from a private metropolitan university on the East Coast participated in this experiment for course credit (see the appendix for details). Participants made a series of choices between an integral (iMac) and a modular (Mac mini) desktop computer that they would upgrade in the future (participants were randomly assigned to $T = 1, 2, \text{ or } 4$ years). The modular product cost more, but it could be upgraded at a lower cost in the future. The quality of the modularly upgraded product was described as comparable to that of the new product, and the upgrade effort was described as minimal. To elicit the maximum up-front premium that respondents were willing to pay for the modular product ($Premium_T$), participants were presented with a sequence of six choice tasks wherein they chose between a modular and an integral computer, with prices of the modular version (P_i^M at choice i) adjusted sequentially to hone in on the respondent’s indifference point (for similar choice titration studies, see Read et al. 2005, Scholten and Read 2006, Weber et al. 2007, Krupka and Stephens 2010). All respondents started with $P_1^M = \$1,500$, and the remaining prices were kept constant ($\$1,200$ for both generations of the integral product; $\$600$ for the modular upgrade). After decision i , P_i^M was adjusted downward (upward) if the integral (modular) product was chosen. The magnitude of the price adjustment (S_i) was reduced by half each time.⁸

3.2. Measures

The premium paid for the modular product was estimated as $Premium_T = P_6^M - 1,200 + S_5/2$ if the modular product was chosen and $Premium_T = P_6^M - 1,200 - S_5/2$ if the integral product was chosen. Given that the modular product saves $\$600$ at time T , the

⁸ The step sizes (S_i) were $\{\$150, \$75, \$37, \$18, \$9\}$. All price points in our studies were pretested for realism.

Table 1 Means for Modularity Premium and Annual Discount Rates

T	N	Premium		R_T	
		Mean	S.E.	Mean	S.E.
1 year	75	444.9	20.9	6.04	2.57
2 years	73	395.6	24.4	1.19	0.31
4 years	59	349.7	30.3	0.49	0.99

effective annual discount rate R_T was imputed as $R_T = \sqrt[T]{600/\text{Premium}_T} - 1$ for $T = 1, 2,$ and 4 . After the choice tasks, the participants also answered questions about the perceived quality of the modular product relative to the integral one (*PercQuality*), the effort involved in upgrading the modular product (*PercEffort*), and the likelihood of eventually upgrading the modular product (*UpgradeCertainty*).

3.3. Results

When asked to recall the time interval between the initial purchase and the upgrade, 96.6% of the respondents correctly identified the time T associated with their experimental condition, suggesting that the time manipulation was successful.

Table 1 presents the average values for the modularity premium (Premium_T) and the annual discount rate (R_T). First, as expected, the modularity premium decreased with the time until the upgrade, T ($M_1 = 444.9$, $M_2 = 395.6$, and $M_4 = 349.7$). A one-way analysis of variance (ANOVA) run on Premium_T yielded a significant time effect ($F_{2,204} = 3.55$, $p < 0.03$). Second, in line with hyperbolic discounting, mean R_T is decreased with the time interval, rather than staying constant, as would be expected under exponential discounting. Participants discount the future savings arising from the modular architecture heavily when the upgrade interval is short ($R_1 = 6.04$), less heavily for intermediate periods ($R_2 = 1.19$), and even less so for longer periods ($R_4 = 0.49$). ANOVA on these discount rates uncovered a significant main effect of time ($F_{2,204} = 3.52$, $p < 0.04$). When the respondents with the most extreme values of premium estimates (i.e., those who selected either the modular or the integral product six times in a row) were excluded from the analysis, the imputed discount rates ($R_1 = 1.18$, $R_2 = 0.51$, and $R_4 = 0.28$) were still decreasing with T as predicted ($F_{2,125} = 3.71$, $p < 0.03$).⁹ Hypothesis 1 was thus supported.

Although the decision between the modular and the integral products is in its essence about cash (i.e., trading off extra payment today for savings in the future), considerations such as quality, effort, and upgrade certainty may also play a role in the choice

⁹ The nonparametric Kruskal–Wallis tests were in agreement with the ANOVA results.

Table 2 Regression Results for Premium_T , R_T , and $\ln(R_T)$ with Respect to Time, with Covariates

T	Premium_T		R_T		$\ln(R_T)$	
	Mean	S.E.	Mean	S.E.	Mean	S.E.
T	−25.7*	10.9	−1.82*	0.78	−0.37**	0.13
<i>PercQuality</i>	72.9***	13.0	−2.15*	0.93	−0.90***	0.16
<i>PercEffort</i>	−18.3	10.7	0.12	0.77	0.27*	0.13
<i>UpgradeCertainty</i>	27.1**	9.5	−0.85	0.68	−0.35**	0.11
Adjusted R^2	0.20		0.04		0.20	

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

between modular and integral products. To check the robustness of the above findings, we ran a series of linear regressions for Premium_T , R_T , and $\ln(R_T)$, including *PercQuality*, *PercEffort*, and *UpgradeCertainty* as covariates.¹⁰ The results are presented in Table 2. All models are significant at $p < 0.05$ or better. The results regarding the effect of time are clear: Both modularity premium and discount rate decrease with time. Hence, we conclude that the relationship between the modularity premium and the upgrade interval (and therefore the valuation of modularity by consumers in general) is in line with hyperbolic discounting.

3.4. Discussion

To summarize our findings in Study 1, we find that in general consumers value modularity, and they are willing to pay a premium for modular products at initial purchase. The modularity premium decreases with the time to upgrade, as the upgrade savings become more distant. However, the discount rates also decrease with the upgrade interval, in accordance with hyperbolic discounting: When upgrades occur in the near future, people exhibit very steep discount rates in valuing the cost savings from modularity; when the time to upgrade is long, the discount rates are significantly lower. This points to systematic biases in consumers' valuation of modularity relative to the time-invariant discount rate, which is the normative benchmark; because of discount rates that vary with delay, consumers may not value modularity sufficiently for short time intervals and may value it too highly for long durations.¹¹ This systematic bias can create an obstacle against the adoption of modular products when the upgrade intervals are short. Conversely, this may facilitate the adoption of modular products when upgrade intervals are long. Hence,

¹⁰ The logarithmic transformation of the discounting rate was made to normalize the variable.

¹¹ These results have been replicated with different designs (within and between subjects), measurement methodologies (matching and choice titration), and populations (undergraduate students, executive MBAs).

Table 3 Means for the Camera (1, 4 Years) and the Air Conditioner (4, 8 Years)

<i>T</i>	Camera					Air conditioner				
	<i>N</i>	<i>Premium_T</i>	S.E.	<i>R_T</i>	S.E.	<i>N</i>	<i>Premium_T</i>	S.E.	<i>R_T</i>	S.E.
1 year	83	\$256.8	6.11	0.27	0.05	—	—	—	—	—
4 years	86	\$227.3	8.90	0.13	0.03	90	\$742.4	20.6	0.09	0.03
8 years	—	—	—	—	—	79	\$663.4	32.0	0.08	0.02

modular upgradeability as a product feature may have a higher profit potential for a slowly improving product over a more rapidly improving one. This finding also has interesting pricing implications; it suggests that by incorporating this consumer bias in its pricing decisions, the firm can increase its profits. We elaborate on these pricing implications and test them in §4.

4. Study 2: Hyperbolic Discounting and Its Pricing Implications

Study 2 seeks further evidence for hyperbolic discounting in the valuation of the future cost savings associated with a modular product. Rather than choosing between modular and integral products, respondents were told they were buying a specific modular product and were asked to make a series of choices between two pricing plans for it: a high purchase price and a low upgrade price (Plan *HL*) versus a low purchase price and high upgrade price (Plan *LH*). Hence, this study keeps perceived quality and effort constant, allowing us to tease out the effect of the time interval on the valuation of the future cost savings. Importantly, we also test the pricing implications that arise from Study 1.

4.1. Participants and Design

One hundred and sixty-nine undergraduate students from a private metropolitan university on the East Coast participated in this experiment for course credit. Participants were presented with a series of choice tasks for two separate modular products, a digital photo camera and an outdoor home air-conditioning unit (A/C), with the two products presented in random order. Participants were randomly assigned to a time condition for each product, [1, 4 years] for the camera and [4, 8 years] for the A/C. The camera’s upgradeable module consisted of its lens/sensor module, whereas the A/C’s upgradeable module was its compressor (see the appendix). As in Study 1, a choice titration algorithm was used to estimate the premium that respondents were willing to pay up front for the modular platform to save money later. For the camera, respondents made six consecutive choices between two pricing plans: a \$1,200 initial price for the modular product purchase and \$400 for the subsequent upgrade (*LH*), or a price

P_i^M greater than \$1,200 for the initial modular purchase and \$100 for the subsequent upgrade (*HL*).¹² Starting from the initial price $P_1^M = \$1,350$, after each decision i , P_i^M was adjusted downward if option *LH* was selected and upward if *HL* was chosen, with decreasing step sizes S_i .¹³ The design was similar for the A/C except that all prices listed were triple those of the camera.

4.2. Measures

After eliciting the premium paid under Plan *HL* ($Premium_T$), the discount rates were estimated as $R_T = \sqrt[3]{300/Premium_T} - 1$. After the choice tasks, participants also answered questions about the extent to which uncertainty about the future weighed in their upgrade choices (*Uncertainty*) and about the level of their product knowledge (*Knowledge*).

4.3. Results

Average premiums and discount rates for the camera and the air conditioner are shown in Table 3. In line with Hypothesis 1, we find larger discount rates for short life cycles and smaller discount rates for long life cycles. Upgrade intervals used for camera involved both short ($T = 1$ year) and long ($T = 4$ years) time horizons. A one-way ANOVA indicates that $Premium_T$ is decreasing with T ($F_{1,167} = 7.34$, $p < 0.01$). ANOVA shows R_T and $\ln(R_T)$ to also be significant over T ($F_{1,167} = 4.56$, $p < 0.04$ and $F_{1,167} = 11.10$, $p < 0.001$, respectively).¹⁴ When *Uncertainty* and *Knowledge* are introduced as covariates, the effect of T on $Premium_T$ and R_T is still statistically significant. Because of the nature of the product, the experimental design for air conditioning involved two long upgrade intervals (4 and 8 years). A one-way ANOVA suggests $Premium_T$ decreases with T ($F_{1,167} = 4.53$, $p < 0.04$). The time effect is not significant for R_T and $\ln(R_T)$ ($F_{1,167} = 0.01$ and $F_{1,167} = 1.57$ respectively, $p > 0.20$), which is not surprising given the relatively large T values of 4 and 8 years—under hyperbolic discounting, the difference between imputed discount

¹² At upgrade time, Plan *HL* saves the consumer $(\$400 - \$100) = \$300$ over Plan *LH* (for the A/C, the savings is \$900).

¹³ The step sizes were {\$75, \$37, \$18, \$9, \$4} for the camera and {\$225, \$112, \$56, \$28, \$14} for the A/C.

¹⁴ The nonparametric Kruskal–Wallis tests were in agreement with the ANOVA results.

rates for two large values of T would be minimal, and thus larger sample sizes are required to establish the time effect on R_T with statistical significance. Summarizing the camera and air-conditioner results, with quality and effort fixed, we continue to find support for Hypothesis 1: Consumers discount future savings more heavily for short time horizons and less heavily for long time horizons.

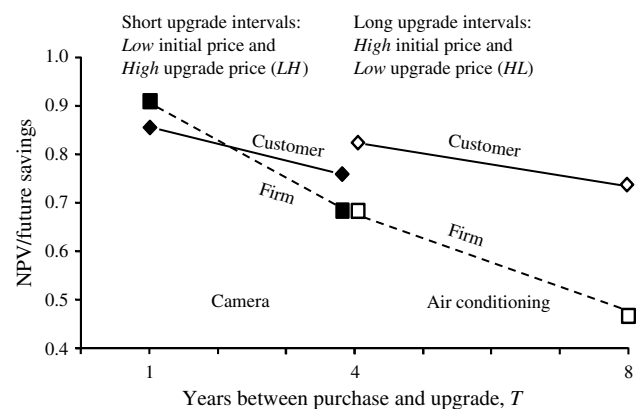
We now turn to testing Hypothesis 2. A lower upgrade price implies future cost savings for consumers and a future revenue loss for the firm. For products with short upgrade intervals (e.g., one year), we expect consumers to value the future savings less than the firm; hence, the firm could increase its total discounted profits by following pricing plan *LH*, lowering the initial price and raising the upgrade price (relative to how it might otherwise price in the absence of this consumer bias). Conversely, for products with long upgrade intervals (e.g., four to eight years), we expect consumers to value future savings more than the firm; in this case, the firm would benefit from a higher up-front price and a lower upgrade price (pricing plan *HL*). To test this hypothesis, we compare the net present value of the consumers' future savings NPV_C (which is equal to *Premium*) to the net present value of the firm's future revenue losses, NPV_F (see Table 4). Although we report the statistical tests assuming a discount rate of $R^F = 10\%$ for the firm, similar results were obtained under a range of discount rate assumptions.

For the camera, when the time interval is short (one year), $NPV_C < NPV_F$ ($t_{82} = -2.61$, $p < 0.01$). Hence, the firm is better off following a pricing strategy wherein a lower price is charged up front, and a higher price is charged for the upgrade (i.e., *LH*). When the time interval is long (four years), $NPV_C > NPV_F$ ($t_{85} = 2.53$, $p < 0.01$). Hence, the firm is better off following a pricing strategy wherein a higher price is charged up front and a lower price is charged for the upgrade (i.e., *HL*). Because of the nature of the product, both upgrade intervals for the A/C were relatively long. For both four and eight years, $NPV_C > NPV_F$; thus, the firm should charge a higher price

Table 4 Comparison of the Firm's and the Consumer's Net Present Values for the Difference Between the Future Upgrade Prices Under Two Pricing Plans

T	NPV_C	NPV_F		Pricing strategy
	(Premium)	($R^F = 10\%$)	($R^F = 12\%$)	
Camera				
1 year	\$256.8	\$272.7	\$267.9	<i>LH</i>
4 years	\$227.3	\$204.9	\$190.7	<i>HL</i>
A/C				
4 years	\$742.4	\$614.7	\$572.0	<i>HL</i>
8 years	\$663.4	\$419.9	\$363.5	<i>HL</i>

Figure 2 Proposed Pricing Strategies for Long and Short Upgrade Intervals ($R^F = 10\%$)



up front and a lower upgrade price in both cases ($t_{89} = 6.21$, $p < 0.001$ for four years; $t_{78} = 7.62$, $p < 0.001$ for eight years). Hypothesis 2 is thus supported. Figure 2 illustrates this finding for the camera and the A/C. To facilitate comparison across products, all NPVs are normalized by the upgrade price differences (i.e., NPVs were divided by \$300 for the camera and \$900 for the A/C).

4.4. Discussion

This study reinforces the finding that consumers use hyperbolic discounting in valuing savings from modularity, isolating the effect of time by keeping effort and quality constant. It also identifies how firms should adjust their pricing policies when facing consumers exhibiting hyperbolic discount functions. We show that in the presence of this consumer bias, the firm could increase its profits by varying its pricing strategy based on the product's upgrade interval. For products with short upgrade intervals (e.g., one year), the optimal policy should reflect people's tendency to undervalue future savings; hence, the initial price should be relatively *lower* and the price for the upgrade relatively *higher* (compared to the optimal pricing absent this consumer bias). By following this strategy, the firm shifts revenues into the future. However, as it has a lower discount rate relative to the buyer over the interval, the firm increases its total discounted profits by charging a higher price in the future. Conversely, for products with long upgrade intervals (e.g., four to eight years), the firm should charge a *higher* price up front for the initial product and sell the upgrade at a *lower* price (or even provide it for free), given that consumers tend to overvalue the price savings for distant upgrades. This time, the firm shifts revenues from the future to the present. We thus provide an "existence proof" for the aforementioned pricing policies for a range of reasonable discount rates for the firm. It is the crossover between the firms' and the consumers' discount functions (due

to a systematic decrease in consumers' discount rates with the time interval) that forms the basis for this pricing policy. If the firm has a much higher discount rate relative to the consumer, then it is possible that this range where the *LH* policy is optimal may not exist; similarly, if the firm has a much lower discount rate, the *HL* policy may never be optimal.¹⁵

5. Study 3: The Impact of Quality and Effort

Study 3 compares the eventual upgrade decision with the upgrade decision anticipated at the point of initial purchase. Building on Studies 1 and 2, it further informs the initial choice between modular and integral products because this depends on consumers' expectations about whether they will actually exercise the upgrade option or purchase a brand new product instead. We explore the effect of temporal distance to the upgrade, as well as those of quality and effort differences across upgraded and new products, manipulating all three factors.

5.1. Participants and Design

Three hundred and forty-seven respondents from Amazon's *Mechanical Turk* online panel were recruited to participate in this experiment and were paid for their participation.¹⁶ Participants were presented with a series of choice tasks wherein they had to select between upgrading a digital photo camera by purchasing a brand new one or by replacing its lens/sensor module. Like in Studies 1 and 2, a titration algorithm presented respondents with different price points. Participants were randomly assigned to one of eight conditions that crossed time (upgrade tomorrow or in two years), upgrade quality (low or high quality), and upgrade effort (low or high effort).

Time Manipulation. Participants in the immediate future condition were told, "Imagine that you own a two-year-old GXR camera. You need a faster lens and more advanced sensors now but the remaining parts of your camera are in perfect shape. You have

two options to upgrade your GXR camera tomorrow." For participants in the distant future condition, the scenario was replaced with the following: "Imagine that you just bought a new GXR camera. After two years of usage, you will need a faster lens and more advanced sensors but the remaining parts of your camera will be in perfect shape. You will have two options to upgrade your GXR camera in two years." Note that the effect we investigate is independent of perceptions of product depreciation (see Okada 2001). In both scenarios, the product is/will be two years old at the time of the upgrade decision, and therefore, it will have depreciated to the same extent.

Quality Manipulation. The high-quality condition involved the following description: "Even if you replace only the lens/sensor, Ricoh renews the warranty for the entire unit as if it were entirely new." For participants in the low-quality condition, this was replaced with: "Since you replace only the lens/sensor, Ricoh does not provide any warranty. The upgraded camera is also about 20% bulkier than a new one."

Effort Manipulation. Participants in the low-effort condition were told, "After you purchase the new more advanced lens/sensor module, you will unplug the old module and plug in the new one. This process should take less than a minute." Meanwhile, those in the high-effort condition were told, "After you purchase the new more advanced lens/sensor module, you will personally disconnect and remove the old module (by unscrewing eight very sensitive miniature screws), locate the connecting pins, align and match the module to the camera body at a perfect angle to avoid damage, carefully drop the module into place, and slowly reinsert the miniature screws. This process will take about 30 minutes" (see the appendix).

5.2. Measures

Willingness to pay for the upgrade (*UpgradeValue*) was estimated through choice titration: Participants made a series of choices between buying a brand new camera for \$900 and upgrading the lens/sensor module at a lower price (starting at \$450 and varying based on responses).¹⁷ Two additional questions captured (on seven-point scales) the extent to which expected money and time budgets at the time of upgrade constrained choices (*CashConstraint* and *TimeConstraint*, respectively). Also, respondents' confidence in their ability to perform the upgrade (*Confidence*), expectation of price changes over time (*PriceChange*), perceptions of relative quality (*PercQual*), and effort levels (*PercEffort*) between the two options were measured on seven-point scales (1 = lower for full replacement, 4 = same, 7 = higher

¹⁵ There may be implementation challenges for both policies. The *LH* policy would require switching costs or insuring that the customer follows through with the eventual upgrade (see Shapiro and Varian 1999). The *HL* policy requires the firm to credibly commit to providing upgrade components, at the promised price and time. Given the implementation issues to be resolved, further research is required to establish the optimal pricing strategies in different contexts.

¹⁶ Amazon.com's M-Turk has been successfully used in academic research in recent years (see Paolacci et al. 2010, Buhrmester et al. 2011). Respondents were paid rates competitive with other panel studies. The sample's demographics represented the adult U.S. consumer well (80% employed full time; 59% female; a median income of \$30,000; 27.7% with a high school diploma; 53.7% with an education level of associates degree or higher). All sample descriptive statistics are available upon request.

¹⁷ The step sizes were {225, 112, 56, 28, 14, 7}.

Table 5 Effects of Quality, Time, and Effort on the Willingness to Pay for the Upgrade in Study 3

Time	Effort	Quality	N	UpgradeValue		%Choosing Modular Upgrade at $P_1^M = \$450$
				Mean	S.E.	%Choosing Modular (%)
Tomorrow	Low	Low	45	643.3	25.8	82.2
		High	41	710.6	22.1	95.1
	High	Low	43	563.7	33.8	34.9
		High	53	653.1	29.4	69.8
In 2 years	Low	Low	48	562.9	33.4	50.0
		High	40	699.1	29.8	90.0
	High	Low	40	460.5	39.9	15.0
		High	37	661.1	33.2	62.2

for modular replacement). Finally, respondents were asked to provide open-ended reasoning for their choices, which were coded into four categories: monetary cost, upgrade effort, quality discrepancy, and others (*CodeCost*, *CodeEffort*, *CodeQuality*, and *CodeOther*, respectively). If a respondent mentioned more than one category, all applicable variables were coded as 1. Agreement between two judges (blind to respondent condition) occurred in over 93% of cases, and disagreements were resolved through discussion (see the appendix for sample codings).

5.3. Results

A manipulation check on the perceived effort associated with the low- and high-effort conditions revealed the expected difference. Perceptions measured on a seven-point scale were significantly different: $M_{LowE} = 4.13$, $M_{HighE} = 5.58$, $t_{345} = 10.10$, and $p < 0.001$. Similarly, perceptions of quality across the low- and high-quality conditions were significantly different: $M_{LowQ} = 3.68$, $M_{HighQ} = 3.92$, $t_{345} = 2.10$, and $p < 0.04$.

An ANOVA on the *UpgradeValue* variable with the three experimental factors as predictors uncovered significant main effects for each factor ($F_{1,339} = 4.42$, $p < 0.04$ for *Time*; $F_{1,339} = 9.71$, $p < 0.01$ for *Effort*; and $F_{1,339} = 30.69$, $p < 0.001$ for *Quality*; see Table 5). As expected, higher quality (suggested via warranty and size) and lower replacement effort (offered via plug-in design) both resulted in higher values for modular upgrade (*UpgradeValue* was \$679.4 versus \$560.4 for high versus low quality; and \$649.8 versus \$588.1 for low versus high effort, respectively).¹⁸ When respondents' confidence in their technical skills (*Confidence*) was included as a covariate, its effect was significant ($F_{1,338} = 55.79$, $p < 0.001$), and the main effect of *Effort* was weakened ($F_{1,338} = 3.80$, $p = 0.05$).

Hypothesis 3 was supported: Modular upgrades were valued more highly for decisions in the immediate future (\$642.5 if upgrading tomorrow versus \$593.1 in two years). Furthermore, a significant

interaction was observed between time and quality ($F_{1,339} = 4.09$, $p < 0.04$), suggesting that the perceived quality difference has less of an effect on upgrade decisions in the present than when planning for a future upgrade; that is, when the modular upgrade resulted in inferior quality, consumers' stated preferences favored a brand new product (i.e., full product replacement) in the distant future, but favored the cheaper modular upgrade in the immediate future. This change in preferences over time was not observed when upgrade quality was high.¹⁹ The interaction between time and effort was not significant.

To assess whether the higher *UpgradeValue* in the tomorrow condition is indeed driven by increased focus on cost considerations (i.e., captured by budget constraints), we performed a mediation analysis (Baron and Kenny 1986). First, we used regression to establish that the time condition was significantly related to the upgrade preference: $\beta = -24.7$, $p < 0.04$. Second, a linear regression confirmed that the time condition predicted *CashConstraint*, the perceived budget constraint, at the time of upgrade: $\beta = -0.19$, $p < 0.02$. Third, *CashConstraint* was a significant predictor of *UpgradeValue*: $\beta = 40.65$, $p < 0.001$. Finally, to examine whether budget constraint perceptions mediate the effect of time condition on upgrade, we simultaneously entered both *Time* and *CashConstraint* into the regression. *CashConstraint* remained predictive ($\beta = 39.17$, $p < 0.001$), whereas the effect of time condition was rendered insignificant ($\beta = -17.41$, $p > 0.12$). A Sobel test of the mediating effect was significant ($z = -2.17$, $p < 0.03$), indicating that expectations of a budget constraint mediate the effect of time condition on *UpgradeValue*. Similar mediating effects were not observed for time budget perceptions, despite the presence of a significant relationship between *TimeConstraint* and *UpgradeValue* ($\beta = -16.2$, $p < 0.01$). Thus we conclude that the relative preference reversal we observe is driven by changes in the salience of monetary cost considerations over time.²⁰

¹⁹ Recall that all respondents saw the same initial upgrade price of \$450. Analysis of choices at this price yields similar results: Overall, a larger fraction of respondents chose the \$450 modular upgrade in the tomorrow condition than in the two-year condition (54% versus 70%, $\chi^2 = 3.82$, $p < 0.05$). The logistic regression coefficients for both time ($\beta = -0.72$, $p < 0.05$) and effort ($\beta = -1.10$, $p < 0.01$) are significant for the low-quality conditions; however, for the high-quality conditions, effort has a significant impact ($\beta = -1.10$, $p < 0.01$), but the time effect is not significant.

²⁰ Respondents expected the average camera price (*PriceChange*) to remain approximately the same over time ($M = 4.11$; contrast versus 4 (middle of the scale): $t(318) = 1.25$, $p > 0.20$). Moreover, using *PriceChange* as a covariate in the main ANOVA did not change any of the observed effects. Thus, the affordability effect observed does not come from prices dropping in the future, but,

¹⁸ The nonparametric Kruskal–Wallis tests were in agreement with the ANOVA results.

Table 6 Participants' Open Thoughts in Study 3

Time	Effort	Quality	Categories of thoughts mentioned (%)			
			CodeCost	CodeEffort	CodeQuality	CodeOther
Tomorrow	Low	Low	93.3	2.2	60.0	6.7
		High	97.6	7.3	46.3	12.2
	High	Low	93.0	44.2	51.2	11.6
		High	94.3	49.1	24.5	7.5
In 2 years	Low	Low	89.6	2.1	62.5	8.3
		High	90.0	5.0	50.0	12.5
	High	Low	87.5	40.0	70.0	7.5
		High	91.9	35.1	32.4	13.5
Tomorrow	Overall	Overall	94.5	26.9	44.5	9.3
In 2 years			89.7	19.4	54.5	10.3
Overall	Low	Overall	92.5	4.0	55.2	9.8
	High		91.9	42.8	43.4	9.8
Overall	Overall	Low	90.9	21.0	60.8	8.5
		High	93.6	25.7	37.4	11.1
Overall	Overall	Overall	92.2	23.3	49.3	9.8

Finally, to provide further process measures, we analyzed participants' open thoughts, which were coded into the four categories described. Table 6 indicates that cost savings (92.2%), perceived quality differences (49.3%), and effort (23.3%) largely capture the reasoning for the choices made, with only 9.8% mentioning other factors (e.g., environmental impact, uncertainty, learning, and resell value). First, as would be expected, respondents were less likely to mention upgrade difficulty when they were presented with the plug-in design that reduced the upgrade effort ($\chi^2_1 = 72.80, p < 0.001$). Second, respondents were more likely to mention quality concerns in the low-quality condition ($\chi^2_1 = 18.95, p < 0.001$). Finally, the effects of time over cost ($\chi^2_1 = 2.79, p < 0.1$), quality ($\chi^2_1 = 3.49, p = 0.06$), and effort ($\chi^2_1 = 3.23, p < 0.1$) were marginally significant; quality was more likely to be mentioned in the two-year conditions, whereas cost and effort were more likely to be mentioned in the immediate future conditions.

These insights complement the ANOVA findings well. In general, upgrading a product is perceived to be a rather effortful task that is to be avoided if possible; furthermore, there may be concerns regarding the reliability and performance of the upgraded product. On the other hand, consumers do acknowledge the cost savings from the modular upgrade. In balancing these cost, quality, and effort considerations, consumers can be swayed to modularly upgrade by reducing effort (e.g., via product design) and improving perceived quality (e.g., through more durable designs and warranty extensions).

as hypothesized, from more budgetary resources being available then. Alternatively, using *PriceChange* as a covariate in the main ANOVA did not change any of the observed effects.

5.4. Discussion

As hypothesized, we find that people prefer full product replacement (i.e., a brand new product) at a distant future, even when it is much more expensive (\$900 versus \$450); yet when the upgrade is imminent, they tend to settle for the lower-cost modular upgrade. This suggests that, at the point of initial purchase, consumers may underestimate their likelihood of making low-cost component upgrades. If a market study were to be conducted at the point of purchase regarding users' thoughts about modular products, the result would underestimate the potential market for such products. This presumably favors integrated products over modular ones, and hence may be a barrier to the development and introduction of modular products. If consumers are to purchase a modularly upgradeable product, they need to be given a priori incentives to do so (e.g., via pricing, warranty, and product design features that facilitate component replacements). Our data also show that the effect of time is more pronounced when there is a large perceived quality difference between the modularly upgraded product and a brand new product; this effect is dampened when this quality gap is eliminated. This suggests that by reducing the perceived quality differences through product design or product warranty, the firm can alleviate preference reversals over time and increase the chances that modular products are adopted. Finally, the effort associated with modular replacement also plays a role in the choice between the two upgrade alternatives. In situations where it is desirable to entice consumers to upgrade their products in a modular fashion (for instance because of environmental considerations), we demonstrate that the preference for modular upgrades can be increased through product designs that simplify component replacement (e.g., plug-and-play designs).

6. Conclusion

Modular upgradeability has been suggested as a design strategy to reduce consumers' cost of keeping up with technological improvements (Ramachandran and Krishnan 2008) and alleviate the environmental harm that results from rapid product obsolescence (Bras and Emblemståg 1995, Newcomb et al. 1996, Agrawal and Ülkü 2012). The rationale is that by replacing only the components that improve and extending the effective life of the rest, the cost of upgrades and environmental impact can be reduced. However, work to date has ignored the influence of decision biases on how consumers value such products. The contribution of this paper is to assess consumers' valuations of, and purchase decisions regarding, modularly upgradeable products. In the

process, we also provide guidance on how firms should alter their design and pricing decisions to account for prevalent consumer decision biases.

To this end, we develop hypotheses rooted in theories from psychology, behavioral economics, and marketing and devise a series of three experiments to test these hypotheses. Study 1 finds that consumers tend to discount the cost savings associated with modular upgrades excessively when the time between the initial purchase and the upgrade is short (and discount insufficiently when the time frame is long). Study 2 expands on the implications of this effect by suggesting normative pricing strategies for modular products. Finally, in Study 3 we observe a preference reversal between the initial purchase and the point of upgrade: At the point of initial purchase, people foresee making a full product replacement in the future, yet, when faced with the actual upgrade decision, they are more likely to revert to modular upgrades. Because consumers weigh product quality differently at the time of the upgrade relative to the initial product purchase moment, preference reversals become possible. We discuss the implications of these results below.

6.1. The Modularity Paradox

Conventional wisdom suggests that modular upgradability is most advantageous for product categories that improve rapidly—a modular design would avert having to fully replace the product after only a short time. Paradoxically, our research indicates that consumers face strong decision biases for such products; with consumers heavily discounting the savings associated with modular upgrades (i.e., consumers undervalue these future savings), present bias is a significant obstacle against the adoption of modularity for rapidly improving (i.e., short-life-cycle) products. Conversely, for long-life-cycle products, consumers' natural tendency is to discount future savings at low discount rates, making such products a better fit for modularity (i.e., consumers overvalue future savings). Thus, when consumer behavior is properly accounted for, modular upgradability as a product feature may have higher profit potential for slowly improving products, and less for rapidly improving ones, counter to intuition.

Implications for Pricing Strategy. If the firm ignores the aforementioned consumer bias when pricing a modular product (e.g., by mistakenly assuming exponential discounting), this would not only lead to a reduction in profits, but also limit the acceptance of modular products. Hence, a firm introducing a modular product should account for this bias in its pricing decisions. Because consumers excessively discount the future savings attributable to modular upgrades for rapidly improving (i.e., short-life-cycle) products,

the firm should keep the initial price low to entice the consumer to purchase the modular product and charge a higher price for the upgrade. Conversely, given that consumers do not discount the future savings sufficiently for slowly improving (i.e., long-life-cycle) products, the pricing strategy should be reversed—the firm can increase its profits by raising the price of the initial product while at the same time reducing the upgrade price.

Implications for Market Research. When there is a substantial difference in the perceived quality of the upgraded product and that of a brand new one, consumers tend to underestimate the likelihood of a future modular upgrade if surveyed at the point of the initial purchase; although people prefer a modular upgrade in the present, they foresee purchasing a brand new product when replacement takes place in the distant future. Hence, despite the potential benefits from modular products, at the point of the initial purchase, people underestimate its full value. Thus, if a market study were to be conducted before product launch to assess consumers' likelihood of exercising their modular upgrade option, its findings would be misleading because they would underestimate both the upgrade likelihood and the firm's potential revenues from the upgrades.

Implications for Product Design and Marketing. Our results suggest that if the perceived future quality difference is minimal, then at the point of initial purchase consumers will more appropriately estimate the likelihood of future component replacement, and therefore will properly assess the future value of the modular product. Hence the firm can prompt consumers to appropriately assess the product's future value by reducing the perceived quality difference between a modularly upgraded product and a brand new product. The perceived quality of the modular upgrade might be enhanced, for example, through product design, warranty, or marketing communications. Alternatively, at the time of initial purchase the firm might address this consumer bias by helping consumers understand (e.g., via consumer testimonials) how favorably they will later (i.e., at the point of upgrade) view the modular product. Once a modular product is adopted, the likelihood of exercising the upgrade is higher than consumers anticipate. Finally, our experimental data show that it is important for the firm to minimize the effort that will be expended by consumers in making the modular upgrade (e.g., introduce plug-and-play modules).

Implications for the Environment. Our research is also informative about specific ways in which firms might better be able to tap into the underlying potential of modular products, in line with recent appeals in the literature on the topic. For example, a review paper by Ramdas (2003) notes that the implications of

modularity for sustainable design are poorly understood, and other researchers also observe inadequate understanding of consumer behavior with respect to end of life product management (Atasu et al. 2008, Agrawal et al. 2009, Ovchinnikov 2011). Although we do not directly address the issue of sustainability, our findings help instruct firms and researchers who are looking at modularity as a possible means of making products more environmentally friendly. Whereas the majority of the literature on sustainable operations takes product design as given (for review, see Kleindorfer et al. 2005, Atasu et al. 2008), our work contributes toward understanding how consumers respond to designs that have the potential to extend product life and reduce waste.

Limitations and Future Research. This research addressed consumers' initial product choice (modular versus integral) and their subsequent upgrade decision (module versus product replacement). The predominant motivation for choosing the modular alternative here is *cost efficiency* in making upgrades: By replacing only the improving components, the overall cost of ownership can be reduced. This is not the only benefit of modular product architectures. As suggested by several authors (e.g., Ulrich 1995, Salvador 2007), modularity can also enable firms to provide a larger variety of products at a low cost (i.e., mass customization). From the consumer perspective, modularity makes it possible to customize and adapt products to changing needs, as well as add new functionalities when necessary. It would be interesting to investigate the value of modular upgradeability for consumers in settings featuring large product variety. Furthermore, behavioral biases of the type we studied may depend on the product type (hedonic versus utilitarian) or on the attributes of the individual (level of product category expertise, variety seeking tendency, price sensitivity, etc.). Finally, it would be beneficial to include the identified behavioral patterns in more complex pricing models, as suggested by the findings in Study 2; further research is required to establish the optimal pricing strategies in different contexts. In short, modularly upgradeable products offer significant potential to save consumers money while being environmentally friendly, but questions remain about the impact that consumer biases have on the acceptance and profit potential of such products. Our work is aimed at providing the initial framework for firms and scholars to begin thinking about these issues of conceptual and practical relevance.

Acknowledgments

The authors thank the department and area editors as well as four anonymous reviewers for their guidance and constructive comments during the review process. They also

acknowledge the feedback from Vishal Agrawal, Atalay Atasu, Kurt Carlson, Abbie Griffin, Prashant Malaviya, Jurgen Mihm, Arul Mishra, Himanshu Mishra, Bill Moore, Selcuk Onay, Keith Ord, Enno Siemsen, Svenja Sommer, Debora Thomson, and Luc Wathieu on earlier drafts. They are particularly grateful to Andrew Long for his help with programming. Finally, this paper has also benefited from comments of seminar participants at HEC Paris, IE Madrid, George Washington University, Texas Christian University, University of Maryland, the Indian School of Business, University of Utah, and POMS, INFORMS, MSOM, and Behavioral Operations Conferences.

Appendix. Procedures

Study 1—The Choice Between Integral and Modular Products

Please consider carefully the following scenario. You are looking to buy a new Apple desktop computer that you will need to upgrade in [1, 2, 4 years] to the latest technology. There are two new versions of the product on the market.

(1) The Apple iMac-I is an integrated computer that has its hard drive and DVD drive built into the 22" flat-screen monitor. After [1, 2, 4 years], the iMac-I will need to be replaced in full to upgrade to the new generation.

(2) The Apple iMac-M is a modular computer that has a separate unit for hard drive and DVD drive and a separate flat-screen monitor. After [1, 2, 4 years], an easy replacement of only one component will effectively upgrade the computer to be fully equivalent to the complete new integral iMac-I computer.

According to Consumer Reports and evaluations by 546 Apple.com customers, the integrated iMac-I and the modular iMac-M versions of the product are very similar in terms of their looks, quality, and overall performance. The integrated iMac-I sells for \$1,200 today and upgrading to the new generation will cost another \$1,200 in [1, 2, 4 years] years. The purchase price of the modular iMac-M today is an amount larger than \$1,200, but upgrading the iMac-M in [1, 2, 4 years] will only cost \$600. Which option do you choose?

Integral product: Pay \$1,200 now and replace it for \$1,200 in [1, 2, 4 years].

Modular product: Pay P_i^M now and replace only the module for \$600 in [1, 2, 4 years].

Follow-up Questions. 1. In the iMac scenario you read, what was the time between the initial purchase and the upgrade?

2. How would you assess the quality of the modular iMac-M when upgraded, relative to a new iMac-I? (1 = extremely inferior, 4 = equal, 7 = superior)

3. How would you assess the effort involved in upgrading the modular iMac-M? (1 = effortless, 4 = acceptable amount of effort, 7 = extremely effortful)

4. If you owned an iMac-M, how certain are you that you would eventually upgrade the module?

Study 2—Hyperbolic Discounting and Its Pricing Implications

Camera. Please consider the following scenario. Ricoh has just launched its new GXR photo camera. This is a

highly unique and innovative camera with an upgradeable lens/sensor module which slides into the core housing that includes the rest of the point-and-shoot elements. Customers will initially buy a complete unit, and as technology advances (better lenses that are faster and more sensitive to light) they will be able to upgrade by buying only the new lens/sensor module.

You are buying the complete GXR camera now and will definitely upgrade it with a new lens/sensor module in [1, 4] year(s). Ricoh offers you the choice between two payment plans.

Plan A: The camera's price is \$1,200. You will pay another \$400 in [1, 4] year(s) to upgrade to a new lens/sensor module.

Plan B: The camera's price is $\$P_i^M$. You will pay another \$100 in [1, 4] year(s) to upgrade to a new lens/sensor module.

Air conditioning. Please consider the following scenario. You own your home and expect to stay in it for the foreseeable future. You are buying a new air-conditioning/heat-pump unit for the house. The most important aspect of the unit is its compressor, which determines how well the unit runs. Compressor technology improves over time, with each successive compressor generation featuring higher energy efficiency and lower noise levels. You can replace just the compressor module of your unit to take advantage of these improvements.

You are buying the complete air-conditioning/heat-pump unit now and will definitely upgrade with a new compressor module in [4, 8] years. You find Haier offers you the choice between two payment plans.

Plan A: The air-conditioning/heat-pump unit's price is \$3,600. You will pay another \$1,200 in [4, 8] years to upgrade to a new compressor module.

Plan B: The air-conditioning/heat-pump unit's price is $\$P_i^M$. You will pay another \$300 in [4, 8] years to upgrade to a new compressor module.

Follow-up Questions. 1. To what extent did you consider the uncertainty about the future in your responses during the (camera/A/C) scenario? (1 = not at all, 7 = extremely)

2. Please rate your knowledge of digital (cameras/A/C). (1 = not at all knowledgeable, 7 = extremely knowledgeable)

Study 3—Impact of Quality and Effort

Ricoh's GXR photo camera is a highly unique and innovative camera with an upgradeable lens/sensor module that slides into the core housing that includes the battery casing and the rest of the more basic point-and-shoot elements. Customers initially buy a complete unit and as technology advances (better lenses that are faster and more sensitive to light) they are able to upgrade by buying only the new lens/sensor module. Of course, they can also choose to purchase a brand new GXR instead.

Imagine that you own a two-year-old GXR camera (you just bought new GXR camera). You need (after two years of usage, you will need) a faster lens and more advanced sensors now but the remaining parts of your camera are (will be) in perfect shape. You (will) have two options to upgrade your GXR camera tomorrow (in two years).

Low Quality, Low Effort (Tomorrow, in Two Years)

(a) Buy a new GXR camera with a faster lens and more advanced sensor for \$900 tomorrow (in two years). The new camera comes with a warranty from Ricoh.

(b) Replace only the lens/sensor module of your GXR camera tomorrow (in two years) at a lower cost. After you purchase the new more advanced lens/sensor module, you will unplug the old module and plug in the new one. This process should take less than a minute. Because you replace only the lens/sensor, Ricoh does not (will not) provide any warranty. The upgraded camera is also (will also be) about 20% bulkier than a new one.

Please choose the option below that you prefer.

Select A: Replace the entire camera tomorrow (in two years), paying \$900.

Select B: Replace only the lens/sensor module tomorrow (in two years), paying $\$P_i^M$.

In the remaining conditions, the only differences in the descriptions were as follows.

Low Quality, High Effort (Tomorrow, in Two Years)

(b) Replace only the lens/sensor module of your GXR camera tomorrow (in two years), at a lower cost. After you purchase the new more advanced lens/sensor module, you will personally disconnect and remove the old module (by unscrewing eight very sensitive miniature screws), locate the connecting pins, align, and match the module to the camera body at a perfect angle to avoid damage, carefully drop the module into place, and slowly reinsert the miniature screws. This process will take about 30 minutes. Because you replace only the lens/sensor, Ricoh does not (will not) provide any warranty. The upgraded camera is also (will also be) about 20% bulkier than a new one.

High Quality, High Effort (Tomorrow, in Two Years)

(b) Replace only the lens/sensor module of your GXR camera tomorrow (in two years), at a lower cost. After you purchase the new more advanced lens/sensor module, you will personally disconnect and remove the old module (by unscrewing eight very sensitive miniature screws), locate the connecting pins, align and match the module to the camera body at a perfect angle to avoid damage, carefully drop the module into place, and slowly reinsert the miniature screws. This process will take about 30 minutes. Even if you replace only the lens/sensor, Ricoh renews (will renew) the warranty for the entire unit as if it were entirely new.

High Quality, Low Effort (Tomorrow, in Two Years)

(b) Replace only the lens/sensor module of your GXR camera tomorrow (in two years), at a lower cost. After you purchase the new more advanced lens/sensor module, you will unplug the old module and plug in the new one. This process should take less than a minute. Even if you replace only the lens/sensor, Ricoh renews (will renew) the warranty for the entire unit as if it were entirely new.

Follow-up Questions. 1. Please describe below the factors that played a role in the choice you made above between full product replacement and component replacement. (open thoughts)

2. My budget was a constraint to my upgrade decision. (1 = completely disagree, 7 = completely agree)

3. My time availability was a constraint to my upgrade decision. (1 = completely disagree, 7 = completely agree)

4. How would you rate the effort involved in upgrading the lens/sensor module in the existing camera relative

to the effort involved in replacing the entire camera? (1 = much less effortful, 4 = same, 7 = much more effortful)

5. How would you rate the quality of the camera upgraded by replacing its lens/sensor module versus the quality of the new camera? (1 = much inferior, 4 = same, 7 = much superior)

6. I am confident that I would be able to make the lens/sensor module upgrade. (1 = completely disagree, 7 = completely agree)

7. Do you expect the price of the typical new camera in 2013 to be more or less than the price of the typical new camera in 2011? (1 = much less, 4 = same, 7 = much more)

Sample Codings. Each participant's statements were evaluated by coders blind to experimental condition. Whenever a participant's response was relevant to more than one category, each category was coded as 1. Below are some coding examples:

Cost: "I based my decision solely on cost."

Quality: "The weight of the camera mostly. I have a hard enough time traveling lightly as it is."

Quality and Effort: "Everything actually important to the camera's performance would be upgraded by buying a new lens module. Furthermore, the actual installation of the replacement lens was described as being fast and easy to do so I inclined even more in that direction."

References

- Agrawal V, Ülkü S (2012) The role of product modularity in green product design. *Manufacturing Service Oper. Management*. Forthcoming.
- Agrawal V, Atasu A, van Ittersum K (2009) The effect of remanufacturing on the perceived value of new products. Working paper, College of Management, Georgia Tech, Atlanta.
- Ainslie GW (1974) Impulse control in pigeons. *J. Experiment. Anal. Behav.* 21(3):485–496.
- Arabsheibani G, de Meza D, Maloney J, Pearson B (2000) And a vision appeared unto them of a great profit: Evidence of self-deception among the self-employed. *Econ. Lett.* 67(1):35–41.
- Atasu A, Guide VDR, Van Wassenhove LN (2008) Product reuse economics in closed loop supply chain research. *Production Oper. Management* 17(5):483–496.
- Baldwin YC, Clark KB (2000) *Design Rules* (MIT Press, Cambridge, MA).
- Baron RM, Kenny DA (1986) The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *J. Personality Soc. Psych.* 51(6):1173–1182.
- Bras B, Emblemståg J (1995) The use of activity-based costing, uncertainty and disassembly action charts in demanufacture cost assessments. 1995 ASME Adv. Des. Automation Conf., Boston, 285–293.
- Buhrmester M, Kwang T, Gosling SD (2011) Amazon's mechanical Turk: A new source of inexpensive, yet high-quality, data? *Perspectives Psych. Sci.* 6(1):3–5.
- Dhebar A (1994) Durable-goods monopolists, rational consumers, and improving products. *Marketing Sci.* 13(1):100–120.
- Ebert JEJ, Prelec D (2007) The fragility of time: Time-insensitivity and valuation of the near and far future. *Management Sci.* 53(9):1423–1438.
- Fixson SK (2003) The multiple faces of modularity—A literature analysis of a product concept or assembled hardware products. Technical Report 03-05, Industrial and Operations Engineering, University of Michigan, Ann Arbor.
- Fixson SK (2007) Modularity and commonality research: Past developments and future opportunities. *Concurrent Engrg.: Res. Appl.* 15(2):85–111.
- Frederick S, Loewenstein G, O'Donoghue T (2002) Time discounting and time preference: A critical review. *J. Econom. Literature* 40(2):351–401.
- Garud R, Kumaraswamy A (1995) Technological and organizational designs for realizing economies of substitution. *Strategic Management J.* 16:93–109.
- Kleindorfer PR, Singhal K, Van Wassenhove LN (2005) Sustainable operations management. *Production Oper. Management* 14(4):482–492.
- Kornish LJ (2001) Pricing for a durable-goods monopolist under rapid sequential innovation. *Management Sci.* 47(11):1552–1561.
- Krupka EL, Stephens M Jr (2010) The stability of elicited discount rates over time. Working paper, Department of Economics, University of Michigan, Ann Arbor.
- Laibson D (1997) Golden eggs and hyperbolic discounting. *Quart. J. Econom.* 112:443–477.
- Langlois RN, Robertson PL (1992) Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries. *Res. Policy* 21(4):297–313.
- Lieberman N, Trope Y (1998) The role of feasibility and desirability considerations in near and distant future decisions: A test of temporal construal theory. *J. Personality Soc. Psych.* 75(1):5–18.
- Loewenstein G, Prelec D (1992) Anomalies in intertemporal choice: Evidence and interpretation. *Quart. J. Econom.* 107(2):573–597.
- McDonough W, Braungart M (2002) *Cradle to Cradle: Remaking the Way We Make Things* (North Point Press, New York).
- Newcomb P, Bras B, Rosen D (1996) Implications of modularity on product design for the life cycle. *Proc. 1996 ASME Design Engrg. Tech. Conf. Comput. Engrg. Conf.*, Irvine, CA, 483–490.
- Norton MI, Mochon D, Ariely D (2011) The IKEA effect: When labor leads to love. Working Paper 11-091, Marketing Unit, Harvard Business School, Boston.
- Okada EM (2001) Trade-ins, mental accounting, and product replacement decisions. *J. Consumer Res.* 27(4):433–446.
- Okada EM, Hoch SJ (2004) Spending time versus spending money. *J. Consumer Res.* 31(2):313–323.
- Ovchinnikov A (2011) Revenue and cost management for remanufactured products. *Production Oper. Management* 20(6):824–840.
- Paolacci G, Chandler J, Ipeirotis PG (2010) Running experiments on Amazon mechanical Turk. *Judgment Decision Making* 5(5):411–419.
- Ramachandran K, Krishnan V (2008) Design architecture and introduction timing for rapidly improving industrial products. *Manufacturing and Service Oper. Management* 10(1):149–171.
- Ramdas K (2003) Managing product variety: An integrative review and research directions. *Production Oper. Management* 12(1):79–101.
- Read D (2004) Intertemporal choice. Koehler D, Harvey N, eds. *Blackwell Handbook of Judgment and Decision Making* (Blackwell, Oxford, UK).
- Read D, Frederick S, Orsel B, Rahman J (2005) Four score and seven years from now: The date/delay effect in temporal discounting. *Management Sci.* 51(9):1326–1335.
- Salvador F (2007) Toward a product system modularity construct: Literature review and reconceptualization. *IEEE Trans. Engrg. Management* 54(2):219–240.

- Samuelson P (1937) A note on measurement of utility. *Rev. Econom. Stud.* 4(2):155–161.
- Scholten M, Read D (2006) Discounting by intervals: A generalized model of intertemporal choice. *Management Sci.* 52(9):1424–1436.
- Shapiro C, Varian H (1999) *Information Rules: A Strategic Guide to the Network Economy* (Harvard Business School Press, Boston).
- Slade G (2006) *Made to Break: Technology and Obsolescence in America* (Harvard University Press, Boston).
- Soman D, Ainslie G, Frederick S, Li X, Lynch J, Moreau P, Mitchell A, et al. (2005) The psychology of intertemporal discounting: Why are distant events valued differently from proximal ones? *Marketing Lett.* 16(3):347–360.
- Tam L, Dholakia UM (2011) Delay and duration effects of time frames on personal savings estimates and behavior. *Org. Behav. Human Decision Processes* 114(2):142–152.
- Trope Y, Liberman N (2000) Temporal construal and time-dependent changes in preference. *J. Personality Soc. Psych.* 79(6):876–889.
- Trope Y, Liberman N (2003) Temporal construal. *Psych. Rev.* 110(3):403–421.
- Ulrich K (1995) The role of product architecture in the manufacturing firm. *Res. Policy* 24(3):419–440.
- Weber EU, Johnson EJ, Milch KF, Chang H, Brodscholl JC, Goldstein DG (2007) Asymmetric discounting in intertemporal choice: A query-theory account. *Psych. Sci.* 18(6):516–523.
- Zauberman G, Lynch JG (2005) Resource slack and propensity to discount delayed investments of time versus money. *J. Experiment. Psych.: General* 134(1):23–37.
- Zhang Y, Fishbach A, Dhar R (2008) When thinking beats doing: The role of optimistic expectations in goal-based choice. *J. Consumer Res.* 34(4):567–578.