A Product Design-Driven Approach to Managing Rapid Sequential Innovation

Vish Krishnan[*], Karthik Ramachandran[†]

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Abstract

Global competition and major technological advances cause substantial performance improvements in many product categories including consumer electronics, computers and software. Rapid sequential innovation refers to the situation when firms launch a sequence of products in time whose performance quality improves not only in absolute terms but also in discounted terms from the perspective of customers. Managing such innovation presents certain unique challenges to profit-maximizing firms designing such products because the seller's choices make buyers reconsider their purchase timing, with some customers possibly regretting their purchase timing decisions at a later time. Prior work has shown that firms planning to launch rapidly improving products without causing customer regret must either restrain their rate of innovation or forego their degrees of freedom in pricing their product upgrades. In this paper, we examine if product design can help firms manage rapid sequential innovation without constraints on the rate of innovation or upgrade pricing. In a two-period setting, we find that by following a product architectural approach called *Modular Upgradability* and by localizing performance improvements a firm can maximize its profits without causing customer regret. Two approaches to modular upgradability are considered that differ in the degree to which industry standard components are used with different implications for prices and profits. We derive conditions under which the modular upgradability approaches dominate other pricing-based approaches to this problem. Our key contribution in this paper is the identification, formalization, and analysis of a product design based approach to intertemporal price discrimination and sequential introduction of rapidly improving products.

(*Keywords:* New Product Development; Product Architecture; Modular Upgradability; Proprietary Systems; Sequential Product Introduction)

[*]University of Texas at Austin, Department of Management CBA 4.202, Austin, TX-78712, vish.krishnan@mccombs.utexas.edu

[†]University of Texas at Austin, Department of Management CBA 4.202, Austin, TX-78712, karthikr@mail.utexas.edu

1 Introduction

Frequent technological advances have resulted in increasingly rapid quality improvements and price reductions for many products. It is well known that speeds of microprocessors have increased orders of magnitude over the last decade. Intel has emerged as the dominant firm in this industry by maintaining the pace of innovation according to *"Moore's Law"* which shows no signs of slowing down (Newsweek, 2002). Sequential introductions of better versions are also routine for many other customer electronics and software products (PC Magazine, 2003). We call such serial introduction of products, whose performance improves over time not only in absolute terms but also in discounted terms, *Rapid Sequential Innovations* (RSI's). Rapid improvements are not limited to the "*high-tech*" sector either. Toyota Motor Corp.'s *Kaizen* approach resulted in significant improvements in qualities and price reduction between the 2003 and 2004 editions of Toyota Sienna (Business Week, 2003).

The unique challenges of firms engaging in RSI have received limited attention. Our specific interest is in the firm's quest to encourage customers to buy the initial versions of products and their upgrade versions as the firm innovates. Dhebar (1994) considered the attempt by a monopolist firm to intertemporally discriminate among a group of vertically differentiated customers using a rapidly improving sequence of products. He showed that a monopolist should not innovate at its own rapid rate, because doing so makes rational customers anticipate the firm's opportunistic behavior and the firm's profit maximizing choices end up causing customer regret. Our interest in this paper is in understanding if product design (and specifically the product architecture decision) can help a monopolist firm manage rapid product improvement and maximize its profits without causing customer regret. Specifically, we examine if making a product upgradable in modules can help a firm engaging in rapid sequential innovation.

The partitioning of rapidly advancing products into improving and stable (industry-standard) modules enable firms to not only focus on their core skills, but also convince customers their investments in products won't be totally obsoleted in short periods of time. Several generations of micro-processors belonging to the same family can be used with the same combination of peripherals like storage devices, motherboards, printers and networking devices; it is also common for users to replace operating systems and other software with newer versions without revisions to other hardware or software components of the computing system. Products whose performance can be improved by replacing a minimal set of components are termed *Modular Upgradable* (MU). A formal mathematical definition of modular upgradability follows later in the paper. Previous researchers have studied the relationship between product architecture and demand in the context of inter-firm dynamics (Langlois and Robertson, 1992; Matutes and Regibeau, Matutes and Regibeau), but we do not know of any prior work that considers the role of product architecture in facilitating the launch of sequential innovations.

The fundamental questions we try to answer in this work are: (i) What is the impact of product architecture on customers' actions when they face a quickly improving sequence of products? (ii) Should the products be sold as separable modules, allowing easy upgradability? (iii) Should the products be designed for restricted use with only proprietary components? A central finding of this work is that the problem of customer regret, common under RSI, is significantly alleviated when the product is designed in a modular-upgradable fashion. However, there are at least two different ways by which the product can be made modular upgradable, with different implications for prices and profits, that we characterize in the paper.

The rest of the paper is organized as follows. The literature related to this work is reviewed in Section 2. We define our constructs and formulate the model in Section 3. The analysis and main results are presented in Section 4 and Section 5. We conclude with a discussion of analytical results and managerial implications in Section 6.

2 Literature Review

The literature related to this paper falls in two categories: (i) product architecture and (ii) rapid sequential innovation that we review in this order.

2.1 Product Architecture

Product architecture is the scheme by which the performance quality (function) of a product is allocated to physical components (Ulrich, 1995). In a modular product, the mapping from performance to components is one to one. Properties of complex modular systems have been studied in detail with respect to coordination and localization of functions (Sanchez and Mahoney, 1996; Simon, 1969). Baldwin and Clark (1999) argue that modularization adds to the real option value of any product's design. While integral products have to be redesigned and tailored for each application, modular architectures can be used as platforms because of their flexibility in several variations of the basic product (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996). Product modularity also induces economies of scale due to component commonality, and these production efficiencies have to be factored into product line decisions (Kim and Chhajed, 2000). Other advantages of modularity arise from the ability to reuse previously designed components, save costs in logistics, and focused knowledge development. A more recent and detailed survey of the literature of modularity can be found in Mikkola and Gassmann (2003). In spite of the advantages of modular systems, an integral product architecture is preferable under certain circumstances (Ulrich and Ellison, 1999; Baldwin and Clark, 1997) .

Products upgradable using industry standard modules have had a long tradition in the personal computer industry (The New York Times, 1991; The Wall Street Journal, 1991). Upgrading in modules is frequently encountered in fast paced industries for a couple of reasons. First, modular innovation can be more effective than systemic innovation because of the ability of the organization to transfer accumulated knowledge across successive generations of new products, resulting in longevity of the platform and wider variety of models(Sanderson and Uzumeri, 1995). Second, customers find the task of adjusting to modular innovations easier than to radical systemic changes. Despite its industrial relevance, modular upgradability has not attracted significant research attention. In this paper, we concern ourselves with the latter advantage of modularity and demonstrate analytically that a careful localization of innovations in a separate module makes the purchase decision simpler for the customer and profit maximization possible for the innovator.

After deciding to make its product upgradable in modules, a firm must still choose between proprietary and industry-standard components to build its modules (Morris and Ferguson, 1993). The answer is straightforward when the proprietary components are superior to the catalogue components, so we try to compare the options when industry standards are better. This variant of the *make-buy* decision can be thought of either as a *design-select* decision (Ulrich and Ellison, 1999), or as a *make-open* decision where the firm might invite open competition with no entry barriers for components that it does not intend to improve. Garud and Kumaraswamy (1993) investigate Sun Microsystems's architectural strategy and conclude that a closed system architecture dissuades rivals and manufacturers of complementary products from making compatible products. Our work identifies the value of using standard components in conjunction with proprietary modules even in the absence of cost side efficiencies due to withdrawal from the production business.

2.2 Rapid Sequential Innovation

Manufacturing durable goods and the related issue of time inconsistency have been analyzed in depth in the economics literature (Coase, 1972; Bulow, 1982). Bulow (1982) suggested leasing as a mechanism to tackle the competition from goods sold in earlier periods. Stokey (1979) proposed that time could be used as an effective medium to price discriminate with one product in a vertically differentiated market. When a firm produces multiple products to discriminate in such a market, low end customers exert a negative externality on the firm's ability to discriminate (Mussa and Rosen, 1978). The effects of cannibalization on new product introduction were studied for static and improving technologies by Moorthy and Png (1992) and Bhattacharya et al. (2003) respectively, and later in the context of development intensive products by Krishnan and Zhu (2003).

Although a significant amount of research attention has been focused on product positioning in vertically differentiated markets, rapidly-improving products have been an exception. As mentioned earlier, Dhebar (1994) pinpointed the problems faced by a monopolist firm in intertemporally discriminating among its customers in the context of rapid sequential innovation. Dhebar showed that a sub-game-perfect equilibrium fails to exist when the product's quality improves in discounted terms, and argued that the only alternative for a firm is to restrain its rate of innovation. Unfortunately, in most industries, especially those that involve nascent technological standards, controlling the pace of development is not an option due to a number of reasons. Firstly, product quality in relatively new industries is closely tied to the underlying technology's properties, knowledge about which could be public. A second characteristic of such technologies is the opportunity for smaller businesses to enter the market if a monopolistic firm fails to offer the best possible quality. Third, selling a durable product with little or no improvement over time can expose the firm to competition from second hand markets in later periods (Coase, 1972; Bulow, 1982).

As an alternative to restraining innovation, Kornish (2001) showed that by foregoing its ability to offer its preferred or installed base customers a special upgrade price for the improved product, a firm will be able to suggest to its customers that their purchase decisions in the first period will not be unduly used to the firm's advantage. Though this solution is applicable to markets where identifying the buyers of the basic product is impossible, special upgrade prices are an important tool for firms to encourage its installed base to make repeat purchases in many industrial settings.

The issue addressed in this work is native to markets with skewed distribution of power[1]. We also consider the commoditization of the stable module of the system when imitators enter in later periods. Purohit (1994) considers the related problem that an innovator faces when lower end products are cloned as they age. Schmidt and Porteus (2000) consider a more direct model of entry in later periods focusing on a technology leader's ability to resist such an attack. It should also be noted that our primary concern is about product selection decisions of customers who derive value by using these products at a personal level. Adoption decisions of organizations that buy improving technologies used in production of other goods and services are not the focus of this research. Balcer and Lippman (1984), in a paper that is archetypal of research on adoption of improving technologies by firms, found that adoption of the current technology is delayed if an advanced technology's imminent arrival is announced; for a recent overview of this line of research, see Hoppe (2002). Optimal pricing policies for a firm selling improving technologies to competing manufacturers have been developed by Erat and Kavadias (2004). The focus in this literature has been to capture decisions made by profit maximizing agents who adopt (industrial) technologies, while we concentrate on rational utility maximizing customers.

Our primary contribution is the unification of the work from the economics literature on time inconsistency with the product development concepts of architecture and modularity. We contribute to the RSI literature by extending previous analyses to a wider class of products, which are not used in isolation. By doing so, we also add to the rich literature in product architecture by identifying another benefit of modularity in managing rapid sequential innovations. In the following section, a basic model of a modular, improving product is developed. Results for the proprietary and non-proprietary approaches are presented in Sections 4.2 and 4.4 respectively. We then compare the benefits and costs of different approaches to managing rapid sequential innovation and discuss some implications.

[1]"The ability to discriminate requires market power, since competitive forces will determine the price at each date if there are many firms", Stokey (1979).

3 Model Setting and Description

We begin the section with a model of purchase decision making by the customer. Modular upgradability is mathematically defined and formulated subsequently. Later, the producer's optimization problem is formulated for the case in which the product is sold as separate modules, followed by the non-proprietary case, where a module sold by the manufacturer is combined with some components sold by others.

3.1 Rapid Sequential Innovation

A sequence of improving products is designed and introduced by a monopolist firm. In any period t, the latest version of the sequence, $\mathcal{P}_t$, is offered by the firm. To maintain a sharp focus and to enable close comparison with prior work on managing rapid sequential innovation (Dhebar, 1994; Kornish, 2001), the following modeling assumptions are made:

- A two period setting is considered and in any period the firm resorts to a product replacement approach by offering only the latest version in the second period. The timing of new product introduction and the length of the periods are exogenous to the model; this is typical of industries in which new products are introduced seasonally or annually. For a discussion of the problem a firm faces in determining the best time to introduce a new version of a durable product, see Wilson and Norton (1989).

- The improvement in performance quality of the product happens between the two periods and depends on exogenous factors; uncertainties about the path of quality improvement are negligible compared to the main effect of rapid improvement.

- There are no second hand markets for the products; rapid quality improvement severely reduces the substitutability of the earlier versions or the firm is able to preempt the resale of these goods through other means.

- The market is vertically differentiated in its valuation for product's performance quality - customers can be rank ordered on their willingness to pay, v, for a unit of product benefit. The customer index v is distributed uniformly between 0 and 1. While some of our analytical results can be extended to more general customer distributions and valuation functions, the linear function is used to simplify the presentation.

- In each period, a customer can buy zero or one unit of the product. All customers discount future product benefits and payments by the same single period discount factor, δ_c. The firm's single period discount factor is δ_f.

The lifetime value a customer v derives by using the product $\mathcal{P}_t$, $W(q_t, v)$, depends on the quality of the product q_t.

$$W(q_t, v) = vf(q_t) \tag{3.1}$$

$W(q_t, v)$ is the reservation price of customer v for a product of quality q_t. The function $f(q_t)$ represents the benefit of a unit of product quality. We limit ourselves to the separable product form of $W(q, v)$ to keep our analyses clear, and in accordance with the RSI literature.

To qualify for rapid improvement, the product's performance quality must improve in customer-discounted terms:

$$\delta_c f(q_2) > f(q_1) \tag{3.2}$$

The sequence of the customer's and firm's actions is shown in Figure 3.1. The product $\mathcal{P}_1$ is sold at time $t = 1$. Customers make their first-period *purchase* or *wait* decisions based on the expected price and quality of the improved (second-period) product and the price and quality price of the first-period product. In accordance with the prior work on rapid sequential innovation, we assume all customers have same expectations for prices and qualities of the second-period product. In the second period, the improved product $\mathcal{P}_2$ is released at a price that the monopolist firm finds optimal. Customers base their second-period purchase decisions based on the announced prices and qualities of the improved product.

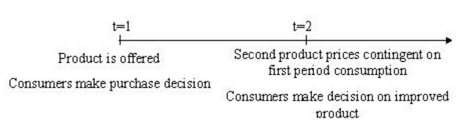

Fig. 3.1 Timeline of decisions

Notion of Customer Regret

When customers evaluate outcomes, they compare what they received with what they expect to have received. The unpleasant discovery that a forgone alternative would have led to a better outcome is the cause of regret in decision making under uncertainty (Landman, 1987). The problem of customer regret is salient to *rapid sequential innovation*, characterized by improvements in performance quality even in discounted terms.

In leading customers to self-select the appropriate versions, firms involved in RSI face a peculiar problem of time inconsistency. Adoption of the first version also depends on the price customers expect to pay for the improved product. To avoid postponement and possible confusion arising from lack of information, the firm indirectly creates expectations for product $\mathcal{P}_2$. customers share this coordinated second-period expected price, p_2^e. Based on p_1 and p_2^e, some customers prefer to wait while others adopt $\mathcal{P}_1$based on their valuation for product quality. However, once the market is segmented in the first-period, the firm may behave opportunistically by exploiting customers who delayed purchase (adopted early) by setting a revised price $p_2 > p_e$ ($< p_e$). Rational customers foresee such incentives, and firms that have not established an inherent credibility are unable to price discriminate effectively (Dhebar, 1996). This is reflected in the absence of a sub-game-perfect equilibrium for the two stage game of sequential innovation and pricing.

A pricing solution to gain some credibility is proposed by Kornish (2001) when "it (is) either too easy for a customer to claim, or too easy to prove he bought in the first period". This is achieved by abdicating the firm's degree of freedom with respect to the product upgrade and offering a single price for the improved version. While this addresses customer concerns effectively under these conditions, it comes at the cost of pricing flexibility and lower profits. In the following sections, we show that product design choices can solve the time inconsistency problem, and more importantly for the firm, without losing upgrade pricing flexibility.

3.2 Modular Upgradability

Prior research on rapid sequential innovation assumes that each version is an integrated product, and older versions of the product are discarded in entirety when they are upgraded. But what we often find in practice with personal computers and other electronics offerings is that rapidly improving products are often comprised of several independently evolving constituents. Our model of modular upgradability is built to reflect this reality:

(a) *Product Partitioning*: The product consists of physically and functionally separable component subsystems. A modular design approach involving a one-to-one mapping from functions to components allows for such product partitioning (Henderson and Clark, 1990; Ulrich, 1995).

(b) *Localized Improvements*: Quality improvement is *localized* in only some of the component subsystems. By this we imply that the older version of the product/system can be upgraded by replacing only a subset of components.

Property 3.1 Modular Upgradability

The sequence of products $\mathcal{P}_t$ is modular upgradable if there are non-empty partitions $\mathcal{I}_t$ and $\mathcal{S}_t$ such that

1. Modularity: $\mathcal{I}_t \cup \mathcal{S}_t = \mathcal{P}_t$ *and* $\mathcal{I}_t \cap \mathcal{S}_t = \emptyset$, $\forall\ t = 1, .., T$

2. Localization: $\mathcal{Q}(\mathcal{P}_{t+1}) = \mathcal{Q}(\mathcal{I}_{t+1} \cup \mathcal{S}_t)$, $\forall\ t = 1, .., T-1$

Instead of considering the product at the component level, we take a consolidated view of the product and assume that each version is separated into a *Stable Module* ($\mathcal{S}_t$) and an *Improving Module* ($\mathcal{I}_t$). We consider modular product systems in which all the significant improvement is localized on a subsystem $\mathcal{I}_t$ produced by the monopolist firm. As mentioned earlier, we consider a two period model and set $T = 2$. The stable module does not undergo functional changes and will be represented by $\mathcal{S}$ ($\mathcal{S} \equiv \mathcal{S}_1 \equiv \mathcal{S}_2$). The different modules are produced at constant marginal costs (c_1, c_2 and c_s for $\mathcal{I}_1, \mathcal{I}_2$ and $\mathcal{S}$ respectively). To achieve compact analytical results, we normalize marginal costs to zero in deriving our main propositions; but at several occasions, we verify that our central intuitions are valid by incorporating positive marginal costs in our analysis. Price of the standard module is denoted by p_s. The improving module prices in the two periods are denoted by p_1 and p_2 respectively.

Modularization has the potential to affect the quality of the product. Technologically, the product may become bulkier and creation of additional interfaces may lower product quality (Baldwin and Clark, 1997; Ulrich and Ellison, 1999). Also, a customer choosing to upgrade the improving module may experience a loss of quality due to additional assembly. We account for these negative effects of modularity by explicitly considering a loss of quality parameter, $\alpha \in [0, 1)$.

Suppose the products introduced in our two period model are of qualities q_1 and q_2 when designed as an integral system. But in a modular system, the quality of the improved version is reduced to q_2^α.

$$\frac{\partial f(q_2^\alpha)}{\partial \alpha} < 0$$

The impact of this quality loss is analyzed in following sections. To consider RSI products alone, in our discussion of modularity, we limit our attention to combinations of α and δ_c such that:

$$\delta_c f\left(q_2^\alpha\right) > f(q_1)$$

A simple form is used in the numerical analysis in section 5. We assume that

$$f(q_2^\alpha) = (1 - \alpha) f(q_2)$$

There are two fundamentally different design alternatives for the modular product described above. $\mathcal{I}_t$ can be designed to work with a stable module $\mathcal{S}$ manufactured by other firms or only with that made by the focal monopolist firm. To investigate the influence of modular upgradability in these two cases, we distinguish between *Proprietary* and *Non-proprietary* modular upgradable products.

3.2.1 Proprietary Modular Upgradable Systems

When the customer must purchase both the improving and stable modules from the monopolist, the firm is said to follow a proprietary modular upgradable approach. The firm manufacturing a modular proprietary system can price the different modules, $\mathcal{S}$ and $\mathcal{I}_t$ optimally. In this model, the firm sells two versions of the improving modules, $\mathcal{I}_1$ and $\mathcal{I}_2$ at prices p_1 and p_2 respectively. $\mathcal{S}$, which can be used in conjunction with any improving module, is sold at the same price p_s (at margin $p_2 - c_2$) in both periods. The price of $\mathcal{S}$ remains the same in both periods. Let $\mathcal{D}_1, \mathcal{D}_2$ and $\mathcal{D}_u$ be the set of customers who buy only the first version, customers who buy only the second version, and those who buy both versions respectively. Let D_1, D_2, and D_u be the corresponding number of customers. In a proprietary system, the firm gets the revenues from the sales of the improving and the stable modules, but delayed benefits are discounted by δ_f per period. The firm's problem in the second period is:

$$R_2^*(p_s) = \max_{p_2} \left(((p_2 - c_2) + (p_s - c_s))\, D_2 + (p_2 - c_2) D_u \right) \tag{3.3}$$

The firm's first period problem is:

$$\Pi^* = \max_{p_1, p_s} \left(((p_1 - c_1) + (p_s - c_s))(D_1 + D_u) + \delta_f R_2^*(p_s) \right) \tag{3.4}$$

In the proprietary approach, the firm in some cases might not have the credibility to convince its customers that the stable module $\mathcal{S}$ will be sold at a constant price over time. To address this doubt, innovating firms might use a collection of industry standard components as a substitute for $\mathcal{S}$ which we consider below

3.2.2 Non-Proprietary Modular Upgradable Systems

When the product is designed so that the stable module is a commodity that can be purchased from the open market, the firm is said to follow a non-proprietary modular upgradable approach. a modular product is improving rapidly over time, the innovator is able to maintain control of the market for $\mathcal{I}_t$. We consider the case of the general purpose module that will be produced and supplied competitively by many firms (at price p_s); this is characteristic of the desktop computer industry where several competitors supply some basic components with standard interfaces and minimal differentiation, and some components that improve with time are produced by a few manufacturers. An industry structure of this type could also be formed when a manufacturer of a modular system opens up the architecture of its system and/or certain functional, spatial, and compatibility specifications to rivals and partners. They are then free to compete in the market for a standard component that can be bought independently by customers. The firm sets prices p_1 and p_2 by solving the following problems in the two periods.

Second period:

$$R_2^*(p_s) = \max_{p_2} \left((p_2 - c_2) \left(D_2 + D_u \right) \right) \tag{3.5}$$

First period:

$$\Pi^* = \max_{p_1} \left((p_1 - c_1)(D_1 + D_u) + \delta_f R_2^*(p_s) \right) \tag{3.6}$$

Customers may be apprehensive about adopting proprietary design choices for a variety of reasons. They may be afraid of locking themselves into a support and service relationship with monopoly vendors of proprietary systems, due to the possibility of higher total costs of ownership. Also, the firm may not have the credibility to convince customers that the stable module $\mathcal{S}$ will be sold at a constant price, p_s, in both periods. The possibility of paying a higher price, receiving lower quality, having limited freedom after purchase and costlier support for proprietary products reduces the value customers derive from these products. We operationalize all of these effects by using a single tolerance parameter ($\delta_p \in (0, 1]$), which represents the loss of quality customers perceive with proprietary solutions. When the non-proprietary choice delivers product qualities q_t, the proprietary solutions, irrespective of the architecture, are capable of delivering only customer perceived quality $\delta_p q_t$.

4 Model Analysis

In this section, equilibrium prices for proprietary and non-proprietary architectures are obtained. The firm derives the demand pattern that will be generated by its prices. customers anticipate the pricing reactions of the firm in the second period based on their consumption decisions in the first period. A consistent set of prices, beliefs and decisions leads to a regret-free resolution of the problem (a subgame perfect equilibrium).

4.1 Marginal customers and Market Segmentation[2]

Based on the qualities of the products and prices of the three modules, purchase patterns of the customer base can be derived. Some basic properties of the different purchase patterns (that hold true for both proprietary and nonproprietary design choices) can be formalized.

Property 4.2 *If there is a customer $\hat{v}$ who buys the first version ($\mathcal{I}_1 + \mathcal{S}$) and upgrades in the second period ($\mathcal{I}_2$), all customers in $v \in [\hat{v}, 1]$ will buy both modules in the first period and upgrade by buying the improved module ($\mathcal{I}_2$) in the second period.*

Proof. The proof is in the Appendix ♢

Property 4.3 *If there is a customer $\hat{v}$ who buys the improved module $\mathcal{I}_2$, then all customers in $v \in [\hat{v}, 1]$ buy $\mathcal{I}_2$.*

Proof. The proof is in the Appendix ♢

Property 4.2 indicates that it is not possible to have a higher valuation customer (with a magnified improvement in benefits from the upgrade) not buying the improved module while a lower valuation customer upgrades by purchasing the improved module. Property 4.3 is driven by similar intuition. However, this does not preclude the possibility that a higher-valuation customer might buy in the second period with the intention of upgrading, when a customer with a lower willingness to pay buys the second period product for the first time. The above properties, while being simple, help limit the number of possible purchase patterns to be considered in Property 4.4 below.

Marginal customers

A marginal customer is one who is indifferent between two consumption actions. The customer who is indifferent between actions i and j is denoted by v_{ij}. Here, i and j represent the decision pairs described above: $i, j \in 0, 1, 2, u \equiv$ *{do not buy any version, buy in first period only, buy improved version only, both in both periods}*. Note that a customer can be indifferent between actions i and j, but perform neither. Marginal customers' indices for the modular system are shown in the

[2]Since the results of section 4.1 are applicable to both proprietary and non-proprietary systems, to make the presentation simpler, we assume that $\delta_p = 1$ in this sections without loss of generality.

table below. (v_{ij} and v_{ji} are used interchangeably throughout the paper.)

Actions	No purchase	Buy in period 1	Buy in period 2
Buy $\mathcal{P}_1$	$v_{01} = \frac{(p_s+p_1)}{f(q_1)}$	-	-
Buy $\mathcal{P}_2$	$v_{02} = \frac{p_s+p_2}{f(q_2^\alpha)}$	$v_{12} = \frac{\delta_c(p_2+p_s)-(p_1+p_s)}{\delta_c f(q_2^\alpha)-f(q_1)}$	-
Buy $\mathcal{P}_1$& $\mathcal{P}_2$	$v_{0u} = \frac{p_s+p_1+\delta_c p_2}{f(q_1)+\delta_c(f(q_2^\alpha)-f(q_1))}$	$v_{1u} = \frac{p_2}{f(q_2^\alpha)-f(q_1)}$	$v_{2u} = \frac{(1-\delta_c)p_s+p_1}{(1-\delta_c)f(q_1)}$

Market Segmentation and Effect of Modularity

First period buyers are not required to reinvest in the stable module if they decide to upgrade their systems when $\mathcal{I}_2$ is launched. Consequently, the market segment for which the option of buying $\mathcal{P}_1$ alone is ideal diminishes as the portion of investment in $\mathcal{S}$ relative to $\mathcal{I}_t$ grows. Segmentation patterns (SP) and corresponding participation constraints for different values of p_s are summarized in property 4.4.

Property 4.4 *Let* $P_1 = \frac{f(q_1)p_2}{f(q_2^\alpha)-f(q_1)} - \frac{p_1}{1-\delta_c}$*, and* $P_2 = \frac{p_2 f(q_1)-p_1 f(q_2^\alpha)}{f(q_2^\alpha)-f(q_1)}$*. For all nonnegative prices* (p_1, p_2, p_s)*, the market is divided according one of the following segmentaion patterns (SP) when the product is improving rapidly.*

SP 1. *If* $p_s \leq P_1$*, then* $\mathcal{D}_1 = [v_{01}, v_{1u})$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{1u}, 1]$.

SP 2. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta_c)p_s \leq (1-\delta_c)f(q_1)$*, then* $\mathcal{D}_1 = [v_{01}, v_{12})$*;* $\mathcal{D}_2 = [v_{12}, v_{u2})$*;* $\mathcal{D}_u = [v_{2u}, 1]$.

SP 3. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta_c)p_s \geq (1-\delta_c)f(q_1)$*, then* $\mathcal{D}_1 = [v_{01}, v_{12})$*;* $\mathcal{D}_2 = [v_{12}, 1]$*;* $\mathcal{D}_u = \emptyset$.

SP 4. *If* $p_s \geq P_2$*, then* $\mathcal{D}_1 = \emptyset$*;* $\mathcal{D}_2 = [v_{02}, v_{u2})$*;* $\mathcal{D}_u = [v_{2u}, 1]$.

Proof. The proof is in the Appendix. $\diamondsuit$

Property 4.4 provides some intuition about the effect of product modularity on consumption decisions. When p_s is larger, more first period buyers are induced to take advantage of $\mathcal{I}_2$ when it is available. Equivalently, if the firm commits to an architecture that will allow customers to retain a significant part of their initial investment when they upgrade, the customer base is retained as the firm moves along a path of rapid innovation. Firms involved in RSI face the problem of *balking* by customers, who temporarily or permanently stop upgrading their products till technological improvements become less turbulent. Dhebar (1996) suggests that producers should pace innovation to match customer ability to adopt; but it is clear that architectural choice can result in the same without costly reduction in innovative efforts.

4.2 Optimal Pricing Policies for the Proprietary System

As noted before, customers who buy the product in the first period pay a price of p_2 to obtain the improved product, but first time customers pay $p_2 + p_s$. Firms cannot offer special upgrade prices for integral products in markets where first period customers cannot distinguish themselves, but modular upgradability can be used in lieu of upgrade pricing even in these circumstances. Proposition 4.1 gives optimal prices when the firm has the ability to commit to a constant price for $\mathcal{S}$ in both periods. For proving it in the appendix, we assume that $c_1 = c_2 = c_s = 0$, but the validity of the main insights behind the results have been tested numerically for several combinations of costs.

Proposition 4.1 *Proprietary modular upgradable products that are rapidly improving in quality can be launched without causing customer regret. The following prices result in a sub-game perfect equilibrium:*

$$p_s^* = \frac{f(\delta_p q_1)}{2}, p_1^* = 0, p_2^* = \frac{(f(\delta_p q_2^\alpha) - f(\delta_p q_1))}{2} \tag{4.7}$$

The equilibrium is unique when $\delta_c = \delta_f$

Further, in this equilibrium, $v_{1u} = v_{12} = v_{01}$ *and* $\mathcal{D}_1 = \mathcal{D}_2 = \emptyset$, $\mathcal{D}_u = [v_{01}, 1]$.

The optimal price for the stable module, p_s^*, is clearly higher than that of the improving module. From a profit maximization perspective, the firm makes the same profit as long as the combined price of $\mathcal{S}$ and $\mathcal{I}_1$ is $\frac{f(\delta_p q_1)}{2}$. Higher p_s makes customer purchase decision easier since it leaves a smaller margin in the second period for the firm to price opportunistically. Consequently, the equilibrium price of $\mathcal{S}$ is set at the upper bound dictated by profit maximization.

The unique equilibrium shown above with the proprietary archiecture and the firm and customer having the same discount factor is however not intertemporally discriminating. The sets of customers who buy the two versions are identical. In this approach, the firm optimally skims the market at the same level in both periods. This result is consistent with previous observations on intertemporal discrimination (without innovation). "The price cuts necessary to attract a wider market induce too many buyers to delay their purchases, making price discrimination unprofitable" (Stokey, 1979). Additionally, we find that an attempt to be aggressive with the first product (in a proprietary architecture) results in unprofitably turning away too many higher end customers of the improved product.

Finally, we note that there could be another intertemporally discriminating equilibrium in the general case when $\delta_c \neq \delta_f$. The firm manages to attract a wider market in the second period in this equilibrium. Although we do not provide closed form results, we numerically consider this later.

While modular upgradability enables the firm to offer special upgrade prices to customers, maintaining proprietary nature of the modules constrains the firm in two ways. (a) The firm has control over both p_s and p_2 when the improved version is launched, thereby retaining an option to price opportunistically in the second period. (b) By committing to keep a module unchanging, the firm might lose its monopolistic ownership of the market for $\mathcal{S}$ in the second period. These problems can be addressed by either designing a non-modular product or by using an off-the-shelf stable module. In section 4.3, we analyze the problem created by lowering the barrier to entry. In section 4.4, the optimal pricing policies while using a widely available product, instead of newly designing $\mathcal{S}$, are developed.

4.3 Entry of Clones

By localizing improvements in one module, the firm makes the market for $\mathcal{S}$ vulnerable to entry by imitation in later periods. A situation in which entry in the stable module market is costless is considered in this section. Purohit (1994) found that the optimal level of innovation is higher for a firm when it faces a threat of competitive entry in the market for low end products. Innovation rates are exogenously determined in our model, but our interest is in determining if the threat of competitive production of $\mathcal{S}$ in later periods affects the choice of product architecture.

Consider entry by a single competitor, who markets an exact imitation of the original $\mathcal{S}$ in the second period. We assume that all customers prefer the cheaper of the two leadsing to a Bertrand pricing game. (More sophisticated representations of competition after entry complicates the model and the basic insights we are after.) In equilibrium, the firms will decide on a single price for $\mathcal{S}$ in the second period. If the prices of $\mathcal{S}$ in the two periods are p_{s1} and p_{s2}, the implicit upgrade discount for second period purchasers who upgrade from the first version is p_{s2}. Therefore, the firm that initially controlled the architecture of the product has no direct influence over the benefits of modular upgradability for the customers.

If the incumbent firm decides to fight entry, it can do so either by engaging in a price war in the second period or by pricing the first product aggressively, thereby eliminating the market for the stable goods in the second period. Note that these actions are equivalent in the sense that neither offers customers an upgrade discount. Under these circumstances, prices correspond to the case in which the incumbent uses a no-special-upgrade-price policy for a non-modular system (since $p^*_{s2} = 0$). The firm can also accommodate the entrant by not manufacturing $\mathcal{S}$ in the second period.

The decision to accommodate or fight the clone depends on the relative patience of the firm and its customers. When customers are willing to wait (high δ_c), a high discount on upgrades (high $\delta_c p_{s2}$) results in higher sales. Allowing the imitator to dictate p_s accomplishes this. But losing a share of second period revenues outweighs this effect for lower levels of δ_c. Similarly, when δ_f is sufficiently high, the additional profit of selling more of the improved version overcomes the value of keeping all of the second period profit by blocking the entrant. In this case, the firm actually benefits by allowing the entrant to usurp the market for $\mathcal{S}$. We formalize this intuition in Proposition 4.2. For simplicity of presentation, we set $\delta_p = 1$ in this section.

Proposition 4.2 *The incumbent's decision to accommodate or deter cloning of the stable module depends on δ_c and δ_f as follows:*

1. *For any δ_c, $\exists\ \delta^*_f$ such that the incumbent accommodates the imitator by not producing the stable module in the second period if $\delta_f \geq \delta^*_f$*

2. *For any δ_f, $\exists\ \delta^*_c$ such that the incumbent accommodates the imitator if $\delta_c \geq \delta^*_c$*

Proof. The proof is in the Appendix. $\diamondsuit$

In the example in fig 4.3, the firm is better off by deterring entry in region D accommodating the entrant in region A. As benefits and profits from the second period become more valuable for customers and the firm, the prospect of imitation is increasingly attractive for the firm. This runs counter to our intuition that the firm would want to resist any entrance in a market that was previously under its control. We have considered the case in which there is only one entrant, which allows for strategic interaction in the second period between the incumbent firm and the entrant. Within the confines of our model, allowing multiple entrants is less interesting and less insightful because multiple entrants engage in Bertrand pricing, thereby leading to $p^*_{s2} = 0$ in all cases.

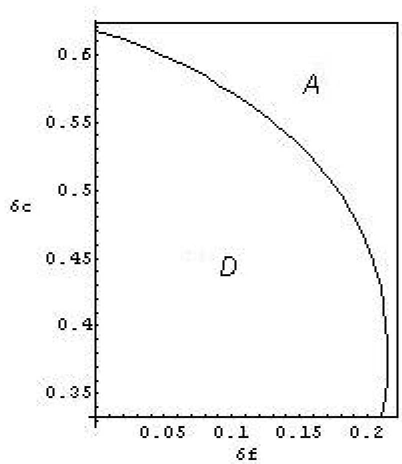

Fig.4.3. Regions of accommodation and deterrence of entry. $f(q_1) = 1, f(q_2) = 3, \delta_p = 1 - \alpha = 1$

4.4 Optimal Pricing Policies for Non-proprietary System

”The point of modular upgradability is easy upgrading and investment protection; it removes the shadow of obsolescence from the users mind and, from a cost standpoint, it extends the depreciation time for the purchased equipment” (Electronic Engineering Times, 1991). But the point is conveyed successfully to customers only if they are convinced that p_s, the price of $\mathcal{S}$, will not be raised later to take advantage of them. Making the stable module widely available as a separate retail product helps address customer concerns.

We model that a competitively supplied version of $\mathcal{S}$ is available. The firm sets prices p_1 and p_2, while the standard module is assumed to be available in both periods at a competitive price of p_s. Customers' investment in $\mathcal{S}$ is taken into consideration by the firm when prices for $\mathcal{I}_t$ are fixed.

The optimal pricing policies that result in sub-game-perfect equilibrium solutions are described in Propositions 4.3.

Proposition 4.3 *Non-Proprietary modular upgradable architecture helps launch a sequence of rapidly improving products without causing customer regret. Two possible intertemporally discriminating subgame perfect equilibrium solutions exist:*

1. *A SP1 price discrimination can be achieved when* $\delta_c < 1$ *and* $\frac{f(q_1)}{2} \geq p_s \geq 0$.

2. *A SP4 price discrimination can be achieved when* $\frac{(2\delta_c-1)f(q_1)f(q_2^{\alpha})}{2\delta_c f(q_2^{\alpha})-f(q_1)} \leq p_s \leq f(q_1)$

Proof. The proofs and expressions for equilibrium prices are provided in the Appendix. ♢

A SP1 purchase configuration corresponds to the case when the high-end customers buy in the first and second periods, while customers in the middle purchase only in the first period. When the cost of procuring the off-the-shelf module is sufficiently high ($p_s > \frac{f(q_1)}{2}$), the first period offering is expensive pushing the market towards delayed adoption. Therefore, it is not profitable to introduce it as the basic product intended for a wider customer base.

Only customers at the higher end of market are interested in the first period version in SP 4. They are motivated by not having to invest in $\mathcal{S}$ again at the point of upgrade. Therefore, a low p_s implies that the firm has to select a lower p_1 to launch $\mathcal{I}_1$ successfully. A tremendously cheap $\mathcal{S}$ (corresponding to the lower bound for p_s in the above proposition) makes launch $\mathcal{I}_1$ unprofitable. The prices of the improving modules derived in the appendix are decreasing in p_s, indicating that costlier stable modules imply reduced revenue per unit produced, although they provide a level of credibility that the firm may not have established.

While comparing prices is a straightforward exercise, the relation between profits in the two types of discrimination is best explained with examples. Figure 4.4 shows profits that can be obtained by using the two approaches for the non-proprietary system, as functions of the price of standard module, p_s. In our example, we consider two systems that result in RSI, $f(q_1) = 1, f(q_2^{\alpha}) = 3$,and $\delta_c = 0.5$, $\delta_f = 0.4$. The production costs in the example are $c_1 = 0.1$, $c_2 = 0.15$, and the price of stable module varies up to $f(q_1)$.

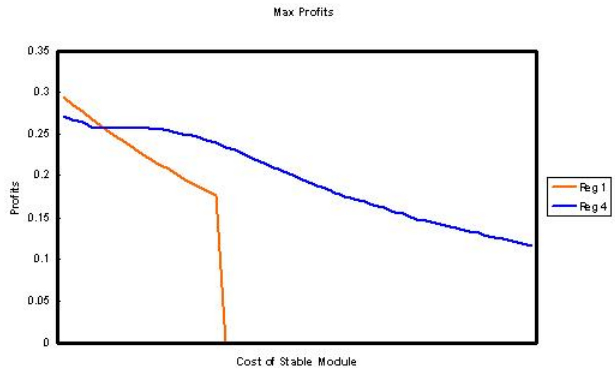

Fig. 4.4. Variation of profit with p_s when $f(q_1) = 1, f(q_2^{\alpha}) = 3$,and $\delta_c = 0.5$, $\delta_f = 0.4$.

Selling to lower end customers in the first period (region 1) is possible when δ_c is sufficiently high and for low values of p_s $\left(p_s < \frac{f(q_1)}{2}\right)$. Accordingly, in the figure the profit curve corresponding to different value of p_s in region 1 stops developing at $p_s + c_1 = 0.5$, beyond which manufacturing the early version results in a loss. The profits in the region 1 equilibrium fall monotonically with an increase in p_s while pricing the first product aggressively. In this case, first period customers are more sensitive to price. Therefore higher costs of $\mathcal{S}$ eat into the surplus that can be extracted by the firm in the first period. Also, higher end customers buying in the second period do not appreciate the presence of modularity, which limits the price of the improved product.

5 Appropriateness of Architectural Decisions

Let the profit from the no-special upgrade price solution[3], the proprietary modular solution and the non-proprietary solution be π_{NU}, π_P and $\pi_{NP}(p_s)$ respectively. The profitability of the three approaches are compared in Proposition 5.4 when there are no costs associated with a proprietary modularity architecture.

Proposition 5.4 *When $\alpha = 0$, $\delta_p = 1$, and $\delta_c = \delta_f$, the profits from the proprietary system, non-proprietary system and non-modular system with no-upgrade price guarantee are ordered as follows:*

$$\pi_P > \pi_{NU} > \pi_{NP}(p_s)\ \forall p_s > 0$$

[3]By this, we mean the pricing solution obtained by committing to not offer a special upgrade price (Kornish, 2001) that can be used for a non-modular system. The profit expressions are not shown explicitly for brevity; but they are simply obtained by setting $p_s = 0$ in Propositions 4.3 and **??**.

Proof. The proof follows from a direct comparison of the profit expressions. ♢

Using a proprietary modular system is more profitable than committing to abstain from offering special upgrade discounts or penalties. The firm manages to alleviate customer regret in the commitment scheme only by suspending an important degree of freedom in pricing. When prices can be set separately for the different modules the firm regains this extra freedom, which makes a wider range of prices feasible. Therefore, the proprietary modular architecture is most profitable, whenever possible. The commitment scheme's profits dominate the profits obtained by using a non-proprietary modular architecture. In our model, this result is a direct outcome of the firm's exit from the market for stable modules. Admittedly, our model is limited in the sense that it fails to capture the effects of development and production costs on profits. It is our belief that the comparison between non-proprietary architecture and the no-upgrade-price commitment is incomplete in this regard. A more careful consideration of costs with respect to this problem is left for future work.

The result is also sensitive to our assumptions that re-architecting the product in a modular fashion has no effect on the perceived quality of the products. Fig 5.1 shows the dominant architectural choice for different combinations of α and δ_c. In region E and F, the no-special upgrade price solution is most profitable. In region D and G, the proprietary and non-proprietary products are preferred.

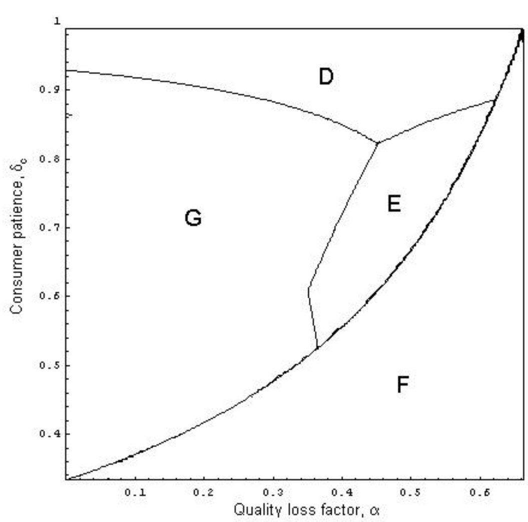

Fig. 5.1. Dominant architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = 0.6$, $p_s = 0.1$ $\delta_p = 0.6$

Since it is a direct measure of the loss of product quality that occurs due to modularization, a high α represents a greater cost of designing a modular product. Therefore, for any δ_c, we observe that modular solutions, proprietary and non-proprietary, are more attractive than the pricing approach for lower levels of α. Further, in region F, significant loss in quality combines with low discounting to make the quality improvement more gradual. Our numerical analysis indicates that the firm should not modularize the product if quality is compromised seriously. Since the choice of product qualities does not constitute the central proposition of this work, we hope to able to address this issue in greater detail in a subsequent paper[4].

When the firm has the option of selecting between a proprietary and non-proprietary approach, customers' ability to leverage any investment in $\mathcal{S}$ becomes more important. The proprietary solution is preferred over the non-proprietary solution for higher levels of δ_c. When customers are more patient, (higher δ_c), purchasing in the first period results in a higher discount, (higher $\delta_c p_s$), if they wish to upgrade their system later. Therefore, when they are more patient, willingness to buy the first system with *the intention of upgrading* is higher. The firm selling a proprietary product is able to charge a higher p_s at higher levels of δ_c. Recall that the customers are prepared to pay a higher price for non-proprietary products. For lower δ_c, the cost of proprietariness is higher than the benefit of being able to set an optimal p_s.

The influence of δ_p can be understood using the example in fig.5.2. The figure shows the dominant architectural solutions for $\delta_p = 0.7$, and $\delta_p = 0.6$. A higher value of δ_p denotes a greater level of acceptance of proprietary products. When customers are less apprehensive about adopting proprietary solutions, i.e. when $\delta_p = 0.7$, the non-proprietary solution is dominant in region A, the proprietary modular solution should be adopted in regions B and D, and a non-modular product should be sold in all other regions. When $\delta_p = 0.6$, the non-proprietary modular architecture is the best alternative for the firm in regions A, B and C. The integral system is sold without special upgrade prices only in region E. The proprietary modular system is sold only in region D, where the customers are more patient which makes the implicit discount offered by the stable module is sufficient. Also note that when $\delta_p = 1$, the non-proprietary solution is not used under any condition,

[4]One of the main issues that are not immediately resolved by numerical analysis is whether the threat of quality loss always makes modular upgradability undesirable beyond a certain level.

while it becomes the ideal choice as δ_p approaches 0.

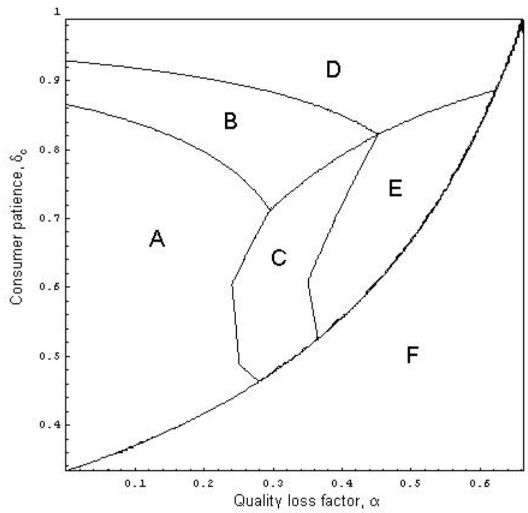

Fig 5.2. Dominant architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = 0.6$, $p_s = 0.1$ $\delta_p = 0.6$ or 0.7

The discontinuity in the boundary between regions A and C is due to the shift in the firm's approach for the non-proprietary module occurs at $\delta_c = 0.5$. When $\delta_c > 0.5$, it is more profitable to target the improved product towards the higher end of the market (type 1 equilibrium). As δ_c falls below 0.5, deferring purchase to the second period becomes attractive for most customers. This makes impossible the idea of selling the improved product exclusively to the higher end. This selection of the most valuable discrimination scheme for the non-proprietary architecture is manifested as a kink in the boundary.

These results show that the firm might have strong reasons to pursue a non-proprietary architecture in spite of the reduced share it obtains from the sales of each unit. Further, the intuition that the non-proprietary solution is more preferable if customers are wary of proprietary solutions (low δ_p) is also confirmed.

6 Conclusions

In this paper we asked the question if product design choices can help a monoplist dealing with rapidly improving products price-discriminate without causing customer regret. We developed a formal model of modular upgradability and its effect on purchases under sequential innovation. The model results help relate a product family's upgradability and sequential consumption behavior in a heterogeneous market. We find that a modular architecture can indeed be a valuable medium for effective intertemporal price discrimination for a firm. The firm's archiectural choice that allows for the product to be upgraded in modules protects early customers' investments for a longer period even when the quality improvement is rapid. Customers find it easier to make their purchase decisions when their initial investment is not completely obsoleted by subsequent introduction of superior products. Therefore, the firm's commitment to localizing performance improvements is more efficient than any pricing commitment in eliminating regret.

Contrary to wisdom that making architectural information openly available can be debilitating to the product line in the long run (Morris and Ferguson, 1993), we find that using standard components might be an attractive option, particularly when customers are relatively impatient (or more myopic). There is a strong incentive to use standard subsystems even when cost-side advantages of using standard components for the system are not considered. Whereas the suggestion from previous research is that firms might indulge in *open-sourcing* to encourage other firms to participate in innovation (Garud and Kumaraswamy, 1993), we find that adopting standard solutions for some modules can help firms achieve inter-temporal discrimination (section 4.4). Further, our numerical tests confirm our intuition that the incentive for modularization and maintenance of proprietary control are not independent of design effects and market parameters.

The main contribution is that were able to obtain several first order insights about the connection between customer behavior and product architecture, which are typically analyzed in mutual isolation. We hope that our framework to analyze the increasingly prevalent feature of improving product, namely modular upgradability, will be useful in studying richer problems regarding closed loop supply chains, re-manufacturing, after sales services, etc. in both intra-firm and inter-firm setups. We conclude with a brief note on constraints to our analysis and possible extensions of our work.

The long-run viability of the architectures is not addressed while drawing conclusions from a restrictive 2-period model. Selling a proprietary modular product results in an equilibrium with the same set of buyers in all periods; although it is successful in a 2-period model, this can lead to a stationary customer base that can wane with customer saturation (Krishnan and Zhu, 2003) and increased competition. Targeting progressively higher-end customers in later periods is likely to become infeasible in the long run, since this corresponds to selling improving products to a portion of an ever diminishing market. The approach of making improvements attractive to an expanding customer base could lead to more stability in the long run. A well established customer base can also counter competitive advances, particularly when there are positive network externalities associated with the use of the product. These arguments can be tested analytically and empirically in future research.

The single product, replacement model considered in this paper is in accordance with previous work on RSI. But this might not be realistic since many firms offer a line of products at each point of time. Stokey (1988) suggests that periodic addition (deletion) of high (low) quality products might be a result of industry wide spillovers of learning experiences that make firms more efficient in transforming technology to products. But we also find this to be the case in industries in which firms with market power are extremely protective. Is offering an improving product line as a series of *Stepping Stones* a viable alternative for modular upgradability in bringing customers along the path of technological improvement? We hope to be able to answer this question in the future.

We have assumed that customers are homogeneous except for their ordered valuations of quality. This gives rise to the question: Is quality always indexed by one variable? By appropriate definition of the relationship between $f(q)$ and $\mathcal{Q}(\mathcal{P})$, our analysis is easily extended to multiple dimensions of performance quality. We have also assumed that there is no resale market for the used products. Although this can be enforced by the manufacturer for many goods, presence of second hand markets can mitigate the effects of monopolistic opportunism for durable goods. Our casual observation suggests that presence of lemons in used goods markets and rapid innovation of products typically restricts the ability of used goods to compete with new and improved ones. Further, the strategy of selling older generations through secondary retail/e-tail channels allows separation of used goods from competing directly with more recent innovations. A more appropriate model is required to consider the effect of these practices on sequential innovation.

The effect of an imitator's entry in the market for stable goods was analyzed in Section 4.3. It might be in the best interest of the a firm to accommodate such entry in some cases. It indicates that there is a rich opportunity to model and understand implicit partnerships among manufacturers of complements, particularly in fast moving industries. Our exclusion of strategic alternatives for entrants was necessary to avoid distractions from the central focus of our work. In reality, innovation rates are dictated by such interactions. Further investigation into this area is certainly needed to understand acceptance of improving technologies by customers.

A Appendix

A.1 Proofs

A.1.1 Proof of Property 4.2

Let $U_a(v)$ denote the net utility obtained by taking action a for consumer with index v. Suppose upgrading is optimal for $\hat{v} \in (0, 1]$.

$$U_u(\hat{v}) \geq \max\{U_1(\hat{v}), U_2(\hat{v}), U_0(\hat{v})\} \Leftrightarrow \hat{v} > \max\left\{\frac{\delta_c p_2}{\delta_c f(q_2) - f(q_1)}, \frac{(1-\delta_c)p_s + p_1}{(1-\delta_c)f(q_1)}\right\}$$

Therefore, all consumer with index greater than $\hat{v}$ prefer to buy both products.

A.1.2 Proof of Property 4.3

1. Suppose $\hat{v}$ buys $\mathcal{I}_2 + \mathcal{S}$ in second period only, and $\hat{v} + \epsilon$ buys $\mathcal{P}_1$ alone. $U_2(\hat{v}) > U_1(\hat{v}) \Leftrightarrow \hat{v} > \frac{\delta_c p_2 - (1-\delta_c)p_s - p_1}{\delta_c f(q_2) - f(q_1)}$. Therefore, no consumer with index $\hat{v} + \epsilon$ buys $\mathcal{P}_1$ alone.
2. Suppose $\hat{v}$ buys $\mathcal{P}_1$ and upgrades with $\mathcal{I}_2$, we know from Property 4.2 that $\hat{v} + \epsilon$ does the same.

A.1.3 Proof of Property 4.4

Region 1. $p_s \leq P_1$

Under these conditions on prices, we know that $v_{01} \leq \min(v_{0u}, v_{02})$ $\Leftrightarrow$The lowest end marginal customer buys in the first period alone. And $v_{01} \leq v_{u1} \leq v_{12}$ $\Leftrightarrow$The next marginal customer buys in both periods. Also, from Lemma A, we know that v_{u1} is the final marginal customer. Therefore, customers in $v \in [0, v_{01})$ do not participate; $v \in [v_{01}, v_{u1})$ buy in the first period; $v \in (v_{1u}, 1]$ buy in the first period and upgrade when the improved product is available.

Region 2. $P_1 \leq p_s \leq P_2$ and $p_1 + (1-\delta)p_s \leq (1-\delta_c)f(q_1)$

In this region, $v_{01} \leq \min(v_{0u}, v_{02}) \Leftrightarrow$The lowest end marginal customer buys the first product only. $v_{01} \leq v_{12} \leq \min(v_{u2}, v_{u1}) \Leftrightarrow$The next marginal customer buys in the second period only. The final marginal customer is indifferent between buying in the second period and buying in both periods. Hence, $v \in [0, v_{01})$ do not buy; $v \in [v_{01}, v_{12})$ buy in the first period; $v \in [v_{12}, v_{u2})$ buy in the second period; $v \in [v_{u2}, 1]$ buy in the first period and upgrade.

Region 3. $P_1 \leq p_s \leq P_1$ and $p_1 + (1-\delta_c)p_s \geq (1-\delta_c)f(q_1)$

In this region, $v_{01} \leq \min(v_{0u}, v_{02}) \Leftrightarrow$the lowest end marginal customer buys in first period alone. $v_{01} \leq v_{12} \leq \min(v_{u2}, v_{u1}) \Leftrightarrow$the next marginal customer buys in the second period only. The customer with the lowest valuation for quality who is indifferent between buying in period 2 and buying in both periods is v_{u2}.

$p_1 + (1-\delta_c)p_s \geq (1-\delta_c)f(q_1) \Leftrightarrow v_{u2} \geq 1$. There is no customer who finds buying in both periods optimal. This results in a consumption pattern in which $v \in [0, v_{01})$ do not buy; $v \in [v_{01}, v_{12})$ buy in the first period; $v \in [v_{12}, 1]$buy in the second period.

Region 4. $p_s \geq P_2$

When second period prices are expected to be sufficiently low, $v_{02} \leq \min(v_{0u}, v_{01}) \Leftrightarrow$ the lowest end marginal customer buys in the second period alone. Also, $v_{01} \leq v_{u1} \leq v_{12} \Leftrightarrow$The next marginal customer buys in both periods. From Lemmas A and B, we know that v_{u2} and v_{02} are the only marginal customers in this region of prices. Therefore, $v \in [0, v_{02})$, do not buy in either period; $v \in [v_{02}, v_{u2})$ buy in the second period; $v \in [v_{u2}, 1]$ buy in the first period and upgrade.

A.1.4 Proof of Proposition 4.1

Pricing in Region 1.

To ensure SPE outcomes, we will begin by solving the second period problem. In the second period, it sells to the higher end customers. Rewriting the second period problem, we obtain the following result:

$$\max_{p_2} \{p_2 (1 - v_{1u})\} = \max_{p_2} \left\{ p_2 \left(1 - \left(\frac{p_2}{f(\delta_p q_2^{\alpha}) - f(\delta_p q_1)} \right) \right) \right\}$$

$p_2^* = \frac{f(\delta_p q_2^\alpha) - f(\delta_p q_1)}{2}$ and $R_2^* = \frac{(f(\delta_p q_2^\alpha) - f(\delta_p q_1))}{4}$

We now turn our attention to the first period problem, while constraining the solution to satisfy the conditions for Region 1.

$$\max_{p_s, p_1} \{(p_s + p_1)(1 - v_{01}) + \delta_f R_2^*\} = \max_{p_s, p_1} \left\{ (p_s + p_1) \left(1 - \left(\frac{p_s + p_1}{f(\delta_p q_1)} \right) \right) + \delta_f R_2^* \right\}$$
$$\text{s.t. } p_s^* \leq P_1$$

The unconstrained solution for this problem satisfies $p_s^* + p_1^* = \frac{f(\delta_p q_1)}{2}$. Now the constraint can be rewritten in terms of the qualities of the two products.

$$p_s^* \leq P_1 \Leftrightarrow p_s^* \leq \frac{f(\delta_p q_1)}{2} - \frac{p_1}{1 - \delta_c} \Leftrightarrow \frac{f(\delta_p q_1)}{2} - p_1^* \leq \frac{f(\delta_p q_1)}{2} - \frac{p_1}{1 - \delta_c}$$
$$p_s^* = \frac{f(\delta_p q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f(\delta_p q_2^\alpha) - f(\delta_p q_1)}{2}$$

Note that this does not constitute an intertemporally discriminating equilibrium because

$$v_{u1}^* = \frac{p_2^* f(\delta_p q_1)}{f(\delta_p q_2^\alpha) - f(\delta_p q_1)} \left(\frac{1}{f(\delta_p q_1)} \right) = \frac{1}{2} = \frac{p_s^* + p_1^*}{f(\delta_p q_1)} = v_{01}^*$$

Pricing in Region 2.

In the second period, the firm tries to sell to $v \in [v_{12}, 1]$. To ensure that it is is able to sell to the available segment of the market while maximizing its revenue, the firm will solve the following problem.

$$\max_{p_2} \{p_2(1 - v_{12}) + p_s(1 - v_{u2})\}$$
$$\text{s.t.}$$
$$v_{12} f(\delta_p q_2^\alpha) \geq p_s + p_2$$
$$v_{u2} \left(f(\delta_p q_2^\alpha) - f(\delta_p q_1) \right) \geq p_2$$

The first constraint ensures that all customers in the segment find the second period product attractive. The second constraint ensures that all customers who bought in the first period with the intention of upgrading find upgrading attractive. These set of constraints are equivalent to the condition $P_1 \leq p_s \leq P_2$. Hence, the firm sets second period price at its upper bound, $(p_1 + (1 - \delta_c)p_s) \left(\frac{f(\delta_p q_2^\alpha) - f(\delta_p q_1)}{(1-\delta_c) f(\delta_p q_1)} \right)$. At this p_2^*, $v_{12} = v_{u2}$. The segment of customers who bought in the second period alone vanishes in this instance, and the resulting scenario belongs to Region 1.

Pricing in Region 3.

There is no equilibrium in this region; for a detailed discussion, see Dhebar (1994).

Pricing in Region 4.

The second period problem and the optimal second period price can be found as follows.

$$\max_{p_2}\left\{p_2\left(1-\left(\frac{p_s+p_2}{f(\delta_p q_2^{\alpha})}\right)\right)+p_s\left(\left(\frac{(1-\delta_c)p_s+p_1}{(1-\delta_c)f(\delta_p q_1)}\right)-\left(\frac{p_s+p_2}{f(\delta_p q_2^{\alpha})}\right)\right)\right\}$$

$$p_2^*=\frac{f(\delta_p q_2^{\alpha})}{2}-p_s \text{ and } R_2^*=\frac{f(\delta_p q_2^{\alpha})}{4}+p_s\left[\frac{(1-\delta_c)p_s+p_1}{(1-\delta_c)f(\delta_p q_1)}-1\right]$$

Based on our solution to the second problem, the first period problem can be written as:

$$\Pi^*=\max_{p_s,p_1}\left\{(p_s+p_1)(1-v_{2u})+\delta_f R_2^{4*}\right\}$$
$$\text{s.t. } p_s^*+p_1^*\geq\frac{f(\delta_p q_1)}{2}$$

The first period objective function derived above is not jointly concave in prices p_1 and p_s, unless $\delta_c=\delta_f$. Closed form expressions are not derived for this region. Numerical solutions are used in the analysis in Section 5.

A.1.5 Proof of Proposition 4.2

First, we observe that all of the following actions have the same effect: The product is not modularized, the incumbent and the imitator engage in a Bertrand price war in the second period, the incumbent prices the first product aggressively and forces the entrant to enter by setting $p_{s2}=0$. The common equilibrium that results is same as the no-special-upgrade-price equilibrium given below:

$$p_1^*+p_{s1}^*=\frac{(1-\delta_c)f(q_1)}{2},\ p_2^*=\frac{f(q_2^{\alpha})-f(q_1)}{2},\ p_{s2}^*=0$$

The firm can accommodate the entrant by not producing the stable module in the second period.

The equilibrium price of the stable module in the second period is given by:

$$p_{s2}^* = \max\left\{0, \frac{f^2(q_2^\alpha)(\delta_c - \delta_f)}{9f(q_1)(1-\delta_c) + f(q_2^\alpha)(6\delta_c - \delta_f)}\right\}$$

The other prices are varied accordingly. The firm's profits for accommodating and fighting entry are:

$$\Pi_{acc} = \frac{9f^2(q_1)(1-\delta_c)^2 + \delta_c f^2(q_2^\alpha)(\delta_c + 4\delta_f) + 2f(q_1)f(q_2^\alpha)(1-\delta_c)(3\delta_c + 4\delta_f)}{4(9f(q_1)(1-\delta_c) + f(q_2^\alpha)(6\delta_c - \delta_f))}$$

$$\Pi_{det} = \frac{f(q_1)(1-\delta_c^2) + \delta_f(f(q_2^\alpha) - f(q_1))}{4}$$

Comparison of the profits gives δ_f^* and δ_c^*. Since the expressions are complex, we refer the reader to the figure 4.3 for more intuition.

A.1.6 Proof of Proposition 4.3

Pricing in Region 1. The second period problem for the firm can be formulated and solved in the following manner.

$$\max_{p_2}\left\{p_2\left(1 - \frac{p_2}{f(q_2) - f(q_1)}\right)\right\}$$
$$\Rightarrow p_2^* = \frac{f(q_2) - f(q_1)}{2}$$
$$R_2^* = p_2^*(1 - v_{1u}) = \frac{f(q_2) - f(q_1)}{4}$$

We now try to solve the first period problem for the firm enforcing the constraint for existence of equilibrium in this region.

$$\max_{p_1}\left\{p_1\left(1 - \left(\tfrac{p_1 + p_s}{f(q_1)}\right)\right)\right\} + \delta_f R_2^{1*}$$
$$\text{s.t. } p_s^* \le P_1$$

The unconstrained solution for this problem is given by $p_1^* = \frac{f(q_1) - p_s}{2}$. When $p_s > f(q_1)$, production in the first period is unprofitable. But this solution satisfies the constraint only when $p_s \ge \frac{\delta_c f(q_1)}{2\delta_c - 1}$. Combining these conditions, $\left(p_s \le f(q_1) \text{ and } p_s \ge \frac{\delta_c f(q_1)}{2\delta_c - 1}\right) \Leftrightarrow \frac{\delta_c f(q_1)}{2\delta_c - 1} \le f(q_1) \Leftrightarrow \delta_c \ge$

1 and $p_s = f(q_1)$. It is impossible to obtain the intertemporally discriminating equilibrium with the unconstrained solution for region 1, unless $\delta_c = 1$.

When $p_s \leq \frac{\delta_c f(q_1)}{2\delta_c - 1}$, the optimal first period solution is obtained form the fact that the constraint is binding. Therefore $p_1^* = \frac{(1-\delta_c)(f(q_1)-2p_s)}{2}$. For the first period price to non-negative, we now need $p_s \leq \frac{f(q_1)}{2}$.

Pricing in Region 2. The available market in the second period is $(v_{12}, 1)$.The second period problem can be written as:

$$\begin{aligned}
&\max_{p_2} \{p_2 (1 - v_{12})\} \\
&\text{s.t.} \\
&f(q_2)v_{12} - (p_2 + p_s) \geq 0 \\
&f(q_2)v_{2u} - p_2 \geq f(q_1)v_{2u}
\end{aligned}$$

The constraints are participation constraints for customers v_{12} and v_{2u} respectively. The solution is to set p_2 at the highest level allowed by the constrains in the second period. Rearranging the terms in the constraints, we obtain:

$$f(q_2)v_{12} - (p_2 + p_s) \geq 0 \Leftrightarrow P \leq p_2$$
$$f(q_2)v_{2u} - p_2 \geq f(q_1)v_{2u} \Leftrightarrow p_2 \leq (p_1 + (1-\delta_c)p_s)\left(\frac{f(q_2) - f(q_1)}{(1-\delta_c)f(q_1)}\right)$$

The optimal second period price of p_2 at this upper bound, and we find that $v_{12} = v_{u2}$. There are no customers who purchase the improved product alone - the problem reduces to the pricing problem in Region 1. Therefore, there is no equilibrium in Region 2.

Pricing in Region 3. There is no equilibrium in this region; for a detailed discussion, see Dhebar (1994).

Pricing in Region 4. The second period pricing problem is formulated and solved below.

$$\max_{p_2} \{p_2(1 - v_{02})\} = \max_{p_2} \left\{p_2 \left(1 - \left(\frac{p_2 + p_s}{f(q_2)}\right)\right)\right\} \Rightarrow p_2^* = \frac{f(q_2) - p_s}{2}$$

$$R_2^* = p_2^*(1 - v_{02}) = \left(\frac{f(q_2) - p_s}{2}\right)\left(1 - \frac{f(q_2) + p_s}{2f(q_2)}\right) = \frac{(f(q_2) - p_s)^2}{4f(q_2)}$$

The constraint for existence of equilibrium in Region 4 will be enforced in the first period problem. The first period pricing problem is

$$\max_{p_1} \{p_1(1 - v_{u2}) + \delta_f R_2^*\}$$
$$\text{s.t. } p_s^* \geq P_2$$

The unconstrained solution to this problem is found as follows.

$$\max_{p_1} \{p_1(1 - v_{u2}) + \delta_f R_2^*\} \Rightarrow p_1^* = \frac{(1 - \delta_c)(f(q_1) - p_s)}{2}$$

The unconstrained optimum is possible when $f(q_1) \geq p_s \geq \frac{\delta_c f(q_2) f(q_1)}{(1+\delta_c) f(q_2) - f(q_1)}$.

Observe that $\frac{\delta_c f(q_2) f(q_1)}{(1+\delta_c) f(q_2) - f(q_1)} > \frac{(2\delta_c - 1) f(q_2) f(q_1)}{2\delta_c f(q_2) - f(q_1)}$. When $\frac{\delta_c f(q_2) f(q_1)}{(1+\delta_c) f(q_2) - f(q_1)} \geq p_s \geq \frac{(2\delta_c - 1) f(q_2) f(q_1)}{2\delta_c f(q_2) - f(q_1)}$, the market-timing constraint is active and

$$p_1^* = \frac{f(q_1)(f(q_2^\alpha) + p_s) - 2p_s f(q_2^\alpha)}{2f(q_2^\alpha)}$$

If $\frac{(2\delta_c - 1) f(q_2^\alpha) f(q_1)}{2\delta_c f(q_2^\alpha) - f(q_1)} \geq p_s \geq 0$, it is impossible to select a price p_1 that satisfies the timing constraint. That is because, for these values of p_s, we can see that $v_{u2} = \frac{(1-\delta_c)p_s + p_1}{(1-\delta_c) f(q_1)} > 1$ for all permissible values of p_1. The profit maximizing solution in this case is to avoid launching the early version.

References

Balcer, Y. and S. A. Lippman (1984). Technological expectations and adoption of improved technology. *Journal of Economic Theory 34*, 292–318.

Baldwin, C. Y. and K. B. Clark (1997). Managing in an age of modularity. *Harvard Business Review 75*(5), 84–93.

Baldwin, C. Y. and K. B. Clark (1999). *Design Rules: The Power of Modularity*, Volume 1. Cambridge, MA: MIT Press.

Bhattacharya, S., V.Krishnan, and V. Mahajan (2003). Operationalizing technology improvements in product development decision-making. *European Journal of Operational Research 149*, 102–130.

Bulow, J. I. (1982). Durable goods monopolists. *Journal of Political Economy 90*(2), 314–332.

Business Week (November 11, 2003). Can anything stop toyota?

Coase, R. H. (1972). Durability and monopoly. *Journal of Law and Economics 15*(1), 143–149.

Dhebar, A. (1994). Durable- goods monopolists, rational consumers, and improving products. *Marketing Science 13*(1), 100–120.

Dhebar, A. (1996, Winter). Speeding high-tech producer, meet the balking consumer. *Sloan Management Review 37*(2), 37–49.

Electronic Engineering Times (28 October 1991). Modular EISA lets PCs pace progress in CPUs.

Erat, S. and S. Kavadias (2004). Introduction of new technologies to competing industrial consumers. Working Paper, Georgia Institute of Technology.

Garud, R. and A. Kumaraswamy (1993). Changing competitive dynamics in network industries: An exploration of sun microsystems' open systems strategy. *Strategic Management Journal 14*(5), 351–369.

Henderson, R. M. and K. B. Clark (1990). Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly 35*, 9–30.

Hoppe, H. C. (2002). The timing of new technology adoption: Theoretical models and empirical evidence. *The Manchester School 70*(1), 56–76.

Kim, K. and D. Chhajed (2000). Commonality in product design: Cost saving, valuation change and cannibalization. *European Journal of Operational Research 125*, 602–621.

Kornish, L. J. (2001). Pricing for a durable-goods monopolist under rapid sequential innovation. *Management Science 47*(11), 1552–1561.

Krishnan, V. and W. Zhu (2003). Designing a family of development-intensive products. University of Texas Working Paper.

Landman, J. (1987). Regret: A theoretical and conceptual analysis. *Journal for the Theory of Social Behavior 17*(2), 135–160.

Langlois, R. N. and P. R. Robertson (1992). Networks and innovation in a modular system: Lessons from the microcomputer and stereo equipment industries. *Research Policy 21*, 297–313.

Matutes, C. and P. Regibeau. Mix and match.

Mikkola, J. H. and O. Gassmann (2003). Managing modularity of product architectures: Toward an integrated theory. *IEEE Transactions on Engineering Management 50*(2), 204–218.

Moorthy, K. S. and I. P. L. Png (1992). Market segmentation, cannibalization, and the timing of product introductions. *Management Science 38*(3), 345–359.

Morris, C. R. and C. H. Ferguson (1993). How architecture wins technology wars. *Harvard Business Review 71*(2), 86–96.

Mussa, M. and S. Rosen (1978). Monopoly and product quality. *Journal of Economic Theory 18*, 301–317.

Newsweek (March 25, 2002). Upholding Moore's law.

PC Magazine (May 6, 2003). Coming attractions.

Purohit, D. (1994). What should you do when your competitors send in the clones? *Marketing Science 13*(4), 392–411.

Sanchez, R. and J. T. Mahoney (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal 17*, 63–76.

Sanderson, S. and M. Uzumeri (1995). Managing product families: The case of the sony walkman. *Research Policy 24*(5), 761–782.

Schmidt, G. M. and E. L. Porteus (2000). The impact of an integrated marketing and manufacturing innovation. *Manufacturing and Service Operations Management 2*(4), 317–336.

Simon, H. A. (1969). *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

Stokey, N. L. (1979). Intertemporal price discrimination. *The Quarterly Journal of Economics 93*(3), 355–371.

Stokey, N. L. (1988). Learning by doing and the introduction of new goods. *Journal of Political Economy 96*(4), 701–717.

The New York Times (June 25, 1991). Tandon's modular upgradability.

The Wall Street Journal (September 10, 1991). Computers: Compaq chases rivals in move to modular PCs.

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

Ulrich, K. T. and D. Ellison (1999). Holistic consumer requirements and the design-select decision. *Management Sci 45*(5), 641–658.

Wilson, L. O. and J. A. Norton (1989). Optimal entry timing for a product line extension. *Marketing Science 8*(1), 1–17.