Design Architecture and Introduction Timing for Rapidly Improving Industrial Products

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Abstract

Technological advances present firms in many industries with opportunities to substantially improve their product's capabilities in short periods of time. Customers who invest in these products may, however, react adversely to rapid improvements that obsoletes their previous versions by deferring their purchase. In industrial markets, there is an emerging trend of sequentially improving products designed to be upgraded in a modular fashion. We study in this paper the impact of product architecture and introduction timing on the launch of rapidly improving products. We find that by localizing performance improvements in a sequence of upgradable modules of the product, a firm can better manage the introduction of rapidly improving products. Specifically, we show that modular upgradability can reduce the need for slowing the pace of innovation or foregoing upgrade pricing. The additional flexibility in pricing and timing makes the modular upgradable approach preferable over an integrated architecture, even in some situations where there may be distinct performance or cost-related disadvantages to pursuing the modular architecture. We differentiate between proprietary and non-proprietary approaches to modular upgradability and consider the implications for profits. Our central contribution in this paper is the innovative integration of product architecture with pricing and timing decisions for managing the introduction of rapidly improving products.

(*Keywords:* New Product Development and Introduction; Product Architecture; Modular Upgradability; Rapidly Improving Products)

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1 Introduction

Major technological advances in the physical and biological sciences and an increasingly digitally networked world-wide R&D community drive rapid quality improvements in many product categories. It is well known that speeds of microprocessors have increased substantially over the last decade, and Intel has emerged as the dominant firm by maintaining a rapid pace of innovation according to *"Moore's Law"* (Newsweek, 2002). Sequential introduction of improved versions are also routine for many other electronics and software products (PC Magazine, 2003). We call such serial commercialization of improving technologies, whose performance improves over time not only in absolute terms but also in customer-discounted terms, *Rapid Sequential Innovation* (RSI).

Firms engaging in RSI face certain unique challenges in persuading their customers to purchase their current product rather than wait for an improved version. Dhebar (1994) showed in a two-period setting that under RSI when rational customers anticipate a monopolist seller's opportunistic pricing behavior, the firm's profit-maximizing pricing scheme results in no sales of one of the versions of products. Facing rapid improvements, prior customers may regret their buying decision and prospective customers could delay their purchase timing. This forces a monopolist - who primarily uses prices to segment markets under rapid sequential innovation - to consider restraining the pace of innovation. In a subsequent paper, Kornish (2001) showed that the firm can partly address this issue of customer balking by committing to not offering special upgrade prices for the improved second-period product. While a firm may avoid artificial introduction delays by placing restrictions on the way products are priced, prior customers have come to expect special upgrade prices in many product categories (such as application software and other technology products). With customer relationship management (CRM) systems in place, firms also increasingly use this data and special upgrade discounts to attract existing customers. Under these circumstances, a monopolist firm may not be able to credibly commit upfront that it will not offer special upgrade prices in the future.

In this paper, we study a product architecture based approach that expands the firm's degrees of freedom to include product design decisions for managing the special challenges associated with rapid sequential innovation. Specifically, we study the case when a firm considers partitioning rapidly advancing products into improving and stable (industry-standard) modules, enabling itself to focus on its core skills and convince customers that their investments in products won't be totally obsoleted in short periods of time. Products thus designed, whose performance can be improved by replacing a minimal set of components are termed *Modular Upgradable* (MU).

The modular upgradable approach is gaining popularity with many industrial products such as rackable computer systems, semiconductor photo-lithography equipment, and optical inspection systems. In each of these categories, customers are able to assimilate sequentially improving technologies by buying specific modules, without obsoleting their entire system purchased earlier. In the computer industry, firms such as IBM and Rackable systems have been advancing the trend of modular upgradability, which allows their customers to selectively and incrementally upgrade their system. In the optical inspection market, for example, the firm ViTechnology designed and launched its new series of products so that the camera modules can be easily upgraded to meet future accuracy requirements for inspections. Similarly, in the semiconductor photo-lithography equipment segment, industrial customers such as Intel and AMD are able to upgrade their systems in a modular fashion by buying from firms such as ASM Lithography, Canon, and Nikon. Given the escalating cost of such equipment and the commoditization of end markets, customers prefer the productivity gains and cost savings achieved by upgrading in modules even while incurring the effort involved in installation and modular upgrades.

We study when and how modular upgradability helps a technology supplier manage rapid sequential innovation. Our approach is to view the commercialization of rapidly improving technologies as a combination of three separate, but related steps: product design, introduction timing, and pricing (going beyond the last pricing step considered in the prior literature). Specifically, we focus on the impact of selecting different product architectures and component sourcing options on optimal introduction timing and pricing. Customers who purchase these products do so for productivity improvements, but may incur both costs of initially integrating and subsequently upgrading the modules. We find that in many instances, the firm may gainfully introduce the new product earlier without adhering to constraining price commitments by using a modular product architecture. A central finding of this work is that combining a modular upgradable product architecture with pricing can alleviate the effects of adverse customer reaction to rapid obsolescence and improve firm profits in a wide range of situations. While such an approach might also apply to consumer markets, there are some additional issues which limit the use of modular upgradability that we discuss in the final section.

Figure 1: Semiconductor Wafer Stepper with an Upgradeable Projection Lens Module

Based on our industry example, we also distinguish between two design and sourcing options that firms offering modular upgradable products employ. Modules that do not change over time may be provided directly to the customers as an off-the-shelf open-market commodity (Modular Non-Proprietary design), or by the focal firm (Modular Proprietary). Both these approaches are prevalent - for example in the semiconductor photo-lithography equipment market, while firms such as Nikon and Canon largely develop the various component modules in-house, the European firm ASML increasingly offers non-proprietary modular systems, in which customers can obtain components from other manufacturers[1]. Similarly, Intel processors - which are known to improve rapidly - can be used in combination with motherboards manufactured by several other firms. We formalize and analyze each of these proprietary choices, identify optimal prices for the sequence of products, and derive conditions under which either product introduction approach is appropriate.

Our results underscore the importance of taking design and introduction timing into consideration and linking them with pricing while launching a product family. Our finding that in many instances optimal launch times are advanced under a modular architecture also highlights a previously ignored demand side advantage to modularity. Our analysis proceeds in two parts. Initially, we temporarily ignore the timing decision to obtain optimal prices for different design choices; in this we invoke the concept of Sub-Game-Perfect equilibrium. Later, we endogenize the introduction timing decision for the different scenarios. 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

[1] One of ASML's stated business strategies is to offer "continuing improvements in productivity"... by "introducing advanced technology, based on the modular, upgradeable design of" ASML products (ASML, 2001). ASML's newly introduced stepper system TWINSCAN^{TM}, is also a modular upgradable system comprised of components from several other manufacturers (ASML, 2005).

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

This paper is related to two separate streams of literature, namely: (i) product design and architecture, and (ii)sequential innovation, which we review in that order.

2.1 Product Design and Architecture

There exists a growing body of literature on the design of new products. Product architecture specifically is the scheme by which the performance quality (function) of a product is allocated to physical components (Ulrich, 1995), and has important implications yet to be uncovered in the literature. In a modular product, the mapping from performance quality to components is one to one. Modularization adds to the real option value of any product's design; while integral products have to be redesigned for each application, modular architectures can be used as platforms in several variations of the basic product (Langlois and Robertson, 1992; Baldwin and Clark, 2000). 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; Desai et al., 2001). Other advantages of modularity arise from the ability to reuse previously designed components, save costs in logistics, and make product variety profitable (Fisher et al., 1999; Kekre and Srinivasan, 1990). 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 due to the adverse impact of modularization on product design (Ulrich and Ellison, 1999) .

Modular architecture has been embraced by the industry for two main reasons (The Wall Street Journal, 1991). 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 coping with radical systemic changes(Sanchez, 1999).

Modular upgradability is a specific form of modularity, in which the product is designed to be upgradable in modules, thereby allowing for longitudinal component reuse. Upon deciding to make its product upgradable in modules, a firm must still choose between proprietary and industry-standard alternatives to source its modules (Morris and Ferguson, 1993). This choice becomes relevant when industry-standard subsystems can become substitutes for a firm's components. Garud and Kumaraswamy (1993) investigate Sun Microsystems' architectural strategy and conclude that an open (non-proprietary) architecture encourages manufacturers of complementary products and even rivals to make and support compatible products. Our work identifies the value from a market and operational perspective of using non-proprietary industry-standard components in conjunction with firm-proprietary improving modules.

2.2 Sequential Innovation

Durable goods manufacturers have been a subject of long-standing interest in the economics literature[2]. Coase (1972) argued that rational expectations of sufficiently patient customers will eliminate the opportunity to sell the good at different prices to customers who value it differently. This competition from goods sold earlier makes leasing a preferable alternative to selling durable goods (Bulow, 1982), and a selling firm also has an incentive to reduce the physical life of an old product compared to a leasing firm (Waldman, 1996). Interference from early sales may be controlled by using mechanisms such as buybacks, planned obsolescence or trade-ins (Fudenberg and Tirole, 1998). These tactics are often not feasible leading to excessively slow product introductions (Fishman and Rob, 2000). Our work proposes product design as an essential ingredient in the sustenance fast new product introduction.

When customer valuations of a product are not uniform, a durable product may be priced dynamically to achieve intertemporal price discrimination (Stokey, 1979). A firm can also use a product line to discriminate in such a market, but low end customers exert a negative externality on the firm's ability do so (Mussa and Rosen, 1978). The effects of cannibalization on new product introduction have been 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). This paper adds to this literature by studying the tradeoffs in timing

[2]Dhebar (1994) provides a more detailed review of this literature.

product launch when the core technology available is improving rapidly.

Although we discuss sequential innovations in general, this work is motivated by critical problems faced by rapidly-improving products in the market, which have not received sufficient attention. Dhebar (1994) highlighted the problems faced by a monopolist firm in intertemporally discriminating among its customers in the context of rapid sequential innovation. Innovators have to be mindful of customers' distaste for rapid improvements that would make an earlier purchase obsolete. Unfortunately, in most industries, especially those that involve nascent technological standards, delaying commercialization of advanced technologies is not an option due to a number of reasons. First, 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 monopolist firm to competition from second hand markets in later periods (Coase, 1972; Bulow, 1982).

Kornish (2001) showed that by foregoing its ability to offer its preferred or installed base customers a special upgrade price for the improved product, the firm will be able to signal to its customers that their purchase decisions in the first period will not be unduly used to the firm's advantage. However, it is not clear if either rapid innovation or intertemporal price discrimination should belong to the set of objectives of a profit maximizing firm. To address these issues, we allow the firm to decide the number of products to launch and rate of improvement in addition to determining the optimal product architecture.

It should be noted that our primary concern is about product selection decisions of customers who derive value by using these products at a personal level. For a recent overview of adoption decisions of organizations that buy improving technologies used in production of other goods and services, 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 and potentially compete among themselves, while we concentrate on rational utility maximizing customers. We also do not consider strategic interactions of the manufacturer-retailer supply chain form, which may influence the structure of the product line (Villas-Boas, 1998).

Our primary contribution is the identification of the linkage between design, pricing, and launch timing for new products. It is interesting to note how combining product design and pricing improves firm profits while also accelerating new product introduction; to the best of our knowledge, this is one of the early efforts in studying the economic benefits of a combined approach to product architecture and pricing. In the following section, we present a basic model of designing and pricing a modular, improving product based on the improving core technology. Results for the proprietary and non-proprietary approaches are presented in Sections 4.2 and 4.3 respectively. Launch times are then derived as a function of the technology's characteristics and development costs.

3 Model Setting and Description

In this section we describe the sequential introduction problem faced by a monopolist firm that has developed an early version of the product $\mathcal{P}_1$, and is in possession of an advanced technology which could be transformed into a new product $\mathcal{P}_2$ with improved performance quality. We first discuss the specific assumptions and their implications before providing a timeline for interaction between the firm and its customers in closing. In the rest of the paper, we use the word *customer* to refer to an industrial customer that purchases the product, and *firm* to refer to the developer who sells these products.

3.1 Modeling Assumptions

The products under consideration (both hardware or software) are purchased by the industrial customers for productivity improvement. The value a customer derives from the productivity improvement of a particular version of the product depends on the version's basic performance quality, the duration for which it is used, the benefits of learning that accrues by using, the rate at which future benefits are discounted, and the effectiveness with which the customer uses the product.

- *Productivity Benefits and Learning by Customers.* The product of quality q provides an instantaneous productivity, or output per unit of time, given by $z(q,t)$. In addition, customers realize productivity improvements over time as they familiarize themselves with the product's capabilities and gain expertise in applying them. Specifically, they experience an instantaneous rate of learning, which we represent as L. When a customer uses a product with a productivity of z per unit time for a duration of t, learning-by-doing increases the per unit productivity to ze^{Lt}. For notational simplicity, customer learning that occurs over a period of length t is captured through the parameter $\gamma(t) = e^{Lt}$. Let the output over a period of duration t of a product of quality q is given by $x_q(t)$.

- The firm and customers may borrow at an interest rate of r. Productivity benefits and payments that are delayed by a period of length t are discounted by a factor of $\delta(t) = e^{-rt}$. $x_q(t)$is related to the the maximum lifetime utility of the product $f(q)$, the learning and discount rates through Equation 1.

$$x_q(t) \quad = \quad (1 - \gamma(t)\,\delta(t))\,f(q) \tag{1}$$

  To ensure that customers who buy the first version do not trivially reject the second version, we restrict our attention to product categories where the learning rate does not exceed the rate of innovation. Specifically, we assume that $\gamma f(q_1) < f(q_2)$. Further, to ensure that $f(q)$ is bounded, we assume that $r > L$.

- Industrial customers that may buy the product differ in their ability to assimilate and apply the product's offerings to improve their productivity. This ability, measured by index v, is uniformly distributed between 0 and 1 [3]. The lifetime value a type v customer derives by using the product depends on the quality of the product q_t. $W(q, v)$, the reservation price of customer v for a product of quality q, is given in Equation 2 below. When the improved product is launched, given that v has $\mathcal{P}_1$, $v(f(q_2) - f(q_1))$ is customer willingness to pay for $\mathcal{P}_2$. The function $f(q_t)$ represents the benefit of a unit of product quality[4].

$$W(q_t, v) = vf(q_t) \tag{2}$$

- Customers incur an installation cost of C_I when a product is installed and an an upgrading cost C_U when upgrading the product. In industrial contexts, product installation requires assem-

[3] While our most important results are valid under general customer distributions and valuation functions, the uniform distribution is used to simplify the presentation.

[4] In a more general multi-period setting, if at time t, customer v owns a product launched at $\tilde{t}$, the willingness to pay is only $v(f(q_t) - f(q_{\tilde{t}}))$.

bling various modules together at the site of installation, re-calibration of sensitive equipment, and customization. However, while customers are required to assemble the modules for each installation in some product categories, other manufacturers also offer installation services for new buyers[5]. We model these two cases separately. In Section 4.4, we consider the effect of these cost parameters C_I and C_U on the optimal design and pricing decisions for the various modules.

- We assume that the marginal production costs are negligible compared to the fixed costs of product development, which is increasingly the case in knowledge-intensive industries. Product development costs depend on t_d, and the relationship is presented in Section 5.2.

Consumption and pricing decisions depend on the rate of sequential improvement. *Rapid* sequential innovations are different from more gradual improvements since performance quality of $\mathcal{P}_2$ exceeds that of $\mathcal{P}_1$ even in present value (Equation 3). We are unaware of the existence of second hand markets for industrial products that motivate this work. Rapid sequential innovation, by rendering older versions obsolete, further reduces the viability of markets for used goods. Therefore, we assume that these do not exist. This assumption is useful to keep the focus on the architecture-innovation interaction.

$$\begin{array}{ll} \text{Rapid Improvement} & \delta f(q_2) > f(q_1) \\ \text{Gradual Improvement} & \delta f(q_2) \leq f(q_1) \end{array} \tag{3}$$

The firm does not condition prices on previous purchases. Therefore, we do not make any assumptions on the level of anonymity involved in repeat purchases. Fudenberg and Tirole (1998) analyze the effect of anonymity on the sequential pricing strategies of the firm, but unlike this work, they (i) do not consider the impact of product architecture on consumption, and (ii) restrict themselves to gradual rates of product improvement.

The sequence of the customer's and firm's actions is shown in Figure 2. The firm first makes its decisions about the inter-generational product architecture (integral or modular architecture) and launches the first period product $\mathcal{P}_1$. Customers then make their first-period *purchase* or *wait* decisions based on the price, quality, and the architecture of the first-period product and the expected price and quality of the improved (second-period) product. In accordance with the prior

[5] Firms commonly offer both product packages and separate modules simultaneously. Customers can avoid incurring the installation cost by purchasing packaged products.

work on rapid sequential innovation, we assume all customers have the same expectations for price and quality of the second-period product. In the second period, the improved product $\mathcal{P}_2$ is released based on the architectural decision made earlier at a price that the firm finds optimal. Customers base their second-period purchase decisions on the announced prices and qualities of the improved product. Prior research on this topic did not include the architectural decision that we consider for the firm at the beginning. The interaction between architecture and pricing offers an additional degree of freedom, which forms the point of departure for this paper.

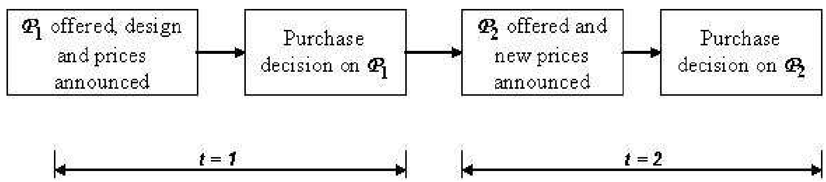

Figure 2: Timeline of decisions

3.2 Architectural Choice and Modular Upgradability

The literature on rapid sequential innovation assumes that each version of the product is an integral unit. Further, the impact of not launching the inferior version is also not considered. Here we explicitly relax both assumptions to capture demand-side forces that shape a product's evolution and its architecture over time. The salient characteristics of sequentially improving modular products are two-fold.

(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.

Each product $\mathcal{P}_t$ of the sequence is an aggregation of components; the relationship between functionalities of the different components and performance qualities is captured by the operator $\mathcal{Q}(\mathcal{P}_t)$. Property 1 is satisfied by this sequence of products when it is Modular Upgradable.

Property 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**: $\mathcal{I}_t \cup \mathcal{S}_t \equiv \mathcal{P}_t$ *and* $\mathcal{I}_t \cap \mathcal{S}_t \equiv \emptyset$, $\forall\, t = 1..T$
2. **Localization**: $\mathcal{Q}\left(\mathcal{P}_{t+1}\right) = Q\left(\mathcal{I}_{t+1} \cup \mathcal{S}_t\right)$, $\forall\, t = 1..T-1$

Instead of considering quality enhancements 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 ($T = 2$). Note that localization implies that the stable module does not undergo major 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). Though our general model is suited for multiple dimensions of quality, we focus on a one-dimensional measure q, which can either be a weighted measure of the constituents or the most dominant element of $\mathcal{Q}$.

Modularization also 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:

$$\delta f\left(q_2^{\alpha}\right) > f(q_1)$$

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

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

The firm decides whether the product sequence would be modular as described above, or if a quality-optimized integral product will be independently developed in each period. If the modular architecture is selected, 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. In the rest of the section, we describe the pricing possibilities and cost side effects for each of these product architectures.

3.2.1 Proprietary Modular Upgradable Systems (MP)

When customers must purchase both the improving and stable modules from the same firm, the firm is said to follow a proprietary modular upgradable approach. The improving modules, $\mathcal{I}_t$, are uniquely designed for each product, $\mathcal{P}_t$. Both versions of $\mathcal{I}_t$ are designed to be compatible with the firm's own stable module, $\mathcal{S}$.

The two versions of the improving modules, $\mathcal{I}_1$ and $\mathcal{I}_2$ are priced at 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 $p_s - c_s$) in both periods. If the price of $\mathcal{S}$ is allowed to change, the firm holds the ability to price the whole product opportunistically in the second period and hence continues to face the same problem associated with selling a sequence of integral products. Our primary interest, therefore, is in situations in which p_s is unchanging between periods.

While modularity allows customers to retain the stable module, replacing the improving module often involves tedious and costly procedures. We model this upgrading effort as a cost C_U incurred by a customer who buys the first version and upgrades in a modular fashion later. Since several manufacturers offer packaged products for new buyers and improving modules for upgraders, we assume that the upgrading cost is not applicable to customers who buy either the first or the second version exclusively. The results presented, however, can be easily extended to a more general case.

Let $\mathcal{D}_0, \mathcal{D}_1, \mathcal{D}_2$ and $\mathcal{D}_u$ be the set of customers who do not buy any product, buy only the first version, buy only the second version, and those who buy both versions respectively. Let D_0, D_1, D_2, and D_u be the corresponding number of customers. In a proprietary system, the firm gets revenues from sales of improving and stable modules, but delayed benefits are discounted. The firm's problem in the second period is:

$$R_2^*(p_s) = \max_{p_2} \left(\left((p_2 - c_2) + (p_s - c_s) \right) D_2 + (p_2 - c_2) D_u \right) \tag{4}$$

While launching the early version, the firm should be mindful of the effect p_s will have on the later sales as well. The firm's first period problem is:

$$\Pi_{MP}^* = \max_{p_1, p_s} \left(((p_1 - c_1) + (p_s - c_s))(D_1 + D_u) + \delta R_2^*(p_s) \right) \tag{5}$$

To make our results comparable to the existing literature on RSI and to achieve compact analytical expressions, we first ignore cost savings and inter-product-line substitutability in our formulation.

A commitment issue still challenges the firm designing MP systems. In an attempt to sell a higher volume of non-improving components when the advanced version is launched, the firm can willfully renege from its previous commitment to make future improving modules compatible with old stable modules. Firms with a weak or insufficient record of credibly upholding these compatibility commitments may use the following architectural approach.

3.2.2 Non-Proprietary Modular Upgradable Systems (MN)

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. 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. The firm sets prices p_1 and p_2 by solving the following problems in the two periods. It foregos not only the ability to price the stable module but also revenues from selling the stable module. Optimal solutions for the problem 6 are found in Section 4.3.

$$\begin{aligned} &Second\ Period: \quad R_2^*(p_s) = \max_{p_2}\left((p_2 - c_2)\left(D_2 + D_u\right)\right) \\ &First\ Period: \quad \Pi_{MN}^*(p_s) = \max_{p_1}\left((p_1 - c_1)(D_1 + D_u) + \delta R_2^*(p_s)\right) \end{aligned} \tag{6}$$

The external firms, by virtue of experience gained by manufacturing $\mathcal{S}$ as a commodity, may be able to deliver a higher overall product quality through its stable module. For example, customers who purchase ASML's micro-lithography equipment for semiconductor manufacturing are able to upgrade the optical elements by purchasing image-sensing components from Carl Zeiss. We represent the technological inferiority of completely proprietary systems using the parameter β ($\beta \in (0, 1]$). 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 βq_t.

Often proprietary modular products deliver higher quality than non-proprietary alternatives ($\beta > 1$). In our context, the non-proprietary designs have no value in these cases for firms which have commitment credibility. We ignore this uninteresting case in the rest of the paper. Further, we appreciate the fact that β is endogenous to technological and market specifications, but reserve its determination for future work.

Selecting, procuring and installing an off-the-shelf stable module entails significant effort and cost for a customer in the non-proprietary case. Each installation of a system results in costs associated with interfacing the open-sourced Stable module with a new Improving module. We represent this cost as C_I. Note that this installation cost is expended twice by an upgrading customer whereas the upgrading cost C_U is incurred only during the upgrading step.

3.2.3 Proprietary Integral Systems

The default option for the firm is to provide an integral product where the stable and improving module are not separable. The advantage is the lack of any quality loss arising from modularity ($\alpha = 0$), and this is the approach that has been studied by prior papers. Specifically, Kornish has shown that the optimal approach is for the firm to not offer special upgrade prices to early buyers. The pricing problem for the firm, which is obtained by adding the constraint $p_s = 0$ in problem

(5,4) above, is shown below.

$$\begin{aligned} &Second\ Period: && R_2^* = \max\nolimits_{p_2}\left((p_2 - c_2)\left(D_2 + D_u\right)\right) \\ &First\ Period: && \Pi_I^* = \max\nolimits_{p_1}\left((p_1 - c_1)(D_1 + D_u) + \delta R_2^*\right) \\ & && s.t.\ p_s = 0 \end{aligned} \tag{7}$$

If the advanced technology represents a significant improvement over the early version and if the costs of accelerated development are not overwhelming, it might be in the firm's best interest to avoid launching the early version. This is simply obtained by setting $D_1 = D_u = 0$ in (7). Note that it is not necessary to modularize the product when only the advanced product is released.

4 Model Analysis

The analysis proceeds in two steps. First we identify the optimal prices for proprietary and non-proprietary modular architectures for fixed $t_1$and t_2. Here, we take the development time ($t_d \doteq t_2 - t_1$) and the corresponding discount and learning factors ($\delta\left(t_d\right)$, $\gamma\left(t_d\right)$) as given. Later we backtrack and find the optimal launch interval, t_d, available for developing a new product from the improved technology for the different architectures. Reducing a significant part of the paper to a two-period model allows closer comparison of profits with other strategies suggested in the literature (Dhebar, 1994; Kornish, 2001), while also making the presentation linear.

The firm first 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. To obtain a consistent set of prices, beliefs and consumption decisions, we look for sub-game-perfect solutions. In Sections 4.2 and 4.3, we specifically focus on role of architecture and normalize the installation costs C_I to zero. Subsequently, we extend our analysis to include installation cost in Section 4.4.

4.1 Modular Design and Market Segmentation[6]

The marginal 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, buy 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 Table 1. (v_{ij} and v_{ji} are used interchangeably throughout the paper.)

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

Table 1: Marginal Customers

Buyers of the early version do not 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 properties 2 and 3.

Property 2. Market Segmentation for Rapid Improvement $\delta f(q_2^\alpha) > f(q_1)$
Let $P_1 = \frac{p_2 f(q_1)(1-\gamma\delta)-p_1\left(f(q_2^\alpha)-\gamma f(q_1)\right)-C_I\left(f(q_2^\alpha)-f(q_1)(1+\gamma-\gamma\delta)\right)}{(1-\delta)(f(q_2)-\gamma f(q_1))}$, *and* $P_2 = \frac{p_2 f(q_1)-p_1 f(q_2^\alpha)-C_I\left(f(q_2^\alpha)-f(q_1)\right)}{f(q_2)-f(q_1)}$.
For all non-negative prices (p_1, p_2, p_s)*, the market is divided according to one of the following segmentation patterns (SP) when the product is improving rapidly.*

SP 1. *If* $p_s \leq P_1$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{1u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{1u}, 1]$

SP 2. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta)p_s \leq (1-\gamma\delta) f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, v_{2u}]$*;* $\mathcal{D}_u = [v_{2u}, 1]$

SP 3. *If* $P_1 \leq p_s \leq P_2$ *and* $p_1 + (1-\delta)p_s > (1-\gamma\delta) f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, 1]$*;* $\mathcal{D}_u = \emptyset$

SP 4. *If* $P_2 \leq p_s$*, then* $\mathcal{D}_0 = [0, v_{02}]$*;* $\mathcal{D}_1 = [v_{02}, v_{2u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{2u}, 1]$

[6] The results from this section are applicable to both proprietary and non-proprietary systems. To make the presentation simpler, we set the proprietariness penalty parameter$\beta = 1$ in this section.
While we derive conditions for products with installation costs, the analogous expressions for products with upgrade cost are derived similarly.

Proof. The proof is provided in the Appendix □

Property 3. Market Segmentation for Gradual Improvement $\delta f(q_2^\alpha) \leq f(q_1)$

For all non-negative prices (p_1, p_2, p_s)*, the market is divided according to one of the following segmentation patterns (SP) when the product is improving rapidly.*

SP 1. *If* $p_s \leq P_2$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{1u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{1u}, 1]$

SP 2. *If* $P_2 \leq p_s \leq P_1$ *and* $p_2 \leq f(q_2^\alpha) - \gamma f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, v_{2u}]$*;* $\mathcal{D}_u = [v_{2u}, 1]$

SP 3. *If* $P_1 \leq p_s \leq P_2$ *and* $p_2 > f(q_2^\alpha) - \gamma f(q_1)$*, then* $\mathcal{D}_0 = [0, v_{01}]$*;* $\mathcal{D}_1 = [v_{01}, v_{12}]$*;* $\mathcal{D}_2 = [v_{12}, 1]$*;* $\mathcal{D}_u = \emptyset$

SP 4. *If* $P_2 \leq p_s$*, then* $\mathcal{D}_0 = [0, v_{02}]$*;* $\mathcal{D}_1 = [v_{02}, v_{2u}]$*;* $\mathcal{D}_2 = \emptyset$*;* $\mathcal{D}_u = [v_{2u}, 1]$

Proof. Similar to proof of Property 2. □

Property 2 provides some intuition about the effect of product modularity when the improvement is deemed rapid. Consider the effect of varying p_s for a given pair improving module prices p_1 and p_2, and suppose that p_1 and p_2 are within reasonable bounds[7]. When $p_s \leq P_1$, only a fraction of first period customers upgrade when $\mathcal{I}_2$ is available. However, if p_s is raised such that $p_s \geq P_2$, all first period customers upgrade their products. If the firm commits to an architecture with a higher stable module price relative to the overall costs of $\mathcal{P}_1$ and $\mathcal{P}_2$, customers can retain a significant part of their initial investment when they upgrade. This enables easier retention of the customer base 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 slowing down the innovative effort.

4.2 Optimal Pricing for Modular Proprietary System (MP)

Special upgrade prices cannot be offered 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 1 gives optimal prices when the firm has the ability to

[7]Note that when p_1 and p_2 are small, SP3 never obtains.

commit to a constant price, p_s. In proving it (Appendix), we assume that $c_1 = c_2 = c_s = 0$, but the validity of the main results has been tested numerically for several combinations of costs.

Proposition 1. Optimal Pricing for Modular Proprietary Systems

The optimal set of prices for the modules that result in a SP 1 sub-game perfect equilibrium are as follows:

$$p_s^* = \frac{(1-\gamma\delta) f(\beta q_1)}{2(1-\delta)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{2} \qquad \text{for } RSI$$

$$p_s^* = \frac{f(\beta q_1)\left(f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)\right)}{2\left(f\left(\beta q_2^\alpha\right) - f(\beta q_1)\right)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right) - \gamma f(\beta q_1)}{2} \qquad \text{for } GSI$$

The optimal set of prices for the modules that result in a SP 4 sub-game perfect equilibrium are as follows:

$$p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right) - f(\beta q_1)}{2} \qquad \text{for } RSI$$

$$p_s^* = \frac{(1-\gamma\delta) f(\beta q_1)}{2(1-\delta)},\ p_1^* = 0,\ p_2^* = \frac{(1-\delta) f\left(\beta q_2^\alpha\right) - (1-\gamma\delta) f(\beta q_1)}{2} \qquad \text{for } GSI$$

These equilibriums are unique in pure-strategies.

Proof. The proof is in the Appendix. □

The optimal price for the stable module (p_s^*) is higher than that of the improving module. Higher p_s makes customer purchase decision easier since it leaves a smaller margin in the second period for the firm to price opportunistically. Further, when p_s is larger, customers are able to protect more of their prior investment when the product is upgraded. For all rates of innovation (t_d) and the product qualities, the profit maximizing strategy for the firm is to set the price of $\mathcal{S}$ at the upper bound dictated by the market participation constraint. Therefore, to induce the maximum number of customers to upgrade their products in a modular fashion, the firm subsidizes the first version of its improving module completely through sales of the stable module[8].

The stable module prices are non-increasing in γ, and therefore in learning rate r_L. To understand this, first note that all of the equilibriums identified in Proposition 1 are intertemporally discriminating, in which high-end customers buy $\mathcal{P}_1$ and upgrade to $\mathcal{P}_2$. These customers, whose preferences are critical in determining the optimal prices, view the first version mainly as a non-durable good that will be used only for a single period. When learning-by-using contributes significantly to the perceived lifetime quality of a product, a larger portion of the benefits are delayed. Recall that the per period productivity of the product (of quality q) is given by $(1-\gamma\delta) f(q)$. As

[8]This result obtains even when nominal, non-zero production costs are included in the model.

a result, the price high-end customers are willing to pay for the first version is lower, resulting in the inverse relationship between p_s^* and r_L for a given $f(q)$.

The relationship between second period price p_2^* and r_L, however, depends on the segmentation pattern chosen by the firm. In SP 1, the second version is sold exclusively to high-end upgraders who not only own the previous version, but have also accumulated expertise in using it. To induce them to overcome this acquired attachment to the old product, the firm is forced to discount the second version further. Therefore, p_2^* in non-increasing in r_L. To further understand the role of r_L, let us consider the special case where $r_L = 0$ ($\gamma = 1$).

Corollary 1. *When customers do not realize productivity gains by using a product, the optimal prices lead to a unique sub-game perfect equilibrium*

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

First, the optimal prices are independent of the rate of improvement when learning effects are absent. This indicates that unlike the manufacturer of an integral product, the producer of such a modular upgradable system need not regulate the pace of innovation or place additional pricing constraints. However, the pricing policy shown above is not intertemporally discriminating. By targeting the same set of customers with either version, 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 or customer learning). "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 turning away too many higher end customers of the improved product.

4.3 Optimal Pricing for Modular Non-proprietary Design (MN)

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. But this point may not be conveyed successfully to customers unless they are convinced that the stable module price p_s will not be lowered later to take advantage of their first period purchase decisions. Making the stable module widely available as a separate retail item or an industry standard commodity could help address customer concerns. In this section, we focus on the use of non-proprietary modular product architectures as a vehicle to facilitate adoption of rapidly improving products.

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 available in the market at a competitive price of p_s. Customers' investment in the stable module $\mathcal{S}$ is taken into consideration by the firm when prices for $\mathcal{I}_t$ are fixed. The optimal pricing policies for RSI are described in Proposition 2.

Proposition 2. Optimal Pricing for Non-Proprietary Systems under RSI

Under Rapid Sequential Innovation, the feasibility of any segmentation pattern and optimal prices depend on the price of the stable module p_s, as follows.

A SP 1 sub-game perfect equilibrium can be achieved when $p_s < \frac{(1-\gamma\delta)f(q_1)}{2(1-\delta)}$. The optimal prices are

$$p_1^*(p_s) = \frac{(1-\gamma\delta)f(q_1)-2(1-\delta)p_s}{2},\ p_2^* = \frac{f\left(q_2^{\alpha}\right)-\gamma f(q_1)}{2}$$

A SP 4 sub-game perfect equilibrium can be achieved can be achieved under the following conditions. For each γ, δ and α, there exist ϕ_1, ϕ_2, ϕ_3 such that the optimal pricing strategies are

$$\begin{aligned} p_1^*(p_s) &= \begin{cases} \frac{(1-\gamma\delta)f(q_1)-(1-\delta)p_s}{2} & if\ \phi_3 \geq p_s \geq \phi_2 \\ \frac{f(q_1)\left(f\left(q_2^{\alpha}\right)+p_s\right)-2p_s f\left(q_2^{\alpha}\right)}{2\delta f\left(q_2^{\alpha}\right)} & if\ \phi_2 \geq p_s \geq \phi_1 \\ Do\ not\ launch\ first\ version & if\ \phi_1 \geq p_s \end{cases} \\ p_2^*(p_s) &= \frac{f\left(q_2^{\alpha}\right)-p_s}{2} \end{aligned}$$

Proof. The proof, along with expressions for ϕ_1, ϕ_2 and ϕ_3, is provided in the Appendix. □

As discussed in Section 4.1, the SP 1 purchase pattern 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 ($p_s > (1-\gamma\delta) f(q_1)/2(1-\delta)$), the first period offering is expensive, thus pushing the market toward delayed adoption. Therefore, it is not profitable to introduce the first version 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. As a result, when $p_s \leq \phi_1$, the low price of the stable module makes launching $\mathcal{I}_1$ unprofitable. Therefore, the prices of the improving modules are non-increasing in p_s, indicating that adopting a costlier stable module results in reduced revenue per unit produced for the focal firm.

4.4 Pricing with Installation Costs

In this section, we extend the results from Sections 4.2 and 4.3 above to more general settings where customers incur either (i) a fixed cost C_I for installing each purchase under non-proprietary design, and (ii) a fixed C_U for disassembling and assembling when a modular proprietary system is upgraded. While C_I reduces the customer's net benefit from each version, C_U affects only customers that upgrade. These costs also increases the customer's resistance to upgrade when the better product is available. In Proposition 3 below, we derive the equilibrium prices charged by the firm when costs incurred by customers are considered.

Proposition 3. Modular Proprietary Systems with Upgrade Cost
The SP1 equilibrium is achievable when $C_U \leq \omega_1^U$. The optimal prices that result in a sub-game perfect equilibrium are as follows:

$$p_s^* = \frac{(1-\gamma\delta)f(\beta q_1)}{2(1-\delta)} - C_U\frac{2\delta f\left(\beta q_2^\alpha\right)-f(\beta q_1)(1+\gamma\delta)}{2(1-\delta)\left(f\left(\beta q_2^\alpha\right)-\gamma f(\beta q_1)\right)},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right)-\gamma f(\beta q_1)}{2} - \frac{C_U}{2}$$

The SP4 equilibrium is achievable when $C_U \leq \omega_4^U$. The optimal prices that result in a sub-game perfect equilibrium are as follows:

$$p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f\left(\beta q_2^\alpha\right)-f(\beta q_1)}{2f\left(\beta q_2^\alpha\right)}$$

where $\omega_1^U = \frac{(1-\gamma\delta)f(\beta q_1)}{2\delta f\left(\beta q_2^\alpha\right)-(1+\gamma\delta)f(\beta q_1)}$ and $\omega_4^U = (1-\gamma\delta)\, f\left(\beta q_1\right)/\delta$.

Proof. Similar to the proof of Proposition 1 □

Note that it is profitable to offer modular upgradability only when the upgrading cost C_U is less than ω_i^U. Naturally, prohibitively high costs of upgrading dissuade customers from exercising this option provided through product design, *even* when the producer packages the modules together for new buyers. When the stable module is non-proprietary, firms seldom offer packaged products to consumers. In Proposition 4 below, we derive optimal prices when installation is performed by customers in each period. While third-party providers may offer the service of integration, a cost is incurred in obtaining this service. Therefore, we do not consider upgrading costs separately.

Proposition 4. Modular Non-Proprietary Systems with Installation Costs.
The SP 1 sub-game perfect equilibrium can be achieved when $C_I \leq \omega_1^I$. *The optimal prices are*

$$p_1^*(p_s) = \frac{(1-\gamma\delta)f(q_1)-2(1-\delta)p_s}{2} - C_I\frac{2f\left(q_2^\alpha\right)-f(q_1)(1+\gamma(2-\delta))}{}, \; p_2^* = \frac{f\left(q_2^\alpha\right)-\gamma f(q_1)-C_I}{2}$$

A SP 4 sub-game perfect equilibrium can be achieved when $C_I \leq \omega_4^I$. *For each* γ, δ, α *and* C_I, *there exist* ϕ_1^I, ϕ_2^I, *and* ϕ_3^I *such that*

$$p_1^*(p_s) = \begin{cases} \frac{(1-\gamma\delta)f(q_1)-(1-\delta)p_s}{2} - \frac{C_I}{2} & if\ \phi_3^I \geq p_s \geq \phi_2^I \\ \frac{f(q_1)\left(f\left(q_2^\alpha\right)+p_s\right)-2p_s f\left(q_2^\alpha\right)-C_I\left(2f\left(q_2^\alpha\right)-f(q_1)\right)}{2\delta f\left(q_2^\alpha\right)} & if\ \phi_2^I \geq p_s \geq \phi_1^I \\ \text{Do not launch first version} & if\ \phi_1^I \geq p_s \end{cases}$$

$$p_2^*(p_s) = \frac{f\left(q_2^\alpha\right)-p_s-C_I}{2}$$

where $\omega_1^I = \frac{f(q_1)(1-\gamma\delta)-2p_s(1-\delta)}{2\left(f\left(q_2^\alpha\right)-f(q_1)(1+\gamma(1-\delta))\right)}$, $\omega_4^I = (2\delta\gamma-1)\,f\left(q_2^\alpha\right)$
and $\phi_1^I = \frac{f(q_1)(1-\gamma\delta)-C_I}{1-\delta}$, $\phi_2^I = \frac{\gamma\delta f(q_1)f\left(q_2^\alpha\right)-C_I\left(f\left(q_2^\alpha\right)-f(q_1)\right)}{(1+\delta)f\left(q_2^\alpha\right)-f(q_1)}$ *and* $\phi_3^I = \frac{f(q_1)\left(f\left(q_2^\alpha\right)(2\gamma\delta-1)-C_I\right)}{2\delta f\left(q_2^\alpha\right)-f(q_1)}$

Proof. Similar to the proof of Proposition 2 □

We find that the prices charged by the firm for either product, and therefore the profits, decrease with C_I and C_U. Further the profits vanish when installation and upgrade costs exceed certain thresholds. This is due to the natural downward pressure that installation costs exert on a customer's willingness to buy or upgrade a product. Industrial customers typically enjoy the services of maintenance crews for testing and calibrating new machines, which lowers the installation cost relative to product quality. However, consumers who buy gadgets for personal use often find the effort and frustration associated with installation and upgrading costly relative to the utility derived. Firms that cater consumer markets might prefer to side-step complication installation instructions by assembling the gadgets before selling them. In that regard, the results from Propositions 3 and 4 offer an explanation for the skewed prevalence of modular upgradability primarily in industrial products.

While the results in this Section are derived assuming that the same cost is incurred equally by new and upgrading customers, the results easily extend to the case in which new installations and modular upgrades require different effort levels. We do not present this case since the more complicated expressions add little value to our discussion.

5 Optimal Architectures and Innovation Rate

In this section, we first compare the profitabilities of the different product design approaches to determine the conditions under which the modular architectures yield higher profit. We then treat the innovation rate as a decision variable to examine how the optimal innovation rates compare under the modular and integral architectures.

5.1 Appropriateness of Different Architectures

A comparison of the profitability of the different product design approaches indicates that under fairly general conditions, the modular design and pricing approaches yield profits superior to the integral design choices. Here we compare different architectures for a pre-specified launch time t_d.

Let the optimal profits from the integral architecture, the modular proprietary architecture, and the modular non-proprietary architecture be π_{IN}, π_{MP}, and $\pi_{MN}(p_s)$ respectively. We assume that the integral product can be sold in the RSI case with a guarantee that special upgrade prices will not be offered later (which is optimal for the integral architecture). The architectural choices can be ordered with respect to the efficiency they allow in price discrimination when there are no adverse effects of modularity ($\alpha = 0$) and when there are no technological disadvantages in adopting proprietary solutions ($\beta = 1$).

Proposition 5. *When $\alpha = 0$ and $\beta = 1$, the profits are ordered as follows:*

1. The modular proprietary architecture results in a higher profit than the integral architecture

$$\pi_{MP} > \pi_{IN} \; \forall \; \delta < 1, \; \gamma \geq 1, \; \gamma\delta < 1$$

2. For all levels of stable module prices, the modular proprietary approach is more profitable than the non-proprietary approach

$$\pi_{MP} > \pi_{MN}\left(p_s\right) \; \forall \, p_s > 0$$

Proof. The proof is in the Appendix. □

The first part of the proposition, which presents the dominance of modular proprietary architecture over the integral architecture, is driven by the additional pricing flexibility of setting p_s in the modular proprietary solution (π_{MP}). Also, when product quality is not impacted due to proprietary architecture, the firm's profit with the non-proprietary architecture ($\pi_{MN}(p_s)$) is lower than that of the proprietary modular architecture (π_{MP}) because the firm does not earn revenues from the stable module (p_s goes to the firm manufacturing $\mathcal{S}$).

We next compare the design choices for different levels of r and α, which capture the customer patience (δ) and any adverse impact of modularization on product quality. Fig 3 shows the dominant architectural choice for different combinations of α and δ. In region *INT*, the integral design solution is most profitable, while in regions *MP* and *MN*, the proprietary and non-proprietary modular solutions are optimal.

Since α is a direct measure of the loss of product quality that occurs due to modularization, a high α represents a greater implicit cost of designing a modular product. Therefore, for any customer discounting factor δ, we observe that modular solutions, proprietary and non-proprietary, are more attractive than the no-upgrade pricing approach for lower levels of α. Since our primary interest is in the efficacy of modular upgradability in managing rapid sequential innovation, we exclude combinations of α and δ that lead to an artificial throttling of innovation[9].

When the firm has the option of selecting between a proprietary and non-proprietary approach, customers' ability to leverage any investment in the stable module $\mathcal{S}$ becomes more important. When the inter-version duration t_d is longer, the present value of the improved version is reduced. This makes customers less willing to plan for upgrades when the new product is launched. The firm can overcome this resistance by allowing the customers to transfer a larger portion of their earlier investment. Recall that the stable module prices offered through the modular proprietary architecture allow the customers to transfer all of their investment to future upgrades. Further,

[9]In other words, Figures 3 and 4 are restricted to parameters that satisfy the condition $\delta f\left(\beta q_2^{\alpha}\right) > f\left(\beta q_1\right)$.

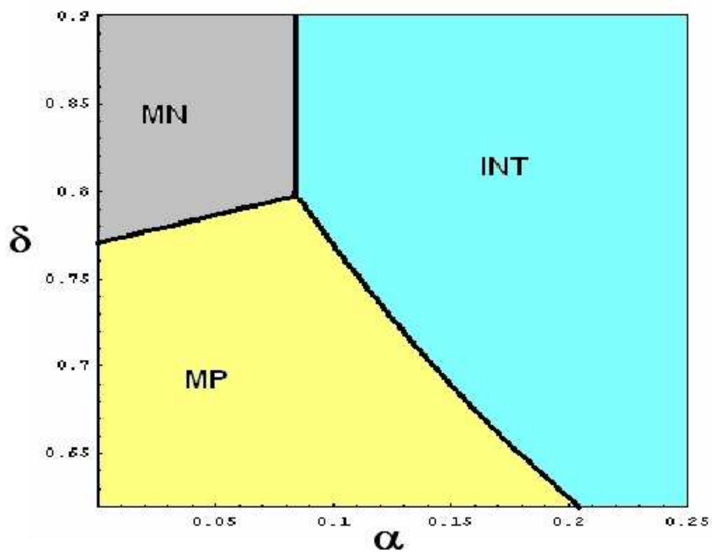

Figure 3: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $p_s = 0.1$, $\beta = 0.85$ and $\gamma = 1$

when t_d is higher, the firm's discounted valuation of its own second period revenues is lower; this lowers the real cost of offering larger upgrade discounts (implicitly, through p_s) in the second period. As a result of these two forces, the firm finds it optimal to offer the proprietary modular architecture for smaller values of δ.

The influence of β can be understood using the example in Figure 4, which shows the variation of architectural decisions between two levels of β. A higher value of β denotes a lower disparity between the firm's ability and the industry standard in producing $\mathcal{S}$ or a greater level of acceptance of proprietary products. When the firm is more competitive, i.e. when $\beta = 0.875$, the non-proprietary solution is dominant in region *MN*, the proprietary modular solution should be adopted in regions *MP* and *B*, and a non-modular product should be sold in all other regions. When β falls to 0.85, the non-proprietary modular architecture is the best alternative for the firm in regions *MN, A* and *B*. The integral system is profitable only in region *INT*. As β approaches 1, the non-proprietary solution is not used under any condition. The non-proprietary approach becomes the ideal choice as β approaches 0.

As we discussed in Section 4.4, the additional benefits customers derive from modular upgradability come at the loss of installation and upgrading services previously performed by the firm itself. Naturally, if the interfaces connecting the modules are complex, these costs are larger and customers are more willing to select one of the versions. In Figure 5, as C_I increases, the non-proprietary so-

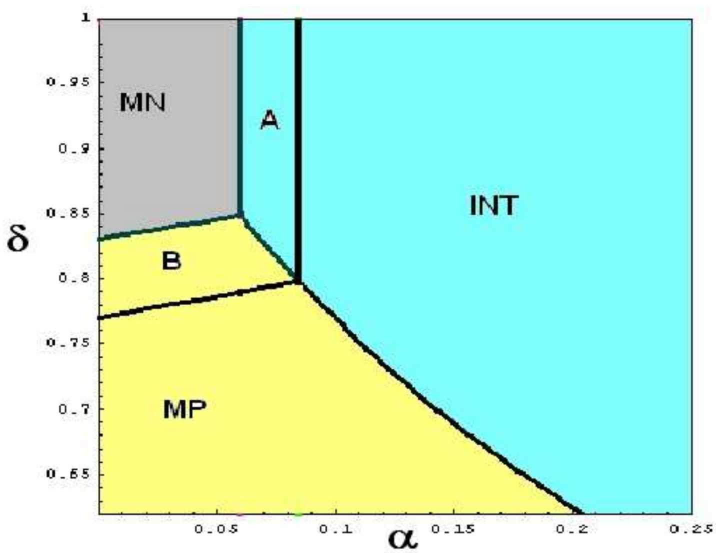

Figure 4: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = 0.6$, $p_s = 0.1$, $\beta = 0.85$ or 0.875, $\gamma = 1$

lution is less profitable than both modular proprietary and integrated designs. Similarly, a larger C_U decreases the attractiveness of the modular proprietary alternative. While these results suggest that modular architectures are perhaps more conducive to certain market and technological environments than others, they also reveal the importance of designing for easy upgradability. We discuss these in further detail in Section 6.

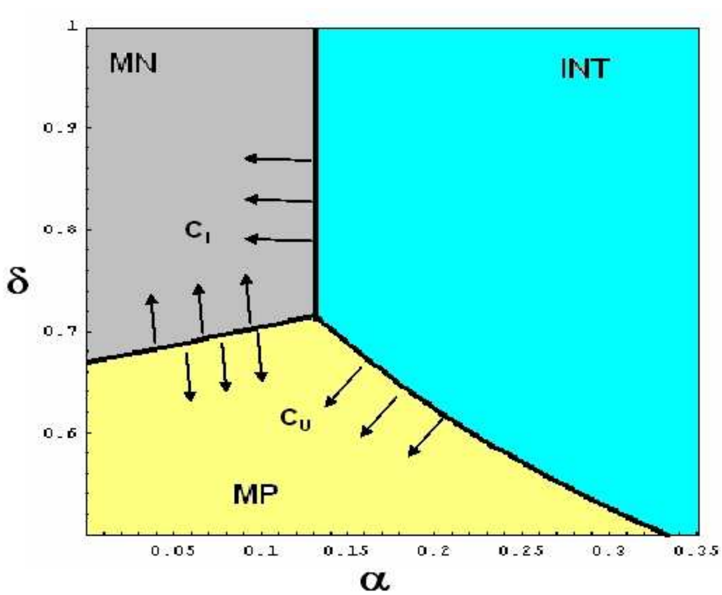

Figure 5: Dominant Architectures for $q_1 = 1$, $q_2 = 3$, $\delta_f = .6$, $p_s = .1$, $\beta = .85$, $\gamma = 1$, $C_I = .05$, $C_U = .01$

These results show that the firm might have strong reasons to pursue a non-proprietary architecture (outsourced stable module) in spite of the reduced revenues it obtains from the sales of each stable module unit. The intuition that the non-proprietary solution is more preferable when customers are wary of proprietary approaches or the firm is less capable in designing the stable module (low β) is indeed confirmed. However, the influence of the customer's discount factor on the choice of the type of modular architecture is quite subtle, and goes to the very core of the benefits of modular upgradability for rapidly improving products. Whereas these results hold when the discount factors of the firm and its customers are correlated through t_d in industrial markets, the results can be different in consumer markets where the firm and individual consumers could differ in their relative patience to receive future benefits. We discuss this issue in Appendix B.

5.2 Optimal Innovation Rates

In the previous sections, we have identified the optimal design architecture and pricing at a given rate of innovation (with $\delta(t_d)$ representing the innovation rate). We now endogenize the innovation rate and treat the inter-version time t_d as a decision variable to study the impact of architecture on the optimal rate of innovation (while addressing customer regret and maximizing firm profit). Specifically, we compare the demand-driven optimal innovation rate t_d^* for the modular proprietary, non-proprietary and integral architectures[10].

Deriving optimal innovation rates requires a model of development cost, and ours is based on the assumption that a specific set of resources will be dedicated to the product development effort. Prior studies have shown that there are diminishing returns to resource investment in product development (Graves, 1989). To develop a product that delivers performance $f(q_2)$ from the technology with potential q_2, we model that the firm incurs a cost that depends on the development time t_d, and the qualities of the early and improved versions, q_1 and q_2. The profit expressions in earlier sections are expressed in terms of δ, which is bounded between 0 and 1; so it is convenient to express the functional form with respect to $\delta(t_d)$. The development cost is modeled to be:

$$C(t_d, q_1, q_2) \doteq C_d(q_1, q_2) g(\delta(t_d))$$
$$g(0) = \infty,\ g(1) = 0,\ g'(.) > 0 \text{ and } g''(.) > 0$$

[10]To make the presentation simpler, we assume that the per-period learning rate $\gamma(t_d)$ is independent of t_d and ignore costs incurred by customers. Incorporating $L > 0$, subject to our assumption that $L < r$ does not change the main results of this section.

Integral and Modular Proprietary Architectures

First, we compare the optimal rates of innovation under Modular Proprietary and Integral architectures. For any given inter-version time t_d, the optimal prices set by the firm for each design choice is given by Propositions 1 and 2 above. The corresponding profits can be derived from Equations 5 and 7 in Section 3.2. The firm's total profit using the proprietary modular architecture as a function of the rate of innovation, t_d, is:

$$\Pi_{MP}(t_d) = \frac{f(\beta q_1)}{4} + \delta(t_d)\frac{f(\beta q_2^{\alpha}) - f(\beta q_1)}{4} - C_d(q_1, q_2)g(\delta(t_d)) \tag{8}$$

Similarly, for the integral architecture, the profit is:

$$\Pi_{IN}(t_d) = \begin{cases} \frac{(1-\delta(t_d))f(\beta q_1)}{2} + \frac{\delta(t_d)(f(\beta q_2)-f(\beta q_1))}{4} - C_d(q_1, q_2)g(\delta(t_d)) & \text{if } \delta(t_d)f(\beta q_2) \leq f(\beta q_1) \\ \frac{(1-\delta(t_d)^2)f(\beta q_1)}{4} + \frac{\delta(t_d)(f(\beta q_2)-f(\beta q_1))}{4} - C_d(q_1, q_2)g(\delta(t_d)) & \text{if } \delta(t_d)f(\beta q_2) > f(\beta q_1) \end{cases}$$

To obtain some basic insights, we compare the innovation rates for the proprietary modular and integral architectures when $\beta = 1$ and $\alpha = 0$. No specific functional forms are required for comparing innovation rates under the two alternatives. We find that when the firm's own modules are not inferior to the industry standards, and when there are no negative consequences of modularity, the firm has an incentive to innovate faster if it adopts a modular architecture for the system.

Proposition 6. Innovation under Modular and Integral Architectures
When there are no quality losses due to modularization ($\alpha = 0$)*, modular proprietary architecture allows for a faster rate of innovation than an integral architecture without causing customer regret.*

$$t_d^{MP*} \leq t_d^{IN*}$$

The above result that a modular design choice allows for faster optimal demand-driven innovation (even when any supply-side efficiencies involved in modular design are not considered) is, to the best of our knowledge a new insight not found in the existing literature. The reason for faster optimal innovation rate under the modular architecture can again be traced back to the additional degree of freedom in pricing this design provides. More pricing freedom results in an increased ability to leverage investments in innovation, thus tilting the tradeoff in the favor of increased development effort.

Modular Proprietary and Non-Proprietary Architectures

When the price of the market-sourced stable module p_s is low (close to 0), the Modular Non-proprietary approach is similar to having an integral architecture because the role of the stable module is insignificant. Therefore, the Modular Proprietary architecture results in faster innovation. On the other extreme, if the stable module is a valuable component of the product (high p_s), the firm again does not benefit much from innovation as a significant portion of the sales goes to the vendor of the stable module. This again leads to faster innovation under Modular Proprietary approach. These observations are captured in the following Proposition.

Proposition 7. Innovation Rates under Proprietary and Non-Proprietary Architectures *The optimal rate of innovation under the Modular Proprietary Design exceeds the rate of innovation under the Non-Proprietary design both for high and low prices of the stable module.*

Proof. The proof (in the Appendix) offers bounds for the stable module prices above and below which the Proprietary approach leads to faster innovation. □

Interestingly, for intermediate values of p_s, we find that the optimal innovation rate under Modular Non-proprietary approach *could* exceed the innovation rate for the Proprietary architecture. Note that a higher price p_s restricts the profitability of both first and second period sales. When the stable module is moderately expensive, under the non-proprietary approach, p_s has a stronger constraining effect on first period prices. The firm, which is now relatively less sensitive to first period profits, makes an unencumbered decision to maximize discounted second period profits resulting in higher innovation rate under the non-proprietary architecture.

6 Conclusions

We investigated the role of product design and introduction timing in managing rapid sequential innovation. Driven by feedback from their investment-conscious customers, firms have begun offering an easier upgrading path using upgradable modules, a trend increasingly seen in industrial markets.

We attempted to formalize and analyze modular upgradability for sequentially improving products that yield customer productivity improvements. Our results provide a nuanced understanding of the role of a product's modular design in segmenting customers in a heterogeneous market when costs may be incurred in installing and upgrading modular products. Localizing product improvements and developing the product to be upgradable in modules ensures that initial investment by customers is not completely obsoleted by subsequent introduction of superior products, often outweighing any additional costs associated with modularity. Consequently, the seller profits more by leveraging the increased pricing freedom to segment customers without restraining the pace of innovation. Furthermore, modular designs are also more conducive to a faster launch of improved versions - while prior research in Operations offers a resource-based motivation for modularity, we offer an alternative explanation for faster innovation in modular products from a market-adoption perspective (Section 5.2).

Our central contributions in this paper are the first order insights that we derived about the connection between product architecture and market segmentation, which are typically analyzed in mutual isolation. With respect to the existing literature, we have added two additional degrees of freedom that include product architecture and introduction timing to help firms manage sequential innovation. Contrary to the suggestion that using industry standard components can be debilitating to the product line in the long run (Morris and Ferguson, 1993), we find that using non-proprietary components might indeed be an attractive option to realize the modular approach. In fact, there is a strong incentive to use standard subsystems when cost-side advantages of standard components are factored in. Whereas the understanding in 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 4.3). Further, our analysis confirmed that the incentive for modularization and maintenance of proprietary control are dependent on design effects, product characteristics like the learning rate and market characteristics such as firm discount rates. When the direct or opportunity costs of modularization and proprietariness are high, non-proprietary or integral architectures may indeed be preferable.

The implication of this work for innovating firms going forward is that modular upgradable product design, introduction timing, and coordinated pricing can be valuable instruments for firms to manage the market launch of rapidly improving products. By identifying regions of appropriateness of the different approaches to upgrading the product in modules, we are able to identify factors that a firm must recognize and influence in designing improving products. We learned exactly how installation and upgrade costs (C_I, C_U) make modular designs less valuable for the customers as well as the firm. In consumer products, even more than industrial products, these costs tend to be larger relative to the utilities derived from the products. While this result is consistent with the observation that modular designs are currently more prevalent in industrial sectors, it provides some basic guidance on pairing technologies and markets through product design. An emphasis on performance attributes alone often leads to complex product designs, and dense and intricate interfaces between functional modules (Simon, 1969). We propose that in order to commercialize rapidly improving sequences of products, a firm should consider *designing its products for upgradability.* In addition to functional modularity and localization of improvements, products designed for upgradability will also enable customers to disassemble and quickly re-install the constituents of a product in an effortless manner.

In these first steps in understanding how architecture influences market segmentation, we have made some stylized assumptions. The long-run viability of product architectures needs to be addressed in the future by going beyond a two-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, performance saturation (Krishnan and Zhu, 2003), and increased competition. The single product, replacement model considered in this paper is in accordance with the body of work on rapid sequential innovation. In a more general replacement setup, Stokey (1988) suggests that periodic addition (deletion) of high (low) quality products results from industry-wide spillovers of learning experiences. We have also assumed that there is no resale market for such rapidly improving products. Although this can be enforced by the manufacturer for some goods, presence of second hand markets can moderate the effects of monopolistic opportunism considered in this paper.

The results presented in the paper are derived under the stylized supposition that production costs are negligible, however, numerical analysis shows that the fundamental results indeed continue to hold when production costs are considered. When marginal costs are negligible, and when modularization degrades product quality, offering trade-ins and buy-backs may, in fact, be more profitable than opting for modular upgradeable designs. However, trade-in alternatives entail distribution, reverse logistics and disposal costs that could make them expensive for some products. Further, the customer's lower incentive to maintain stable modules that will be returned through the trade-in creates undesirable moral hazard issues. Our discussion is focused on durable products such as industrial assembly systems which cannot be bought back without considerable risk for the firm and expense for the customer.

The insights generated from the paper offer a new and previously unknown rationale for modularizing the architecture in the context of rapid sequential innovation. The results also help decide when to use a proprietary modular architecture versus using an open systems approach. The application of these ideas can help ensure that rapid improvements can be realized without discouraging customers from purchasing these products, thereby stimulating market growth and profits for firms.

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A Appendix

A.1 Proof of Property 2: Segmentation Patterns for RSI

SP-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.

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

In this pattern, $v_{01} \leq \min(v_{0u}, v_{02}) \Leftrightarrow$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.

SP-3. $P_1 \leq p_s \leq P_1$ and $p_1 + (1-\delta)p_s \geq (1-\gamma\delta)f(q_1)$

In this SP, $v_{01} \leq \min(v_{0u}, v_{02}) \Leftrightarrow$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}.

$p_1 + (1-\delta)p_s \geq (1-\gamma\delta)f(q_1) \Leftrightarrow v_{u2} \geq 1$. 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.

SP-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 range 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.2 Proof of Proposition 1: Proprietary Modular Architecture

We present the proof for the Rapid Improvement case below. The proof for Gradual Improvement is similar and straightforward.

Pricing in SP 1. To ensure SPE outcomes, we will begin by solving the second period problem:

$$R_2^* = \max_{p_2} \{p_2 (1 - v_{1u})\}$$

Solving this, we obtain $p_2^* = \frac{f(\beta q_2^\alpha) - \gamma f(\beta q_1)}{2}$ and $R_2^* = \frac{f(\beta q_2^\alpha) - \gamma f(\beta q_1)}{4}$. We now turn our attention to the first period problem, while constraining the solution to satisfy the conditions for SP 1.

$$\begin{aligned} \Pi^* &= \max_{p_s, p_1} \{(p_s + p_1)(1 - v_{01}) + \delta R_2^*\} \\ &s.t. \quad p_s^* \le P_1 \end{aligned}$$

The unconstrained solution for this problem satisfies $p_s^* + p_1^* = f(\beta q_1)/2$. As shown below, any solution of this type violates the constraint $p_s^* \le P_1$.

$$p_s^* \le P_1 \Leftrightarrow p_s^* \le \frac{f(\beta q_1)(1 - \gamma\delta)}{2(1 - \delta)} - \frac{p_1^*}{1 - \delta} \Leftrightarrow \frac{\delta p_1^*}{1 - \delta} \le -\frac{f(\beta q_1)\gamma}{2} < 0$$

The optimal constrained equilibrium prices and profit are

$$\begin{gathered} p_s^* = \frac{f(\beta q_1)}{2},\ p_1^* = 0,\ p_2^* = \frac{f(\beta q_2^\alpha) - \gamma f(\beta q_1)}{2} \\ \Pi^* = \frac{f(\beta q_1)}{4} + \delta \frac{f(\beta q_2^\alpha) - \gamma f(\beta q_1)}{4} \end{gathered}$$

Pricing in SP 2. In the second period, the firm tries to sell to $v \in [v_{12}, 1]$. To ensure that it is able to sell to the available segment of the market while maximizing its revenue, the firm will solve the following problem.

$$\max_{p_2}\{p_2(1-v_{12})+p_s(1-v_{u2})\}$$

$$\text{s.t.}$$

$$v_{12}f(\beta q_2^\alpha)\geq p_s+p_2$$

$$v_{u2}(f(\beta q_2^\alpha)-\gamma f(\beta q_1))\geq p_2$$

These constraints are equivalent to the condition $P_1 \leq p_s \leq P_2$. The optimal price p_2 is its upper bound, $p_2=(p_1+(1-\delta)p_s)\left(\frac{f(\beta q_2^\alpha)-\gamma f(\beta q_1)}{(1-\gamma\delta)f(\beta q_1)}\right)$. 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 SP 1.

Pricing in SP 3. There is no equilibrium in this SP; Dhebar (1994) proved that when no customer buys in both periods, the firm always behaves opportunistically, causing regret.

Pricing in SP 4. The second period problem and the optimal second period price can be found as follows.

$$\max_{p_2}\{p_2(1-v_{02})+p_s(v_{u2}-v_{02})\}$$

$$p_2^*=\frac{f(\beta q_2^\alpha)}{2}-p_s \text{ and } R_2^*=\frac{f(\beta q_2^\alpha)}{4}+p_s\left(\frac{(1-\delta)p_s+p_1}{(1-\gamma\delta)f(\beta q_1)}-1\right)$$

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

$$\begin{aligned}\Pi^* &= \max_{p_s,p_1}\{(p_s+p_1)(1-v_{2u})+\delta R_2^*\}\\ s.t.&\quad p_s^*+p_1^*\geq\frac{f(\beta q_1)}{2}\end{aligned}$$

The unconstrained solution for the problem satisfies

$$p_s^u=\frac{f(\beta q_1)(1-\gamma\delta)-2p_1^u}{2(1-\delta)};\quad p_1^u=\frac{f(\beta q_1)(1-\gamma\delta)-2p_s^u(1-\delta)}{2}$$

However this violates the constraint for SP 4. The constrained optimal solution is

$$p_s^*=\frac{f(\beta q_1)}{2},\ p_1^*=0,\ p_2^*=\frac{f(\beta q_2^\alpha)-f(\beta q_1)}{2}$$
$$\Pi^*=\frac{f(\beta q_1)(1-\delta)(1-\delta(2\gamma-1))+\delta f(\beta q_2^\alpha)(1-\gamma\delta)}{4(1-\gamma\delta)}$$

A.3 Proof of Proposition 2: Non-Proprietary Architecture

We provide the expressions for the RSI case alone. The expressions for GSI are obtained analogously.

Pricing in SP 1. The second period problem price and profit are $p_2^* = \frac{f(q_2^\alpha)-\gamma f(q_1)}{2}$ and $R_2^* = \frac{f(q_2^\alpha)-\gamma f(q_1)}{4}$. The first period optimization problem is

$$\begin{aligned} \Pi^* &= \max_{p_s,p_1} \left\{ (p_s + p_1)(1 - v_{01}) + \delta R_2^* \right\} \\ s.t. &\quad p_s \le P_1 \end{aligned}$$

The unconstrained solution for this problem is $p_1^u = (f(q_1) - p_s)/2$. When $p_1 = p_1^u$, to satisfy $p_s \le P_1$ with $p_1 \le f(q_1)$, we need $\delta(2-\gamma) \ge 1$. This is not satisfied for any $\delta < 1$ and $\gamma > 1$. Therefore, $p_s = P_1$ in equilibrium. The constrained optimal solution is

$$p_1^* = \tfrac{(1-\gamma\delta)f(q_1)-2(1-\delta)p_s}{2},\ p_2^* = \tfrac{f(q_2^\alpha)-f(q_1)}{2}$$
$$\Pi^* = \tfrac{(1-\gamma\delta)((1+\gamma\delta)f(q_1)-2p_s)}{4} + \delta\tfrac{\left(f(q_2^\alpha)-f(q_1)\right)\left(f(q_2^\alpha)-(2\gamma-1)f(q_1)\right)}{4\left(f(q_2^\alpha)-\gamma f(q_1)\right)}$$

Pricing in SP 2 and SP 3. Arguments in A.2 hold. No sub game perfect equilibrium exists in these patterns.

Pricing in SP 4. The optimal price and profit from the second period are $p_2^* = (f(q_2^\alpha) - p_s)/2$ and $R_2^* = \frac{\left(f(q_2^\alpha)-p_s\right)^2}{4f(q_2^\alpha)}$. The first period problem is

$$\begin{aligned} \Pi^* &= \max_{p_1} \left\{ p_1(1 - v_{u2}) + \delta R_2^* \right\} \\ s.t. &\quad p_s \ge P_2 \end{aligned}$$

The unconstrained solution to this problem is $p_1^u = ((1-\gamma\delta) f(q_1) - (1-\delta) p_s)/2$. Let $\phi_1 := \frac{(2\gamma\delta-1)f(q_1)f(q_2^\alpha)}{2\delta f(q_2^\alpha)-f(q_1)}$ and $\phi_2 := \frac{\gamma f(q_1)f(q_2^\alpha)}{(1+\delta)f(q_2^\alpha)-f(q_1)}$ and $\phi_3 := \frac{f(q_1)(1-\gamma\delta)}{(1-\delta)}$. Price p_1^u is feasible if $\phi_3 \ge p_s \ge \phi_2$. When $\phi_2 \ge p_s \ge \phi_1$, the constraint is active and $p_1^c = (f(q_1)(f(q_2^\alpha) + p_s) - 2p_s f(q_2^\alpha)) / (2f(q_2^\alpha))$.

For p_s such that $\phi_1 \ge p_s \ge 0$, 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.

$$p_1^* = \begin{cases} \frac{(1-\gamma\delta)f(q_1)-(1-\delta)p_s}{2} & if\ f(q_1) \geq p_s \geq \phi_2 \\ \frac{f(q_1)\left(f\left(q_2^\alpha\right)+p_s\right)-2p_s f\left(q_2^\alpha\right)}{2f\left(q_2^\alpha\right)} & if\ \phi_2 \geq p_s \geq \phi_1 \\ \text{First version not launched} & if\ \phi_1 \geq p_s \geq 0 \end{cases}$$

$$\Pi^* = p_1^* \left(1 - \frac{p_1^* + (1-\delta)\, p_s}{(1-\gamma\delta)\, f(q_1)}\right) + \delta R_2^*$$

A.4 Proof of Proposition 5: Comparison of Architectural Choices

Assumptions: $\alpha = 0$; $\beta = 1$.

1. First, note that the pricing problem for the no-special-upgrade prices solution is same as Problem (4,5) with the additional constraint that $p_s = 0$. It is now easily verified that $\pi_{MP} > \pi_{IN}$.

2. Finally, note that the non-proprietary solution is a lower bound to the proprietary solution since (a) p_s is fixed at a predetermined value and (b) Revenue from unit sale may be higher by p_s for the proprietary product. Therefore, $\pi_{MP} > \pi_{MN}(p_s)\ \forall\ p_s > 0$

A.5 Proof of Proposition 6: Integrated and Modular Architectures

The first order optimality for optimality of inter-version times (t_d) the MP and IN cases can be written in terms of δ.

$$\frac{\partial \Pi_{MP}(\delta)}{\partial \delta} = 0 \Rightarrow \frac{f(\beta q_2) - f(\beta q_1)}{4} - C_d(q_1, q_2) g'(\delta) = 0$$

$$\frac{\partial \Pi_{IN}(\delta)}{\partial \delta} = 0 \Rightarrow \begin{cases} \frac{f(\beta q_2)-3f(\beta q_1)}{4} - C_d(q_1, q_2) g'(\delta) = 0 & \text{if } \delta f(\beta q_2) \leq f(\beta q_1) \\ \frac{f(\beta q_2)-(1+2\delta) f(\beta q_1)}{4} - C_d(q_1, q_2) g'(\delta) = 0 & \text{if } \delta f(\beta q_2) > f(\beta q_1) \end{cases}$$

Since $g''(\delta) > 0$, the second order conditions are satisfied. Further, it follows from above that at any δ_{MP}^* that is optimal for the MP architecture, $\frac{\partial \Pi_{IN}(\delta_{MP}^*)}{\partial \delta} < 0$. This implies $\delta_{MP}^* > \delta_{IN}^* \Rightarrow t_d^{MP*} < t_d^{IN*}$. Therefore, it is optimal to delay introduction of the advanced product more in the integral system.

A.6 Proof of Proposition 7: Proprietary and Non-Proprietary Architectures

We use C_d to represent $C_d(q_1, q_2)$ in this proof. The expressions below are derived for $\beta = 1$ and $\alpha = 0$, but can be extended to these cases without loss of generality. We have established before that the optimal innovation rate under the MP choice is given by

$$\delta^{MP*} = \delta(t_d^{MP*}) = \frac{f(q_2) - f(q_1)}{4C_d}$$

We consider the two market segmentation patterns possible under MN separately.

SP-1.

$$\Pi^{SP1*} = \tfrac{(1-\delta)\delta p_s^2}{f(q_1)} + \tfrac{(1-\delta^2-\delta)f(q_1)+\delta f(q_2)-2(1+\delta-2\delta^2)p_s}{4}$$

$$\delta^{SP1*} = \frac{8p_s^2 + 2p_s f(q_1) + f^2(q_1) - f(q_1)f(q_2)}{2f(q_1)(4p_s - f(q_1) - 2C_d)}$$

Define $\omega_1 \doteq f(q_1)f(q_2) - C_d f(q_1) - f^2(q_1)$ and $\omega_2 \doteq f(q_1)\sqrt{c_d^2 - 6C_d(f(q_2) - f(q_1)) + (f(q_2) - f(q_1))^2}$. By comparing the expressions above, $\delta^{MP*} \geq \delta^{MN1*}$ if $p_s^{UB1} \leq p_s$ or if $p_s \leq p_s^{LB1}$, where

$$p_s^{UB1} = min\left(\frac{f(q_1)}{2}, \frac{\omega_1 + \omega_2}{8C_d}\right) p_s^{LB1} = max\left(0, \frac{\omega_1 - \omega_2}{8C_d}\right)$$

SP-4. Since the expressions under SP-4 are hard to interpret, we find a weak bound on p_s^{UB4} above which δ^{MP*} is greater and argue that a meaningful bound for p_s^{LB4} may exist below which δ^{MP*} is greater.

$$\Pi^{MN4*} = \begin{cases} \frac{(1-\delta)(f(q_1)-p_s)^2}{4f(q_1)} + \delta R_2^* & \text{, if } f(q_1) \geq p_s \geq \phi_2 \\ \frac{\left[p_s(2f(q_2^\alpha)-f(q_1))-f(q_1)f(q_2^\alpha)\right]\left[p_s(f(q_1)-2\delta f(q_2^\alpha))+(2\delta-1)f(q_1)f(q_2^\alpha)\right]}{4(1-\delta)f(q_1)f^2(q_2^\alpha)} + \delta R_2^* & \text{, if } \phi_2 \geq p_s \geq \phi_1 \\ \delta R_2^* & \text{, if } \phi_1 \geq p_s \geq 0 \end{cases}$$

where $R_2^* = \frac{(f(q_2)-p_s)^2}{4f(q_2)}$

Let $p_s^{UB4} = \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$. First, note that if $p_s \geq \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$, then $p_s \geq \phi_2 \;\forall\, \delta$. When $f(q_1) \geq p_s \geq \frac{f(q_2^\alpha)f(q_1)}{2f(q_2^\alpha)-f(q_1)}$,

$$\delta^{MP*} = \frac{f(q_2) - f(q_1)}{4C_d} \geq \frac{(f(q_2) - p_s)^2}{4C_d f(q_2)} - \frac{(f(q_1) - p_s)^2}{4C_d f(q_1)} = \delta^{MN4*}$$

If $\phi_1 \geq p_s \geq 0$, comparison of innovation rates depends on the relative magnitudes of $f(q_1)$, $f(q_2)$ and p_s.

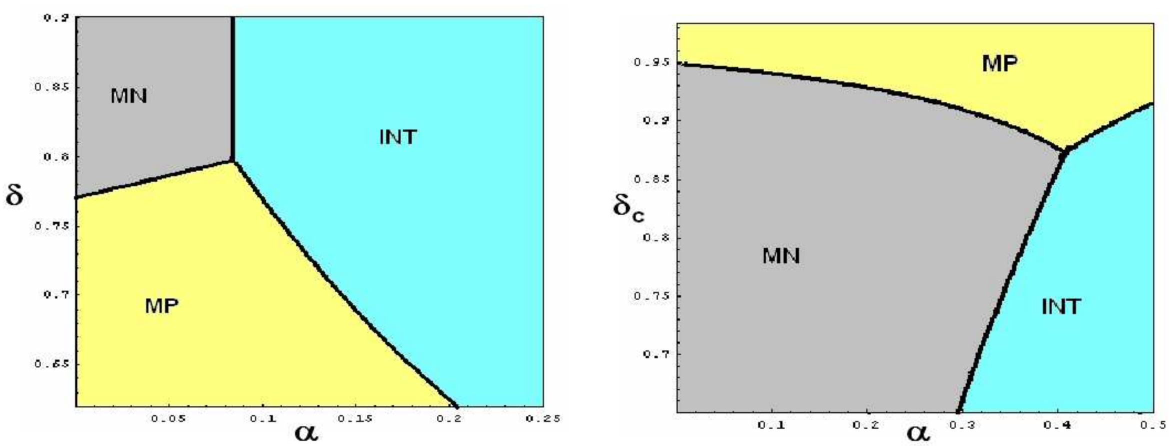
But $lim_{p_s \to 0} \left(\Pi^{MN1*} - \Pi^{MN4*}\right) = \frac{(1-\delta)(f(q_2)-f(q_1)+\delta^2 f(q_1)}{4} > 0$, the firm will prefer SP1 over SP4 segmentation for any δ at this limit. Therefore, as $p_s \to 0$, MP results in faster innovation than MN. Therefore, we know that there exists a bound $p_s^{LB4} \in \left[0, p_s^{LB1}\right]$ such that δ^{MP*} is higher for all $p_s \in \left[0, p_s^{LB4}\right]$.

B A Note on the Appropriateness of Product Architectures

While the thrust of this paper is to model and explain the modular upgradable features present found in products in several industrial categories, we also believe that our model easily lends itself to application in consumer markets. However, in evaluating the appropriateness of various product design alternatives to the two situations, some crucial differences must be acknowledged. While discounting rates in industrial markets are derived by considerations of interest rates, individual consumers differ both from the seller and from each other in their temporal preferences. As a result, it may not be reasonable to assume that δ for the firm and its consumers are similar or correlated. Using the following examples, we show the impact of this assumption on our results in Section 5.1.

Let δ_c and δ_f denote the per period discount rates for consumers and the firm respectively. In Figure 6 below, we show the regions in which it is optimal to offer a modular proprietary architecture (MP), a non-proprietary modular design (MN) and an integrated architecture (INT) for the case in which $\delta_c = \delta_f$ and δ_c varies independently from δ_f. In Section 5.1, we presented the former case and found that MP is optimal when δ and α are lower. However, when δ_c and δ_f are not correlated, we find that MN could be optimal when δ_c and α are small. In consumer markets, a firm may be able to influence δ_c by tweaking consumer patience through marketing levers such as advertisement campaigns. If consumers become relatively more patient for the new product than the firm, the firm can afford to offer large implicit discounts (high p_s) through the proprietary modular system without significantly affecting the net present cost of these discounts. As a result, the proprietary strategy could become more optimal when customers are relatively more patient than the firm.

Further, users of consumer products - unlike businesses - also vary widely in their ability to learn by using a product. However, we believe that segmenting consumers based on their ability to learn



$\delta_c \equiv \delta_f$ $\delta_c \neq \delta_f = 0.6$

Figure 6: Comparing Correlated and Independent Discount Factors

deserves dedicated attention in a separate work.