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A Model-Based Framework for Designing Products and Services: The Role of Multiple Quality Dimensions

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A Model-Based Framework for Designing Products and Services: The Role of Multiple Quality Dimensions

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In this dissertation, I examine the challenges of designing products in development-intensive settings and where tight integration with services is necessary.

The first problem studied is the design of development-intensive products, for which the fixed costs of development far outweigh the unit-variable costs.

Examples of such development-intensive offerings abound in a number of industries including the pharmaceutical, information, and entertainment sectors of the economy.

It is shown that the design problem presents some unique managerial challenges. Specifically, I find that managerial insights from the traditional approach to product line design developed for unit-variable cost intensive products do not carry over to development-intensive products.

I present new mechanisms and managerial guidelines for designing a family of such products for which development costs cannot be ignored, and illustrate the insights

with an extended industry case-study. Specifically, I show that the design approach based on degrading (or subtracting value from) a high-end product to obtain a *subsumed low-end edition*, discussed in the literature to be an effective approach for designing unit cost intensive products leads to a sub-optimal line of development-intensive products.

As an alternative to a subsumed product design strategy, I propose the *overlapped product design approach*, in which the low-end product is not completely subsumed in the high-end product, but differentiated on additional vertical quality dimensions.

The second problem studied is the design of product lines with after-sale service offerings. I show that a multi-dimensional quality model can help a firm design a more profitable product line and after-sale services.

I specifically study the performance and conformance quality dimensions, as well as the interaction between the dimensions. I find that substitute after-sale services have opposite impacts on the optimal quality levels in performance and conformance quality dimensions.

With important after-sale services the firm has quite different strategies for its product line and service line that are sold through a distribution channel. The so-called quality distortion from uncoordinated supply chain can be alleviated because of the service offerings.

The contribution of this work is to unearth the crucial role of multiple quality dimensions in designing product lines in today's knowledge and service economy.

Table of Contents

Chapter 1: Introduction

1.1. DEVELOPMENT-INTENSIVE PRODUCTS

Intensifying global competition and increasing power of customers place firms in a bind. On the demand side, customers armed with information and saturated with higher performance are reluctant to pay ever-increasing prices for higher quality products. On the supply side, the emergence of foreign and generic low-cost competitors accelerates commoditization, so firms must invest in creating innovative new products. In this context, the addition of digital and information components offers an opportunity to create differentiated, customized, and flexible products. However, this also makes a firm's offerings more development intensive, and in some cases the costs of development begin to far outweigh the unit-variable production costs.

In some industries, the cost of new product development (NPD) forms an overwhelming part of the total costs. A branded drug sold to a customer at $300 per case can cost less than $25 dollars to manufacture, and the high contribution margins help offset the huge research and development of such products (SIIA 2001). Pfizer Inc., for example, spends 15% of its revenue on R&D (Pfizer 2002). In comparison, General Motors and Caterpillar spent only 3.5% and 3.4% of their revenue on R&D, respectively (GM 2002 and Caterpillar 2001). NPD constitutes a significant portion of the operating costs of packaged software firms. For instance, Adobe Systems Inc. spent 22.1% of its revenue on R&D in the year 2001, far outweighing its (variable) cost of revenue of just 7.8% (Adobe 2002). Microsoft announced an increase in R&D spending leading to the development budget being over 20% of its annual sales (Waters 2003). I refer to the products of such firms, *Development Intensive Products (DIP's)*, which have the following characteristics:

Quality of a DIP is primarily determined by the development effort and directly influences the product's development cost, but does not have a significant impact on unit-variable costs[1].

The unit variable costs of a development-intensive product are very small compared to its development costs, and they may be considered negligible for aggregate planning purposes.

I contrast DIPs with Marginal-Cost Intensive products (MIPs) for which the development cost is a relatively small portion of the overall cost of product quality. While development may critically influence product quality, especially robustness, the cost of development is often insignificant compared to the variable costs of production and assembly for MIP's.

When a firm faces a heterogeneous, vertically differentiated market (in which customers can be sorted on their willingness to pay for product quality), it usually designs a line of products as a means of price discrimination. In offering the product line, the firm must carefully position and price its products so that low-end products will not draw customers with high willingness to pay away from high-end products. Much of the research in product line design studies marginal-cost intensive products (Mussa and Rosen (1978), Moorthy and Png (1992)); specifically, the results of these and other authors shows that to mitigate market cannibalization, a firm must (a) limit the low-end product's quality such that the low-end product is a lesser version/subset of the high-end product and (b) offer a level of quality to the low-end customer that is even below the

[1] Here I use the term product quality to mean performance quality dimensions such as features, ease of use, etc. Development costs of such products, while independent of the number of units sold, are not totally fixed in the sense that they *are* a function of the quality of the product. A higher quality product costs more to develop both because it has more components and more complex individual components.

level which would be offered to the low-end customer if the high-end market were to not exist. I call this the *subsumed product line approach*, in which the low-end product is a subsumed and limited version of the high-end product. Deneckere and McAfee (1996) offer several examples of how companies may even damage their high-end good to obtain a crimped and subsumed low-end variant.

Although there is little theoretic research in product line design for development-intensive products, some managerially oriented articles recommend such quality degradation, especially for information goods. For example, Shapiro and Varian (1998) and John, et al. (1999) mention that limiting the quality of the low-end good is the rule for such goods. They also advocate "*value subtraction*" approach to designing low-end products in which the high-end product is designed first and valuable components are deliberately removed (or "turned off") from the high-end offering to attain the low-end variant. Value-subtraction goes beyond quality degradation to suggest a sequence in which a product line should be developed (high-end followed by low-end). However, I observe some unique challenges to practicing subsumed product line design and value subtraction for development-intensive products, as illustrated in the following example.

1.2. CHALLENGES IN DESIGNING A DIP FAMILY: THE CASE OF ADOBE SYSTEMS

As one of the world's largest software companies with annual revenues exceeding US$1.2 billion, Adobe Systems has dominated the desktop publishing and digital imaging markets in the last decade. Its highly successful and industry leading Photoshop® product, initially designed for the professional graphic designer and sold at a list price of $800-$1000, is now according to the New York Times "a professional editing program so widely used in the graphics world that it has become a verb" (Pogue 2002). For several times in the last five years, Adobe has attempted to target the small business and consumer market segments with a subsumed low-end version achieved by downgrading its high-end professional Photoshop product. Its first attempt, PhotoDeluxe, which was a feature-reduced version of the high-end Photoshop (but with the same interface) was reviewed by a design magazine as a "cut down Photoshop" that was too limited in its capability and much too complex to use (Arah 1998). Disappointed by PhotoDeluxe's revenues2, Adobe tried for a second time in 1999 to introduce a Photoshop Limited Edition (LE) with more editing capabilities than PhotoDeluxe but with a subset of the features contained in Photoshop. Photoshop LE was also disappointing and had to be "put to sleep" because it was "little more than a lobotomized Photoshop, offering only some of the features but 100 percent of the complexity" (Pogue 2002). Learning from these difficulties associated with quality degradation (specifically the inadequacy of value-subtraction in taming complexity) and threatened by prospective entrants, Adobe has since then taken some steps to overcome its challenges in the low-end of the market. Later in this article, I discuss how these steps taken by Adobe illustrate the concepts presented in this paper on designing a DIP family.

Adobe's experiences with subsumed product line design and value subtraction described above are not unique to one firm. Wolfram Research, used to crimp the high-end enterprise version of its Mathematica symbolic programming software to obtain the low-end student version (by disabling the math co-processor to make the student version slower as cited in Deneckere and McAfee (1996) and Shapiro and Varian (1998)). However, I find that Wolfram has stopped this approach of crimping the low-end market, and their web site indicates that they now offer a student version with no difference in functionality from the enterprise version (Wolfram 2003). There are other examples of firms such as Macromedia and Computer Associates recently stopping the practice of

[2] Adobe finally decided in July 2002 to discontinue selling the PhotoDeluxe product (Adobe, 2002, Adobe photodeluxe,).

deliberately downgrading their low-end versions, while this has not attracted research attention.

Product line design by subsumption and value-subtraction is focused on minimizing cannibalization and protecting the sales of the high-end product, but as seen in the above examples, faces some challenges in helping firms penetrate the low-end market. It is indeed true that the cost of value subtraction is negligible for development-intensive products (which is why the prior literature, such as in Shapiro and Varian 1998, found it to be attractive). However, unit variable costs of DIPs are also negligible, so even a firm that enjoys a monopoly position can generate greater profits from its low-end customers by offering them higher performance quality. Doing so would have the effect of lowering the price or units sold of the high-end product, so the firm must trade-off these costs against higher profits generated from the low-end of the market. Under threat of entry from competition, a monopolist faces even more pressure to not crimp the low-end product, lest it encourages entry. In addition, the low-valuation segment may place greater emphasis (almost equaling or only slightly lower than the value placed by the high-valuation market segment) on other quality dimensions (such as product's ease of use), which may be traded off against functionality and features of the product. It is the combination of these factors that I model in this paper to derive insights on how a firm should design a family of development-intensive products. I tackle three main research questions in the first part of the dissertation:

How does an environment in which the costs of development of new products are substantial and cannot be ignored impact a firm's product family design?

What effect does a firm's customer's unwillingness to pay for ever increasing amounts for better performance have on its product line design decisions?

When should the firm practice value-subtraction (derive its low-end version by subtracting from the high-end) and a subsumed product line strategy? What alternatives exist to differentiate the products and earn greater profits in such vertically differentiated markets?

In answering these questions, I seek to go beyond the simplistic version-standardize dilemma, and unearth some of the nuances of DIP family design in vertically differentiated markets. After a brief literature review, I present the details of the model, the analytical results, and an extended example from Adobe that brings out the implications of our model from chapter 3 to chapter 6.

1.3. AFTER-SALE SERVICES AND SUPPLY CHAIN

For many manufacturing companies, after-sale services are becoming an important part of their business. Servicing durable goods may generate 30% or more of the total revenue. In some industries, the service market can be four or five times larger than the product market (Knecht, et al. 1993). In the automobile industry, after-sale services account for almost 80 percent of the revenue opportunity and more than 50 percent of average automobile dealer's profits. For example, General Motors' greatest return on capital does not come from selling cars. Although after-sale parts and services comprise a small amount of GM's sales, they are by far the largest contributors to shareholder value on a percentage-rate basis. In fact, an Accenture study of GM shareholder value revealed that 9 billion dollar in after-sale revenue produced 2 billion dollar in profits. Profits from the company's 150 billion dollar in car sales are relatively lower (Dennis and Kambil 2003).

Examples of companies with important after-sale services are numerous. Manufacturers of razors almost all consistently generate high margin revenue streams from the follow-up sales of razor blades. Retailers such as Best Buy derive the largest margins from their sales of extended warranties. Manufacturers such as Epson and Hewlett-Packard sell their printers at such low prices that sometimes are below costs in order to profit from the continuing sales of toner cartridges.

After-sale services can be defined broadly to include many activities that follow a product's sale, delivery and installation. For example, they can be customer support, training, maintenance and repair, upgrades, product disposal, and sales of complementary goods.

In this paper, I consider two types of after-sale services: substitute services and complementary services. The demand for substitute services decreases with the conformance quality of the product. For example, the maintenance and repair of automobiles is substitute service – if the product quality is better, the demand for repair services becomes smaller. On the other hand, the demand for complementary services increases with product quality. Examples of complementary services include OnStar for GM automobiles, and wireless services for mobile phones.

To study the impact of after-sale services, especially the substitute after-sale services, I use a two-dimensional quality model to capture the relationship between demand for substitute services and conformance quality. Unlike Clark, et al. (1990), who propose the design-related quality dimension (performance quality) and the production-related quality dimension (conformance quality), I define quality dimensions only from the perspective of product development.

When a firm provides both products and after-sale services, it operates in two different industries that each requires very different core competence. Furthermore, there are potential conflicting objectives between product development and after-sale services. For example, one of the urban legends says that Gillette bought a Japanese patent for a new razor blade and locked the patent away forever simply because the new blade was capable of lasting forever. Clearly, a company such as Gillette has very little incentive to develop a long-lasting razor blade. Therefore, with profitable after-sale services, a firm may find its product strategies impacted by the sales of the services.

Another impact of after-sale services is on a firm's supply chain decisions. In an uncoordinated supply chain, the supplier and its retailer have different incentives to segment the market. The lack of coordination forces the firm to change its product strategies. When after-sales services are becoming more and more important, it will be very important for us to ask the rarely raised question: how should a supplier's product line strategies respond to the service revenue stream?

I study a firm's decisions for a product line, an after-sale service line, and the coordination of supply chain considered jointly. The first research question is when after-sale services become important part of a firm and how should the firm adapt its product line strategy accordingly. The second research question is when a firm sells its product line through a retailer who also provides profitable after-sale services to the end consumers, what will be the coordination problems, and how the problems affect the firm's product line strategy. The interactions between these three decisions bring new insights for those firms with important after-sale service business.

Chapter 2: Literature Review

Managerial decisions in product design and development have been important research topics in the operations management community. Krishnan and Ulrich (2001) offer a review of recent research in product development. Early work in product line design can be traced to the seminal work of Mussa and Rosen (1978), who studied a monopolist's product quality decision. Moorthy (1984) and Moorthy and Png (1992) pioneered the discrete market segment model in the management literature, which has been further developed by Kim and Chhajed (2002), Raghunathan (2000), Bhargava and Choudary (2001), Krishnan and Gupta (2001), and Desai, et al. (2001). However, most of this literature ignores product development costs (or at best treats it as a constant that is independent of product quality). As seen in this paper, development costs can be crucial to understanding product line design decisions.

There is also an emerging stream of work in the Operations literature that uses economic modeling and empirical methods to study product development, capture costs more realistically, and to weigh in on the product line design problem. While there has been a long tradition of research on modeling development costs from a technical perspective in the engineering literature, Gomes and Joglekar (2003) adopt a transaction cost economics perspective to studying the drivers of development cost in distributed software development. Their analysis is, however, at the level of an individual product/project, not the entire product line. Fisher et al. (1999) study component sharing in product family design from a cost reduction point of view.

This paper also is related to the recent stream of work on modeling multiple dimensions of product quality. Chen (2001) models the trade-off between normal and green quality attributes. Kim and Chhajed (2002) extend the work of Moorthy and Png (1992) on variable cost intensive products to multiple quality dimensions, and find that the results from a one-dimensional model extend for the most part when there is strict vertical differentiation. However, their results of a horizontal product line requires different ranking of quality dimensions for different types of customers, which I do not need in this paper. Weber (2002) considers the case of joint vertical and horizontal differentiation, and finds that with linear utility, linear development cost and uniformly distributed consumers, either pure vertical differentiation (with quality degradation) or pure horizontal differentiation dominates "mixed differentiation" if all products are launched at the same time. In contrast, our model considers non-linear development cost and utility functions and deals primarily with vertically differentiation. Varian (1993) considers two special dimensions of software quality, which he terms ease of use and ease of learning, and finds that a monopolist may have different incentives to provide quality on these dimensions. I show that the approaches advocated by Shapiro and Varian (1998) and John, et al. (1999), quality degradation and value subtraction, can be sub-optimal for development-intensive products. Once the dependence of development costs on product quality is captured, a firm can version on multiple vertical quality dimensions without quality degradation.

Services are gaining increasing importance for the following reasons (Oliva and Kakkenberg 2003). First, there is substantial revenue generated from an installed base of products with a long life cycle (Knecht, et al. 1993). Second, services usually have higher margins than products (Anderson, et al. 1997). Services also provide a more stable source of revenue and are less affected by economic cycle (Quinn 1992). Higher specialization leads to higher degree of interdependence and a higher demand for services. Finally, services are less visible and more labor dependent. Therefore, services are more difficult to imitate and provides relatively sustainable competitive advantage. As a result, firms start to integrate services into their core product offerings (Wise and Baumgartner 1999). As after-sale services gain importance, it is imperative to extend the prior research on the product strategy of pure product companies to firms that offer both products and after-sale services. I am particularly interested in the tensions between the incentives to provide a high quality product and to accrue more revenue through servicing the installed base during a product's life cycle. However, very little literature exists in this area. The most relevant research is in reliability study in engineering literature. For example, the bathtub model is widely used to show the relationship between amount of repair needed and the reliability of the product (Amstadter 1977, Barlow and Savits 1975, Henley and Kumamoto 1981, Mann, et al. 1974, Lamberson and Kapur 1977, Nelson 1982).

Decisions for product and service strategies often involve different companies in the supply chain. Many firms rely on their distribution channels to deliver their products and after-sale services to the installed base. Channel coordination is another relevant area that has been widely studied. Earlier studies show the sources of coordination problems (Tirole 1988, Spengler 1950, Jeuland and Shugan 1983, Moorthy 1987, Gerstner and Hess 1995, Lal 1990, Vernon and Graham 1971). I focus on the different market segmentation strategies of the supply chain partners as in Villas-Boas (1998).

One of the consequences of non-coordination in supply chain is the quality distortion in a product line. In order to induce the retailer to adopt the same market segmentation strategy the supplier has to increase the quality difference between its product line (Villas-Boas 1998). However, I find that the so-called quality distortion is not always happening when after-sale services are included in the firm's decision-making. Specifically the quality distortion in conformance quality dimension is reduced or even reversed. This impact of after-sale services is not only exhibited in substitute services but also in complementary services.

Chapter 3: Modeling Development-Intensive Products (DIPs)

In this chapter, our focus is on a profit-maximizing monopolist using the design of a new development-intensive product to segment a heterogeneous market of vertically differentiated customers. (We consider the case of competitive entry in a later section.) This section describes how the product's quality, market, and customer demand are modeled.

3.1. Model of Product Quality and Cost for Development Intensive Product

We conceptualize product quality as a multidimensional construct with measurable characteristics on more than one dimension that differentiate a firm's product, and for which customers are willing to pay more for higher levels of quality. Specifically in this paper, I consider those "vertical" quality dimensions in which customers agree in their preference ranking of product quality (Abbott 1953). Therefore, quality in our paper can be performance attributes, such as functionality, or even "objective" usability attributes, such as user-friendliness on which customers agree on the ranking of what is higher quality. To bring out the multi-dimensional aspect of quality while keeping the analytical expressions compact, I focus our attention without loss of generality on two major dimensions of quality. This could be interpreted as the aggregation of multiple quality dimensions into two major dimensions, as in Kim and Chhajed (2002). Later, I discuss the extension of our model to more than two dimensions. In two quality dimensions, I model two cases: when dimensions are independent, and second, when they are coupled. I find that the design decisions differ significantly for these two cases.

We model quality as a vector with two dimensions, which I index with subscripts 1 and 2. Quality for product A is $\mathbf{q}_A(q_{A1}, q_{A2})$, where q_{A1} and q_{A2} are the quality levels in dimensions 1 and 2, respectively. As discussed earlier, for development-intensive products, the cost of providing quality consists only of development costs that are independent of the number of units sold. I assume that the development cost is a quadratic function of product quality. Later in this paper, I show that our results hold for a general increasing convex cost function as Ill as a linear-cost function (with a non-linear utility function). The quadratic function, besides being used in the prior literature Motta (1993), is explained by the fact that higher quality is associated with more product components as Ill as more complex components (or an involved product architecture). For instance, in software product development, the costs are usually estimated using the concept of function points (see Albrecht and Gaffney 1983). Function points are a proxy for software scope and almost linear to development cost (Kemerer 1987). They are calculated by multiplying two characteristics both of which are linearly increasing for a greater performance quality product: unadjusted function point (UAF), which is a proxy for component complexity and value adjustment factor (VAF) which reflects the number of components.

The coupling between the quality dimensions can be modeled in a number of ways. I use a *super-modular cost function*, wherein the cost of jointly providing the quality in two dimensions for a coupled product is more than the cost of individually supplying quality in each of the dimensions. For instance, it costs much more to develop a product that simultaneously has both higher performance (features), and higher ease of use than to individually improve along each of these dimensions, as more features contribute to greater complexity of the product. The cost to provide product A with quality $\mathbf{q}_A(q_{A1}, q_{A2})$ is represented in our model as follows:

$$C(q_{A1}, q_{A2}) = c_1 q_{A1}{}^2 + c_2 q_{A2}{}^2 + 2d q_{A1} q_{A2} \qquad (3\text{-}1)$$

Where parameter d ($0 \le d < \sqrt{c_1 c_2}$) is the degree of coupling/supermodularity of the cost function. To make the comparison with the existing literature easier, I use the same quadratic function $c_{vi} q_{Ai}^{\ 2}$ ($i = 1,2$) for variable cost of Marginal-Cost Intensive products, as used by researchers in the prior literature (Mussa and Rosen 1978, Moorthy and Png 1992).

Our conceptualization of product quality differs from and builds on the prior literature in two important ways. In earlier work on variable-cost intensive products, higher quality product implies more/expensive material, or finer workmanship, which is more expensive to produce (Abbott 1953). However, a higher-quality development-intensive product does not incur a higher variable production cost as new product development plays a pivotal role in shaping the quality of DIPs. As I find later in the paper, this simple difference has a variety of implications for managers planning development-intensive products. In the Marketing and Operations literature, product quality is often treated as a one-dimensional variable, much like the tactical variables of price and quantity. This treatment has been adequate for marginal-cost Intensive products, since a single-dimensional model brings out most of the issues. However, I find that the one-dimensional model of quality, while useful to highlight the differences between development and marginal-cost intensive goods, misses many important aspects for DIPs and may lead to the conclusion that design efforts should be focused on the high-end product only. It becomes important to consider more than one quality dimension and the coupling between them for development-intensive products.

3.2. MODEL OF MARKET DEMAND AND CUSTOMER UTILITY

Although customers in the vertically differentiated market agree on the ranking of product quality, they differ in their willingness or ability to pay for quality. This heterogeneity in the market can be characterized by the distribution of consumer type t with density function $d(t)$. A special case is a discrete market consisting of two market segments H and L, within which there are n_H and n_L homogenous consumers, respectively. As in the prior literature on product positioning, I assume without loss of generality that the market is comprised of two discrete market segments (high and low) with differing willingness to pay (WTP) for product quality. Our results are generalized to the case of more than two segments in Appendix A-10.

As in the previous literature on product positioning, the utility derived by each segment and its willingness to pay is assumed to be largely a linear function of product quality. However, a key contribution of our paper is the notion of *saturation and reservation qualities* in the model of customer utility. Specifically, I define *saturation quality* as that level of quality beyond which the customer's willingness to pay for product quality tapers off. For analytical compactness, the customer's marginal willingness to pay is zero beyond its saturation quality. *Reservation quality*, on the other hand, is conceptualized as the level of quality below which a customer (segment) would not even consider buying the product. The customer derives zero utility from a quality level offered below the reservation quality.

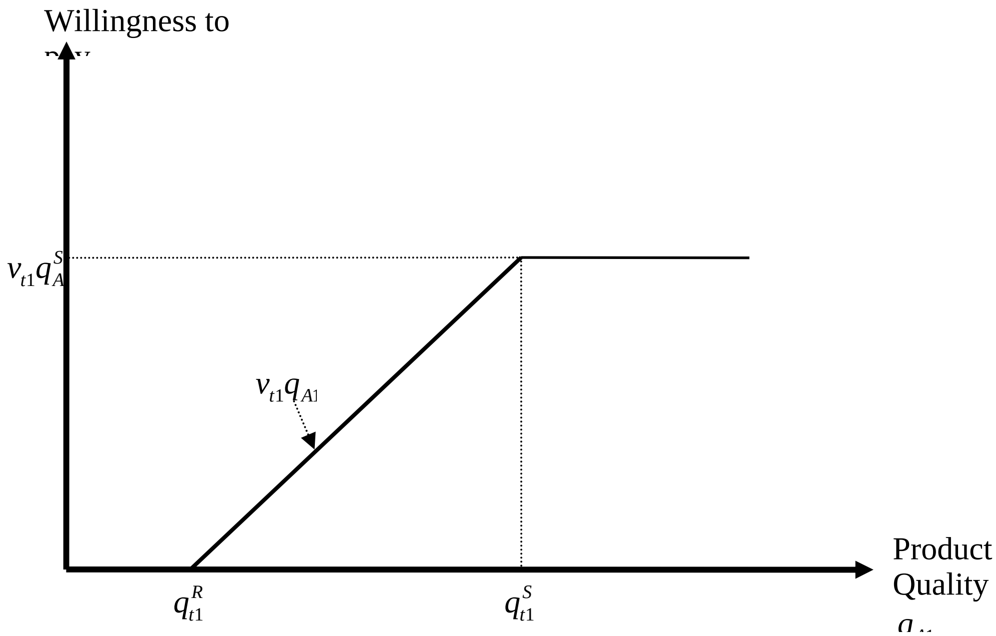
The cumulative willingness to pay of consumer type t for product A with quality $\mathbf{q}_A(q_{A1}, q_{A2})$ is denoted by $U_t(q_{A1}, q_{A2})$, and is a function of consumer t's reservation qualities in the two dimensions (q_{t1}^R and q_{t2}^R), saturation qualities in the two dimensions (q_{t1}^S and q_{t2}^S), and marginal willingness to pay for quality (v_{t1} and v_{t2}), as follows:

$$U_t(q_{A1}, q_{A2}) = \begin{cases} 0 & \text{if } \exists q_{Ai} < q_{Ai}^R,\ i = 1,2. \\ v_{t1}(q_{A1} - q_{t1}^R) + v_{t2}(q_{A2} - q_{t2}^R) & \text{if } q_{Ai} \in [q_{Ai}^R, q_{Ai}^S],\ i = 1,2. \\ v_{ti}q_{ti}^S + v_{tj}(q_{Aj} - q_{tj}^S) & \text{if } q_{Ai} \in (q_{Ai}^S, \infty),\ q_{Aj} \in [q_{Aj}^R, q_{Aj}^S],\ i, j \in \{1,2\} \\ v_{t1}q_{t1}^S + v_{t2}q_{t2}^S & \text{if } q_{Ai} \in (q_{Ai}^S, \infty),\ i = 1,2 \end{cases}$$

(3-2)

From the above willingness to pay function, I can see that consumers are only willing to pay for product with quality level of at least q_{ti}^{R}. They are willing to pay more for quality improvement until quality reaches q_{ti}^{S}, after which they are not willing to pay for any quality improvement (see Figure 1).

Figure 1: WTP $U_t(q_{A1}, q_{A2})$ projection in dimension 1 for type t



For the analysis below, I define high-end customers as those with higher marginal willingness to pay for quality than low-end customers. I assume that high-end customers also have higher saturation quality, and lower reservation quality than low-end customers. Later in the paper, I relax this assumption and consider the case when the high-end customers may have higher reservation quality than the low-end customers. I also assume that once the qualities match or exceed the reservation level, the consumer utility is additive in the different dimensions (similar to the a conjoint analysis treatment of utility in a number of classical papers as Ill as the recent work of Chen 2001 and Kim and Chhajed 2002).

3.3. MODEL FORMULATION

To cover two market segments with a product line, the profit maximizing company either positions and prices a dedicated product for each segment, in which customers will self-select from these two products, or offers a single product. For the two products case, I use the same notation for the market segment and the product designed for it. The company will design a high-end product H with quality $\mathbf{q}_H(q_{H1}, q_{H2})$ and price p_H, and a low-end product L with quality $\mathbf{q}_L(q_{L1}, q_{L2})$ and price p_L. I model the company's optimal product line design as follows:

Product Line

P2-1: $$\prod^{PL} = \max_{q_{H1}, q_{H2}, p_H, q_{L1}, q_{L2}, p_L} n_H(p_H - c_{v1}q_{H1}^2 - c_{v2}q_{H2}^2) - c_1 q_{H1}^2 - c_2 q_{H2}^2 - 2dq_{H1}q_{H2}$$

$$+ n_L(p_L - c_{v1}q_{L1}^2 - c_{v2}q_{L2}^2) - c_1 q_{L1}^2 - c_2 q_{L2}^2 - 2dq_{L1}q_{L2} \quad (3\text{-}3)$$

Subject to:

ICH: $$U_H(q_{H1}, q_{H2}) - U_H \geq U_H(q_{L1}, q_{L2}) - p_L \quad (3\text{-}4)$$

ICL: $$U_L(q_{L1}, q_{L2}) - p_L \geq U_L(q_{H1}, q_{H2}) - p_H \quad (3\text{-}5)$$

IRH: $$U_H(q_{H1}, q_{H2}) - p_H \geq 0 \quad (3\text{-}6)$$

IRL: $$U_L(q_{L1}, q_{L2}) - p_L \geq 0 \quad (3\text{-}7)$$

$$q_{tj}^R \leq q_{tj} \leq q_{tj}^S \text{ for } t \in \{H, L\},\ j \in \{1, 2\} \quad (3\text{-}8)$$

(3-4) and (3-5) are incentive-compatibility constraints that ensure each customer segment will buy only the product designed for them, where $U_t(q_{A1}, q_{A2})$ is as in (3-2). (3-6) and (3-7) are individual-rationality constraints that ensure participation of each of the customer segments.

Independently Optimal Quality

Next, I introduce an important benchmark concept: independently optimal quality (IOQ), sometimes referred in the prior literature as "efficient quality" (Moorthy and Png 1992). IOQ is the quality level a company would offer a customer segment if it Ire the only one targeted, unconstrained by cannibalization from other segments, and reservation or saturation qualities. Solving the maximization problem (3-3) with only the individual-rationality constraints (3-6) and (3-7), I get the IOQ for the two segments as follows (superscript IOQ used for independently optimal quality):

$$q_{H1}^{I} = \frac{n_H[v_{H1}(c_2 + c_{v2}n_H) - dv_{H2}]}{2(c_1 + c_{v1}n_H)(c_2 + c_{v2}n_H) - 2d^2} \tag{3-9}$$

$$q_{H2}^{I} = \frac{n_H[v_{H2}(c_1 + c_{v1}n_H) - dv_{H1}]}{2(c_1 + c_{v1}n_H)(c_2 + c_{v2}n_H) - 2d^2} \tag{3-10}$$

$$q_{L1}^{I} = \frac{n_L[v_{L1}(c_2 + c_{v2}n_L) - dv_{L2}]}{2(c_1 + c_{v1}n_L)(c_2 + c_{v2}n_L) - 2d^2} \tag{3-11}$$

$$q_{L2}^{I} = \frac{n_L[v_{L2}(c_1 + c_{v1}n_L) - dv_{L1}]}{2(c_1 + c_{v1}n_L)(c_2 + c_{v2}n_L) - 2d^2} \tag{3-12}$$

From the above IOQs, I can see when development cost is negligible ($c_i = 0$ and $d = 0$, $i = 1,2$) IOQ is not a function of market size. On the other hand, when variable cost is negligible ($c_{vi} = 0, i = 1,2$) IOQ is in proportion with the market size. Re-writing the expressions for MIP's and DIP's, I have:

Marginal-Cost Intensive Products ($c_i = 0$, $d = 0$)	Development-Intensive Products ($c_{vi} = 0$)
$q_{H1}^{I} = \frac{v_{H1}}{2c_{v1}}$	$q_{H1}^{I} = \frac{n_H(c_2 v_{H1} - dv_{H2})}{2c_1c_2 - 2d^2}$

$q_{H2}^{I}=\frac{v_{H2}}{2c_{v2}}$	$q_{H2}^{I}=\frac{n_H(c_1v_{H2}-dv_{H1})}{2c_1c_2-2d^2}$
$q_{L1}^{I}=\frac{v_{L1}}{2c_{v1}}$	$q_{L1}^{I}=\frac{n_L(c_2v_{L1}-dv_{L2})}{2c_1c_2-2d^2}$
$q_{L2}^{I}=\frac{v_{L2}}{2c_{v2}}$	$q_{L2}^{I}=\frac{n_L(c_1v_{L2}-dv_{L1})}{2c_1c_2-2d^2}$

Lemma 1: Independently optimal quality for development-intensive products is proportional to the size of the market segment.

Proof: The firm's IOQ problem in the high-end market segment is formulated as follows:

F1-1 $$\Pi^{IOQ}=\max_{q_{H1},q_{H2},p_H} n_H(p_H-c_{v1}q_{H1}{}^2-c_{v2}q_{H2}{}^2)-c_1q_{H1}{}^2-c_2q_{H2}{}^2-2dq_{H1}q_{H2} \quad (3\text{-}13)$$

Subject to:

$$v_{H1}q_{H1}+v_{H2}q_{H2}-p_H\geq 0 \quad (3\text{-}14)$$

We use (3-14) to substitute qualities for price in (3-13). From first order conditions (FOC) I have optimal qualities as follows:

$$q_{H1}^{I}=\frac{n_H[v_{H1}(c_2+c_{v2}n_H)-dv_{H2}]}{2(c_1+c_{v1}n_H)(c_2+c_{v2}n_H)-2d^2} \quad (3\text{-}15)$$

$$q_{H2}^{I}=\frac{n_H[v_{H2}(c_1+c_{v1}n_H)-dv_{H1}]}{2(c_1+c_{v1}n_H)(c_2+c_{v2}n_H)-2d^2} \quad (3\text{-}16)$$

For DIPs, the IOQ can be derived from the above by setting $c_{vi}=0$, $i=1,2$:

$$q_{H1}^{I}=\frac{n_H(c_2v_{H1}-dv_{H2})}{2c_1c_2-2d^2} \quad (3\text{-}17)$$

$$q_{H2}^{I}=\frac{n_H(c_1v_{H2}-dv_{H1})}{2c_1c_2-2d^2} \quad (3\text{-}18)$$

For MIPs, the IOQs can be derived by setting $c=0$ and $d=0$.

In a similar fashion, I can derive the IOQs for the low-valuation market segment, details are omitted.

The above lemma is a significant reason why planning a line of development-intensive products is different from that of planning a line of Marginal-Cost Intensive products. Quite simply, it suggests that the independently optimal low-end product may not always be a subset of or inferior to the high-end product (independently optimal low-end quality may be equal or even be better than that of the high-end segment, if the size of the low-end segment is significantly larger than that of the high-end segment). This result is due to the lack of variable costs for DIP's, and can never be the case for Marginal-Cost Intensive products, because their independently optimal quality is only a function of the willingness to pay of each of the segments (independent of segment sizes).

Conceptualizing a Product Line and Inter-Product Relationships

Because the low-end development-intensive product may not always be an inferior version of the high-end product, I need new terminology to describe a product line. When the optimal quality of the low-end product is strictly below the high-end product optimal quality ($q_{H1}* > q_{L1}*$ and $q_{H2}* > q_{L2}*$), I term this a *subsumed product line* (SPL). When a feasible product line is not subsumed (either $q_{H1}* \leq q_{L1}*$ or $q_{H2}* \leq q_{L2}*$), I call the product line an *overlapped product line* (OPL). If a particular market segment receives a product quality that is below its independently optimal quality, it is said to have experienced (and the firm is said to practice) *quality degradation*. For instance, the low-end segment faces "quality degradation" if $q_{L1}* \leq q_{L1}^{I}$ or $q_{L2}* \leq q_{L2}^{I}$. As I see in the next section, the absence of quality degradation is an important distinguishing characteristic of DIPs.

Multi-Segment (Standard) Product

As alternatives to the product line, a company may design a standard product with quality $\mathbf{q}_S(q_{S1}, q_{S2})$ for both segments. The firm's standard-product problem is as follows:

$$\text{P2-2: } \prod^{STD} = \max_{p_S, q_{S1}, q_{S2}} (p_S - c_{v1}q_{S1}{}^2 - c_{v2}q_{S2}{}^2)(n_H + n_L) - c_1 q_{S1}{}^2 - c_2 q_{S2}{}^2 - dq_{S1}q_{S2} \tag{3-19}$$

Subject to:

$$U_L(q_{S1}, q_{S2}) - p_S \geq 0 \tag{3-20}$$

$$q_{Sj}^R \leq q_{Sj} \leq q_{Sj}^S \text{ for } j \in \{1, 2\} \tag{3-21}$$

We solve this problem and compare it with a product line in later sections.

Single Segment (Niche) Product Solution

A firm can adopt niche-product approach to concentrate only on one segment, ignoring the other one. However, the firm will not use niche-product strategy for the low-end segment, as the high-end customers will then buy the low-end product. Therefore, when the company uses the niche-product strategy, it will only serve the high-end segment. Moorthy and Png (1992) show that a firm will adopt the niche-product strategy for marginal-cost Intensive products only when the market cannibalization is high. The condition for the dominance of the niche-product approach is the same for both development and marginal-cost Intensive product (high levels of cannibalization, see Moorthy and Png 1992), so I will not discuss niche-product approach in detail in the rest of the paper.

3.4. UNIQUENESS OF DEVELOPMENT-INTENSIVE PRODUCTS: SINGLE QUALITY DIMENSION

In this subsection, I consider the single-dimensional quality case to bring out the uniqueness of product family design for development-intensive products. The fact that the independently optimal quality for DIP's is a function of the size of the market segment has several surprising implications for product line optimality.

Designing development-intensive product line in single quality dimension

Studying the single quality dimension case is useful for two reasons. First, analytical expressions available are particularly compact, and easy to interpret. Second, prior work has studied the same single dimensional quality case for MIP's, making comparisons easier across the two classes of products. This line of work for MIP's (with negligible development costs and no reservation or saturation qualities) has shown two important results. First, to manage cannibalization, a monopolist's optimal product line contains a quality-degraded low-end product (the low-end product quality falls below the independently optimal quality). Second, it is never optimal to offer a multi-segment (standard) product, because its profit is always lower than that of the quality-degraded product line or the high-end niche (premium) product. Moorthy and Png (1992) introduced the parameter $R = n_H / n_L (v_H / v_L - 1)$ to describe cannibalization, that helps make the analytical expression simpler and more easily comparable. To make a head-to-head comparison with the results for Marginal-Cost Intensive products, I also assume in this section, for the most part, that reservation and saturation effects are absent. Appendix A-2 contains the revised formulation for a DIP along a single quality dimension. The optimal qualities for the high-end and low-end DIP (not impacted by saturation) are as follows:

$$q_H{}^* = \frac{n_H v_H}{2c} \tag{3-22}$$

$$q_L{}^* = \frac{(n_H + n_L)v_L - n_H v_H}{2c} = \frac{n_L v_L (1-R)}{2c} \tag{3-23}$$

The company's multi-segment standard-product quality is as follows:

$$q_S{}^* = \frac{(n_H + n_L)v_L}{2c} \tag{3-24}$$

Once again, the optimal quality for a development-intensive product is proportional to its market segment size. As shown in Appendix A-2, the standard multi-segment product will have higher quality than high-end product, whenever a product line is feasible.

Proposition 1: In *a single quality dimension, a single product that pools both segments is more profitable than a product line when saturation constraints are not active.*

Proof: The firm's product-line problem along a single quality dimension is formulated as follows (in absence of saturation effects and with reservation quality setting to zero):

F2-1:

$$\Pi^{PL} = \max_{q_H, p_H, q_L, p_L} n_H p_H + n_L p_L - c q_H{}^2 - c q_L{}^2 \tag{3-25}$$

Subject to:

$$v_H q_H - p_H \geq v_H q_L - p_L \tag{3-26}$$

$$v_L q_L - p_L \geq v_L q_H - p_H \tag{3-27}$$

$$v_H q_H - p_H \geq 0 \tag{3-28}$$

$$v_L q_L - p_L \geq 0 \tag{3-29}$$

The firm's multi-segment standard product decision and niche product decision are formulated as F2-2 and F2-3, respectively:

F2-2:

$$\Pi^{STD} = \max_{q_S, p_S} (n_H + n_L) p_S - c q_S{}^2 \tag{3-30}$$

Subject to: $$v_L q_S - p_S \geq 0 \quad (3\text{-}31)$$

F2-3: $$\prod^{NC} = \max_{q_N, p_N} n_H p_N - c q_N^{\;2} \quad (3\text{-}32)$$

Subject to: $$v_H q_N - p_N \geq 0 \quad (3\text{-}33)$$

By FOC the optimal quality offerings are as follows:

$$q_H * = q_N * = \frac{n_H v_H}{2c} \quad (3\text{-}34)$$

$$q_L * = \frac{n_L v_L (1-R)}{2c} \quad (3\text{-}35)$$

$$q_S * = \frac{(n_H + n_L) v_L}{2c} \quad (3\text{-}36)$$

where $R = (n_H / n_L)(v_H / v_L - 1)$. It is easy to see that $q_S * = q_H * + q_L *$. When $R > 1$, product-line is not feasible, and is reduced to a niche-product. The profits of standard-product and product-line approaches and their profit difference are as follows:

$$\prod^{STD} = \frac{(n_L + n_H)^2 v_L^{\;2}}{4c} = c q_S *^2 \quad (3\text{-}37)$$

$$\prod^{PL} = \frac{n_H^{\;2} v_H^{\;2}}{4c} + \frac{n_L^{\;2} v_L^{\;2} (1-R)^2}{4c} = c(q_H *^2 + q_L *^2) \quad (3\text{-}38)$$

$$\prod^{STD} - \prod^{PL} = 2c q_H * q_L * \quad (3\text{-}39)$$

Therefore, the standard-product approach dominates when $R \leq 1$. When $R > 1$, the profit difference between standard-product and niche-product approach is as follows:

$$\prod^{STD} - \prod^{NC} = \frac{n_L v_L (1-R)[(n_L + n_H) v_L + n_H v_H]}{4c} < 0$$

The niche-product approach dominates for $R > 1$.

The above result contrasts with the one for marginal-cost intensive products where a multi-segment standard offering is never more profitable than a product line.

Robustness of Single Product Optimality

Next, I will discuss the robustness of proposition 1 under two scenarios: when there are economies of scope in product line development, and when there is saturation in demand. By economies of scope in development, I mean the reduction in the cost of designing a line of development-intensive products (specifically the low-end variant), potentially making a product line more attractive. Some researchers have argued that a derivative low-end product may be easily obtained from a high-end one by switching off features, and this sequence of development and introduction explains the attractiveness of versioning (see Varian 1997, John, et al. 1999). Scope economies could simply reduce the development cost and boost product line profitability. I model economies of scope by a cost reduction factor β associated with the low-end development cost (hence $\beta c q_L^{\,2}$).

Lemma 2: ***Economies of scope do not affect the non-optimality of a product-line for development-intensive products in a two-segment market, even when low-end variant can be derived from the high-end product without incremental development cost.***

Proof: When there are economies of scope in development, I replace the cost function in formulation F2-1 with $cq_H^{\,2} + \beta c q_L^{\,2}$. The profit difference between standard-product approach and product-line approach is as follows:

$$\prod^{STD} - \prod^{PL} = \frac{n_L v_L (1-R)(n_H v_H (1+\beta) - (n_H + n_L) v_L (1-\beta))}{4c\beta} \qquad (3\text{-}40)$$

$q_H > q_L$ leads to $(1+\beta) n_H v_H - (n_H + n_L) v_L > 0$. Therefore, standard-product is more profitable.

Thus, even in the presence of scope economies, a standard multi-segment product enjoys greater profitability than a quality differentiated product line.

For the above analysis, I have assumed that the decisions are unconstrained by customer's tendency to be saturated by increasing quality. What happens when customers (low-end customers especially) are not willing to pay for increasing levels of quality? This limits the attractiveness of the standard multi-segment product and makes a product line more attractive. Specifically, a product line is more profitable than a standard multi-segment product when:

$$q_L^S \le q_S * - \sqrt{2q_H * q_L * - 2q_H * (q_L^R - q_H^R)} \quad (3\text{-}41)$$

Where $q_H *$, $q_L *$ and $q_S *$ are as in A2-10 to A2-12 (Appendix A-2). Note that the phenomenon of customer saturation is an essential reason behind offering a product line along a single quality dimension. (To our knowledge, customer saturation has not been mentioned in the literature as a primary rationale for offering a product line along a single quality dimension.)

Lemma 3: ***With a single quality dimension, a product line will be conditionally more profitable tha***

Proof: With saturation quality binding for standard product, or $q_L^S < (n_H + n_L)v_L / 2c = q_S *$ ($q_S *$ is unconstrained optimal quality for standard product), the profit of standard-product and its difference from product-line approach becomes the following:

$$\prod^{STD} = cq_S *^2 - 2cq_S * q_L^R - c(q_S * - q_L^S)^2 \quad (3\text{-}42)$$

$$\prod^{STD} - \prod^{PL} = 2cq_H * q_L * - 2cq_H * (q_L^R - q_H^R) - c(q_S * - q_L^S)^2 \quad (3\text{-}43)$$

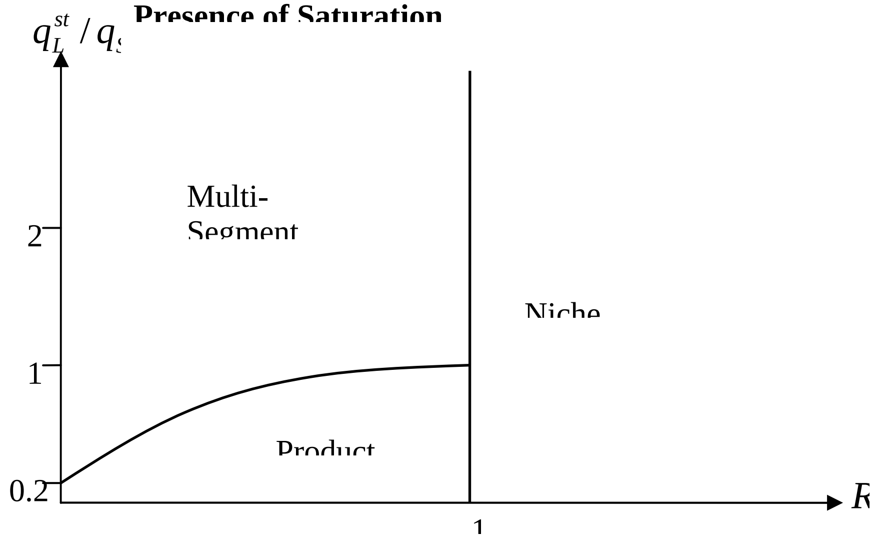
Condition for standard product approach to dominate is as follows:

$$q_L^S \le q_S * - \sqrt{2q_H * q_L * - 2q_H * (q_L^R - q_H^R)} \quad (3\text{-}44)$$

RHS of (3-44) is always positive since $q_S * = q_H * + q_L * \ge 2\sqrt{q_H * q_L *}$, and reservation quality (q_L^R and q_H^R) is relatively small.

Figure 2 shows the regions of optimality of standard multi-segment product, product-line, and niche-product strategy in the presence of saturation quality effects and market cannibalization (we use parameters: $n_H = 200$, $v_H = 4$, $v_L = 2$, $q_H^R = q_L^R = 0$, $c = 20$). As seen in figure 2, low-end customers' tendency to saturate with higher levels of quality makes a product line approach optimal for a limited set of situations.

Figure 2: Optimal Product Choice In the Presence of Saturation



3.5. PRODUCT LINE DESIGN IN TWO QUALITY DIMENSIONS

In last subsection I use a single-dimensional quality model to demonstrate the unique properties of development-intensive products. The key finding is that a firm must consolidate its development efforts to design a single product (either a multi-segment standard product or a high-end niche product) with higher quality in the absence of saturation effects. However, the limitation of this model becomes apparent when I try to reconcile with the product-line practice for DIPs. Many firms offer product lines far more widely than is explained by this single dimensional model and by other authors such as Bhargava and Choudary (2001). In this section, I present a more nuanced model that examines product lines in two quality dimensions. I continue our focus on the vertically differentiated market, with customers agreeing on the ranking of product quality along each quality dimension. However, multiple quality dimensions present significant analytical complexity due to the coupling between the dimensions on the cost side and the differing relative preference of the two market segments for the different quality dimensions[3]. I provide necessary and sufficient conditions for product line optimality in this section.

With the high-end and low-end segments indexed *H* and *L*, and the two quality dimensions indexed 1 and 2, the willingness to pay of the two segments in a vertically differentiated market satisfies the following condition: $v_{H1} > v_{L1}$, $v_{H2} > v_{L2}$. For

[3] While customers agree on the ranking of overall quality for a product ($v_{H1} > v_{L1}$, $v_{H2} > v_{L2}$), they need not agree on the relative ranking of the two quality dimensions; it is possible for one customer segment to value the first quality dimension more and the other segment to value the second quality dimension, i.e. $v_{H1} > v_{H2}$ but $v_{L2} > v_{L1}$. This would correspond to the high-end segment placing a greater emphasis on the performance dimension and the low-end segment valuing the ease of use dimension more.

notational convenience, I refer to quality dimension 1 as the one with $v_{H1}/v_{L1} > v_{H2}/v_{L2}$. Defining non-dimensional parameter $R_i = \frac{n_H}{n_L}(\frac{v_{Hi}}{v_{Li}} - 1)$, $i = 1, 2$, I have: $R_1 > R_2$.

Necessary Conditions for Product Line Optimality in Two Quality Dimensions

When none of the reservation and/or saturation constraints are binding at the optimal solution, the optimal standard product quality equals the sum of high and low-end product for development-intensive products (refer Appendix A-3). As in the case of a single quality dimension, the single product solution tends to be very attractive to the profit-maximizing firm. I show in the appendix that the product line offers greater profits only when the high-end reservation quality is greater than the low-end reservation quality.

Proposition 2: ***With two quality dimensions, a necessary condition for product line profitability to exceed single product profits is that reservation or saturation constraints be binding or the high-end customer's reservation quality be greater than the low-end reservation quality.***

Proof: The firm's product line and standard product problems, modeled as F4-1 and F4-2, are as follows:

F4-1: $$\prod^{PL} = \max_{q_{H1}, q_{H2}, q_{L1}, q_{L2}, p_H, p_L} n_H p_H + n_L p_L - c_1 q_{H1}^2 - c_2 q_{H2}^2 - 2d q_{H1} q_{H2} - c_1 q_{L1}^2 - c_2 q_{L2}^2 - 2d q_{L1} q_{L2} \tag{3-45}$$

Subject to:

$$v_{H1}(q_{H1} - q_{H1}^R) + v_{H2}(q_{H2} - q_{H2}^R) - p_H \geq v_{H1}(q_{L1} - q_{H1}^R) + v_{H2}(q_{L2} - q_{H2}^R) - p_L \tag{3-46}$$

$$v_{L1}(q_{L1} - q_{L1}^R) + v_{L2}(q_{L2} - q_{L2}^R) - p_L \geq v_{L1}(q_{H1} - q_{L1}^R) + v_{L2}(q_{H2} - q_{L2}^R) - p_H \tag{3-48}$$

$$v_{H1}(q_{H1} - q_{H1}^R) + v_{H2}(q_{H2} - q_{H2}^R) - p_H \geq 0 \tag{3-49}$$

$$v_{L1}(q_{L1}-q_{L1}^R)+v_{L2}(q_{L2}-q_{L2}^R)-p_L \geq 0 \quad (3\text{-}50)$$

$$q_{ij} \geq q_{ij}^R,\ i=H,L;\ j=1,2 \quad (3\text{-}51)$$

$$q_{ij}^S \geq q_{ij},\ i=H,L;\ j=1,2 \quad (3\text{-}52)$$

F4-2:

$$\Pi^{STD}=\max_{q_{S1},q_{S2},p_S}(n_H+n_L)p_S-c_1q_{S1}^2-c_2q_{S2}^2-2dq_{S1}q_{S2} \quad (3\text{-}53)$$

Subject to:

$$v_{L1}(q_{S1}-q_{L1}^R)+v_{L2}(q_{S2}-q_{L2}^R)-p_S \geq 0 \quad (3\text{-}54)$$

$$q_{Sj} \geq q_{Lj}^R,\ j=1,2 \quad (3\text{-}55)$$

$$q_{Lj}^S \geq q_{Sj},\ \ j=1,2 \quad (3\text{-}56)$$

The following conditions hold from the problem formulation in the body of the paper:

Because I consider a vertically differentiated market, I have $v_{H1}>v_{L1},\ v_{H2}>v_{L2}$.

$d<\sqrt{c_1c_2}$.

For notational convenience, I refer to quality dimension 1 as the one with $v_{H1}/v_{L1}>v_{H2}/v_{L2}$. Defining $R_i=n_H/n_L(v_{Hi}/v_{Li}-1)$, $i=1,2$, I have $R_1>R_2$.

When none of the reservation and saturation constraints (A8-6, A8-7, A8-10, and A8-11) are binding, the optimal "*unconstrained qualities*" for problems F4-1 and F4-2 are as follows:

$$q_{H1}*=\frac{n_H(c_2v_{H1}-dv_{H2})}{2(c_1c_2-d^2)} \quad (3\text{-}57)$$

$$q_{H2}*=\frac{n_H(c_1v_{H2}-dv_{H1})}{2(c_1c_2-d^2)} \quad (3\text{-}58)$$

$$q_{L1}*=\frac{c_2n_Lv_{L1}(1-R_1)-dn_Lv_{L2}(1-R_2]}{2(c_1c_2-d^2)} \quad (3\text{-}59)$$

$$q_{L2}* = \frac{c_1 n_L v_{L2}(1-R_2) - d n_L v_{L1}(1-R_1)}{2(c_1 c_2 - d^2)} \tag{3-60}$$

$$q_{S1}* = \frac{(n_H + n_L)(c_2 v_{L1} - d v_{L2})}{2(c_1 c_2 - d^2)} \tag{3-61}$$

$$q_{S2}* = \frac{(n_H + n_L)(c_1 v_{L2} - d v_{L1})}{2(c_1 c_2 - d^2)} \tag{3-62}$$

A necessary condition for product line optimality is that reservation and/or saturation constraints must bind or low-end optimal quality must be higher than high-end reservation quality.

When none of the reservation or saturation constraints bind and the high-end customers' optimal quality is lower than the low-end customers' reservation quality, the optimal profit for standard-product and product-line approaches (using A8-12 to A8-17) are as follows:

$$\prod^{STD} = \frac{(n_L + n_H)^2[(c_2 v_{L1}{}^2 + c_1 v_{L2}{}^2) - 2d v_{L1} v_{L2}]}{4(c_1 c_2 - d^2)} - (n_L + n_H)(v_{L1} q_{L1}^R + v_{L2} q_{L2}^R) \tag{3-63}$$

$$\prod^{PL} = \frac{n_H{}^2[(c_2 v_{H1}{}^2 + c_1 v_{H2}{}^2) - 2d v_{H1} v_{H2}]}{4(c_1 c_2 - d^2)}$$

$$+ \frac{n_L{}^2 v_{L1}{}^2 (1-R_1)^2 + c_1 n_L{}^2 v_{L2}{}^2 (1-R_2)^2}{4(c_1 c_2 - d^2)} - \frac{2d n_L{}^2 v_{L1} v_{L2}(1-R_1)(1-R_2)}{4(c_1 c_2 - d^2)}$$

$$+ n_H [v_{H1}(q_{L1}^R - q_{H1}^R) + v_{H2}(q_{L2}^R - q_{H2}^R)] - (n_L + n_H)(v_{L1} q_{L1}^R + v_{L2} q_{L2}^R) \tag{3-64}$$

The difference of optimal profit between standard-product and product-line approaches is as follows:

$$\prod^{STD} - \prod^{PL} == n_H (v_{H1} q_{L1} * + v_{H2} q_{L2} *) + n_H [v_{H1}(q_{L1}^R - q_{H1}^R) + v_{H2}(q_{L2}^R - q_{H2}^R)] \tag{3-65}$$

When the high-end customers' reservation quality q_{Hi}^{R} $(i=1,2)$ are below the low-end customer's reservation quality q_{Li}^{R}, the above profit difference is always positive and the standard product approach is always more profitable than the product line solution.

Therefore, a necessary condition for product line to dominate the standard product solution is that either the reservation or saturation constraints bind or the high-end customers' reservation quality be greater than the low-valuation customers' reservation quality.

The intuition of the proof is as follows. High reservation qualities for the high-end customer reduce the cannibalization between the customer segments, making the product line solution more attractive. Binding saturation quality constraints limit the quality and profits of the standard product solution. When none of the reservation or saturation constraints bind and the high-end customers' reservation quality is below the low-end customers' reservation quality, I find that the profit from the single product solution far exceeds the profitability of the product line solution.

High reservation qualities for the high-end customer correspond to a trivial reason for product line optimality. I now derive sufficient conditions for product line optimality for the case when the high-end reservation quality is below the low-end reservation quality (specifically with reservation qualities binding at the optimal solution). Two special cases arise corresponding to whether the coupling between the quality dimensions is low or high.

Independent quality dimensions (Low to No Coupling)

We term the quality dimensions "independent" if they are independently additive from both the customers' utility and the firm's cost sides. For instance, when the different quality dimensions correspond to different features of a software product, they maybe viewed as independent, since modern software engineering makes feature modularity a recommended practice. For independent quality dimensions, I solve the firm's product-line strategy from P2-1 using a quadratic cost function $c_1 q_{A1}{}^2 + c_2 q_{A2}{}^2$ for product quality $\mathbf{q}_A(q_{A1}, q_{A2})$, setting the parameter *d* and all variable costs to zero.

A key result in the analysis of two or more independent quality dimensions is that a product line can dominate the standard multi-product solution even in the absence of saturation effects. Conditions are provided in Appendix A-3 to show that when the difference in willingness to pay between the two segments is high for one of the quality dimensions ($R_1 >> 1$), product-line enjoys greater profitability than the single product options. This result holds even for the case when the coupling between quality dimensions is low, but not zero. The optimal product line is subsumed, with the low-end being inferior to the high-end product on both quality dimensions. These results may be combined into a single proposition for independent quality dimensions that contrasts the case of a single quality dimension.

Proposition 3: ***With two independent dimensions of quality ($d = 0$), the optimal product line profit exceeds single product profit when $v_{H1} / v_{L1} \geq \underline{v_1}$ and $\overline{v_2} > v_{H2} / v_{L2} > \underline{v_2}$, where $\underline{v_1}$, $\underline{v_2}$, and $\overline{v_2}$ are given in Appendix A-3; The optimal product line is subsumed.***

With low coupling, the sufficient condition for product line approach to be more profitable is $d < \overline{d}$ and $v_{H1} / v_{L1} \geq \underline{\underline{v_1}}$, where $\overline{d}$ and $\underline{\underline{v_1}}$ are defined as below.

Proof: I show that when the sufficient condition in proposition 3 is satisfied ($\overline{v_2} > v_{H2} / v_{L2} > \underline{v_2}$ and $v_{H1} / v_{L1} \geq \underline{v_1}$), two of the qualities $q_{S1}*$ and $q_{L1}*$ will be driven to reservation level while all the other qualities remain above reservation level, and product line profitability exceeds standard product and niche product approaches.

First, from (3-60) I can rewrite $q_{L2}* > q_{L2}^R$ as follows:

$$\frac{v_{H2}}{v_{L2}} < 1 + (1 - \frac{q_{L2}^R}{q_{L2}^I})\frac{n_L}{n_H} \tag{3-66}$$

Where $q_{L2}^I = n_L v_{L2} / 2c_2$. (3-66) also makes $q_{S2}* > q_{L2}^R$ since $q_{S2}* > q_{L2}*$ (it is easy to see from (3-60) and (3-62)). From (3-57) and (3-61) I combine the expression of $q_{S1} < q_{L1}^R$ (q_{S1} is the unbounded optimal solution) and $q_{H1}^I > q_{H1}^R$ to derive the following condition:

$$\frac{v_{H1}}{v_{L1}} \geq (1 + \frac{n_L}{n_H})\frac{q_{H1}^R}{q_{L1}^R} \tag{3-67}$$

(3-67) also makes $q_{L1} < q_{L1}^R$ since $q_{L1} < q_{S1}$ (again q_{L1} is unbounded optimal solution).

We assume that $q_{Hi}^I > q_{Hi}^R$ for $i \in \{1,2\}$ so that it is feasible to provide optimal products. Therefore, (3-66) and (3-67) drive only $q_{S1}*$ and $q_{L1}*$ to reservation level.

Next, I show when only $q_{S1}*$ and $q_{L1}*$ are set at reservation levels under what condition the profit of product line approach will exceed standard product approach. The profit expression from each approach is as follows:

$$\prod^{PL} = \frac{n_L{}^2 v_{L2}{}^2 (1-R_2)^2}{4c_2} + \frac{n_H{}^2 (c_2 v_{H1}{}^2 + c_1 v_{H2}{}^2)}{4c_1 c_2} - n_H(v_{H1}q_{H1}^R + v_{H2}q_{H2}^R) - c_1(q_{L1}^R)^2 - n_H v_{H2} q_{L2}^R \tag{3-68}$$

$$\prod^{STD} = \frac{(n_L + n_H)^2 v_{L2}{}^2}{4c_2} - (n_H + n_L)v_{L2}q_{L2}^R - c_1(q_{L1}^R)^2 \tag{3-69}$$

The profit difference between standard product approach and product line approach becomes:

$$\prod^{PL} - \prod^{STD} = n_H[c_2 n_H v_{H1}{}^2 - 2c_1 n_L v_{L2} v_{H2}(1-R_2)]/4c_1c_2 + n_H(v_{H2}(q_{L2}^R - q_{H2}^R) - v_{H1}q_{H1}^R) \tag{3-70}$$

The condition for (3-70) to be positive is as follows (we use the definition $R_2 = (n_H / n_L)(v_{H2} / v_{L2} - 1)$):

$$\frac{v_{H2}}{v_{L2}} > 1 + \frac{n_L}{n_H}[1 - \frac{c_2 n_H v_{H1}{}^2 - 4c_1 c_2 (v_{H1} q_{H1}^R - v_{H2}(q_{L2}^R - q_{H2}^R))}{2c_1 n_L v_{L2} v_{H2}}] \qquad (3\text{-}71)$$

The niche product approach offers the firm the following profit:

$$\prod^{NP} = \frac{n_H{}^2 (c_2 v_{H1}{}^2 + c_1 v_{H2}{}^2)}{4c_1 c_2} - n_H (v_{H1} q_{H1}^R + v_{H2} q_{H2}^R) \qquad (3\text{-}72)$$

The profit difference between product line approach and niche product approach is as follows:

$$\prod^{PL} - \prod^{NP} = \frac{[n_L v_{L2}(1 - R_2)]^2}{4c_2} - c_1 (q_{L1}^R)^2 + n_H v_{H2} q_{H2}^R - (n_H + n_L) v_{L2} q_{L2}^R \qquad (3\text{-}73)$$

(3-73) is positive when the following condition holds:

$$\frac{v_{H2}}{v_{L2}} < 1 + \frac{n_L}{n_H}[1 - \frac{2\sqrt{c_1 c_2 (q_{H1}^R)^2 + (n_H + n_L) v_{L2} q_{L2}^R - n_H v_{H2} q_{H2}^R}}{c_1 n_L v_{L2}}] \qquad (3\text{-}74)$$

Finally I define $\overline{v_2}$ from the condition (3-74) and (3-66) as follows:

$$\overline{v_2} = \min\{1 + \frac{n_L}{n_H}[1 - \frac{2\sqrt{c_1 c_2 (q_{H1}^R)^2 + (n_H + n_L) v_{L2} q_{L2}^R - n_H v_{H2} q_{H2}^R}}{c_1 n_L v_{L2}}], 1 + (1 - \frac{q_{L2}^R}{q_{L2}^I}) \frac{n_L}{n_H}\}$$

(3-75)

We also define the following bounds from (3-67) and (3-71):

$$\underline{v_1} = (1 + \frac{n_L}{n_H}) \frac{q_{H1}^R}{q_{L1}^R} \qquad (3\text{-}76)$$

$$\underline{v_2} = 1 + \frac{n_L}{n_H}[1 - \frac{c_2 n_H v_{H1}{}^2 - 4c_1 c_2 (v_{H1} q_{H1}^R - v_{H2}(q_{L2}^R - q_{H2}^R))}{2c_1 n_L v_{L2} v_{H2}}] \qquad (3\text{-}77)$$

Therefore, when $\overline{v_2} > v_{H2} / v_{L2} > \underline{v_2}$ and $v_{H1} / v_{L1} \geq \underline{v_1}$ the profit of product line approach exceeds the other single product approaches. Notice that when reservation quality is relatively small, this condition is feasible.

Conditions for product line approach to be more profitable than the other approaches can also be derived for low coupling case in a similar fashion to the above proof. For simplicity, I show the conditions with all reservation quality levels set to zero. The first condition is $d < \overline{d}$, and $\overline{d}$ is defined as follows:

$$\overline{d} = \min\{\frac{v_{H1}c_2}{v_{H2}}, \frac{v_{H2}c_1}{v_{H1}}, \frac{v_{L1}c_2}{v_{L2}}, \frac{v_{L2}c_1}{v_{L1}}, \frac{v_{L2}(1-R_2)c_1}{v_{L1}(1-R_1)}\} \tag{3-78}$$

(3-78) and $v_{H1} / v_{L1} \geq \underline{\underline{v_{1-1}}}$ drives only $q_{L1}*$ to reservation level, where v_{1-1} is as follows:

$$\underline{\underline{v_{1-1}}} = 1 + \frac{n_L}{n_H}\{1 - \frac{c_1 v_{L2}(1-R_2)}{c_2 v_{L1}}\} \tag{3-79}$$

Next I compare the profit between product line approach ($\prod^{PL}$) and standard product approach ($\prod^{STD}$), the condition for $\prod^{PL} \geq \prod^{STD}$ is $v_{H1} / v_{L1} \geq \underline{\underline{v_{1-2}}}$, where $\underline{\underline{v_{1-2}}}$ is as follows:

$$\underline{\underline{v_{1-2}}} = 1 + \frac{n_L}{n_H}\{1 - \frac{\Delta_1 - \Delta_2 + c_1 c_2[(n_H + n_L)v_{L2} + n_H v_{H2}]n_L v_{L2}(1-R_2)}{c_2{}^2[(n_H + n_L)v_{L1} + n_H v_{H1}]n_L v_{L1}}\} \tag{3-80}$$

Where

$$\Delta_1 = \frac{(c_1c_2 - d^2)(q_{L1}^R)^2 + c_2 n_H[(v_{H1} + v_{H2})q_{H1}^R - v_{H2}q_{L2}^R] - c_2(n_H + n_L)v_{L1}q_{L1}^R + dq_{L1}^R n_L v_{L2}(1-R_2)}{c_2}$$

and $\Delta_2 = 2c_2 d[v_{L1}v_{L2}(n_H + n_L)^2 - v_{H1}v_{H2}n_H{}^2] + [n_L v_{L2}(1-R_2)]^2(c_1c_2 - d^2)$. It is easy to verify that product line approach is always more profitable than niche product approach in this case. Therefore, condition $d < \overline{d}$ and $v_{H1} / v_{L1} \geq \underline{\underline{v_1}}$ make product line approach more profitable, where $\underline{\underline{v_1}}$ is defined below:

$$\underline{\underline{v_1}} = \max\{\underline{\underline{v_{1-1}}}, \underline{\underline{v_{1-2}}}\} \quad (3\text{-}81)$$

The intuition is as follows. When the coupling between the quality dimensions is zero or low, one of the dimensions is driven to reservation (or minimum level) quality when the willingness to pay of the low-end segment is significantly below that of the high-end segment. The reduced cannibalization ensuing from the low-end product being reduced to reservation quality along one dimension makes the product line attractive enough to have greater profitability than a standard single-product solution. However, the sufficient conditions ensure that only one of the dimensions is driven to reservation quality, otherwise when both dimensions are driven to reservation quality for the low-end segment, then a single segment (niche or high-end) product solution becomes dominant (it does not involve the cost of a second low-end product that a product line entails).

Coupled dimensions of quality (High coupling case)

Improvements in different dimensions of quality are often coupled and even traded-off in design. For example, adding more features in software usually increases its complexity and reduces its ease of use. There are different ways to model such coupled/conflicting quality dimensions. The simple approach is to assume that quality improvement in one dimension will always hurt the quality in the other dimension: $q_{t1} + q_{t2} = 1 \quad t \in \{H, L\}$, as in Chen (2001). Clearly, such a model of coupling is likely to move the two products in diagonally opposite directions along the two quality dimensions. However, this treatment of conflicting quality dimensions yields corner-point solutions and is less interesting. Alternatively, the coupling between the quality dimensions may be captured as a supermodular cost function, $c_1 q_{A1}{}^2 + c_2 q_{A2}{}^2 + 2d q_{A1} q_{A2}$ as in section 2. In this case, an increase in optimal quality in one dimension leads to more than a proportional increase in cost due to the presence of the other quality dimension. I obtain the firm's product-line and standard-product decisions for a DIP by solving P2-1 and P2-2 with variable costs set to zero. The optimal quality offerings in the absence of saturation effects (non-binding saturation constraints) are as follows:

$$q_{H1}* = \max\{q_{H2}^R, \frac{n_H(c_2 v_{H1} - d v_{H2})}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}82)$$

$$q_{H2}* = \max\{q_{H2}^R, \frac{n_H(c_1 v_{H2} - d v_{H1})}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}83)$$

$$q_{L1}* = \max\{q_{L1}^R, \frac{n_L(c_2 v_{L1}(1-R_1) - d v_{L2}(1-R_2))}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}84)$$

$$q_{L2}* = \max\{q_{L2}^R, \frac{n_L(c_1 v_{L2}(1-R_2) - d v_{L1}(1-R_1))}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}85)$$

$$q_{S1}* = \max\{q_{L1}^R, \frac{(n_H + n_L)(c_2 v_{L1} - d v_{L2})}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}86)$$

$$q_{S2}* = \max\{q_{L2}^R, \frac{(n_H + n_L)(c_1 v_{L2} - d v_{L1})}{2(c_1 c_2 - d^2)}\} \quad (3\text{-}87)$$

We show in Appendix A3 that above a minimal level of supermodularity/coupling in the cost function (condition stated in the Proposition below), the optimal approach for the firm would be to offer a product line and the optimal product line is overlapped.

Proposition 4: ***With highly coupled quality dimensions (*** $d > \underline{d}$ ***defined in Appendix A-3), profitability of an optimal product line exceeds a single product solution when:***

$v_{H1}/v_{L1} \geq v_7$ ***and*** $v_5 > v_{H2}/v_{L2} \geq v_4$ ***where*** v_5***,*** v_4***, and*** v_7 ***are defined bellows.***

The optimal product line is overlapped.

Proof: I consider two cases to show that the sufficient conditions above will result in three optimal qualities driven to reservation levels and making the product line more profitable. First, note that the partial derivative of the optimal qualities (expressions (3-82) to (3-87) with respect to d indicates that the first partial derivative is negative when $d = 0$. I see that when d is large and following conditions relating to the discriminant in the expression for partial derivative are satisfied, the unconstrained optimal qualities satisfy certain monotonicity properties.

$q_{H1}*$ is monotone decreasing in d and $q_{H2}*$ conditionally monotone increasing in d when:

$$v_{H1} / v_{H2} - \sqrt{c_1 / c_2} > 0 \tag{3-88}$$

$q_{L1}*$ is monotone decreasing in d and $q_{L2}*$ conditionally monotone increasing in d when:

$$v_{L1} / v_{L2} - \sqrt{c_1 / c_2} > 0 \tag{3-89}$$

$q_{S1}*$ is monotone decreasing in d and $q_{S2}*$ conditionally monotone increasing in d when:

$$v_{L1}(1-R_1) / v_{L2}(1-R_2) - \sqrt{c_1 / c_2} > 0 \tag{3-90}$$

The conditions for monotone increasing are presented below. When the left hand side (LHS) of the above expressions are negative, the opposite direction of monotonicity prevails.

When the LHS of expression (3-88) is positive while the LHS of (3-89) and (3-90) are negative, $q_{H2}*$, $q_{L1}*$ and $q_{S1}*$ are monotone decreasing with d and will be driven to reservation levels when d is large enough. The LHS of expression (3-90) being negative can be rewritten after I substitute for R_1 and R_2 as follows:

$$\frac{v_{H1}}{v_{L1}} \geq v_3 = 1 + \frac{n_L}{n_H} - \frac{\sqrt{c_1}[(n_H + n_L)v_{L2} - n_H v_{H2}]}{n_H v_{L1} \sqrt{c_2}} \tag{3-91}$$

q_{H1}* (from expression (3-92)) is monotone increasing in d when $d_2 \le d \le (c_2 v_{H1} + \sqrt{c_2(c_2 v_{H1}{}^2 - c_1 v_{H2}{}^2})/v_{H2}$, where:

$$d_2 = (c_2 v_{H1} - \sqrt{c_2(c_2 v_{H1}{}^2 - c_1 v_{H2}{}^2})/v_{H2} \qquad (3\text{-}93)$$

The upper bound of d in (3-93) will never bind since the following will be satisfied by definition of d:

$$\frac{c_2 v_{H1} + \sqrt{c_2(c_2 v_{H1}{}^2 - c_1 v_{H2}{}^2}}{v_{H2}} \ge \frac{c_2 v_{H1}}{v_{H2}} > \sqrt{c_1 c_2} > d$$

Similarly, q_{S2}* (from expression (3-87) is monotone increasing in d when $d_3 \le d \le (c_1 v_{L2} + \sqrt{c_1(c_1 v_{L2}{}^2 - c_2 v_{L1}{}^2})/v_{L1}$, where

$$d_3 = (c_1 v_{L2} - \sqrt{c_1(c_1 v_{L2}{}^2 - c_2 v_{L1}{}^2})/v_{L1} \qquad (3\text{-}94)$$

Also, the upper bound of d in (3-94) will never bind because of the definition of d.

q_{L2}* (from expression (3-60) is monotone increasing in d when $d_4 \le d \le [c_2 v_{L1}(1-R_1) + \sqrt{c_2{}^2 v_{L1}{}^2 (1-R_1)^2 - c_1 c_2 v_{L2}{}^2 (1-R_2{}^2}]/v_{L2}(1-R_2)$, where:

$$d_4 = [c_2 v_{L1}(1-R_1) - \sqrt{c_2{}^2 v_{L1}{}^2 (1-R_1)^2 - c_1 c_2 v_{L2}{}^2 (1-R_2{}^2}]/v_{L2}(1-R_2) \qquad (3\text{-}95)$$

Again, the upper bound of d in (3-95) will never bind because of the definition of d.

We solve d from $q^*_{H2} = q^R_{H2}$, $q^*_{S1} = q^R_{S1}$, and $q^*_{L1} = q^R_{L1}$, respectively (see (3-58), (3-59), and (3-61) for optimal qualities).

When $d > d_1$ ($d_1 = \max\{d_2, d_3, \mathrm{d}_4, \arg\{q^*_{H2} = q^R_{H2}\}, \arg\{q^*_{S1} = q^R_{S1}\}, \arg\{q^*_{L1} = q^R_{L1}\}\}$) the optimal qualities are $q_{H1}{*} = n_H v_{H1}/2c_1$, $q_{S2}{*} = (n_H + n_L)v_{L2}/2c_2$, $q_{L2}{*} = [(n_H + n_L)v_{L2} - n_H v_{H2}]/2c_2$, $q_{H2}{*} = q^R_{H2}$, $q_{S1}{*} = q^R_{L1}$, $q_{L1}{*} = q^R_{L1}$.

The profits of the product line approach and the standard product approach are as follows:

$$\prod^{PL} = \frac{[(n_H + n_L)v_{L2} - n_H v_{H2}]^2}{4c_2} + \frac{{n_H}^2 {v_{H1}}^2}{4c_1} + \frac{(d^2 - c^2)(q_{L2}^R)^2 - n_H v_{H1}(cq_{H1}^R + dq_{H2}^R)]}{c_1}$$

$$+ \frac{d^2 (q_{L1}^R)^2 - c^2 (q_{L1}^R)^2 + dn_H v_{H2} q_{L1}^R + cn_H v_{H2} q_{L2}^R - (n_H + n_L)v_{L2}(dq_{L1}^R + cq_{L2}^R)}{c_2} \quad (3\text{-}96)$$

$$\prod^{STD} = \frac{(n_H + n_L)^2 {v_{L2}}^2}{4c_2} + \frac{(d^2 - c^2)(q_{L1}^R)^2 - (n_H + n_L)v_{L2}(dq_{L1}^R + cq_{L2}^R)}{c_2} \quad (3\text{-}97)$$

$$\prod^{STD} - \prod^{PL} = \frac{2c_1 n_H v_{H2}[(n_H + n_L)v_{L2} - n_H v_{H2}] - {n_H}^2 (c_2 {v_{H1}}^2 - c_1 {v_{H2}}^2)}{4c_1 c_2} + \Delta_4 \quad (3\text{-}98)$$

Where $\Delta_4 = c_2 (q_{H2}^R)^2 + n_H (v_{H1} q_{H1}^R - v_{H2} q_{L2}^R) + \frac{dq_{H2}^R (dq_{H2}^R - n_H v_{H1})}{c_1} - \frac{dn_H v_{H2} q_{L1}^R}{c_2}$.

(3-98) is negative when $v_{H2} / v_{L2} \geq v_4$, where v_4 is given as follows:

$$v_4 = 1 + \frac{n_L}{n_H}[1 - \frac{{n_H}^2 (c_2 {v_{H1}}^2 - c_1 {v_{H2}}^2) - 4c_1 c_2 \Delta_4}{2c_1 n_L n_H v_{H2} v_{L2}}] \quad (3\text{-}99)$$

We also need $v_5 > v_{H2} / v_{L2}$ to ensure $q_{L2}*$ is above reservation level, where v_5 is given as follows:

$$v_5 = 1 + \frac{n_L}{n_H}(1 - \frac{c_2 q_{L2}^R}{n_L v_{L2}}) \quad (3\text{-}100)$$

The resulting product line is overlapped: $q_{L2}* > q_{L2}^R > q_{H2}^R = q_{H2}*$, and $q_{H1}* = n_H v_{H1} / 2c_1 > q_{L1}^R$ for any feasible product line.

Note that the condition $v_5 > v_4$ is feasible. I can verify it if I set all reservation qualities to zero and I find $v_5 - v_4 = n_L {n_H}^2 (c_2 {v_{H1}}^2 - c_1 {v_{H2}}^2) / 2c_1 {n_L}^2 v_{H2} v_{L2} > 0$.

To show that $d > d_1$ is feasible. , I show a stronger case by set reservation qualities to zero. $q_{H2}* \le 0$ leads to $d \ge v_{H2}c_1 / v_{H1} < \sqrt{c_1 c_2}$, $q_{S1}* \le 0$ leads to $d > v_{L1}c_1 / v_{L2} < \sqrt{c_1 c_2}$, $q_{L1}* \le 0$ leads to $d > v_{L1}(1-R_1)c_1 / v_{L2}(1-R_2) < \sqrt{c_1 c_2}$.

To sum up the results in case 1, when $d > d_1$, $v_5 > v_{H2} / v_{L2} \ge v_4$, $v_{H1} / v_{H2} > \min\{v_3, \sqrt{c_1 / c_2}\}$, and $v_{L1} / v_{L2} < \sqrt{c_1 / c_2}$ product line approach is more profitable.

Consider case 2 in which LHS of expressions (3-88) and (3-89) are positive while LHS of (3-90) is negative, unconstrained $q_{H2}*$, $q_{L1}*$ and $q_{S2}*$ is monotone decreasing with d. I can show that when d is large enough and when additional conditions given below are satisfied, unconstrained $q_{H1}*$, $q_{L2}*$ and $q_{S1}*$ are monotone increasing with d in a similar manner as shown above.

$q_{H1}*$ is monotone increasing with d when $d_2 \le d \le (c_2 v_{H1} + \sqrt{c_2(c_2 v_{H1}^2 - c_1 v_{H2}^2}) / v_{H2}$, the upper bound of d in this condition will never bind because of the definition of d .

$q_{S1}*$ is monotone increasing with d when $d_6 \le d \le (c_2 v_{L1} + \sqrt{c_2(c_2 v_{L1}^2 - c_1 v_{L2}^2}) / v_{L2}$,

where d_6 is given a follows:

$$d_6 = (c_2 v_{L1} - \sqrt{c_2(c_2 v_{L1}^2 - c_1 v_{L2}^2}) / v_{L2} \tag{3-101}$$

The upper bound of d in (3-101) will never bind because of the definition of d .

$q_{L2}*$ is monotone increasing in d when $d_4 \le d \le [c_2 v_{L1}(1-R_1) + \sqrt{c_2^2 v_{L1}^2 (1-R_1)^2 - c_1 c_2 v_{L2}^2 (1-R_2^2}] / v_{L2}(1-R_2)$ - again the upper bound of d in this condition will never bind because of the definition of d .

Therefore, in case 2 when $d > d_7$, where d_7 is given as follows:

$$d_7 = \max\{d_2,\ d_4, d_6,\ \arg\{\ q_{H2}^* = q_{H2}^R\}, \arg\{q_{S2}^* = q_{S2}^R\}, \arg\{q_{L1}^* = q_{L1}^R\}\} \tag{3-102}$$

$q_{H2}*$, $q_{S2}*$ and $q_{L1}*$ are driven to reservation levels, and the rest of the optimal qualities are

$q_{H1}* = n_H v_{H1}/2c_1$, $q_{S1}* = (n_H + n_L)v_{L1}/2c_1$, $q_{L2}* = [(n_H + n_L)v_{L2} - n_H v_{H2}]/2c_2$.

The profit of product line is the same as (3-96), and standard product in this case is as follows:

$$\prod^{STD} = \frac{(n_H + n_L)^2 v_{L1}{}^2}{4c_1} + \frac{(d^2 - c^2)(q_{L2}^R)^2 - (n_H + n_L)v_{L1}(dq_{L2}^R + cq_{L1}^R)}{c_1} \quad (3\text{-}103)$$

$$\prod^{STD} - \prod^{PL} == \frac{[(n_H + n_L)v_{L1} + n_H v_{H1}]n_L v_{L1}(1 - R_1)}{4c_1} - \frac{[n_L v_{L2}(1 - R_2)]^2}{4c_2} + \Delta_3 \quad (3\text{-}104)$$

Where $\Delta_3 = c_2[(q_{H2}^R)^2 - (q_{L2}^R)^2] + \frac{dq_{L1}^R[n_L v_{L2}(1 - R_2) - dq_{L1}^R]}{c_2} + \frac{d^2[(q_{L2}^R)^2 - (q_{H2}^R)^2]}{c_2}$

$+ \frac{d[n_H v_{H1} q_{H2}^R - (n_H + n_L)v_{L1} q_{L2}^R] + c[q_{H2}^R n_L v_{L2}(1 - R_2) - q_{H1}^R n_L v_{L1}(1 - R_1) + c(q_{L1}^R)^2]}{c_2}$

When $v_{H1}/v_{L1} \geq v_6$ (3-104) will be negative and the product line will be more profitable, where v_6 is given as follows:

$$v_6 = \sqrt{\frac{(n_H + n_L)^2}{n_H{}^2} + \frac{4c_1 c_2 \Delta_3 - c_1[(n_H + n_L)v_{L2} - n_H v_{H2}]^2}{4c_2 n_H{}^2 v_{L1}{}^2}} \quad (3\text{-}105)$$

The resulting product line is overlapped: $q_{L2}* > q_{H2}* = q_{H2}^R$, and I must have $q_{H1}* > q_{L1}* = q_{L1}^R$ for any feasible product line. Similar to case 1, I can show $d \geq d_7$ is feasible.

To sum up the results in case 2, when $d \geq \underline{d_7}$, $v_5 > v_{H2}/v_{L2} \geq v_4$, $v_{H1}/v_{L1} \geq \max\{v_6, \sqrt{c_1/c_2}\}$, and $v_{L1}/v_{L2} > \sqrt{c_1/c_2}$ product line approach is more profitable.

Therefore, combining the results in case 1 and case 2, I define:

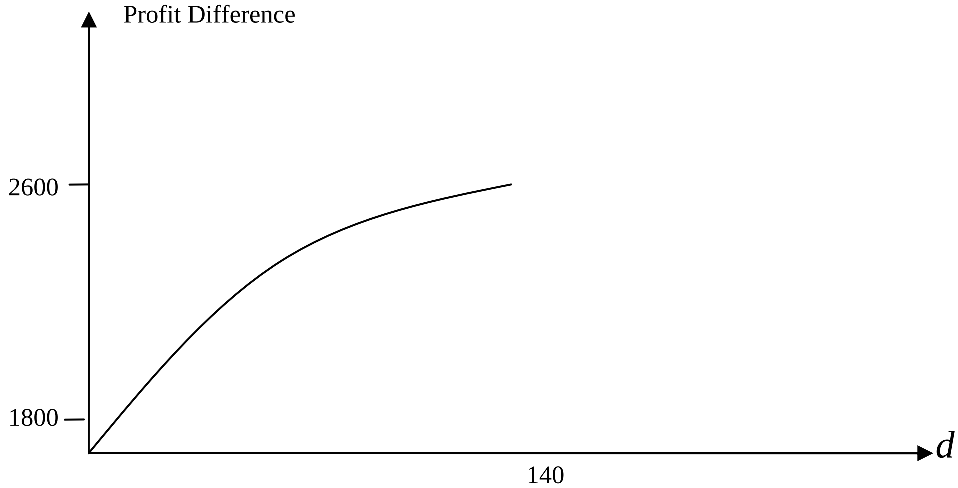
$$\underline{d} = \max\{d_1, d_7\} \quad (3\text{-}106)$$

$$v_7 = \max\{v_6, v_3, \frac{v_{H2}}{v_{L1}}\sqrt{\frac{c_1}{c_2}}\} \qquad (3\text{-}107)$$

When $d > \underline{d}$, $v_5 > v_{H2} / v_{L2} \geq v_4$, and $v_{H1} / v_{L1} \geq v_7$ product line approach is more profitable.

We supply a numerical result similar to Figure 2 as follows. I use $n_H = 200$, $n_L = 500$, $v_{H1} = 4$, $v_{L1} = 2$, $v_{H2} = 3$, $v_{L2} = 2.5$, $c_1 = c_2 = 1$, $q_{H1}^R = q_{H2}^R = 1$, $q_{L1}^R = q_{L2}^R = 1.5$ in figure A-1.

Figure 3: Profit Difference between Product Line and standard product approach



Coupled quality dimensions force the firm to reduce the quality offerings in one quality dimension. When coupling is high enough, a product line's quality along one dimension is driven to reservation level. This sometimes leads to an extremely overlapped product line, in which high-end product has minimum quality level in dimension 2 and low-end product has minimum quality level in dimension 1. As a result, market cannibalization decreases to such an extent that the product-line becomes more profitable, but the product line is also overlapped in that low-end product is not subsumed in the high-end product. When saturation effects limit the quality offering in a standard product ($q_{L1}^{S} \leq q_{S1}* - \sqrt{\frac{c_2 n_H (v_{H1} q_{L1}* + v_{H2} q_{L2}*)}{c_1 c_2 - d^2}}$), again the product-line becomes more profitable.

Thus, it behooves the firm to profit from the two quality dimensions, and emphasizes different dimensions in each of the segments when the dimensions are closely coupled and the customer relative willingness to pay differs significantly between high-end and low-end customers.

Chapter 4: After-Sale Services, Product Quality, and Supply Chain Coordination

With increasing importance of after-sale services, companies no longer treat the decisions of after-sale services as peripheral strategies to assist the sales of their products. Instead, firms are trying to integrate their service strategy and product strategy to achieve higher profits level.

In this chapter, I model a firm's integrated decision-making process for a product line and the associated after-sale service line. I consider a monopolistic company manufacturing and servicing durable products that can be characterized with two-dimensional quality $Q(q_1, q_2)$, of which the ranking is agreed upon by all consumers. q_1 indicates the performance quality of the product and q_2 measures the conformance quality. The performance quality refers to the primary operating characteristics of a product and the "bells and whistles" that supplement those basic functions. Therefore, the performance quality I defined in this dissertation includes both the performance and features dimension in Garvin (1987). On the other hand, the conformance quality refers to all the controllable characteristics that determine how much effort is needed for a product to remain in perfect working condition. In this sense, the conformance quality here includes the reliability (probability of product malfunctioning or failing during a specified period), durability (a measure of product life), and conformance dimensions (the degree to which a product's design and operating characteristics meet established standards) in Garvin (1987).

It is not the first time that quality is viewed as with multiple dimensions. For example, Garvin (1987) proposes eight dimensions of quality. Clark, et al. (1990) propose a conceptual framework of performance and conformance dimension of quality similar to this dissertation. However, there is a significant difference between the conformance quality in Garvin (1987) or Clark, et al. (1990) and the conformance quality in this dissertation.

The conformance quality used in Garvin (1987) or Clark, et al. (1990) is determined during the production process. Low conformance quality is due to factors such as irregularity in production, problems in the designing, poor management of production processes, and to a less degree, a bad product design. Usually the conformance quality cannot be improved by higher investment level, but only marginally by incremental efforts to improve all those areas mentioned above. Low conformance quality is not intentional, but the result of mistakes and glitches. The consequences of imperfect conformance quality are mostly the failures happening during the burn-in period in the bathtub model, sometimes also the unexpected higher level of repairs during the effective lifetime of the products.

However, in this dissertation I focus only on the conformance quality that is the result of a firm's choice. The firm chooses the material, level of workmanship, engineering processes, and product architecture, etc that achieve an expected level of maintenance and repair services during the effective lifetime of the products. The consequences of such imperfect conformance quality are mostly not the failures during the burn-in period in the bathtub model.

Therefore, intentional lowering the conformance quality in this context is not as unrealistic as it sounds. It just reflects the firm's choices of product positioning in the dimension of conformance quality during the product development period.

The cost function to provide product A with quality level $\mathbf{q}_A(q_{A1}, q_{A2})$ is $C(q_{A1}, q_{A2})$, which is modeled as super-modular function. I assume that $C_{q_{Ai}}(q_{A1}, q_{A2}) > 0$, $C_{q_{Ai}q_{Ai}}(q_{A1}, q_{A2}) \geq 0$, and $C_{q_{Ai}q_{Aj}}(q_{A1}, q_{A2}) \geq 0$ for $i, j \in \{1, 2\}$ and $i \neq j$.

One example of this type of cost functions is $C(q_{A1}, q_{A2}) = c_1 q_{A1}{}^2 + c_2 q_{A2}{}^2 + 2c_3 q_{A1} q_{A2}$. I also assume that $c_3 < \sqrt{c_1 c_2}$. This cost function implies that the cost of quality improvement in performance (conformance) dimension increases with the level of conformance (performance) quality.

There are two discrete market segments: *high-end* and *low-end* segment. Subscript H and L are used for the variables associated with high-end and low-end segment, respectively. For example, the size of high-end and low-end market segment is n_H and n_L, respectively. I assume that high-end consumers have higher willingness to pay for both the products and the after-sale services than the low-end customers.

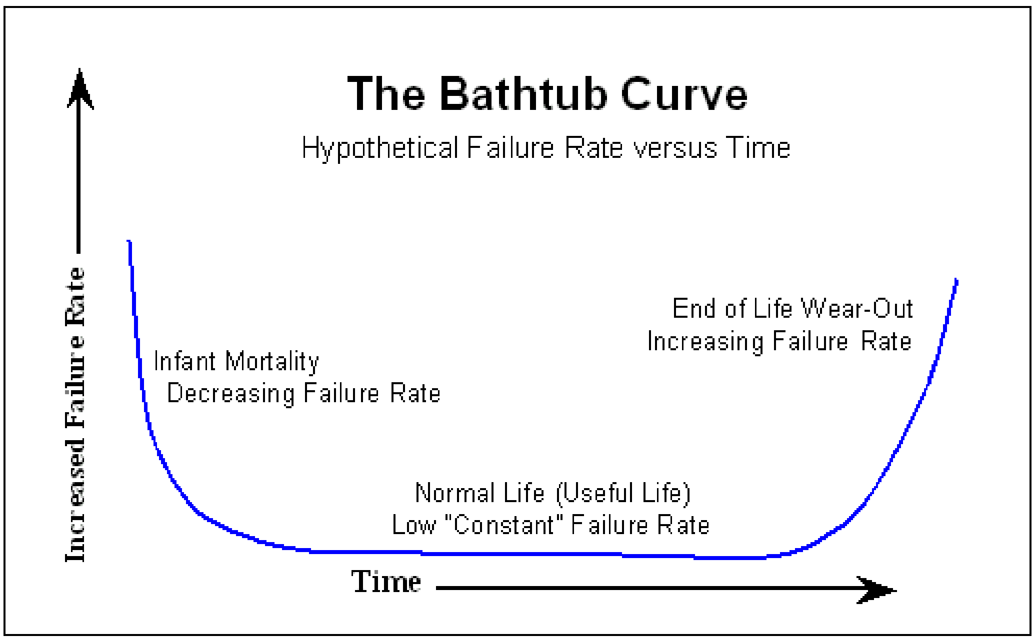
4.1. SUBSTITUTE SERVICES FOR EXPERIENCED CONSUMERS

The first type of after-sale services I consider is *substitute service*, for which the demand decreases in a monotone manner with conformance quality. I assume that substitute services have zero price elasticity. Substitute services keep the durable goods in good condition and in this sense are substitutable for conformance quality. For instance, a product with higher conformance quality has less need for maintenance and repair services. On the other hand, higher level of repair services compensate for the low conformance quality of the product.

For substitute services, the service demand for one installed base of product A is $M(q_{A2}, x)$, where x is the level of care a user provides to the product. I assume that $M_{q_{A2}}(q_{A2}, x) \le 0$, $M_{q_{A2}q_{A2}}(q_{A2}, x) \le 0$. I also assume $M_x(q_{A2}, x) \le 0$, $M_{xx}(q_{A2}, x) \le 0$. Therefore, higher conformance quality and higher level of user's care both reduce the demand for substitute after-sale services with diminishing speed. An example of such demand function is $M(q_{A2}, x) = d - aq_{A2} - bx + \varepsilon$, where ε is a random variable with distribution $\Phi(0, \sigma_\varepsilon)$. I assume that the products have constant demand for after-sale services during their lifetime of services, as in the flat (useful) part of the bathtub model.

The bathtub is a textbook model in product reliability literature. The lifetime of a population of products is described using a graphical representation called the bathtub curve as in the Figure 3. The bathtub curve consists of three periods: an infant mortality period with a decreasing failure rate followed by a normal life period (also known as "useful life") with a low, relatively constant failure rate and concluding with a wear-out period that exhibits an increasing failure rate (Wilkins 2002).

Figure 4: Bathtub Model



The consumers' utility function for product A with quality $Q(q_{A1}, q_{A2})$ is $U(q_{A1}, q_{A2}, t)$, where $t \in \{H, L\}$ is the type of consumer. I assume that utility function satisfies the standard single crossing property ($[U(q_{A1}, q_{A2}, H) - U(q_{A1}, q_{A2}, L)][U_{q_{Ai}}(q_{A1}, q_{A2}, H) - U_{q_{Ai}}(q_{A1}, q_{A2}, L)] > 0$, $i \in \{1,2\}$). The surplus of type t consumers for services with r is $W(M(q_{A2}, x), t) - r$. An example of utility function is $U(q_{A1}, q_{A2}, t) = v_{t1} q_{A1} - \lambda r_0 (e + g\sigma) M(q_{A2}, x)$ and $W(M(q_{A2}, x), t) = r_0 (e + g\sigma) M(q_{A2}, x) - c_x x^2$, which will be defined and explained later.

The consumers of higher type will have higher willingness to pay for both the product and the service. Therefore, both $U(q_{A1}, q_{A2}, t)$ and $W(M(q_{A1}, q_{A2}, x), s, t)$ are monotone increasing in t. Specifically, H is higher than L in consumer type. I also assume that $W_s(...) > 0$, $W_{ss}(...) \leq 0$, $W_M(...) > 0$, and $W_{MM}(...) = 0$. Consumers have decreasing marginal utility for service quality but constant marginal utility for service volume.

In the following analysis, I omit the conditions for establishment of convexity in every objective functions hereafter.

4.2. EXPERIENCED CONSUMERS WITH COMPETITIVE INDEPENDENT SERVICE PROVIDERS

Experienced consumers take into account the total ownership costs when they make decision to buy the products. They have prior belief of the service demand and I model their belief by a distribution $\Phi(e, \sigma)$. Consumers do not know the actual demand $M(q_{A2}, x)$. Instead, their estimation of service demand is $\Phi(e, \sigma) M(q_{A2}, x)$.

There is a competitive service market in which independent service providers charge a published rate r_0 per unit of service volume. The published service rate serves as a mental benchmark for the experienced consumers in their decision-making.

Consumers of the same type are homogenous in their degree of risk aversion while the firm is risk neutral. I measure the degree of risk aversion of consumers by the value they assign to the marginal reduction in variance.

I assume that experienced consumers are fully capable of incorporating the total ownership cost in their purchase decision. The willingness to pay of consumers of type t for product A is $v_{t1} q_{A1} - \lambda r_0 (e + g_t \sigma) W(q_{A2}, x)$, where g_t is the measurement of the degree of risk aversion and $0 < \lambda < 1$ is the mental accounting discount factor for future cost of service. For simplicity, we focus on mental accounting instead of time discounting. The term $\lambda(e+g_t\sigma)$ is the consumer's effective estimation of service demand. When $\lambda(e+g_t\sigma)\geq 1$, consumers overestimate the service demand (or underestimate the conformance quality). Otherwise, consumers underestimate the service demand (or overestimate the conformance quality).

I require $2c_1c_3 >> a^2\lambda r_0(e+g_t\sigma)$ so that quality improvement will not result in zero or negative demand of service.

The firm has complete information about the service demand function and the consumers' prior beliefs. However, the firm cannot observe the level of users' effort to take care of the products.

The consumers' problem of optimal level of effort to take care of the product is as follows:

$$\Pi_1^C = \max_x v_{t1}q_{A1} - (e+g_t\sigma)rM(q_{A2},x) - c_x x^2 - p \qquad (4\text{-}1)$$

The optimal effort for consumers can be solved through the FOC of (4-1): $x^* = \arg\{2c_x x + (e+g_t\sigma)rM_x(q_{A2},x)=0\}$. With demand function in the form of $M(q_{A2},x) = d - aq_{A2} - bx + \varepsilon$, the optimal customers' effort is as follows:

$$x^* = \frac{b(1-\lambda)(e+g_t\sigma)r_0}{2} \qquad (4\text{-}2)$$

Firm Only Provides Products

If the firm does not enter the service market, its optimal qualities for a product line are as follows:

$$q_{H1}^* = \frac{c_2 v_{H1} - c_3 a r_0 \lambda(e+g_H\sigma)}{2(c_1c_2 - c_3{}^2)} \qquad (4\text{-}3)$$

$$q_{H2}^* = \frac{c_1 a r_0 \lambda(e + g_H \sigma) - c_3 v_{H1}}{2(c_1 c_2 - c_3^2)} \tag{4-4}$$

$$q_{L1}^* = \frac{c_2 v_{L1}(1 - R_1) - c_3 a r_0 \lambda[e + g_L(1 - R_g)\sigma]}{2(c_1 c_2 - c_3^2)} \tag{4-5}$$

$$q_{L2}^* = \frac{c_1 a r_0 \lambda[e + g_L(1 - R_g)\sigma] - c_3 v_{L1}(1 - R_1)}{2(c_1 c_2 - c_3^2)} \tag{4-6}$$

Where $R_1 = n_H (v_{H1} - v_{L1}) / n_L v_{L1}$ and $R_g = n_H (g_H - g_L) / n_L g_L$.

Lemma 4:

When a product-only firm offers a product line in a market served by competitive independent service providers, the optimal conformance and performance quality are given by (4-3) through (4-6)***. Specifically:***

1. ***Both the service rate charged by the independent service provider and the degree of risk aversion of the consumer monotone increases the optimal conformance quality but monotone decreases the performance quality.***
2. ***Both the service rate charged by the independent service provider and the degree of risk aversion of the consumer monotone increase the consumers' optimal effort to take care of their products.***
3. ***The coupling between conformance and performance quality increases the above-mentioned impacts of service rate and degree of risk aversion on performance quality, but does not impact the conformance quality.***

Points (1) and (2) of the above conclusions are quite intuitive if the consumer's "*conformance quality estimation*" (CQE) is defined as $\lambda(e + g_t \sigma)$. Higher CQE implies that consumers have a lower perception of the conformance quality. Lemma 4 concludes that if consumers have lower perception of the conformance quality of the product, the best strategy for the firm is to design a product with higher conformance quality but lower performance quality. In fact, the Lemma suggests that a firm with low conformance quality image should avoid high-end product market. On the other hand, a firm with high conformance quality image should enter high-end product market and profit from a higher service demand.

Firm Offers Services on Rate Basis

If the firm provides substitute after-sale services and prices the services on a rate per service volume basis, then the firm cannot charge service rate higher than the independent service suppliers can. We assume the firm incurs constant variable cost with unit cost c_{sv}. The firm's profit maximization problem is as follows:

$$\Pi_1^F = \max_{p_H, p_L, r, q_{H1}, q_{H2}, q_{L1}, q_{L2}} n_L[p_L - C(q_{L1}, q_{L2}) + (r - c_{sv})W(q_{L2}, x_L)]$$

$$+ n_H[p_H - C(q_{H1}, q_{H2}) + (r - c_{sv})W(q_{H2}, x_H)] \quad (4\text{-}7)$$

Subject to:

$$v_{H1}q_{H1} - r(e + g_H\sigma)W(q_{H2}, x_H) - p_H \geq v_{H1}q_{L1} - r(e + g_H\sigma)W(q_{L2}, x_H) - p_L \quad (4\text{-}8)$$

$$v_{L1}q_{L1} - r(e + g_L\sigma)W(q_{L2}, x_L) - p_L \geq v_{L1}q_{H1} - r(e + g_L\sigma)W(q_{H2}, x_L) - p_H \quad (4\text{-}9)$$

$$v_{H1}q_{H1} - r(e + g_H\sigma)W(q_{H2}, x) - p_H \geq 0 \quad (4\text{-}10)$$

$$v_{L1}q_{L1} - r(e + g_L\sigma)W(q_{L2}, x_L) - p_L \geq 0 \quad (4\text{-}11)$$

$$r \leq r_0 \quad (4\text{-}12)$$

The firm will make service free of charge if the following is satisfied:

$$[\lambda(e + g_L\sigma) - 1][n_H d + n_L(d - aq_{L2})] - [\lambda(e + g_H\sigma) - 1]n_H q_{H2} a - an_H \lambda\sigma q_{L2}(g_H - g_L) \geq 0$$

A sufficient condition of the above expression is as follows:

$$\lambda(e+g_L\sigma)\geq 1 \tag{4-13}$$

The firm will enter the service market with free service if the following sufficient condition also holds:

$$r_0\lambda(e+g_L\sigma)\geq c_{sv} \tag{4-14}$$

The optimal qualities of the product line and service price are as follows:

$$q_{H1}*=\frac{c_2v_{H1}-ac_3\{c_{sv}+r*[\lambda(e+g_H\sigma)-1]\}}{2(c_1c_2-c_3{}^2)} \tag{4-15}$$

$$q_{H2}*=\frac{ac_1\{c_{sv}+r*[\lambda(e+g_H\sigma)-1]\}-c_3v_{H1}}{2(c_1c_2-c_3{}^2)} \tag{4-16}$$

$$q_{L1}*=\frac{c_2v_{L1}(1-R_1)-ac_3\{c_{sv}+r*\lambda[e+g_L(1-R_g)\sigma]-r*]\}}{2(c_1c_2-c_3{}^2)} \tag{4-17}$$

$$q_{L2}*=\frac{ac_1\{c_{sv}+r*\lambda[e+g_L(1-R_g)\sigma]-r*]\}-c_3v_{L1}(1-R_1)}{2(c_1c_2-c_3{}^2)} \tag{4-18}$$

$$r*=\begin{cases}0 \text{ if } \lambda(e+g_L\sigma)\geq 1\\ \mathrm{r}_0 \text{ if } \lambda(e+g_L\sigma)<1\end{cases} \tag{4-19}$$

Lemma 5: ***For a market of experienced consumers, the firm will enter the service market if (4-14) is satisfied. In this case, the firm will provide free service if consumers underestimate the conformance quality ((4-13) is satisfied). If consumers overestimate the conformance quality ((4-13) is satisfied), the firm will charge highest possible service rate.***

4.3. MYOPIC AND SEMI-MYOPIC CONSUMERS

Consumers may not be able to incorporate the total ownership cost fully into their product purchase decision. For myopic and semi-myopic consumers, they do not consider the explicit total ownership cost in their utility function for the product. Instead, myopic and semi-myopic consumers only vaguely value the conformance quality in term of a linear willingness to pay for conformance quality, but not in the term of expected service cost that may occur during the life cycle of the product. The only difference between myopic and semi-myopic consumers is that the latter also make purchase decision of product independent of the cost of services.

I model the utility function of those consumers of type t when they buy product A as follows:

$$U(q_{A1}, q_{A2}, t) = v_{t1} q_{A1} + v_{t2} q_{A2} \quad (4\text{-}20)$$

Where v_{tj} is the marginal willingness to pay for product quality in dimension j.

The utility function for after-sale services is as follows:

$$W(M(q_{A2}, x), t) = w_t M(q_{A2}, x, t) \quad (4\text{-}21)$$

Where w_t is the marginal willingness to pay for after-sale services.

Now we use demand function $M(q_{A2}, x) = d - a q_{A2} - bx + \varepsilon$. When the firm offers product line and after-sale services to myopic consumers, the optimal qualities of the product line are as follows:

$$q_{H1}{*} = \frac{c_2 v_{H1} - c_3 v_{H2} - a c_3 (c_{sv} - w_H)}{2(c_1 c_2 - c_3{}^2)} \quad (4\text{-}22)$$

$$q_{H2} = \frac{c_1 v_{H2} - c_3 v_{H1} + ac_1(c_{sv} - w_H)}{2(c_1 c_2 - c_3{}^2)} \tag{4-23}$$

$$q_{L1} = \frac{c_2 v_{L1}(1-R_1) - c_3 v_{L2}(1-R_2) - ac_3[c_{sv} - w_L(1-R_w)]}{2(c_1 c_2 - c_3{}^2)} \tag{4-24}$$

$$q_{L2} = \frac{c_1 v_{L2}(1-R_2) - c_3 v_{L1}(1-R_1) + ac_1[c_{sv} - w_L(1-R_w)]}{2(c_1 c_2 - c_3{}^2)} \tag{4-25}$$

Where $R_w = n_H(w_H - w_L)/n_L w_L$.

In the remaining of chapter 4, I will only consider myopic or semi-myopic consumers. The reason that experienced consumers are no longer considered is that the assumption of experienced consumers is too strong. The experienced consumers must explicitly incorporate the total ownership cost of the after-sale services in their utility function of products.

Proposition 5: ***For a firm providing a product line in a market served by competitive independent service providers:***

1. ***Both the service rate charged by the independent service provider and the degree of risk aversion of the consumer monotone increases the optimal conformance quality but monotone decreases the performance quality.***
2. ***Both the service rate charged by the independent service provider and the degree of risk aversion of the consumer monotone increase the consumers' optimal effort to take care of their products.***
3. ***The coupling between conformance and performance quality increases the above-mentioned impacts of the service rate and the degree of risk aversion on performance quality, but does not affect the impacts on conformance quality.***

4. ***The firm will enter the service market of experienced consumers if*** (4-14) ***is satisfied. It will provide service free if its conformance quality is underestimated or provide service at highest possible rate if otherwise.***

The intuition of the above result is straightforward. If consumers are fully capable of incorporating the total ownership costs in their utility of the product the degree of risk aversion and the published service rate will reduce the consumers' willingness to pay for the product. Therefore, the firm has the incentive to increase the conformance quality and the level of care provided for the product in order to reduce the expected service costs. Because of the coupling between performance and conformance quality, the firm will compromise its performance quality in order to achieve higher conformance quality.

When the revenue from a potential service offering overweighs the cost of providing the service, the firm will enter the service market. With experienced consumers, the firm's service offering serves an ambivalent role: the service generates new revenue while the service revenue is also explicitly considered as cost (disutility) by consumers in their willingness to pay for the product. Therefore, the firm will provide the service free if consumers overestimate the service costs. In doing so, the firm is better off by being able to set higher price for their products although it does not make any profit from the sales of its services. If consumers underestimate the service costs the firm will be able to charge a highest possible price for its service without hurting its product price.

Next, I take a closer look at a firm's decision-making in both the product and after-sale service market, followed by the decision-makings in a supply chain settings.

4.4. MODEL OF PRODUCT LINE AND SUBSITUTE AFTER-SALE SERVICE LINE

In this subsection, I study the substitute after-sale service offered by a firm in the form of extended warranty backed by promised service level (service quality). The quality for high-end and low-end product are $\mathbf{q}_H(q_{H1}, q_{H2})$ and $\mathbf{q}_L(q_{L1}, q_{L2})$, respectively. We continue our notions, using dimension 1 for performance quality and dimension 2 for performance quality. The quality (service level) of after-sale services offered to the buyers of high-end and low-end products are s_H and s_L, respectively.

Retail prices for high-end and low-end products are p_H and p_L, while the prices for after-sale services offered for high-end product and low-end product are r_H and r_L, respectively.

The supply chain offers a short period of limited warranty free and the warranty covers $1-\tau$ portion of the total service demand.

I use a quadratic production cost function $C(q_{i1}, q_{i2}) = c_1 q_{i1}^2 + c_2 q_{i2}^2 + 2c_3 q_{i1} q_{i2}$, where $i \in \{H, L\}$. The demand of the services for one installed base is $M(q_{i2}) = d + \varepsilon - a q_{i2}$, where constant d is the maximal service demand for any feasible product while constant a is the marginal service reduction of conformance quality. ε is a random variable with zero expectation and variance of σ_r^2 that captures the uncertainty that are coming from the product itself, the condition in which the product is working, or some unknown sources.

This model reflects the fact that a product with higher conformance quality requires less services. The expectation and variance of service demand for n stalled base is $n(d - a q_{i2})$ and $n(\sigma_r)^2$, respectively, as service demand for individual customer is independent.

Service level is primarily determined by the inventory level of spare parts, material and service personnel (with service outsourcing, more and more firm, such as Dell use inventory model instead of queuing model for after-sale service). The expected cost to provide substitute after-sale services with quality level s is $E[CS(M(q_{i2}), s_i)]$, which includes two parts: the cost of acquiring inventory level (hereinto referred to as the cost of service quality) $c_s(E[M(q_{i2})] + h_i s_i^2 \sqrt{Var[M(q_{i2})]})$, and the variable costs

$c_{sv}E[M(q_{i2})]$. Here c_s is unit holding cost and h_i is marginal willingness to pay for service quality. c_{sv} is the marginal variable cost of the services. For the above cost of service quality, I use an approximation of stock holding cost model, with demand uncertainty and an unvaried lead-time, which I normalized to one.

I assume that the firm gives a period of free services in the form of limited warranty incorporated in the product offerings, and charges the service afterwards in the form of extended warranty. A portion of τ of the service happens after the limited warranty period depending on how long the firm gives limited warranty.

Customers have linear WTP function for product with quality $\mathbf{q}_i(q_{i1}, q_{i2})$: $v_1 q_{i1} + v_2 q_{i2}$, where v_j ($j = 1, 2$) is the marginal WTP. The consumers' surplus for a product with quality $\mathbf{q}_i(q_{i1}, q_{i2})$ and price p_i is $v_1 q_{i2} + v_2 q_{i2} - p_i$.

Now I model the utility function for after-sale services of the product buyers. The indirect expected utility function for services in the form of extended warranty with quality s_i, demand M and price r_i is $k_i s_i + w_i(e + g_i\sigma)E[M] + g_i Var[M] - r_i$, where k_i is the marginal WTP for service quality, w_i is the marginal WTP for the service work itself and g_i is risk aversion constant. When $g_i = 0$ the consumer is risk neutral.

4.5. BENCHMARK: COORDINATED SUPPLY CHAIN WITH SUBSTITUTE SERVICES

Myopic Consumers

Myopic consumers will make decision of product purchase without explicitly considering the cost of after-sale service. Then they make separate decision to buy after-sale services.

When consumers are myopic, the coordinated supply chain maximizes its profit by solving the following problem:

$$\Pi_B^F = \max_{q_{H1}, q_{H2}, p_H, q_{L1}, q_{L2}, p_L, s_H, s_L} n_H(p_H - c_1 q_{H1}{}^2 - c_2 q_{H2}{}^2 - 2c_3 q_{H1} q_{H2})$$

$$+n_L(p_L - c_1 q_{L1}{}^2 - c_2 q_{L2}{}^2 - 2c_3 q_{L1} q_{L2}) + n_H[r_H - c_{sv}(d - aq_{H2})]$$

$$+n_L[r_L - c_{sv}(d - aq_{L2})] - c_s a n_H[(d - q_{H2}) + h_H \sigma s_H{}^2] - c_s a n_L[(d - q_{H2}) + h_L \sigma s_L{}^2]$$

(4-26)

Subject to:

$$v_{H1} q_{H1} + v_{H2} q_{H2} - p_H \geq v_{H1} q_{L1} + v_{H2} q_{L2} - p_L \tag{4-27}$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_L \geq v_{L1} q_{H1} + v_{L2} q_{H2} - p_H \tag{4-28}$$

$$v_{H1} q_{H1} + v_{H2} q_{H2} - p_H \geq 0 \tag{4-29}$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_L \geq 0 \tag{4-30}$$

$$\tau w_H (e + g_H \sigma)(d - aq_{H2}) + k_H s_H - r_H \geq 0 \tag{4-31}$$

$$\tau w_L (e + g_L \sigma)(d - aq_{L2}) + k_L s_L - r_L \geq 0 \tag{4-32}$$

The optimal product qualities and service qualities are as follows:

$$q_{H1}^M = \frac{c_2 v_{H1} - c_3 v_{H2} - ac_3[c_{sv} + c_s - (e + g_H \sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \tag{4-33}$$

$$q_{H2}^M = \frac{c_1 v_{H2} - c_3 v_{H1} + ac_1[c_{sv} + c_s - (e + g_L \sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \tag{4-34}$$

$$q_{L1}^M = \frac{c_2 v_{L1}(1 - R_1) - c_3 v_{L2}(1 - R_2) - ac_3[c_{sv} + c_s - (e + g_L \sigma)\tau w_L]}{2(c_1 c_2 - c_3{}^2)} \tag{4-35}$$

$$q_{L2}^M = \frac{c_1 v_{L2}(1 - R_2) - c_3 v_{L1}(1 - R_1) + ac_1[c_{sv} + c_s - (e + g_L \sigma)\tau w_L]}{2(c_1 c_2 - c_3{}^2)} \tag{4-36}$$

$$s_L^M = \frac{k_L}{2ac_s h_h \sigma} \tag{4-37}$$

$$s_H^M = \frac{k_H}{2ac_s h_l \sigma} \tag{4-38}$$

Semi-Myopic Consumers

Semi-myopic consumers make decision of product purchase and after-sale services at the same time, but in their utility function of the product there is no explicit cost of after-sale services.

When consumers are semi-myopic, the coordinated supply chain maximizes its profit by solving the following problem:

$$\Pi_B^{F2} = \max_{q_{H1},q_{H2},p_H,q_{L1},q_{L2},p_L,s_H,s_L} n_H(p_H - c_1 q_{H1}{}^2 - c_2 q_{H2}{}^2 - 2c_3 q_{H1} q_{H2})$$

$$+n_L(p_L - c_1 q_{L1}{}^2 - c_2 q_{L2}{}^2 - 2c_3 q_{L1} q_{L2}) + n_H[r_H - c_{sv}(d - aq_{H2})]$$

$$+n_L[r_L - c_{sv}(d - aq_{L2})] - c_s a n_H[(d - q_{H2}) + h_H \sigma s_H{}^2] - c_s a n_L[(d - q_{H2}) + h_L \sigma s_L{}^2] \tag{4-39}$$

Subject to:

$$v_{H1}q_{H1} + v_{H2}q_{H2} + \tau w_H(e + g_H\sigma)(d - aq_{H2}) + k_H s_H - r_H - p_H$$

$$\geq v_{H1}q_{L1} + v_{H2}q_{L2} + \tau w_H(e + g_H\sigma)(d - aq_{L2}) + k_H s_L - r_L - p_L \tag{4-40}$$

$$v_{L1}q_{L1} + v_{L2}q_{L2} + \tau w_L(e + g_L\sigma)(d - aq_{L2}) + k_L s_L - r_L - p_L$$

$$\geq v_{L1}q_{H1} + v_{L2}q_{H2} + \tau w_L(e + g_L\sigma)(d - aq_{H2}) + k_L s_H - r_H - p_H \tag{4-41}$$

$$v_{H1}q_{H1} + v_{H2}q_{H2} + \tau w_H(e + g_H\sigma)(d - aq_{H2}) + k_H s_H - r_H - p_H \geq 0 \tag{4-42}$$

$$v_{L1}q_{L1} + v_{L2}q_{L2} + \tau w_L(e + g_L\sigma)(d - aq_{L2}) + k_L s_L - r_L - p_L \geq 0 \tag{4-43}$$

The optimal product qualities and service qualities are as follows:

$$q_{H1}^M = \frac{c_2 v_{H1} - c_3 v_{H2} - ac_3[c_{sv} + c_s - (e + g_H\sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \tag{4-44}$$

$$q_{H2}^M = \frac{c_1 v_{H2} - c_3 v_{H1} + ac_1[c_{sv} + c_s - (e + g_L\sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \tag{4-45}$$

$$q_{L1}^{M} = \frac{c_2 v_{L1}(1-R_1) - c_3 v_{L2}(1-R_2) - ac_3\{c_{sv} + c_s - [ew_L(1-R_w) + g_L w_L \sigma(1-R_{wg})]\tau\}}{2(c_1 c_2 - c_3{}^2)}$$

(4-46)

$$q_{L2}^{M} = \frac{c_1 v_{L2}(1-R_2) - c_3 v_{L1}(1-R_1) + ac_1\{c_{sv} + c_s - [ew_L(1-R_w) + g_L w_L \sigma(1-R_{wg})]\tau\}}{2(c_1 c_2 - c_3{}^2)}$$

(4-47)

$$s_L^M = \frac{k_L(1-R_k)}{2ac_s h_h \sigma} \qquad (4\text{-}48)$$

$$s_H^M = \frac{k_H}{2ac_s h_l \sigma} \qquad (4\text{-}49)$$

Where $R_w = n_H(w_H - w_L)/n_L w_L$, $R_{wg} = n_H(w_H g_H - w_L g_L)/w_L g_L$.

Lemma 6: ***Substitute after-sale services decreases the optimal conformance quality but increases the performance quality if services are profitable enough. However, when consumers are less myopic, the above impact of after-sale services is decreased.***

4.6. NON-COORDINATED SUPPLY CHAIN WITH SUBSTITUTE SERVICES

In a non-coordinated supply chain, a firm sells its product line through a retailer. The retailer provides the product line and the after-sale services to the final consumers. I do not explicitly model the transaction of parts for the after-sale services between the firm and the retailer.

I use the following notations: product wholesale price y_i, product retail price p_i and service retail price r_i ($i \in \{H, L\}$).

One of the consequences of lack of coordination in the supply chain is the disaccord of the market segmentation strategy between the firm and the retailer.

Therefore, the firm has to modify its strategy in coordinated supply chain so that the retailer is willing to adopt the same market segmentation strategy.

To do that, the firm has to anticipate the reactions of the retailer to its product line decisions.

Once the firm announces its product line and the wholesale prices, the retailer maximizes its profits by setting retail price, planning and pricing of the after-sale services. The retailer can have the following six choices:

1. Carrying the product line and a service line to serve all the market segments:

$$\prod_1^R = n_H(p_H - y_H + r_H - CS(M(q_{H2}), s_H)) + n_L(p_L - y_L + r_L - CS(M(q_{L2}), s_L))$$

2. Carrying only the high-end product and high-end service to serve the high-end market segment:

$$\prod_2^R = n_H(p_H - y_H + r_H - CS(M(q_{H2}), s_H))$$

3. Carrying only the high-end product as a standard product and standard service to serve all the market segments:

$$\prod_3^R = (n_H + n_L)(p_S - y_H + r_S - CS(M(q_{H2}), s_S))$$

4. Carrying only the high-end product as a standard product and a service line to serve all the market segments:

$$\prod_4^R = (n_H + n_L)(p_S - y_H) + n_H(r_H - CS(M(q_{H2}), s_H)) + n_L(r_L - CS(M(q_{H2}), s_L))$$

5. Carrying only the low-end product as a standard product and standard service to serve all the market segments:

$$\prod_5^R = (n_H + n_L)(p_S - y_L + r_S - CS(M(q_{L2}), s_S))$$

6. Carrying only the low-end product as a standard product and a service line to serve all the market segments:

$$\prod_6^R = (n_H + n_L)(p_S - y_L) + n_H(r_H - CS(M(q_{L2}), s_H)) + n_L(r_L - CS(M(q_{L2}), s_L))$$

When the firm anticipates the retailer's reactions, the firm has to make sure that the retailer will be better off to carry the product line. Therefore, the following conditions have to be satisfied:

$$\prod_1^R \geq \max\{\prod_i^R, \exists\, i \in \{2,3,4,5,6\}\} \tag{4-50}$$

From $\prod_1^R \geq \prod_4^R$ I find an upper bound for $y_H - y_L$, and from $\prod_1^R \geq \prod_2^R$ I find an upper bound for y_L. I can solve the wholesale prices from the above two conditions ($\prod_1^R \geq \prod_6^R$ is redundant). For simplicity, I do not consider the fifth and the third cases because in both cases service line is not optimal even for coordinated supply chain.

On the other hand, the firm's decision is as follows:

$$\prod_S^F = \max_{q_{H1}, q_{L1}, q_{H2}, q_{L2}} n_H(y_H - c_1 q_{H1}{}^2 - c_2 q_{H2}{}^2 - 2c_3 q_{H1} q_{H2}) + n_L(y_L - c_1 q_{L2}{}^2 - c_2 q_{H2}{}^2 - 2c_3 q_{H1} q_{H2}) \tag{4-51}$$

Semi-myopic Consumers

When consumers are semi-myopic, the retailer's decision is formulated as follows:

$$\prod_2^R = \max_{p_H, s_H} n_H[p_H - y_H + n_H r_H - c_{sv}(d + \varepsilon - a q_{H2}) - c_s a[n_H(d + \varepsilon - q_{H2}) + g\sigma s_H{}^2] \tag{4-52}$$

Subject to:

$$v_{H1}q_{H1} + v_{H2}q_{H2} + k_H s_H + \tau w_H (e + g_H \sigma)(d - aq_{H2}) - p_H - r_H \geq 0 \qquad (4\text{-}53)$$

$$\Pi_4^R = \max_{p_S, s_H, s_L, r_H, r_L} (n_H + n_L)(p_S - y_S) + n_H (r_H - c_{sv}(d + \varepsilon - aq_{L2}) + n_L (r_L - c_{sv}(d + \varepsilon - aq_{L2})$$

$$-c_s a[(d + \varepsilon - q_{H2}) + g\sigma s_H{}^2] - c_s a[(d + \varepsilon - q_{L2}) + g\sigma s_L{}^2] \qquad (4\text{-}54)$$

Subject to:

$$v_{H1}q_{L1} + v_{H2}q_{L2} + k_H s_H + \tau(e + g_H \sigma) w_H (d - q_{L2}) - p_S - r_H$$

$$\geq v_{H1}q_{L1} + v_{H2}q_{L2} + k_H s_L + \tau(e + g_H \sigma) w_H (d - q_{L2}) - p_S - r_L \qquad (4\text{-}55)$$

$$v_{L1}q_{L1} + v_{L2}q_{L2} + k_L s_L + \tau w_L (e + g_L \sigma)(d - q_{L2}) - p_S - r_L$$

$$\geq v_{L1}q_{L1} + v_{L2}q_{L2} + k_L s_H + \tau w_L (e + g_L \sigma)(d - q_{L2}) - p_S - r_H \qquad (4\text{-}56)$$

$$v_{H1}q_{L1} + v_{H2}q_{L2} + k_H s_H + \tau(e + g_H \sigma) w_H (d - q_{L2}) - p_S - r_H \geq 0 \qquad (4\text{-}57)$$

$$v_{L1}q_{L1} + v_{L2}q_{L2} + k_L s_L + \tau w_L (e + g_L \sigma)(d - q_{L2}) - p_S - r_L \geq 0 \qquad (4\text{-}58)$$

$$\Pi_1^R = \max_{p_H, p_L, s_H, s_L, r_H, r_L} n_H (p_H - y_H) + n_L (p_L - y_L) + n_H (r_H - c_{sv})(d + \varepsilon - aq_{H2}) + n_L (r_L - c_{sv})(d + \varepsilon - q_{L2})$$

$$-c_s a[n_H (d + \varepsilon - q_{H2}) + g\sigma s_H{}^2 - c_s a[n_L (d + \varepsilon - q_{L2}) + g\sigma s_L{}^2 \qquad (4\text{-}59)$$

Subject to:

$$v_{H1}q_{H1} + v_{H2}q_{H2} + k_H s_H + \tau w_H (e + g_H \sigma)(d - aq_{H2}) - u_H - r_H$$

$$\geq v_{H1}q_{L1} + v_{H2}q_{L2} + k_H s_L + \tau w_{H(e + g_H \sigma)}(d - aq_{L2}) - u_L - r_L \qquad (4\text{-}60)$$

$$v_{L1}q_{L1} + v_{L2}q_{L2} + k_L s_L + \tau w_L (e + g_L \sigma)(d - aq_{L2}) - u_L - r_L$$

$$\geq v_{L1}q_{H1} + v_{L2}q_{H2} + k_L s_H + \tau w_L (e + g_L \sigma)(d - aq_{H2}) - u_H - r_H \qquad (4\text{-}61)$$

$$v_{H1}q_{H1}+v_{H2}q_{H2}+k_H s_H+\tau w_H(e+g_H\sigma)(d-aq_{H2})-u_H-r_H\geq 0 \quad (4\text{-}62)$$

$$v_{L1}q_{L1}+v_{L2}q_{L2}+k_L s_L+\tau w_L(e+g_L\sigma)(d-aq_{L2})-u_L-r_L\geq 0 \quad (4\text{-}63)$$

The firm will set p_H and p_L so that $\prod_1^R \geq \max\{\prod_i^R, \exists\, i\in\{2,4\}\}$. After solving y_H and y_L, the optimal qualities for product line are solved from (4-51) as follows:

$$q_{H1}{*}=\frac{c_2v_{H1}-c_3v_{H2}-ac_3[c_{sv}+c_s-(e+g_H\sigma)\tau w_H]}{2(c_1c_2-c_3{}^2)} \quad (4\text{-}64)$$

$$q_{H2}{*}=\frac{c_1v_{H2}-c_3v_{H1}+ac_1[c_{sv}+c_s-(e+g_H\sigma)\tau w_H]}{2(c_1c_2-c_3{}^2)} \quad (4\text{-}65)$$

$$q_{L1}{*}=\frac{c_2[n_L{}^2v_{L1}-n_H(n_H+2n_L)(v_{H1}-v_{L1})]+c_3[n_H(n_H+2n_L)(v_{H2}-v_{L2})-n_L{}^2v_{L2}]}{2(c_1c_2-c_3{}^2)n_L{}^2}$$

$$-\frac{ac_3\{n_L{}^2(c_s+c_{sv})+\tau[[(e+g_H\sigma)w_H-(e+g_L\sigma)w_L]n_H(n_H+3n_L)-n_L{}^2w_L(e+g_L\sigma)]\}}{2(c_1c_2-c_3{}^2)n_L{}^2}$$

(4-66)

$$q_{L2}{*}=\frac{c_3[n_H(n_H+2n_L)(v_{H1}-v_{L1})-n_L{}^2v_{L1}]+c_1[n_L{}^2v_{L2}-n_H(n_H+2n_L)(v_{H2}-v_{L2})]}{2(c_1c_2-c_3{}^2)n_L{}^2}$$

$$-\frac{ac_1\{n_L{}^2(c_s+c_{sv})+\tau[[(e+g_H\sigma)w_H-(e+g_L\sigma)w_L)]n_H(n_H+3n_L)-n_L{}^2w_L(e+g_L\sigma)]\}}{2(c_1c_2-c_3{}^2)n_L{}^2}$$

(4-67)

The optimal service quality will remain the same as in the coordinated supply chain. The high-end optimal product quality is also not changed. However, the low-end product quality is no longer the same as in the coordinated supply chain. The difference between the low-end quality in a non-coordinated supply chain and a coordinated supply chain is as follows:

$$\Delta q_{L1} = -\frac{n_H\{c_2(n_H + n_L)(v_{H1} - v_{L1}) + c_3[a\tau(n_H + 2n_L)((e + g_H\sigma)w_H - (e + g_L\sigma)w_L) - (n_H + n_L)(v_{H2} - v_{L2})]\}}{2(c_1c_2 - c_3^{\ 2})n_L^{\ 2}}$$

(4-68)

$$\Delta q_{L2} = \frac{n_H\{c_3(n_H + n_L)(v_{H1} - v_{L1}) + c_1[a\tau(n_H + 2n_L)((e + g_H\sigma)w_H - (e + g_L\sigma)w_L) - (n_H + n_L)(v_{H2} - v_{L2})]\}}{2(c_1c_2 - c_3^{\ 2})n_L^{\ 2}}$$

(4-69)

A sufficient condition for (4-69) to be positive and (4-68) to be negative is as follows:

$$a\tau(n_H + 2n_L)[(e + g_H\sigma)w_H - (e + g_L\sigma)w_L] > (n_H + n_L)(v_{H2} - v_{L2}) \qquad (4\text{-}70)$$

The above condition implies that the differential importance of the after-sale service is higher than that of the product.

Lemma

When a firm provides a product line and a line of substitute after-sale services through a retailer to semi-myopic consumers:

1. ***Quality difference between high-end and low-end product increases in performance dimension but decreased in conformance dimension if*** (4-70) ***is satisfied.***
2. ***The coupling between quality dimensions reinforces the above effects.***
3. ***The degree of risk aversion of consumers increases the quality difference mentioned in 1 in performance quality dimension but decreases in conformance quality dimension.***

Therefore, the quality distortion in a product line because of the non-coordination of supply chain is mixed when after-sale service is important. In conformance quality dimension, the quality gap between high-end and low-end product is even decreased. This result contrast with the prior literature that quality distortion always happens in a non-coordinated supply chain as in Villas-boas (1998).

Myopic Consumers

When consumers are myopic, the retailer's decision problem changes only in the constraints.

$$\Pi_2^R = \max_{p_H, s_H} n_H [p_H - y_H + n_H r_H - c_{sv}(d + \varepsilon - a q_{H2}) - c_s a [n_H (d + \varepsilon - q_{H2}) + g\sigma {s_H}^2]$$

Subject to:

$$v_{H1} q_{H1} + v_{H2} q_{H2} - p_H \geq 0 \tag{4-71}$$

$$k_H s_H + \tau w_H (e + g_H \sigma)(d - a q_{H2}) - r_H \geq 0 \tag{4-72}$$

$$\Pi_4^R = \max_{p_S, s_H, s_L, r_H, r_L} (n_H + n_L)(p_S - y_S) + n_H (r_H - c_{sv}(d + \varepsilon - a q_{L2}) + n_L (r_L - c_{sv}(d + \varepsilon - a q_{L2})$$

$$- c_s a [(d + \varepsilon - q_{H2}) + g\sigma {s_H}^2] - c_s a [(d + \varepsilon - q_{L2}) + g\sigma {s_L}^2]$$

Subject to:

$$v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \geq v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \tag{4-73}$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_S - r_L \geq v_{L1} q_{L1} + v_{L2} q_{L2} - p_S \tag{4-74}$$

$$v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \geq 0 \tag{4-75}$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_S \geq 0 \tag{4-76}$$

$$k_H s_H + \tau w_H (e + g_H \sigma)(d - a q_{H2}) - r_H \geq k_H s_L + \tau w_{H(e + g_H \sigma)} (d - a q_{L2}) - r_L \tag{4-77}$$

$$k_L s_L + \tau w_L (e + g_L \sigma)(d - aq_{L2}) - r_L \geq k_L s_H + \tau w_L (e + g_L \sigma)(d - aq_{H2}) - r_H \quad (4\text{-}78)$$

$$k_H s_H + \tau w_H (e + g_H \sigma)(d - aq_{H2}) - r_H \geq 0 \quad (4\text{-}79)$$

$$k_L s_L + \tau w_L (e + g_L \sigma)(d - aq_{L2}) - r_L \geq 0 \quad (4\text{-}80)$$

$$\Pi_1^R = \max_{p_H, p_L, s_H, s_L, r_H, r_L} n_H (p_H - y_H) + n_L (p_L - y_L) + n_H (r_H - c_{sv})(d + \varepsilon - aq_{H2}) + n_L (r_L - c_{sv})(d + \varepsilon - q_{L2})$$

$$-c_s a[n_H (d + \varepsilon - q_{H2}) + g\sigma s_H{}^2 - c_s a[n_L (d + \varepsilon - q_{L2}) + g\sigma s_L{}^2$$

Subject to:

$$v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \geq v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \quad (4\text{-}81)$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_S - r_L \geq v_{L1} q_{L1} + v_{L2} q_{L2} - p_S \quad (4\text{-}82)$$

$$v_{H1} q_{L1} + v_{H2} q_{L2} - p_S \geq 0 \quad (4\text{-}83)$$

$$v_{L1} q_{L1} + v_{L2} q_{L2} - p_S \geq 0 \quad (4\text{-}84)$$

$$k_H s_H + \tau (e + g_H \sigma) w_H (d - q_{L2}) - r_H \geq 0 \quad (4\text{-}85)$$

$$k_L s_L + \tau w_L (e + g_L \sigma)(d - q_{L2}) - r_L \geq 0 \quad (4\text{-}86)$$

We derive the firm's optimal product qualities in the same way as for the semi-myopic consumers, and they are as follows:

$$q_{H1}* = \frac{c_2 v_{H1} - c_3 v_{H2} - ac_3 [c_{sv} + c_s - (e + g_H \sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \quad (4\text{-}87)$$

$$q_{H2}* = \frac{c_1 v_{H2} - c_3 v_{H1} + ac_1 [c_{sv} + c_s - (e + g_H \sigma)\tau w_H]}{2(c_1 c_2 - c_3{}^2)} \quad (4\text{-}88)$$

$$q_{L1}* = \frac{c_2 [n_L{}^2 v_{L1} - n_H (n_H + 2n_L)(v_{H1} - v_{L1})] + c_3 [n_H (n_H + 2n_L)(v_{H2} - v_{L2}) - n_L{}^2 v_{L2}]}{2(c_1 c_2 - c_3{}^2) n_L{}^2}$$

$$-\frac{ac_3\{n_L{}^2(c_s+c_{sv})-\tau[n_L w_L g_L(1-R_{wg})\sigma-n_L w_L(1-R_w)e]\}}{2(c_1c_2-c_3{}^2)n_L{}^2} \tag{4-89}$$

$$q_{L2}*=\frac{c_3[n_H(n_H+2n_L)(v_{H1}-v_{L1})-n_L{}^2v_{L1}]+c_1[n_L{}^2v_{L2}-n_H(n_H+2n_L)(v_{H2}-v_{L2})]}{2(c_1c_2-c_3{}^2)n_L{}^2}$$

$$+\frac{ac_1\{n_L{}^2(c_s+c_{sv})-\tau[n_L w_L g_L(1-R_{wg})\sigma-n_L w_L(1-R_w)e]\}}{2(c_1c_2-c_3{}^2)n_L{}^2} \tag{4-90}$$

The impact of supply chain non-coordination on low-end product is as follows:

$$\Delta q_{L1}=-\frac{n_H\{c_2(n_H+n_L)(v_{H1}-v_{L1})+c_3[a\tau n_L((e+g_H\sigma)w_H-(e+g_L\sigma)w_L)-(n_H+n_L)(v_{H2}-v_{L2})]\}}{2(c_1c_2-c_3{}^2)n_L{}^2} \tag{4-91}$$

$$\Delta q_{L2}=\frac{n_H\{c_3(n_H+n_L)(v_{H1}-v_{L1})+c_1[a\tau n_L((e+g_H\sigma)w_H-(e+g_L\sigma)w_L)-(n_H+n_L)(v_{H2}-v_{L2})]\}}{2(c_1c_2-c_3{}^2)n_L{}^2} \tag{4-92}$$

A sufficient condition for (4-92) to be positive and (4-91) to be negative is as follows:

$$a\tau n_L[(e+g_H\sigma)w_H-(e+g_L\sigma)w_L]>(n_H+n_L)(v_{H2}-v_{L2}) \tag{4-93}$$

We have the following conclusion after we combine the results for semi-myopic and myopic consumers:

Proposition 6:

When a firm provides a product line and a line of substitute after-sale services through a retailer to a market with consumers with myopic behavior:

- ***Non-coordination of supply chain has no impact on the firm’s optimal high-end product qualities.***

- ***Quality difference between high-end and low-end product is increased in performance dimension but decreased in conformance dimension if*** (4-70) ***is satisfied for semi-myopic consumers or if*** (4-93) ***is satisfied for myopic consumers.***
- ***The coupling between the quality dimensions reinforces the effects in 2.***
- ***The degree of risk aversion of consumers increases the quality difference above mentioned in performance quality dimension but decreases in conformance quality dimension.***
- ***The above impact in 1 and 4 are stronger if consumers are less myopic.***

In an uncoordinated supply chain that not only provide a product line but also a substitute after-sale service line to myopic or semi-myopic consumers, the supplier does not always reduce the low-end quality in order to induce coordination of market segmentation strategy in the supply chain. In fact, the supplier may increase the low-end product quality in conformance dimension to achieve channel coordination.

The reduced or even reserved quality distortion is due to the substitute service offering but not limited to substitute service, as we will find in the next subsection.

4.7. Complementary After-Sale Services

The second type of services I consider in this dissertation is the complementary after-sale services. Complementary services are value-adding after-sale services. Examples of complementary services are wireless service for cell phones, TV programs for televisions, internet services for personal computers, GM’s On-star service for automobiles, Kodak’s photo printing services for digital cameras, etc. Higher product quality induces more usage of the product, and subsequently more complementary services. In this subsection, I only consider the case in which the service levels in the service line are exogenous.

The price elasticity of the demand for complementary service is non-zero. For type t consumers, the demand function of complementary service with product quality q, service quality s, and price r is $M(q,s,t,r)$. I assume that $M_q(q,s,t,r) \geq 0$, $M_{qq}(q,s,t,r) \leq 0$. Example of demand function $M(q,s,t,r) = d_t s - fr + b(q - q_0)$, where constant f and b are demand elasticity for price and quality, respectively, d_t is the marginal demand enhancement of service quality, q_0 is the minimal product quality to induce complementary service, r is the price of the service charged. Without loss of generosity I set $q_0 = 0$. Therefore, product quality increases the demand for complementary services with diminishing speed while service price linearly decreases the demand for complementary services.

In this subsection, only one-dimensional quality model is considered. The quality of complementary services is different from the quality of substitute services. For complementary services, it is not the response time and availability but the features and coverage that determine the service quality. Examples of service quality are coverage and airtime for wireless services, the speed and limit of download/upload for internet services, or the numbers and the types of TV channels for cable TV subscription.

The cost function of complementary services is defined in unit cost: $CS(s)$. I assume that $CS'(s) \geq 0$, $CS''(s) \geq 0$. One example of service cost function is $CS(s, M(q,s,t,r) = c_s s^2 + c_{sv} M(q,s,t,r)$.

The consumers' surplus for complementary services with service quality s, demand $M(q,s,t,r)$ and unit price r is $M(q,s,t,r)(w_t s - r)$, where the w_t is the marginal willingness to pay for service quality.

For the discussion afterwards, I will use only the explicit functions given above as examples. I also assume that all consumers are myopic since it is difficulty to incorporate the usage information in product purchase decision.

4.8. BENCHMARK: COORDINATED SUPPLY CHAIN WITH COMPLEMENTARY SERVICES

The coordinated supply chain optimizes its product line and service line for a market with myopic consumers by solving the following problem:

$$\Pi_{BC}^{F} = \max_{q_H, p_H, q_L, p_L, r_H, r_L} n_H (p_H - c{q_H}^2) + n_L (p_L - c{q_L}^2)$$

$$+ n_H (r_H - c_{sv})(d_H s_H + bq_H - fr_H - c_s {s_H}^2) + n_L (r_L - c_{sv})(d_L s_L + bq_L - fr_L - c_s {s_H}^2) \tag{4-94}$$

Subject to:

$$v_H q_H - p_H \geq v_H q_L - p_L \tag{4-95}$$

$$v_L q_L - p_L \geq v_L q_H - p_H \tag{4-96}$$

$$v_H q_H - p_H \geq 0 \tag{4-97}$$

$$v_L q_L - p_L \geq 0 \tag{4-98}$$

$$(w_H s_H - r_H)(d_H s_H + bq_H - fr_H) \geq 0 \tag{4-99}$$

$$(w_L s_L - r_L)(d_L s_L + bq_L - fr_L) \geq 0 \tag{4-100}$$

For simplicity, I do not consider the case when (4-99) and (4-100) are binding (When these two constraints are binding the boundary-solution results can be easily derived). The optimal product qualities and service qualities are as follows:

$$q_H^M = \frac{2fv_H - bs_H(c_s fs_H - d_H)}{4cf - b^2} \tag{4-101}$$

$$q_L^M = \frac{2fv_L(1-R) - bs_L(c_s fs_L - d_L)}{4cf - b^2} \tag{4-102}$$

$$r_H^M = \frac{bv_H + 2cs_H(c_s fs_H + d_L) - b^2 c_s^{\,2} s_H^{\,2}}{4cf - b^2} \tag{4-103}$$

$$r_L^M = \frac{bv_L(1-R) + 2cs_L(c_s fs_L + d_L) - b^2 c_s^{\,2} s_L^{\,2}}{4cf - b^2} \tag{4-104}$$

4.9. NON-COORDINATED SUPPLY CHAIN WITH COMPLEMENTARY SERVICES

Again, we consider a supplier (the firm) selling product through a retailer that also provides complementary after-sale services to the end consumers. Similar to the case for substitute after-sale services, we have the retailer's options formulated as follows:

$$\Pi_2^{RC} = \max_{p_H, r_H} n_H(p_H - y_H) + n_H(r_H - c_{sv})(d_H s_H + bq_H - fr_H - c_s s_H^{\,2})$$

Subject to:

$$v_H q_H - p_H \geq v_H q_L - p_L \tag{4-105}$$

$$(w_H s_H - r_H)(d_H s_H + bq_H - fr_H) \geq 0 \tag{4-106}$$

$$\Pi_4^R = \max_{p_S, r_H, r_L} (n_H + n_L)(p_S - y_S)$$

$$+ n_H(r_H - c_{sv})(d_H s_H + bq_H - fr_H - c_s s_H^{\,2}) + n_L(r_L - c_{sv})(d_L s_L + bq_L - fr_L - c_s s_H^{\,2})$$

Subject to:

$$v_H q_H - p_H \geq v_H q_L - p_L \tag{4-107}$$

$$v_L q_L - p_L \geq v_L q_H - p_H \tag{4-108}$$

$$v_H q_H - p_H \geq 0 \tag{4-109}$$

$$v_L q_L - p_L \geq 0 \tag{4-110}$$

$$(w_H s_H - r_H)(d_H s_H + bq_H - fr_H) \geq (w_H s_L - r_L)(d_H s_L + bq_L - fr_L) \tag{4-111}$$

$$(w_L s_L - r_L)(d_L s_L + bq_{L2} - fr_L) \geq (w_L s_H - r_H)(d_L s_H + bq_H - fr_H) \tag{4-112}$$

$$(w_H s_H - r_H)(d_H s_H + bq_H - fr_H) \geq 0 \tag{4-113}$$

$$(w_L s_L - r_L)(d_L s_L + bq_L - fr_L) \geq 0 \tag{4-114}$$

$$\Pi_1^R = \max_{p_H, p_L, s_H, s_L, r_H, r_L} n_H (p_H - y_H) + n_L (p_L - y_L)$$

$$+n_H (r_H - c_{sv})(d_H s_H + bq_H - fr_H - c_s s_H{}^2) + n_L (r_L - c_{sv})(d_L s_L + bq_L - fr_L - c_s s_H{}^2)$$

Subject to:

$$v_H q_H - p_H \geq v_H q_L - p_L \tag{4-115}$$

$$v_L q_L - p_L \geq v_L q_H - p_H \tag{4-116}$$

$$v_H q_H - p_H \geq 0 \tag{4-117}$$

$$v_L q_L - p_L \geq 0 \tag{4-118}$$

$$(w_H s_H - r_H)(d_H s_H + bq_H - fr_H) \geq 0 \tag{4-119}$$

$$(w_L s_L - r_L)(d_L s_L + bq_L - fr_L) \geq 0 \tag{4-120}$$

$$q_H^M = \frac{2 f v_H - b s_H (c_s f s_H - d_H)}{4cf - b^2} \tag{4-121}$$

$$q_L^M = \frac{2 f n_H n_L v_L (1-R) - 4 f n_H n_L (v_H - v_L) - b c_s f n_L [(n_H + n_L) s_L{}^2 - n_H s_H{}^2] + b n_L d_L (1 - R_w)}{(4cf - b^2) n_L{}^2} \tag{4-122}$$

The impact of non-coordination of the supply chain on low-end product quality is as follows:

$$\Delta q_L = \frac{n_H\{-2f(n_H + n_L)(v_H - v_L) + bn_L(s_H - s_L)[c_s f(s_H + s_L) - d_H]\}}{(4cf - b^2)n_L{}^2}$$

In this case, I find the quality distortion is reduced as a result of complementary services if the following condition is satisfied:

$$c_s f(s_H + s_L) \geq d_H \qquad (4\text{-}123)$$

Proposition 7: ***When a firm provides a product line and a line of complementary services through a retailer, quality distortion is reduced for myopic consumers if the condition*** (4-123) ***is satisfied. Higher price elasticity for the services and higher service quality help reduce the quality distortion.***

Contrary to Villas-Boas (1998), the quality distortion in an uncoordinated supply chain does not always happen when complementary after-sale service is provided to myopic consumers.

Chapter 5: Managerial Implication

5.1. Managerial Implications of Our Model for development-intensive products

The economics and marketing literature on positioning and designing a product line has maintained that the optimal approach for a monopolist is to version by value subtraction and to offer a subsumed product line. In such a product line, the high-end market segment is offered the independently optimal quality, while the low-end segment is offered a quality-degraded product. Our contribution in this paper is to show that when the development costs are included in the model, a subsumed product line would be dominated by other design options. On a single dimension of quality, a standard multi-segment product generally yields a greater profit than the product line solution. Only when consumer saturation effects are modeled (with saturation constraints binding) do I find that a product line starts becoming attractive and dominant. These results are due to the fact that the independently optimal quality for a development-intensive product is a function of the size of the market segment (or cumulative willingness to pay of the entire market segment).

The dominance of a standard multi-segment development-intensive product along a single quality dimension does not mean that a firm cannot resort to a product line approach in catering to a heterogeneous market. I show that when the firm innovates along multiple vertical quality dimensions, it can benefit from the trade-off among the two dimensions in the cost function and the difference in relative willingness to pay along the two quality dimensions. Our findings on product line design in multiple quality dimensions can be distilled into a conceptual/managerial framework presented in Figure

3. As seen in this framework, the product family development approach depends on both the product and market characteristics. The vertical axis of this framework is the market segment's differential willingness to pay for the two dimensions of product quality. A high value along this axis means that one of the segments has a much greater willingness to pay than the other segment for the quality dimension 1 (with a greater spread in the willingness to pay with the other quality dimension 2 having a moderate spread in willingness to pay)[4]. The horizontal axis corresponds to whether the quality dimensions are independent or coupled and traded off against one another from a cost standpoint.

When the quality dimensions are independent and the differential willingness to pay between the two customer segments for product quality is high, it would be optimal for the firm to design a subsumed product line, with the low-end product being designed with merely the reservation quality along the first quality dimension. However, when the quality dimensions are independent but the differential willingness to pay between the two customer segments for product quality is low along both of the quality dimensions, it would be optimal for the firm to design a standard multi-segment product. This case resembles the single quality dimension case.

When the quality dimensions are coupled and conflicting (captured using a supermodular cost function), it would be optimal for the firm to offer an overlapping product line when the differential willingness to pay is high along one of the quality dimensions. In this case, from the supply perspective, it would be expensive to offer higher levels of quality along both dimensions, so it behooves the firm to emphasize one of the quality dimensions in each of its products. Besides minimizing cannibalization, such an approach also helps lower costs and maximizes profit as seen in Proposition 4.

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[4] When the difference in willingness to pay in both quality dimensions (v_{H1}/v_{L1} and v_{H2}/v_{L2}) are both very high, the single segment niche product becomes more profitable even in multiple dimensions. v_{H2}/v_{L2} must be bounded below and above as discussed in the Appendix to avoid corner point solutions.

Finally, with coupled quality dimensions and a low differential willingness to pay between the two quality dimensions, it would be optimal for the firm to offer a standard product common to both segments. Thus, the coupling between the quality dimensions and the differential willingness to pay of the two customer segments play a role in determining the type of approach the firm uses to segment the market.

Figure 4: Conceptual Framework for Designing a Development-Intensive Product Line

Customer's Willingness to Pay for Quality in the first quality dimension, v_{H1} / v_{L1}	Independent Quality Dimensions (zero coupling or low coupling)	Coupled Quality Dimensions (High coupling)
High	Subsumed Product Line	Overlapped Product Line
Low	Standard Multi-Segment Product	Standard Multi-Segment Product

In §1.1, I discussed the challenges Adobe Systems faced in designing and introducing a low-end Photoshop product during the mid to late 1990's. Essentially, Adobe had unsuccessfully resorted to the classic value subtraction and quality degradation strategy, removing features from the high-end enterprise version to create a "subsumed" low-end version for the hobbyist market. Adobe had correctly diagnosed that the low-end market made up of nonprofessionals had much lower willingness to pay for high-end features. However, the low-end segment also wanted a simpler product that was easy to learn and use, and the stripping of features (quality degradation) did not reduce the complexity of Photoshop's low-end editions resulting in very weak sales.

Recognizing that the low-end segment's willingness to pay for usability dimensions of quality was comparable to that of the high-end segment, Adobe invested the effort to make the low-end product more accessible by planning and designing a new user-interface from scratch for the low-end product. In the new low-end product, christened *Photoshop Elements*, Adobe made a number of new design changes as summarized by the PC Magazine (Simone (2002)):

".. commonly used image-correction functions (like Auto Focus or Adjust Backlighting) are gathered together in a single convenient dialog box called Quick Fix. Numbered steps and explanatory tips let you easily apply the appropriate corrections to a flawed image. Other new help features include a glossary that explains underlying concepts, a quick-search field that's located in the shortcut menu, and smart error messages that give you the option of letting Elements fix a problem automatically. Experienced users, on the other hand, can ignore these hand-holding mechanisms and use tools (such as Levels) that are nearly identical to those found in Photoshop…. The new tool in the Elements toolbox—the Selection Brush—is a welcome addition.. Stellar image-editing tools coupled with a more supportive help system make this version of Elements a win/win proposition for both new and returning users."

Figure 5: Design Differences between Adobe Photoshop and Photoshop Elements (2002)

Features Present Only in PhotoShop	Features Present Only in PhotoShop Elements
Control of effects and styles Actions Palette and Recordable Actions Channel Editing Flexible masking Professional-level printing	Ability to import photos from digital cameras Auto correction tools for photos ("QuickFix") Creation of PDF slide shows Multiple-image layouts; Auto conversion of photos for the web and e mail distribution

Using our terminology, Adobe faced a market where the differential willingness to pay for the one of the dimensions of quality was high (high-end enterprise customers Ire willing to pay far more for performance quality and features than the low-end users). Also, the quality dimensions Ire coupled in the sense that introducing more features cluttered the user interface and compromised usability (it would cost much more to design a new product that offered much features and a simple user interface). Adobe eventually responded by offering a high-end product with greater performance quality and a low-end product with greater ease of use (an overlapping product line solution). A number of usability features found in the low-end Elements product have not (yet) been offered in the high-end Photoshop product. I compare these two products and summarize the differences in Figure 4. Photoshop Elements, it must be noted, has been received extremely Ill by the market, and has helped Adobe maintain growth and profitability during the tough economic years of 2001-2002.

In summary, our modeling and analysis in this paper indicates that managerial recommendations from the traditional approach to product line design developed for variable-cost intensive products on quality degradation and value subtraction do not carry over directly to development-intensive products. To be successful in addressing a low-end emerging market with a lower ability or willingness to pay, the firm must identify additional quality dimensions such a product's usability that the low-end customer cares about. Our results and the Adobe case study show that a firm can go beyond standard multi-segment products and profitably address emerging low-end customers by designing products with overlapping quality characteristics.

To achieve closed-form analytical results, I had to make a number of modeling assumptions as discussed earlier in the paper. More study of industry examples is needed to gauge the shape of utility and development cost functions along the lines of Gomes and Joglekar (2003). Specifically, the notion of reservation and saturation qualities proposed in this paper seem to offer a nice way to capture the challenges firms face in today's markets, and need further investigation. Also, the study of development-intensive products in markets that are both vertically and horizontally differentiated deserves additional attention. Our modeling and results, however, show the importance of including development costs and consumer reservation and saturation effects, in the design of development-intensive products.

5.2. MANAGERIAL IMPLICATION FOR OUR MODEL OF AFTER-SALES SERVICE IN SUPPLY CHAIN

The strategic implications of after-sale services are rarely discussed in the operations literature. Cohen and Whang (1997) is one of the few papers that study the impact of services on products. Our research studies the interactions among the decisions of products, after-sale services, and supply chain coordination. I find that after-sale service can have a significant impact on a firm's product strategy and supply chain decisions.

Similar to double marginalization, the retailer will try to serve fewer consumers in order to maximize its profit. Therefore, the firm has to pay a price to induce the retailer to carry all the products. The inclusion of service offerings in the firm's integrated decision-making changes the decisions of its product line.

When the firm has a product line and an after-sale service line, the company want to price discriminate the consumers twice. Therefore, the firm may pay the information rent only once and profit on both the product and the after-sale services if consumers are myopic.

The impacts of service offerings on the firm in non-coordinated supply chain can be characterized in the following table:

Impact on quality distortion	Semi-Myopic Consumer	Myopic Consumer
Substitute Services	Increase for Performance w/condition; Decrease for Conformance w/condition; (all to less degree than myopic consumers)	Increase for Performance w/condition Decrease for Conformance w/condition
Complementary Services	Not discussed	Decrease w/condition

Figure 6: Quality Distortion

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