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Ram Bala
Santa Clara University, rbala@scu.edu

V. Krishnan

Wenge Zhu

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Distributed Development and Product Line Decisions

Ram Bala[*] V. Krishnan[†] Wenge Zhu[‡]

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Abstract

Distributed product development is becoming increasingly prevalent in a number of industries. We study how the global distribution of product development impacts the profit-maximizing product line that a firm offers. Specifically, we formulate a model to understand the linkage between cost arbitrage as a driver of distributed development and consequent market implications such as customer perceived quality loss to remotely developed products. Analysis of the model reveals that a firm should expand the product line for a development-intensive good only at intermediate values of cost advantage and quality loss. We modify the base model to include development capacity constraints as a driver of distributed development and find that the results are robust to this change. Our analysis affirms the need for product managers to incorporate the implications of distributed development in making their product line design decision.

[*]Leavey School of Business, Santa Clara University, CA. e-mail: rbala@scu.edu
[†]Rady School of Management, UC San Diego, CA. e-mail: vkrishnan@ucsd.edu
[‡]College of Business Administration, Cal Poly Pomona, CA. e-mail: wenge.zhu@gmail.com

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1 Introduction & Related Literature

The practice of distributed development, in which more than one geographic location contributes to the design and launch of new offerings, has been expanding in recent years with increasing contributions from far-flung regions (Eppinger and Chitkara 2006). Several factors drive this trend: first, product design processes are getting more digital and networked, enabling distributed development; second, firms are getting more comfortable with globally distributed work given their past experiences with offshoring lower-level manufacturing and support activities; and third, the pressure of an intensely competitive marketplace forces firms to look for new ways to lower R&D costs and expand development capacity.

There is a large literature focusing on the motivations for distributing research and development activities. For instance, Julian & Keller (1991) list a number of factors that contribute to the distribution of R&D locations such as national market importance, local considerations like government incentives and modes of implementation. Kumar (2001) studies the determinants of location of overseas R&D in multinational enterprises of US and Japanese origin and finds the following key drivers: large domestic market, abundance of low-cost R&D manpower, and scale of national technological effort. Bas & Sierra (2002) find that companies decide to invest in R&D after comparing relative advantages of home and host countries on dimensions such as technological capability and market potential. Santos et al (2004) elaborate on several benefits of distributing new product development, such as the ability to harness diverse viewpoints, potential of locating design centers closer to manufacturing centers, and cost reduction. To summarize, the reasons for distributed development can be classified into two broad buckets: "demand" side reasons, which relate to the discovery of new markets and market needs; and "supply" side reasons, which relate to cost savings, capacity addition or process improvement.

The benefits of distributed development are well-known but there are challenges and subtle interactions as well. The general consensus is that distributed development leads to greater communication and coordination issues in product development. Amaral et al (2011) discuss how the coordination issues increase as a function of coupling of different product development activities, the contractual relationship between different teams and the physical and / or cultural distance between different locations. Potential solutions to alleviate these coordination problems are provided by Komi-Sirvio & Tihinen (2005), Kommeren and Parviainen (2007), Cusumano (2008) and Jimenez et al (2009). Recent work in software engineering highlights the negative impact of communication and coordination issues on product quality (Herbsleb and Mockus 2003, Damian and Zowghi 2003, Cataldo and Nambiar 2009, Gotel et al 2009), where the role of cultural distance between different development locations in negatively impacting the quality of the product is vividly described. This negative impact on quality is further exacerbated by consumer reaction to products developed remotely. This occurs because consumers are concerned about the standards and procedures used in remote locations during the design, development and manufacture of these products and are actively seeking this information. This has forced firms to provide information about exactly how and where their products were developed and manufactured including detailed information about the origin of individual components in their products (Clifford 2013).

The connection between the structure of product development and market outcomes has also been recognized in the literature. Hise et al (1990) show that better interaction between R&D

and marketing leads to higher new product success rates. Market outcomes often depend on the breadth of products targeted towards different segments and empirical studies in software engineering such as Berenbach (2007) have recognized the impact of global product development on the product line decision. We focus on this last linkage between distributed development and product line strategy by appealing to the extant literature on product line design that straddles operations management, marketing, and information systems.

The design of a broader product line typically hinges on the following trade-off: the ability to extract greater consumer surplus across multiple segments by offering them a product closer to their willingness to pay versus the loss in pricing power due to cannibalization. This trade-off is significantly moderated by the cost of offering an additional version of the product and/or the cost of adding more features to an existing product. While reducing the costs of development would increase the ability to offer more variety in the product offering, it may also intensify the price competition between the products. Thus, the use of a low cost remote development center may increase or decrease variety depending on the level of cost / capacity advantage and other market factors. There is a significant literature on the monopolist's product line design problem for a vertically differentiated market (for example, see: Moorthy & Png 1992, Desai et al. 2001). The basic conclusion from this stream of research is that it is conditionally optimal for a profit-maximizing monopolist to offer a product line as a way of segmenting a vertically differentiated market and extracting the surplus of lower willingness to pay (WTP) customers. Early research in this area looks at products with significant variable costs but ignores development costs, which are significant for knowledge-intensive products such as in the software and the life-sciences industries.

Extending this modeling context, it is suboptimal for a firm to offer a product line for goods with negligible variable costs (Bhargava & Choudhary 2001). Krishnan & Zhu (2006) show that product-lines can be conditionally optimal with multiple vertical quality dimensions. Chen & Seshadri (2007) show that versioning is optimal for the seller when customers have multiple outside options or, more generally, convex reservation utilities.

We contribute to the literature on product line design for development-intensive products in the context of distributed development. While other papers such as Netessine & Taylor (2007) have considered supply side factors in the product line design decision, their focus has been on production intensive goods with significant variable costs of production. To the best of our knowledge, ours is the first paper to address supply-demand interactions driving the product line design decision in the context of fixed cost-intensive goods. In the next section, we provide an example from our field work that illustrates our problem context.

2 Distributed Development Field Study

To understand the intricacies of managing distributed development, we pursued a field study with a firm in the software industry, which we now discuss to bring out the managerial issues. Our research on distributed development was catalyzed by our discussions with Microsoft, which faced challenges distributing development work of its Windows Vista product to its India Development Center (IDC) when its premium customers were still in developed countries[1]. While the company had moved a significant part of its development work to the lower-wage location (like IDC), developers there were less attuned to the needs of the developed markets, which could result in a less attractive product for premium customers.

[1] http://inhome.rediff.com/money/2007/mar/14inter.htm

Traditionally, Microsoft's approach to product line decision making seems to have been largely made heuristically and did not take development cost structure into account. Over the course of the project, it became apparent that the increased development activity at IDC not only warrants much greater level of coordination but also impacts the level of product variety in several product categories. The lower-cost development location lowers the bar for more products to be developed and launched, but these benefits must be carefully weighed against the demand-side factors that drive the level of product variety. Managers at Microsoft grappled with the question: how does the use of a remote development location affect the design and development of its product line?

The rest of the paper is organized as follows. Section 3 frames the main model while Section 4 highlights important benchmark results. Section 5 analyzes the results of the main model. Section 6 considers some important modifications to the main model and finally, Section 7 concludes the paper and suggests directions for future research. Proofs of all propositions are in Appendix B.

3 The Main Model

We develop a model of a monopolist firm that has two existing development locations, one of which is located geographically further away from the original market. Thus, the firm does not have to make a decision on opening up a new location since both locations are already in existence. Rather, the firm's decision is to choose the distributed development approach and its product strategy for a specific new product category. Any unused development capacity in either location can always be used for a different product category offered by the firm and hence there is no cost to not using this capacity. Also, to stay focused on distributed development, any other product category offered by the firm is assumed to not strategically interact with the product category under consideration. We begin with a description of consumers in the market in which the firm sells its products, which we deliberately make consistent with the standard model of vertically differentiated products.

3.1 Description of Market and Customer Utility

Our focal firm sells one or more products to a market in which consumers are heterogeneous in their willingness to pay for the quality of the product. While our model can be generalized to consider a continuous distribution of consumers, we simplify the market by modeling it with 2 discrete segments of consumers, differentiated by their willingness-to-pay (WTP) for a unit of performance quality of the product that is offered by the firm. The WTP or valuation of a segment L of consumers is θ_L per unit of product performance quality (measured by the number of features and attributes in the product) and that of segment H is θ_H per unit of product performance quality with $\theta_L < \theta_H$. The number of consumers in the low-end and high-end customer segments are n_L and n_H respectively. Although no assumptions are needed for the relationship between the two segment sizes, some of our later results are contingent on the relative sizes and valuations of these segments.

Given a single product of performance quality q, a consumer of type θ derives the following utility $u(\theta, q)$ in the tradition of vertical differentiation models, as discussed in Mussa & Rosen (1978):

$$u(\theta, q) = \theta \cdot q \tag{1}$$

If the product is offered at a price p, then a consumer with WTP θ purchases the product if the net surplus (utility minus price) is non-negative: $u(\theta, q) - p \geq 0$.

Suppose now that part of the product q is developed in a distributed manner - specifically, developed remotely by a subdivision of the focal firm. In all further analysis, this is the only form of distributed development we assume: that of a remote subdivision of the parent firm developing the product in conjunction with the main or "headquarters" location of the focal firm which is proximate to the customer's market. To focus on the issues of distributed development, we do not consider a outsourcing relationship in this model so as to not confound the contractual and inter-organizational issues that may arise in such a relationship.

The fact that at least some of the development work is distributed has potentially negative implications for the product's performance quality due to the associated managerial challenges of coordination and synchronization and this indirectly impacts the customer's willingness to pay. To capture the quality loss from distributed development, we first model the base case when any loss in quality applies to the entire product to model the fact that the overall physical design of the product itself is impacted due to the less than perfect integration of components developed in different regions. In Section 6, we analyze the case in which product quality is affected only to the extent of development effort at the remote location. We assume that a firm's high-end (premium) customers are much more prone to punishing such a quality loss. Such a heightened sensitivity can be traced to the consumer behavior and psychology literature, specifically the General Evaluability Theory (GET) summarized in Hsee and Zhang (2010). As per the General Evaluability Theory (GET), a customer's evaluation and value sensitivity of a product depends on the mode of evaluation of the product (joint or separate), the customer's level of detailed product knowledge and the customer's internal psychological scale of evaluation of a product. More sophisticated, higher-end customers, who invest more resources and have specialists for evaluation, are more likely to resort to joint evaluation and have richer knowledge about the product in question. Consequently, they are more sensitive to real or perceived quality losses from distributed development. This is consistent with evidence from the popular press (Clifford 2013) that states that discerning consumers actively seek detailed information on the development origins of a product. To allow for differential sensitivity to quality loss from distributed development, we model that the utility loss could be (but may not always be) different across the high-end and low-end customers. The utility of each segment can be represented as:

$$u(\theta_L, q) = \theta_L \cdot \eta_L \cdot q \tag{2}$$

$$u(\theta_H, q) = \theta_H \cdot \eta_H \cdot q \tag{3}$$

Here, η_L and η_H are segment specific WTP loss parameters that occur in the range $[0, 1]$. A lower η indicates greater loss. In particular, we assume that the proportional WTP loss for the high end segment is no less than that of the low-end segment implying that $\eta_H \leq \eta_L$. Further, to make the model tractable, we also assume $\theta_H \cdot \eta_H > \theta_L$ implying that $\frac{\theta_L}{\theta_H} < \eta_H \leq \eta_L$. With the consumer's utility function laid out, we begin a closer examination of the reasons for such distributed development. To do so, we describe the relationship between development effort levels, costs and performance qualities.

3.2 Development effort, cost and performance quality relationships

A number of geographic locations in developing countries offer product development capacity at a lower cost partly due to a difference between nominal and purchasing parity exchange rates. Even in the absence of manpower capacity constraints, firms have an incentive to take advantage of such cheaper sources of labor. However, there may be other costs associated with coordination of labor across locations which must be factored in as well, as discussed below. We assume that a performance quality q is an outcome of development effort q and a corresponding convex increasing cost of performance quality q in the original country of design when only one location is involved:

$$c(q) = k \cdot q^2 \tag{4}$$

Since we consider only development-intensive goods, the cost term $c(q)$ is a fixed cost rather than a variable cost of production. We set the variable cost to zero in all further analysis. k is a strictly positive cost coefficient. Suppose now that the firm develops the product by combining effort q_o exerted in the original location and effort q_r exerted in the remote location. The overall effort is $q = q_o + q_r$ but customers perceive a quality lower than q and experience a WTP loss as given by equations (2) and (3). We model the cost of development as functions of location-specific efforts q_o (primary location) and q_r (remote location):

$$c(q) = k \cdot \left(q_o^2 + \alpha \cdot q_r^2 + \beta_C \cdot q_o \cdot q_r - \beta_S \cdot q_o \cdot q_r\right) \tag{5}$$

where $\alpha \in [0, 1]$ is a cost advantage parameter associated with effort exerted at the remote location. β_S reflects the fact that costs can be reduced by splitting work across two locations in an arbitrary fashion even if the remote location has no cost advantage associated with it. This represents an aspect of real product development situations where designers from a different location could add a fresh perspective and this leads to better design outcomes. Thus, for the same budget, they are able to create better quality products. Such economies can occur only if work is split across locations. Consequently, it is represented by a cross-term of effort at both locations. β_C represents coordination costs across teams in different locations working on the same product. In many situations, this coordination cost can be significant. Coordination costs depend on the level of effort exerted simultaneously by both locations (more work leads to more interaction). Thus, the coordination cost is also an interaction term of effort at the two locations. Amaral et al (2011) provide a review of these coordination and communication problems that occur in distributed development. We can simplify the expression in equation (5) by setting $\beta = \beta_C - \beta_S$.

$$c(q) = k \cdot \left(q_o^2 + \alpha \cdot q_r^2 + \beta \cdot q_o \cdot q_r\right) \tag{6}$$

Thus, β reflects the "net cost of distributed development" which is the differential between the coordination costs of distributed development and design benefits of splitting work across locations.

The above cost function assumes that only a single product is produced. Suppose that a product line of qualities q_H and q_L is developed. The cost incurred by the firm in developing both products is given by $c(q_H) + \mu \cdot c(q_L)$ where $c(q_H)$ and $c(q_L)$ refer to individual product related costs as defined in equation (6). $\mu < 1$ reflects the fact there might be design commonalities across the high-end and low-end products such that once the high-end product has been built, the cost to build a unit of quality of the low-end product reduces (as compared to the high-end product) given the common components that are retained. In the extreme case, $\mu = 0$ and the low-end product is a completely degraded version of the high-end product. However, it can be easily shown that "with complete degradation", it is never optimal to offer a product line. Further, several real world examples of development intensive products do not adhere to the complete degradation assumption (for examples, see Krishnan & Zhu 2006). So we set μ to be strictly positive. Further, in the interest of simplifying the parameter space, we set both parameters μ and k to 1 in all further analysis[2]. Now that we have described the customer segments and the firm's costs, we analyze the firm's optimal decision.

3.3 The Firm's Decision

The firm faces choices about how to distribute its development work as well as the number of products to offer to cater to the market diversity. The firm also sets a price for each product that it offers and along with the product quality levels, this determines customer purchase decisions. The firm can offer a single product such that one of the customer segments is left out (*niche* product strategy) or one product that is used by both customer segments (*standard* product strategy). In the *niche* product strategy, the firm offers a product q_N at a price p_N such that only the high-end segment with WTP θ_H buys the product. Thus, the

[2] An analysis of the case where μ is strictly < 1 is provided in Appendix D.

firm's objective is:

$$\max_{p_N, q_N} \quad p_N \cdot n_H - c(q_N)$$

Subject to the individual rationality constraints.

In the *standard* product strategy, the firm offers a product q_S at a price p_S such that both the high-end and low-end segments with WTP θ_H and θ_L respectively buy the product. Thus, the firm's objective is:

$$\max_{p_S, q_S} \quad p_S \cdot (n_H + n_L) - c(q_S)$$

Subject to the individual rationality constraints.

Since there are 2 customer segments that differ in their WTP, the firm can potentially offer a product line (*full product line* strategy) - in this case 2 products, each product catering to a particular segment. In this strategy, the firm offers two products of differing qualities q_H and q_L at prices p_H and p_L respectively such that the high-end segment with WTP θ_H buys product q_H and the low-end segment with WTP θ_L buys product q_L. Thus, the firm's objective is:

$$\max_{p_L, p_H, q_L, q_H} \quad p_H \cdot n_H + p_L \cdot n_L - c(q_H) - c(q_L)$$

Subject to the individual rationality and individual compatibility constraints.

In the basic problem with just one primary development location, we have exactly three strategies to compare. With the option of a remote location, the number of cases that we need to compare increases significantly[3]. At this point, we provide some baseline results

[3] A general nonlinear mixed-integer programming formulation of this problem that considers n customer segments is available with the authors.

which can be used as benchmarks for further analysis.

4 Benchmark Scenarios

Suppose that the firm does not have access to a remote location and has to use only the primary location for development. The optimal solution is similar to prior results obtained by Krishnan and Zhu (2006) without distributed development.

Remark 1 *When there are no capacity constraints and the primary location alone is used for product development, offering both products is* ***not*** *optimal. The optimal product strategy is to offer a niche product when $R \geq 1$ and a standard product when $R < 1$ where $R = \frac{n_H}{n_L}\left(\frac{\theta_H}{\theta_L} - 1\right)$.*

Thus, our baseline result is that a product line is **never** optimal with a linear utility function and a single location. Given that product lines are quite common even with development-intensive goods, we seek to understand if and when distributed development can make product lines profit maximizing. We begin with the case of a capacitated primary location. We model the capacity constraint by imposing an upper bound on the cumulative effort undertaken at the primary location. In the niche and standard product strategies, this amounts to an upper bound on individual product effort at the primary location. However, in the product line strategy, this constraint goes across products. With this in mind, we introduce a baseline result that has not been developed in the literature thus far. Suppose that the development capacity available at the primary location is K.

Proposition 1 *With only a single primary development location that has a capacity constraint K, offering both products is* ***not*** *optimal for a development-intensive good with a*

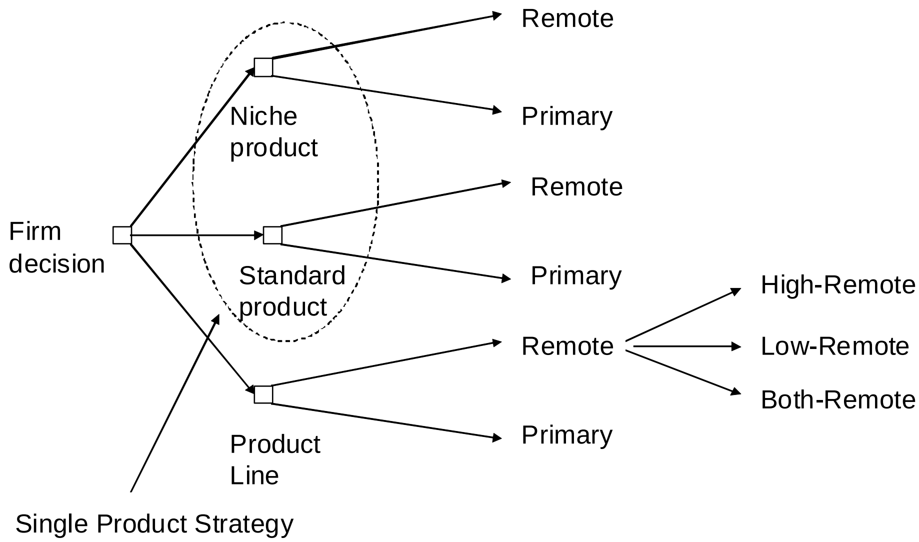

Figure 1: Firm's distributed development / product line options

linear consumer utility function.

This shows that the imposition of a capacity constraint in itself does not change the key result that a full product line is not optimal for a development intensive good with a linear utility function. This result is not only new but will also serve as a benchmark for further analysis. Yet another benchmark result relates to the case where the primary location is not capacitated but a remote location can be used at a cost advantage α and the two consumer segments do not vary in their proportional WTP loss due to remote development (implying that $\eta_H = \eta_L$). To analyze this case, we need to lay out the different options that result as a consequence of remote location availability. Figure 1 lists the firm's distributed development - product line options when a remote development location is available. Each product strategy (*niche*, *standard* or *full product line*) can be implemented either exclusively by the original location (indicated by *primary*) or with shared development work at the remote location (indicated by *remote*). Thus, we now have 8 possible joint product line

- distributed development strategies as opposed to the original problem which had only 3 options. Each of the 8 options listed results in a non-linear programming problem (with a concave objective function to be maximized) in the prices and performance quality levels with its own set of individual rationality (IR) and incentive compatibility (IC) constraints. The IR and IC constraints for each of the above 8 strategies is stated in Appendix A. The profits of these 8 options at optimal prices and qualities have to be compared to obtain the optimal distributed development - product strategy. Based on this, we describe the optimal strategy when $\eta_H = \eta_L = \eta$. This requires the following threshold definition:

$$
\begin{aligned}
\alpha^* &= \frac{4\eta^2 (1-\beta) + \beta^2}{4(1-\eta^2)} \text{ when } 0 \leq \beta < 2\alpha \\
&= \eta^2 \text{ when } \beta \geq 2\alpha
\end{aligned}
$$

Proposition 2 *1) When $\eta_H = \eta_L = \eta$, the optimal joint distributed development-product strategy is to develop the standard product when $R < 1$ and the niche product when $R \geq 1$ with distributed development used only when $\alpha \leq \alpha^*$. The product line strategy is **not** optimal when there is no differential in proportional WTP loss due to distributed development across the high and low-end segments.*

2) Partial allocation of work to the remote location occurs when $\beta < 2\alpha$ and complete allocation of work to the remote location occurs when $\beta \geq 2\alpha$.

Once again, we find that the lack of product line optimality is quite robust, even when a remote development location is introduced as long as the proportional WTP loss perceived by each segment is the same. Further, partial allocation of work to the remote location occurs when $\beta < 2\alpha$ and complete allocation of work to the remote location occurs when $\beta \geq 2\alpha$. The α^* threshold for distributed development changes accordingly. A detailed characterization of this result is available in Lemma **??** in Appendix C. In the next section, we will show that differential consumer response due to remote development is a necessary condition for product line optimality, but is not sufficient. Later, we will derive other conditions that are required to make a product line optimal. This is described in the next section.

5 Analysis of the main model

We focus attention on the main model where there is no capacity constraint binding on the development effort at the primary location, a remote location at lower cost is available for development and η_H is strictly less than η_L. We elaborate on the conditions under which a remote development location is used for a single product strategy based on a comparison of profits. Profit expressions for both single and multiple product strategies are provided in Appendix A. A niche product is developed remotely (either partially or completely) only when cost reduction parameter $\alpha < \alpha_N^*$ and developed at the primary location otherwise. A standard product is developed remotely (either partially or completely) only when $\alpha < \alpha_S^*$ and developed at the primary location otherwise. Here α_N^* and α_S^* are given by:

$$\begin{aligned} \alpha_N^* &= \frac{4\eta_H^2(1-\beta)+\beta^2}{4(1-\eta_H^2)} \text{ when } 0 \leq \beta < 2\alpha \\ &= \eta_H^2 \text{ when } \beta \geq 2\alpha \end{aligned}$$

$$\begin{aligned}\alpha_S^* &= \frac{4\eta_L^2(1-\beta)+\beta^2}{4(1-\eta_L^2)} \text{ when } 0 \le \beta < 2\alpha \\ &= \eta_L^2 \text{ when } \beta \ge 2\alpha\end{aligned}$$

Since $\eta_H < \eta_L$, we can show that $\alpha_N^* < \alpha_S^*$. This then allows us to derive the effort allocation across locations for a product line strategy. Both products in a product line strategy are developed remotely (either partially or completely) when $\alpha < \alpha_N^*$. Only the low-end product is developed remotely (either partially or completely) when $\alpha_N^* \le \alpha < \alpha_{PL}^*$[4]. Both products are developed at the primary location otherwise. The threshold α_{PL}^* is given by:

$$\begin{aligned}\alpha_{PL}^* &= \frac{4X(1-\beta)+\beta^2}{4(1-X)} \text{ when } 0 \le \beta < 2\alpha,\ X < 1 \\ &= X \text{ when } \beta \ge 2\alpha,\ X < 1 \\ &= 1 \text{ when } X \ge 1\end{aligned}$$

where $X = \frac{[\eta_L\theta_L\cdot(n_H+n_L)-\eta_H\theta_H\cdot n_H]^2}{[\theta_L\cdot(n_H+n_L)-\theta_H\cdot n_H]^2}$. The optimal effort allocation for a product line strategy under different development configurations is given in Appendix A. In all the above cases, partial allocation of work to the remote location occurs when $\beta < 2\alpha$ and complete allocation of work to the remote location occurs when $\beta \ge 2\alpha$. A detailed characterization of this result is available in Lemma **??** in Appendix C. This allows us to characterize the optimal joint distributed development-product strategy. First, we analyze the case where the cost advantage from the remote location is either too high or too low (low or high α respectively).

Proposition 3 *1) When $\alpha \ge \alpha_{PL}^*$, the optimal joint distributed development-product strat-*

[4] It can be shown easily that $\alpha_N^* < \alpha_{PL}^*$ when $\eta_H < \eta_L$.

egy is to offer a standard product developed completely in the primary location when $\theta_L \cdot (n_H + n_L) > \theta_H \cdot n_H$ *and a niche product developed completely in the primary location when* $\theta_L \cdot (n_H + n_L) \leq \theta_H \cdot n_H$*.*

2) When $\alpha < \alpha_N^*$*, the optimal joint distributed development-product strategy is to offer a standard product using distributed development when* $\eta_H < \eta_L \left[\frac{\theta_L \cdot (n_H + n_L)}{\theta_H \cdot n_H}\right]$ *and a niche product using distributed development when* $\eta_H \geq \eta_L \left[\frac{\theta_L \cdot (n_H + n_L)}{\theta_H \cdot n_H}\right]$*.*

We find that a full product line is not optimal when cost advantage is either very high or very low. The rationale is as follows. When cost advantage is low (high α) distributed development is not optimal under every product strategy and consequently the conventional intuition of single product optimality from Krishnan and Zhu (2006) applies. When cost advantage is high (low α), remote development is used for all products under every product strategy. Hence, the utility of each customer type is scaled similarly (though not equally since $\eta_H < \eta_L$) under every product strategy and so is the cost function. The final outcome is a scaled version of the conventional product line design problem with a single development location and consequently, the product line is suboptimal. In other words, at high cost advantage, cannibalization issues within the product line again play a dominant role leading to single product optimality. Further, when cost advantage from a remote location is high, a product line is not optimal *even* when the two segments differ in the proportional WTP loss due to remote development. Thus, a differential in proportional WTP loss due to remote development is far from sufficient for product line optimality. This is true even when the cost advantage due to remote development is sufficiently high (low α). This has implications for firms such as Microsoft who are seeking to expand their development activity to far flung locations that may provide significant cost advantages. The resulting cost structure may not enable an increase in product variety *even* when there is significant cost reduction due to such development *and* customer segments vary in proportional WTP loss due to remote development.

Next, we study product line optimality for intermediate cost advantage. Given the number of functions that need to be compared consisting of several parameters, it is analytically messy to derive the entire parameter space that allows product line optimality. However, we do know that a product line strategy is not optimal for two different situations: the baseline case where only the primary development location is available and also the case where the remote location is available but the cost advantage is too high or too low. Consequently, showing that a product line strategy may be optimal for some intermediate parameter values significantly adds to our insight. We state this fact formally in the next proposition. The proposition requires the following threshold definition:

$$\begin{aligned}\alpha_F^* &= \frac{4Y\left(1-\beta\right)+\beta^2}{4\left(1-Y\right)} \text{ when } 0 \leq \beta < 2\alpha,\ Y<1 \\ &= Y \text{ when } \beta \geq 2\alpha,\ Y<1 \\ &= 1 \text{ when } Y \geq 1\end{aligned}$$

where Y is given by:

$$Y = \frac{\eta_L\theta_L\left(n_H+n_L\right)-\eta_H\theta_H n_H}{\theta_H n_H}$$

Proposition 4 *There exists a sufficient set of conditions for the optimality of a product line using distributed development. In particular, this set of conditions involves an intermediate* *range on cost advantage α and high-end customer WTP loss η_H.*

$$\frac{\theta_L}{\theta_H} < \eta_H < \min\left\{\eta_L\left[\frac{\theta_L\cdot(n_H+n_L)}{\theta_H\cdot n_H}\right] - \left[\frac{\theta_H n_H - \theta_L\,(n_H+n_L)}{\theta_H n_H}\right]^2, \eta_L\left[\frac{2\theta_L\cdot(n_H+n_L)}{\theta_H\cdot n_H} - 1\right]\right\}$$

$$\max\{\alpha_S^*, \alpha_F^*\} < \alpha < \alpha_{PL}^*$$

The optimal effort allocation involves developing the high quality product completely at the primary location and low quality product either partially or completely (based on the value of α and β) at the remote location.

The entire parameter space described in Proposition 4 is available in Appendix D. This parameter space only provides a sufficient set of conditions for product line optimality and other conditions can be developed resulting in the same outcome. However, the characteristics of each condition set remain the same: product line optimality occurs at an intermediate level of cost advantage and customer WTP loss. There exists an upper bound on high-end consumer WTP loss in order to allow product line optimality. The magnitude of this WTP loss is such that it differentially degrades the utility function across different product strategies. This differential degradation reduces cannibalization by decreasing the quality perception of the low quality product for the high-end customer segment. From the perspective of the low-end segment, the quality enjoyed under distributed development is higher than under centralized development. Thus the firm is able to implement a strategy where the low-end segment receives a product of higher quality and yet the firm is able to minimize the level of cannibalization. The strategic mechanism through which this result occurs is that a differential response to remote development creates a middle range of cost advantage where differential remote development may occur across the two products in a product line. Under these conditions, a product line is optimal. Either factor by itself, a differential response across the two segments or cost advantage as a consequence of remote development, is not sufficient to show this result. The above results have important implications for firms such as Microsoft when they make future product variety decisions in a distributed development environment.

6 Modifications to the main model

We now turn our attention to modifications to our main model that allow us to extend our basic insights to other relevant scenarios.

6.1 Development capacity constraint at the primary location

As in Section 4, we model a capacity constraint by imposing an upper bound on the cumulative effort undertaken at the primary location. In the niche and standard product strategies, this amounts to an upper bound on individual product effort at the primary location. However, in the product line strategy, this constraint goes across products. This complicates the analysis considerably and makes the derivation of a closed form parameter space that involves product line optimality quite difficult. To keep our focus on the key insights, we make some tractability assumptions: $\alpha = 1$ (no cost advantage at remote location), $\beta \geq 2\alpha$ (no distributed development at the individual product level), $\eta_L = 1$ (reduction in the number of parameters), $\theta_L \cdot (n_H + n_L) > \theta_H \cdot n_H$ (simplification of the parameter space). Proposition 1 sets the stage for further analysis involving a remote development location when the primary development location is capacitated. If we discover a parameter space such that the use of remote development location results in product line optimality, then we have shown that product line optimality is not driven by just a cost argument but also based on a development capacity argument.

Proposition 5 *1) When $K > \frac{\theta_L \cdot (n_H + n_L)}{2}$, the optimal joint distributed development - product strategy is to develop a standard product at the primary location when $\theta_L \cdot (n_H + n_L) > \theta_H \cdot n_H$ and a niche product at the primary location when $\theta_L \cdot (n_H + n_L) \leq \theta_H \cdot n_H$.*

2) When $0 < K \leq \frac{\theta_L (n_H + n_L) - \theta_H n_H}{2}$, the optimal joint distributed development - product strategy is a standard product developed remotely.

3) There exists a sufficient set of conditions such that a product line using distributed development outperforms all other single product strategies. In particular, this set of conditions involves an intermediate range on primary location capacity K and high-end customer quality loss η_H.

$$\frac{\theta_H \cdot n_H}{2} < K < \frac{\theta_L \cdot (n_H + n_L)}{2}$$

$$\frac{\theta_L \cdot (n_H + n_L)}{\theta_H \cdot n_H} - 1 < \eta_H < \frac{\theta_L \cdot (n_H + n_L)}{\theta_H \cdot n_H} - \sqrt{\left(\frac{\theta_L \cdot (n_H + n_L)}{\theta_H \cdot n_H}\right)^2 - 1}$$

The effort allocation in this product line strategy involves developing the high quality product completely at the primary location and low quality product either partially or completely at the remote location.

Once again, as in the cost advantage scenario, we observe that at either very high or very low capacity, the product line is not optimal. At high capacity, there is no binding capacity constraint in the context of any product strategy, distributed development is not used and hence the conventional result from Krishnan & Zhu (2006) applies. On the other hand, at very low capacity, distributed development is used under every product strategy resulting in a similar (but not necessarily equal since $\eta_H \leq \eta_L$) scaling of the utility function for every product strategy. This increases cannibalization and results in single product optimality. Part 3) of the above proposition analyzes the occurrence of product line optimality for intermediate values of capacity K. Given the tractability issues with this model, we demarcate a set of sufficient conditions such that a product line strategy outperforms all possible single product strategies[5]. Once again, a product line strategy outperforms all other single product strategies for an intermediate region of quality loss η_H and capacity K. Thus, our primary results are robust to the addition of a capacity constraint.

6.2 Quality loss proportional to remote location effort

Thus far, we have made the assumption that any loss of quality due to the use of a remote development location affects not just the components developed by the remote location but the whole product. This reflects the nature of the overall physical design of the product which might involve a tight integration of components developed in different regions, a scenario that is widely observed. However, it is possible in some settings that the components developed in different regions are loosely coupled and hence quality loss occurs only to the extent that remote development is used. The utility functions of the low-end and high-end customers as laid out in equations (2) and (3) are modified to give:

$$u(\theta_L, q) = \theta_L \cdot (q_o + \eta_L \cdot q_r) \tag{7}$$

[5] The complete condition set is available in Appendix D

$$u(\theta_H, q) = \theta_H \cdot (q_o + \eta_H \cdot q_r) \tag{8}$$

We go back to the main model where η_L is restrained only by $\eta_H \leq \eta_L \leq 1$, α is restrained only by $0 < \alpha < 1$ and β is free to take on any positive value. An analysis similar to the main model can be undertaken to provide the joint optimal distributed development - product strategy. We report only those results that clarify the connections between this case and the main model[6]. The results for the optimal joint distributed development-product strategy in this context are subsets of situations discussed previously at least for low or high values of β. The intuition for this is as follows: when the distributed development cost β is high, effort allocation across locations for the same product is no longer optimal. Consequently, only one location is used for development for a particular product. If only one location is used per product, then it does not matter whether quality loss affects the entire product or is proportional to remote location effort. Hence, the resulting insights are similar to the main model with high β. At low β and with quality loss proportional to remote location effort, distributed development is always used at the individual product level irrespective of the value of α. As a result, the profit functions for each product strategy are scaled similarly (though not equally), the conventional result applies and the product line is never optimal. For intermediate values of β distributed development outcomes different from the main model may occur. However, it is possible once again to show that product line optimality occurs at intermediate values of cost advantage and perceived quality loss due to remote development. Thus, the basic results of our main model can be extended to this case in a straightforward way.

[6] An exact analysis of this setting is available with the authors.

7 Discussion

Our focus in the paper has been to understand the implications of the growing practice of distributed development of development-intensive products on the level of product variety offered by the firm. The field study example discussed earlier showed how firms wrestle with the issues of managing distributed development and product line design separately at the outset and over time realizing the coupling between these issues. Our work shows how distributed development, motivated by cost advantages at remote locations or relieving capacity constraints, and the associated quality loss can impact the product line design problem. Specifically, we find that the conventional wisdom about the standard single product's optimality does not hold when distributed development is pursued either to obtain a cost advantage or to alleviate a capacity constraint. Interestingly, this occurs at intermediate values of cost advantage, capacity and customer perception of quality loss. The primary driver of this result is the fact that firms can selectively distribute development work for a product line. In particular, if only the low-end product is developed in a secondary location, cannibalization is lower because the 'perceived' quality difference by the high-end customer between the two versions increases even though the low-end customer gets to enjoy a product of higher quality than if remote development were not used. In the context of the product development literature, the capacitated case breaks new ground by emphasizing the importance of supply side factors beyond cost reduction for product line design decisions.

In recent times, firms like Microsoft are beginning to use distributed development not just for cost advantage or capacity enhancement but as a way to understand product needs in emerging markets. Our model can be extended to address these questions as well. Once again, product line optimality may be found at an intermediate value of cost advantage when only the low quality product in the product line is developed at the remote location. Thus, the main insights are robust to the consideration of a customer segment situated in the remote location. In the long run, the emergence of such customers will result in macroeconomic changes which will further alter the product development landscape that the firm operates in. Studying these issues would be an important objective for future research.

References

[1] Amaral, J., E. G. Anderson Jr., G. G. Parker. 2011. "Putting it together: How to succeed in distributed product development". *Sloan Management Review* 52(2): 51–58.

[2] Bas, C. L. and C. Sierra. 2002. "Location versus Home Country Advantages in R&D Activities: Some Further Results on Multinationals Locational Strategies". *Research Policy.* 31(4) 589-609.

[3] Berenbach, B. 2007. "An Introduction to Global Product Lines Requirements Engineering". *International Conference on Global Software Engineering.* 27-30 Aug. 2007 300-301.

[4] Bhargava, H. and V. Choudhary. 2001. "Information Goods and Vertical Differentiation". *Journal of Management Information Systems.* 18(2) 89-106.

[5] Cataldo, M. and S. Nambiar. 2009. "Quality in Global Software Development Projects: A Closer Look at the Role of Distribution". *Fourth IEEE International Conference on Global Software Engineering.* 163-172.

[6] Chen, Y. and S. Seshadri. 2007. "Product Development and Pricing Strategy for Information Goods Under Heterogeneous Outside Opportunities". *Information Systems Research.* 18(2) 150-172.

[7] Clifford, S. 2013. "Some Retailers Say More About their Clothing's Origins". http://www.nytimes.com/2013/05/09/business/global/fair-trade-movement-extends-to-clothing.html?pagewanted=all&_ro . Accessed September 11, 2013.

[8] Cordell, V. 1992. "Effects of Consumer Preferences for Foreign Sourced Products". *Journal of International Business Studies.* 23(2) 251-269.

[9] Cusumano, M. 2008. "Managing Software Development in Globally Distributed Teams". *Communications of the ACM.* 51(2) 15-17.

[10] Damian, D. and D. Zowghi. 2003. "Requirements Engineering Challenges in Multi-site Software Development Organizations". *Requirements Engineering Journal.* 8 149-160.

[11] Desai, P., S. Kekre, S. Radhakrishnan and K. Srinivasan. 2001. "Product Differentiation and Commonality in Design: Balancing Revenue and Cost Drivers". *Management Science.* 47(1) 37-51.

[12] Druehl, C. and G. Schmidt. 2008. "A Strategy for Opening a New Market and Encroaching on the Lower End of the Existing Market". *Production and Operations Management.* 17(1) 44-60.

[13] Eppinger, S. and A. Chitkara. 2006. "The New Practice of Global Product Development". *MIT Sloan Management Review*, 47(4) 22-30.

[14] Gotel, O. V. Kulkarni, M. Say, C. Scharff and T. Sunetnanta. 2010. "Quality Indicators on Global Software Development Projects: Does 'Getting to Know You' really matter?". *International Conference on Global Software Engineering*. 24(2) 169-184.

[15] Han, C. and V. Terpstra. 1988. "Country-Of-Origin Effects for Uni-National and Bi-National Products". *Journal of International Business Studies*, 19(2) 235-254.

[16] Herbsleb, J. and A. Mockus. 2003. "An Empirical Study of Speed and Communication in Globally Distributed Software Development". *IEEE Transactions on Software Engineering*. 29(6) 481-494.

[17] Hise, R. T., L. O'Neal, A. Parasuraman and J. McNeal. 1990. "Marketing / R&D Interaction in New Product Development: Implications for New Product Success Rates". *Journal of Product Innovation Management*. 7(2) 142-155.

[18] Hsee, C. and J. Zhang. 2010. "General Evaluability Theory". *Psychological Science*. 5(4) 343-355.

[19] Jiminez, M., M. Piattini and A. Vizcaino. 2009. "Challenges and Improvements in Distributed Software Development: A Systematic Review". *Advances in Software Engineering*. Article ID 710971.

[20] Julian, S. and R. T. Keller. 1991. "Multinational R&D Siting: Corporate Strategies for Success". *The Columbia Journal of World Business*, Fall, 47-57.

[21] Komi-Sirvio, S. and M. Tihinen. 2005. "Lessons Learned by Participants of Distributed Software Development". *Knowledge and Process Management*. 12(2) 108-122.

[22] Kommeren, R. and P. Parviainen. 2007. "Philips experiences in global distributed software development". *Empirical Software Engineering.* 12 647-660.

[23] Krishnan, V. and W. Zhu. 2006. "Designing a Family of Development-intensive Products". *Management Science.* 52(6) 813-825.

[24] Kumar, N. 2001. "Determinants of Location of Overseas R&D Activity of Multinational Enterprises: The Case of US and Japanese Corporations". *Research Policy,* 30(1) 159-174.

[25] Moorthy, S. and I. Png. 1992. "Market Segmentation, Cannibalization and the Timing of Product Introductions". *Management Science.* 38(3) 345-359.

[26] Netessine, S. and T. Taylor. 2007. "Product Line Design and Production Technology". *Marketing Science.* 26(1) 101-117.

[27] Papadopoulos, N. and L. Heslop. 1990. "A Comparative Image Analysis of Domestic vs. Imported Products". *International Journal of Research in Marketing,* 7(4) 283-294.

[28] Santos, J., Y. Doz and P. Williamson. 2004. "Is Your Innovation Process Global". *MIT Sloan Management Review*, 45(4), 31-37.

[29] von Zedwitz, M. and O. Gassmann. 2002. "Market versus Technology Drive in R&D Internationalization". *Research Policy.* 31(4) 569-588.