World Review of Business Research
Vol. 4. No. 2. July 2014 Issue. Pp. 222 – 240

Compatibility of Modular Products in a Vertically Differentiated Industry: The General Case of Quality Leadership

Farooq Sheikh*

This article is a study of firms' incentives for proprietary or common interface in a vertically differentiated duopoly. Modelling the firms' behaviour as a single-period non-cooperative game of complete information we show that standard interface obtains as a unique Nash equilibrium under complete quality leadership. However, adoption of a common interface is feasible when firms are module-wise cost competitive; else proprietary interface will obtain. Thus we add to the extant literature by considering vertical differentiation of modules and assembled products; further we demonstrate that the industry choice of standard or proprietary interface is a function of whether quality leadership is concentrated or distributed.

JEL Codes: D21 and C72

1. Introduction

Modular products comprise detachable functional components or modules that are generally easy to assemble, often by end-users themselves. Examples of such products are SLR camera systems, home theater systems, PC systems etc. To facilitate coordination and communication between inter-connecting modules in a modular product, the modules need to be equipped with compatible *interfaces*; two complementary modules can be usefully assembled only if they have the matching interface. The interface that is in use in an industry thus critically influences the product space. The question of compatibility of interfaces arises specifically with regard to matching modules produced by different manufacturers. Arguments are generally made both in favor of and against the use of a standard interface. Indeed, manufacturers of modular products consider the use of standard interface both from the profit stance as well as that of strategy. Among industries that use modular architecture, some use standard interface allowing free matching between complementing modules regardless of origin, while others use proprietary interfaces. In principle, even if an industry uses a standard interface, an individual manufacturer is free to use a proprietary interface; however, instances of manufacturers as such are not common. For an individual firm, the choice of interface-type is influenced by long term strategy considerations as well as short term competitive profits considerations. For instance, in case of a two-module product, it is conceivable that a firm manufacturing modules of different levels of quality can secure market for its lower quality module by restricting buyers through use of proprietary interface; by this it can induce buyers to acquire its lower quality module via the appeal of its higher quality module. Under a standard interface, on the other hand, the firm would not be able to push the sale of its lower quality module except through the usual means of competitive pricing. Consequently, sale of the lower quality module could suffer on account of the module's inferior quality. In the early days of Internet Explorer, Microsoft's strategy of adapting its OS to provide agility to its browser at the expense of Netscape browser reflects a similar motivation where Microsoft attempted to effect benefits of interface ownership. Clearly, quality competition is intensified under standard interface where each seller is competing individually in the market of each module and buyers can match complementing modules

* SUNY Geneseo, NY, USA. E-mail: sheikh@geneseo.edu

from different manufacturer. Taking this view, one can argue that manufacturers would tend to prefer proprietary interfaces.

How do buyers' view the two types of interfaces? Standard interface instigates module-based competition between manufacturers and hence promises better prices for buyers; moreover, products can be assembled from any arbitrary set of complementing modules regardless of origin, and consequently can be obtained in a wide range of quality choices. In short, under standard interface buyers get access to the full spectrum of qualities at competitive prices; under proprietary interfaces, on the other hand, products are restricted in quality offerings, and hence price competition is likely to be blunted in comparison to that of standard interface. One could argue that consumer benefits under standard interface well exceed those under proprietary interface.

It is worthwhile, even if for comparison's sake, to point out that with *horizontally* differentiated products or in a market that is sensitive to horizontal preferences, the optimal choice of interface might be quite different. In a milieu characterized by the dominance of horizontal differentiation (of customer preference or of product) firms would find standard interface attractive because standard interface increases product variety in their appeal to buyers of idiosyncratic preferences. Increasing the number of horizontally differentiated products reduces transportation costs for buyers and effectively increases their willingness to pay. In this scenario, standard interface increases size of the potential market of the modules and, in addition, effectively increases valuation of products in the eyes of the buyers. Indeed, contrary to our observation in quality differentiated products, the profit gains to firms using standard interface clearly exceeds that of proprietary interface. The buyers obviously prefer the use of standard interface because it increases their chance of getting a product that is closest to their subjective preference. The buyers and the sellers all agree on the benefits of standard interface!

From the sellers' perspective, there are arguments that can be made for both standard interface as well as proprietary interface depending on the nature of *product differentiation*. Evidently, the issue of interface selection is not a trivial matter. In this article, we attempt to understand the interface preference of firms, by studying a *vertically* differentiated duopoly of a two-module durable product under different structures of quality leadership. It is important to note at the outset that a standard interface can be sustained only if *all* firms agree on the use of standard interface; short of a consensus, only proprietary interface will prevail!

As noted, use of both types of interfaces is well evidenced. The use of proprietary interface is well exemplified by the SLR camera industry. Typically SLR cameras consist of two modules[1], the lens system and the camera body; end-users can easily fit out a camera body with a lens system they desire provided the components or modules are compatible. In practice, in the SLR systems in the market manufacturers[2] do not use a standard interface that would have allowed buyers to cross match lenses and camera bodies from different manufacturers. Interestingly however, manufacturers of camera bodies let third party lens manufacturers (like Tamron, Sigma etc.) to make lenses that can be fitted to their camera bodies! For a good example of standard interface, the IBM PC industry stands out prominently. In contrast to SLR manufacturers, the PC makers use a standard interface for all components across the industry. So indeed, it is not quite clear why manufacturers in some industries prefer to use proprietary interface for their products, while manufacturers in other industries prefer a standard interface. It is also probable that in some industries, proprietary interfaces may be too costly to enforce and thus a common interface emerges by default. For instance, in the home theater industry it is not clear if a proprietary interface is indeed enforceable, since the interface comprises copper wires carrying electromagnetic signals which can be decoded easily. We suspect that industries so constrained will adopt quality strategies to optimize profits under the assumption of standard interface. In this paper, we specifically direct our attention to an industry of a modular product where manufacturers have clear quality ranking in the eyes of the buyers and the product technology can support use of proprietary interfaces if a manufacturer so desires.

In the literature, interface compatibility has been considered mostly with regard to horizontally differentiated products predominantly with a view to underscore its salubrious effect on increasing product variety. As pointed out earlier, by using compatible interfaces, manufacturers increase the variety of available products, effectively reducing transportation costs for buyers in the Hotelling sense and thereby increase their profits. In this setting either products are horizontally differentiated, or buyers are idiosyncratic in their valuation of modules. When buyers are in common agreement about the quality differentiation of the products, the prospect of mutual gain from compatible interface is not obvious. In this paper, which integrates findings of a preceding sister paper (Sheikh, 2014), we show that product heterogeneity and consumer subjective preferences are not the only forces influencing the adoption of interface; the choice of interface is equally affected by the quality leadership structure prevailing in the industry. Our research is particularly relevant to technological products where quality perception, mediated by expert reviews and consumer reports, has resulted in unanimous consumer agreement on product/module quality and the nature of industry quality leadership. Surprisingly, this aspect of industry dynamics in interface election has not been addressed before.

In the remainder of the article the organization will be as follows: section 2 presents a survey of relevant literature, section 3 explains the details of the setup, section 4 analyzes the two cases of quality leadership in duopoly and provides the results, and section 5 includes conclusion and discussion.

2. Literature Review

The literature on compatibility of modular products has mostly concentrated on the salutary effect of compatibility on product variety, in the horizontal sense. This approach has resulted in demonstrating an overall preference for standard interface. The problem of product compatibility in modular products differentiated in quality alone (free of consumer idiosyncratic preferences) has not been fully considered; the contribution of this article is to address this aspect of the issue. In the context of this modular products, there are four papers that are closely related to our work. These are Matutes and Regibeau, 1985; Economides, 1989; Einhorn,1992; and Farrell, Saloner and Shapiro, 1998.

Most of these papers focus on horizontally differentiated products---differentiation arising either out of difference of product features or as a consequence of buyer *idiosyncrasy*. In contrast to our model, all these papers (with the exception of Einhorn) analyze models assuming consumer to be *homogeneous* in regard to their willingness to pay. Below, we discuss the main distinguishing features of each of these papers and their contributions; finally we discuss how our research extends the extant literature.

Matutes *et el* considers buyers to be homogeneous in their reservation prices but heterogeneous in their product preferences: the same product may be valued differently by different buyers for quite subjective reasons. It is shown that with compatibility both firms earn higher profits and equilibrium prices are likely to be higher. Economides models an *n*-firm oligopoly with similar heterogeneity of preferences among buyers. The modeling approach of this paper is different from that of Matutes *et el*; however, the major result is the same. The prices and profits are in general higher with compatibility; the intuition is that of the well-known Hotelling model where buyers are distributed spatially (on a line) to denote their ideal product preference. By consuming a product at variance with their ideal preference buyers incur a dis-utility measured by how different the product is from their ideal preference; the dis-utility incurred is the so called transportation cost. Increased offering in product variety results in lower average transportation costs since buyers are more likely to find a product close to their ideal preference than when there is no product variety; the savings in transportation costs are partly transferred to firms as increased profits.

Einhorn generalizes the models of Matutes *et el* and Economides to include quality, but without buyers' unanimity, that is buyers do not agree about the quality level of the modules or products available; they, however, are homogeneous in their willingness to pay. The main result is that profits weakly increases with compatibility or standard interface. The intuition is the same as that of other papers---compatibility increases product variety and hence increased profits. This paper is the closest to ours in the sense that it considers quality, but differs by modeling subjective assessment of quality.

The Farrel, Saloner and Shapiro (1998) paper primarily addresses the issue of industry preference for compatibility from the cost perspective; however, the results are shown to be applicable to quality differentiated products by way of establishing correspondence between high quality and low cost, and low quality and high cost. Like Matutes *et el*, the authors assume buyers' homogeneity, but don't assume horizontal differentiation of the components. It models an environment where firms make decisions about compatibility *before* the realization of cost or quality. Markets under both duopoly and oligopoly are considered. It is shown that under duopoly, firms prefer an open organization (compatible products) but the preference reverses as the number of firms increase.

Our paper has two major departures from these papers. First we model buyers to be heterogeneous in their reservation prices. Second, in our model firms are differentiated in quality and buyers *unanimously agree* on the quality of each module as well as the quality of the fully *assembled* product. This second difference is notable in reference to Einhorn. In addition, we assume an environment of complete information, which is different from that of Farrel *et el*. Our results are quite in contrast with the results of these papers. Our main result is to show that in duopoly standard interface is inevitable if firms have *consistent* quality ranking across modules as well as assembled *pure* products, else proprietary interface will obtain even though the total industry profits are higher with a standard interface. These results can shed light on practices in the SLR camera industry as well as the PC industry. Our findings offer insights to managers with regard to the problem of compatibility and quality choices of their products. These results are also relevant in the determination of procurement strategies in the context of supply chain management.

Since the publication of the above papers, the focus of the interested research community was captivated by popular debate over the use of open-platform and open-source in the software industry, where products are inherently modular in nature; subsequent research has been prolific in that area leaving unanswered many of the questions pertaining to “physical” modular products as addressed by this article. There have been a couple of papers that have focused on exploring relationship between “degree of modularity” of a product and its complexity or adaptation for outsourcing, but none on the choice of interface strategies. There is one paper by the author (2014) which addresses the problem of interface strategy in case of a vertically structured industry; the analysis and results of the research is included in this article to complement the case of distributed quality leadership in order to render a coherent narrative and present a complete analysis of the general problem.

The importance of quality ranking of modules themselves have not been addressed by any of the papers; we show that if quality leadership resides in a single firm, then "standard interface" will prevail to the benefit of all firms; on the other hand distributed leadership will instigate coordination concerns akin to the Prisoner's Dilemma game which will result in proprietary interface.

3. The Methodology and Model

Our modeling approach and analysis largely follows that of extant literature on the same subject. In the literature firms have been modeled as either selling integrated products or individual modules as the only products, and the standard approach has been to compare the profits under each product regime. Generally, gain from the sale of individual modules as the only products, has been construed as a proxy for a preference for the open standard format and vice versa. In our paper we have adopted an approach similar to this; however, we have also considered the regimes when firms would sell both modules and individual products.

Products*:* We consider a product consisting of two modules, X and Y where, for example Y_j is the Y module produced by firm, $j: j \in \{a, b\}$. Module X_j is associated with the quality factor α_j and module Y_j is associated with quality factor, β_j. An assembled product is denoted by P_{ij} and is understood to have been assembled from modules X_j and Y_j, where the first subscript i identifies the source of X module and the second subscript identifies the source of Y module. The quality associated with product P_{ij} is the sum of the quality factors of the constituting modules, that is $\alpha_i + \beta_j$. A product P_{jj} having both the components originating with the same manufacturer is referred to a *pure* product, and a product $P_{ij}: i \neq j$ is referred to as a *mixed* product.

Buyers*:* Buyers are heterogeneous in their willingness to pay for an assembled product. The willingness to pay is parameterized by θ which is to be understood as the valuation for a product of unit quality factor; for a buyer of willingness θ the valuation of a product P_{ij} of quality factor, $\alpha_i + \beta_j$. is given by $\theta(\alpha_i + \beta_j)$. In general θ is distributed in the interval [$\underline{\theta}$, $\bar{\theta}$], with cumulative distribution function $F(\theta)$ and continuous density function $f(\theta)$. For our analysis we assume θ to be uniformly distributed in the interval [0,1], with $f(\theta) = 1$ and $F(\theta) = \theta$. Buyers buy only one product and are net utility maximizers.

Sellers/Firms The number of manufacturers/sellers may be two or more, depending on the type of industry being considered, and the manufacturers might be active in manufacturing both the modules (in the two-module context considered in this paper) or just one module. In this paper, we restrict ourselves to considering a duopoly comprising two manufacturers who for exogenous reasons prefer and are capable of manufacturing both the modules. We thus exclude from our consideration equilibrium outcomes where it is best for one firm to manufacture only one module. Sellers are labelled by uppercase Roman letters (*A* or *B*); all decision variables, parameters and products pertaining to a firm are subscripted in lower case by its letter-label. Marginal costs of production of the module(s) are assumed asymmetric across firms with the qualification that a higher quality module costs no less than a corresponding module of lower quality. Sellers are assumed to be risk neutral and net profit maximizers.

3.1 Solution Concept

We model the process as a single-period, simultaneous move game of complete information; sellers engage in a Bertrand price competition. The equilibrium notion is that of Nash equilibrium. The notion of interface types is as follows. Standard interface or open standard, is freely available to any firm that chooses to be in the industry. Proprietary interface, on the other hand, is subject to legal control by the originating firm, who retains absolute right over its use, and may offer its use to any other firm on contractual terms for a flat fee or some other payment basis.

When do firms prefer a standard interface? The answer to this question may not be simple and there are diverging wisdom on this issue. However, it is obvious that firms will have incentives to adopt a common or standard interface when there are gains from market of mixed products formed by assembling modules from multiple sources; and when this is sustainable under individual rationality constraint of the manufacturers. The aim of this research is to identify conditions when such gains accrue to the firms in a duopoly. In this sense, open standard would be unequivocally viable if there is a clear preference for it amongst all members of the industry and when there is no additional gain from deviation; else proprietary interface will prevail.

In our analysis use of proprietary interface is modelled by requiring the manufacturers to sell assembled pure products only. Use of standard interface is modelled by requiring manufacturers to sell their products in whatever manner a customer might demand, single modules or as bundles of modules; however, we require manufacturers to price their modules individually without offering price discounts to those who buy *both* of their modules in pair or their pure product, this would be referred to as "additivity" constraint. In equilibrium this, indeed, is feasible only when there is no gain from bundling their modules. Under standard interface, the firms price each individual module and the pure product such that the price of the pure product is simply the sum of the prices of the individual modules. In our analysis of the standard interface, we also study the same problem by relaxing the price additivity constraint on the pure product to examine the *ex post* robustness of the equilibrium.

It is worth noting here, that in some industries, proprietary interface may not be enforceable in the sense that physical design of proprietary interface is not feasible. However, firms may induce the same outcome as proprietary interface by simply choosing to sell their modules assembled as a product or as a pre-assembled *set of modules* only. If, indeed, there is gain to standard interface they will sell the modules individually as well. It can be shown that under standard interface, *ex post* equilibrium, even if firms sell *individual* modules and assembled products (or modules as a set), the price of the assembled product (or modules as a set) is the same as the sum of the prices of the individual modules.

Our approach in analysis is as follows. We calculate profits for each firm assuming a standard interface employing the price additivity constraint on the price of the pure product, and then we analyse the problem by relaxing the price additivity constraint to examine if, *ex poste* any of the firms would deviate from the equilibrium to increase its profits. Note that a single deviation is enough to establish the inevitability of proprietary interface. If any one of the firms appears to have higher profits with proprietary interface, we conclude that the industry would operate with proprietary interfaces. Thus firms have veto power in the adoption of a standard interface. In our modelling approach, the use of standard interface is to be inferred from the equilibrium strategies. Specifically, we model a simultaneous move game of complete information to analyse for equilibrium strategies of the firms. The strategy space of each firm or manufacturer includes {MP,IMP,IP}, where MP and IMP strategies assume standard interface; these strategies are explained below.

MP: The seller prices the modules only; employs the price additivity constraint that ensures that the price of its pure product is exactly equals to the sum of the prices of its modules.

IMP: The seller prices the modules as well as its pure product by bundling its modules; price additivity constraint is relaxed to allow the price of its pure product to be equal or *less* than the sum of the prices of its modules.

IP: The seller sells only it pure products bundled or pre-assembled ; this is a case of using proprietary interface.

Note that **MP** and **IMP** both presuppose standard interface. An equilibrium outcome that proves both the firms to be indifferent between MP and IMP strategies with a dominated IP-strategy (for both firms), is a clear indication of an equilibrium adoption of standard interface. Any other equilibrium outcome would be an indication of the industry's adoption of proprietary interface. An equilibrium in IMP-strategy needs to be understood in the context of how quality leadership is distributed in the industry. In general IMP-strategy always induces the ownership or sale of pure product of the firm. So resorting to IMP-strategy has the likelihood of (i) decreasing profits of the rival firm, and (ii) isolating the market of one of its modules; both these happen simultaneously when the effect is adverse. Unless a firm is indifferent between MP-strategy and IMP-strategy, adoption of the latter would switch the equilibrium to the adoption of proprietary interface.

3.1.1 Assumptions and Nomenclature

In this section we state the underlying assumptions of our analysis. Our study is of a duopoly where both manufacturers are capable of manufacturing and have invested capital on the production of both the modules.

Assumption 1**:** *There is negligible cost difference between proprietary and standard interface, at least not in any way detrimental to the selection of a standard interface.*
This assumption has been common to the literature and is helpful for the normative study of the effect of standard interfaces in modular products without distractions.

Assumption 2**:** *Firms have strategic preference to sell their pure products (both the modules) to some buyers even; they will accept a deviation from this preference if the industry converges on pricing modules only without applying pricing discounts to promote or increase sale of pure products or bundled modules.*

In this article both the players are manufacturers of original equipment (OEM) and they will be interchangeably referred to as firm(s), seller(s) or manufacturer(s); modules refer to the components of the product; mixed product refers to an assembled product comprising one module from each of the firms; pure product refers to a product assembled by using modules from the same firm; a full product refers to an assembled product.

4. Analysis and Findings

In a vertically stratified duopoly of a two-module product, by assumption one of the pure products would be of a higher quality than that of the other; and so one firm would be a quality leader in the domain of pure products. However, higher quality pure product does not necessarily imply that the same firm produces both the higher quality modules. The total quality of the pure product is the sum of the qualities of both the modules assembled. In module-wise comparison, the higher quality modules might be produced by the same firm or each of the firms might each produce a higher quality module. We refer to the former regime as that of **Single Quality Leadership (SQL)**, and the latter as that of **Divided Quality Leadership (DQL)**. Under the use of standard interface, both Single Quality Leadership (SQL) and Divided Leadership (DQL) will result in three qualities of products that would be owned in equilibrium; the ranking of the products, however, are different by comparison of their constitution. In SQL the highest quality and the lowest quality products obtainable are both pure products; in DQL, however, the highest quality and the lowest quality products obtainable are both **mixed** products. For our purposes and without loss of generality, we assume firm A to be the "overall quality leader" **OQL** in both the regimes.

The integrated product of firm A, P_{aa}(assembled from X_a and Y_a) is of a higher quality than the integrated product of firm B, P_{bb} (assembled from X_b and Y_b), which implies that, $\alpha_a + \beta_a > \alpha_b + \beta_b$. In SQL**,** in addition, $\alpha_a > \alpha_b$ and $\beta_a > \beta_b$. In DQL, either $\alpha_a > \alpha_b$ and $\beta_a < \beta_b$ hold, or $\alpha_a < \alpha_b$ and $\beta_a > \beta_b$ hold, besides the assumed condition that $\alpha_a + \beta_a > \alpha_b + \beta_b$hold in pursuance of an overall quality leadership. WLOG, for DQL in our analysis we assume, $\alpha_a > \alpha_b$ and $\beta_a < \beta_b$.

In this article we investigate the propensity among firms to use proprietary interface (**PI**) or standard interface. Use of **PI** is tantamount to selling integrated or bundled pure products. It is now important that we define as to what preferences or actions we consider to be indicative of a preference for standard interface (**SI**). In proprietary interface there are only pure products in the market; with standard interface, the sellers might sell only modules or both modules and bundled pure products. In our paper, (**SI**) must be sustainable without explicit contracts or agreements; it is an equilibrium outcome if...

(i) None of the companies can deviate to using proprietary interface unilaterally without also inflicting losses to itself if the other retaliates, or
(ii) None of the companies can deviate to bundling its pure product or using proprietary interface in a way that enables it to extract rents from the other firm to the extent of reducing its profit to a value arbitrarily close to its profits with proprietary interface.

We will refer to the first condition as **non-deviation** condition and the second as **double-deviation** condition. The **non-deviation** condition implies that **SI** will be sustained because deviation by one of the firms will not *automatically* increase its profits without some kind of previous **agreement** with the other firm which would require it to yield a part of its share of profit gains to the deviating firm. The **double-deviation** implies that deviation might earn higher profits to the deviating firm without any previous agreement with the other firm whose profits could decrease considerably; whenever conditions supporting such deviations exist, firms would inevitably switch to the adoption of **PI**. Our analysis will proceed by first obtaining profits for each firm under proprietary interface. We will then analyze equilibrium profits assuming a standard interface with price additivity constraint. To test whether standard interface will hold in equilibrium, we will proceed in two steps. In step 1 we will compare **SI**-profits to that of **PI**-profits; if at least one seller is better off with using proprietary interface, we stop and conclude that the industry will use proprietary interface since standard interface requires a consensus. If both firms are better off with standard interface, we proceed to the second step and analyze to see if any of the firms has any incentive to switch to some pricing mechanism to extract rent from the rival firm without at the same time decreasing its own profits. To check for this, we analyze the standard interface formulation by relaxing the price additivity constraint. If our analysis proves a positive incentive for some firm to extract rents by bundling it pure product with price discount, we conclude that the use of standard interface will be rejected by one of the firms and proprietary interface will be adopted; else, we conclude that standard interface will be embraced by both firms. The strategies corresponding to each objective are explained below.

Our starting assumption is that the product in question comprises two functional modules that can communicate via a standard interface or a proprietary interface that are cost equivalent. Firms' strategies, however, are modeled through their preference over prices of their modules and combination of modules. There are three possible strategies: a firm can use (i) MP-strategy and sell individually priced modules without giving price breaks to customers for buying *both* the modules, or (ii) IMP-strategy where it prices the modules individually but gives price breaks when customers buy both the modules (we assume no arbitrage), or (iii) IP-strategy of selling their modules bundled as *pairs only* or sold as an integrated product. Use of MP-strategy is the best proof of preference for standard interface. Adoption of MP-strategy by both the firms when none wants to deviate, knowing that the other firm is playing MP-strategy, would be a clear statement of preference for **IS**. However, in a non-cooperative game, each firm will consider deviating if it can increase its profit by doing so. Potentially (as will be shown later) a deviating firm would choose IMP-strategy against MP-strategy adopted by its rival. Use of IMP-strategy by one form may or may not trigger the adoption of IMP-strategy by the rival firm. Reactive adoption of IMP}-strategy would only occur when switching to IMP-strategy by one firm has adverse effect on the profit of the other firm. Switching to IMP-strategy by both the firms is an indication that both want to sell their pure products disregarding the full gains of **SI** via the use MP-strategy. Hence, equilibrium adoption of IMP-strategy is a proxy for the adoption of **PI**, or proprietary interface. Thus, **SI** would be sustainable if a firm finds no difference between IMP-strategy or MP-strategy given that the rival firm is playing MP-strategy. Using our criteria for the sustainability of **SI**, we can rephrase our condition for *ex poste* sustainability of **SI** as follows: **SI** is sustainable only if IMP-strategy is profit-equivalent to MP-strategy for both the firms.

4.1 Single Quality Leadership (SQL)

Under SQL with standard interface, in equilibrium buyers own products of at most three qualities. Since modules are ranked by quality there is exactly one mixed product, and it occupies the middle-level of quality, attracting the mid-segment of buyers in the active market. This is illustrated by figures 1 and 2. Basically, the mixed product would be the one arising from the more highly demanded of the two modules by each firm. For instance, if module $X_a$of firm is in greater demand than module, Y_a, and module Y_b, is the more highly demanded module of firm B, the resulting mixed product in demand would be P_{ab}, and vice versa. The demand for a module, however, is determined by how buyers view it against price-quality mix of the rival module.

Figure 1: Distribution of sold modules: number of $X_a$units exceeding units of Y_a

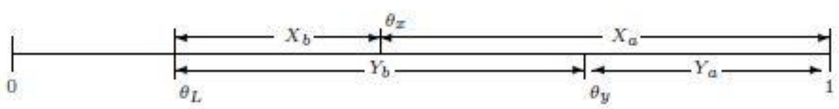
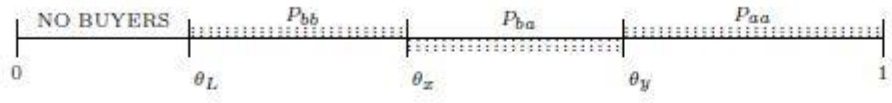


Figure 2: Distribution of corresponding assembled products sold



In the figures buyers between 1.0 and θ_x buy $X_a$module while those between $\theta_x$and θ_L, buy the module X_b; the buyer at θ_x is indifferent between the two qualities of X-modules. Buyers are similarly segmented in case of Y modules; in this case the buyer indifferent between the two qualities is denoted by, θ_y.The buyer at θ_L is indifferent between buying a product and not buying anything at all. In the outcome reflected by figure 1, buyers own one of the three final products, P_{aa}, P_{ab} or P_{bb}. Figure 3, on the other hand, depicts a scenario with market forP_{ba}, in addition to that of the two pure products. Figure 4 corresponds to figure 1 except that it reflects segments of buyers by the make of the *assembled* products they prefer to buy. We can see that in any given scenario, there exists a market for only *one* mixed product but not both. The following Lemma reflects this property.

***Lemma 1*:** In equilibrium the number of different quality levels of products that will be owned by buyers cannot exceed three.

Figure 3: Distribution of sold modules: number of $Y_a$units exceeding units of X_a

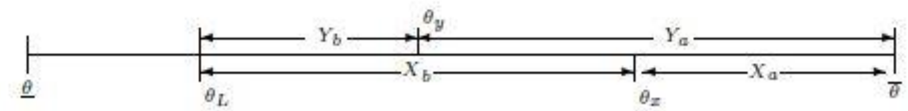
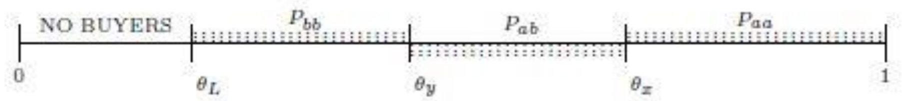


Figure 4: Distribution of corresponding assembled products sold



4.1.1 Proprietary Interface

In the regime of proprietary interface manufacturer i sells only its pure product, P_{ii}; in effect it sells its modules bundled as a single product at one price, p_{ii}. The profit functions of the two firms are as follows.

(a) $\pi_{pa} = (1 - \theta_{ab})(p_{aa} - c_{aa})$

(b) $\pi_{pb} = (\theta_{ab} - \theta_{Lp})(p_{bb} - c_{bb})$

In the above equations θ_{ab} is index referring to the marginal buyer indifferent between products P_{aa} and P_{bb}, and $\theta_{Lp}$is the index of the buyer indifferent between buying product P_{bb} and not buying anything at all and are defined as, $\theta_{ab} = \frac{p_{aa} - p_{bb}}{(\alpha_a + \beta_a) - (\alpha_b + \beta_b)}$ and $\theta_L = \frac{p_{bb}}{(\alpha_b + \beta_b)}$ where $p_{aa}$is the price of the pure product P_{aa}consisting X_a and Y_a, p_{bb} is the price of the pure product P_{bb} consisting X_b and Y_b; the costs of the products are given by, $c_{aa} = c_{xa} + c_{ya}$and $c_{bb} = c_{xb} + c_{yb}$. The point of market segmentation between buyers' group is θ_{ab}, determined by employing *individual incentive compatibility constraint* (ICC): $\theta(\alpha_a + \beta_a) - p_{aa} \geq \theta(\alpha_b + \beta_b) - p_{bb}$; all buyers indexed by θ higher than θ_{ab}buy the higher quality product P_{aa}, and those with θ lower than θ_{ab}buy the lower quality product P_{bb}. The identity of the buyer indifferent between P_{aa} and P_{bb} is obtained by solving for θ_{ab}while holding the IC constraint at equality. For each buyer the *individual rationality constraint* (IRC) must hold true as well, i.e. $\theta(\alpha_i + \beta_i) - p_{ii} \geq 0$. The IRC constraint when held at equality for buyers of the lower quality product P_{bb} in turn determines the marginal buyer of index θ_L that is indifferent between buying product P_{bb} and not buying anything at all.

Proposition 1: Under proprietary interface the equilibrium prices and the consequent marginal buyers are as follows:

(i) $p_{aa} = \frac{(\alpha_a+\beta_a)(2c_{aa}+c_{bb}+2(\alpha_a-\alpha_b)+2(\beta_a-\beta_b))}{4(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}$

(ii) $p_{bb} = \frac{2c_{bb}(\alpha_a+\beta_a)+(\alpha_b+\beta_b)(c_{aa}+(\alpha_a-\alpha_b)+(\beta_a-\beta_b))}{4(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}$

(iii) $\theta_{ab} = 1 + \frac{1}{3}\left(\frac{c_{aa}-c_{bb}}{(\alpha_a+\beta_a)-(\alpha_b+\beta_b)} + \frac{(2c_{aa}+c_{bb}-6(\alpha_a+\beta_a))}{4(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}\right)$

(iv) $\theta_{Lp} = p_{bb}$

Proof: The proof is simply obtained by applying the first order conditions (FOC) from calculus on the profit functions, and solving the resulting linear equations in prices to obtain the equilibrium prices. Substitution of the equilibrium prices in the ICC constraint and IRC constraint held at equality yield equilibrium values of marginal buyers θ_{ab} and θ_{Lp} respectively. ■

The equilibrium values obtained are used to calculate the equilibrium profits which we skip here but can be provided by the author on request. We will, however, use the equilibrium prices and profits in proprietary interface as a benchmark to establish the admissibility of equilibrium prices and hence profits under standard interface.

4.1.2 Standard Interface

Under Standard Interface, we first start by assuming that all sellers primarily price their modules without offering any price discount to customers buying both of their modules. In this setup, as discussed earlier, only three qualities of assembled products can be owned by customers: the two *pure* products of each manufacturer or seller and the mixed product comprising the cost efficient complementing modules from each manufacturer or seller. Since the firms or sellers will be selling the individually priced modules, the marginal buyers indifferent between the different qualities of X and Y modules, and the buyer indifferent between acquiring a product and not acquiring any product are as follows: The marginal buyer indifferent to buying the lower quality product comprising $\{X_b \text{and } Y_b\}$ is given by $\theta_{Ls} = \frac{p_{xb}+p_{yb}}{(\alpha_b+\beta_b)}$. The marginal buyers indifferent between X_a & X_b and Y_a & Y_b are respectively θ_x and θ_y; where $\theta_x = \frac{p_{xa}-p_{xb}}{\alpha_a-\alpha_b}$ and $\theta_y = \frac{p_{ya}-p_{yb}}{\beta_a-\beta_b}$. The profit functions of the two manufacturers are given by:

(i) $\pi_{sa} = (1-\theta_x)(p_{xa}-c_{xa}) + (1-\theta_y)(p_{ya}-c_{ya})$

(ii) $\pi_{sb} = (\theta_x-\theta_{Ls})(p_{xb}-c_{xb}) + (\theta_y-\theta_{Ls})(p_{yb}-c_{yb})$

Proposition 2: Under standard interface the equilibrium prices and the consequent marginal buyers are given as follows:

(i) $p_{\text{xa}} = \frac{((\alpha_a-\alpha_b)(12\alpha_a-6\alpha_b+6\beta_a-2c_{\text{ya}}-c_{\text{yb}})+2c_{\text{xa}}(6\alpha_a-3\alpha_b+4\beta_a-\beta_b)+c_{\text{xb}}(6\alpha_a-3\alpha_b+4\beta_a-\beta_b))}{(3(7\alpha_a-4\alpha_b+4\beta_a-\beta_b))}$

(ii) $p_{\text{ya}} = \frac{2c_{\text{ya}}(7\alpha_a-4\alpha_b+3\beta_a)+c_{\text{yb}}(7\alpha_a-4\alpha_b+3\beta_a)-(2c_{\text{xa}}+c_{\text{xb}}-12\alpha_a+6\alpha_b-6\beta_a)(\beta_a-\beta_b)}{3(7\alpha_a-4\alpha_b+4\beta_a-\beta_b)}$

(iii) $p_{\text{xb}} = \frac{c_{\text{xa}}(3\alpha_a+4\beta_a-\beta_b)+2c_{\text{xb}}(6\alpha_a-3\alpha_b+4\beta_a-\beta_b)+(\alpha_a-\alpha_b)(-4c_{\text{ya}}-2c_{\text{yb}}+3(\alpha_a+\beta_b))}{3(7\alpha_a-4\alpha_b+4\beta_a-\beta_b)}$

(iv) $p_{\text{yb}} = \frac{2c_{\text{yb}}(7\alpha_a-4\alpha_b+3\beta_a)+c_{\text{ya}}(7\alpha_a-4\alpha_b+3\beta_b)+(-\beta_a+\beta_b)(4c_{\text{xa}}+2c_{\text{xb}}-3(\alpha_a+\beta_b))}{3(7\alpha_a-4\alpha_b+4\beta_a-\beta_b)}$

(v) $\theta_{Ls} = \frac{(c_{\mathrm{xa}}+c_{\mathrm{ya}}+2c_{\mathrm{yb}}+\alpha_a+2c_{\mathrm{yb}}\alpha_a-\alpha_b-2c_{\mathrm{yb}}\alpha_b+\beta_a+2c_{\mathrm{yb}}\beta_a+2c_{\mathrm{xb}}(1+\alpha_a-\alpha_b+\beta_a-\beta_b)-\beta_b-2c_{\mathrm{yb}}\beta_b)}{(3+4\alpha_a-4\alpha_b+4\beta_a-4\beta_b)}$

(vi) $\theta_x = \frac{((\alpha_a-\alpha_b)(3+2c_{\mathrm{ya}}+c_{\mathrm{yb}}+6\alpha_a-6\alpha_b+6\beta_a-6\beta_b)+c_{\mathrm{xa}}(3+6\alpha_a-6\alpha_b+4\beta_a-4\beta_b)+c_{\mathrm{xb}}(-3-3\alpha_a+3\alpha_b-4\beta_a+4\beta_b))}{(3(\alpha_a-\alpha_b)(3+4\alpha_a-4\alpha_b+4\beta_a-4\beta_b))}$

(vii) $\theta_y = \frac{(c_{\mathrm{ya}}(3+4\alpha_a-4\alpha_b+6\beta_a-6\beta_b)+(3+2c_{\mathrm{xa}}+c_{\mathrm{xb}}+6\alpha_a-6\alpha_b+6\beta_a-6\beta_b)(\beta_a-\beta_b)+c_{\mathrm{yb}}(-3-4\alpha_a+4\alpha_b-3\beta_a+3\beta_b))}{(3(3+4\alpha_a-4\alpha_b+4\beta_a-4\beta_b)(\beta_a-\beta_b))}$

Sketch of Proof**:** The proof is obtained by applying FOC on the profit functions after substituting the marginal buyers. The resulting linear equations are then solved for equilibrium prices.■

To facilitate our analysis in establishing manufacturer seller preferences for the interface type we computed the profit differential for each seller, $\Delta_i = \pi_{si} - \pi_{pi}$. We use the equilibrium values obtaining some relations that are useful in our analysis that follows: $\theta_x - \theta_y = \frac{\rho_x}{\delta_x} - \frac{\rho_y}{\delta_y}$, where $\rho_x = c_{xa} - c_{xb}$, $\rho_y = c_{ya} - c_{yb}$, $\delta_x = \alpha_a - \alpha_b$ and $\delta_y = \beta_a - \beta_b$.

Proposition 3**:** The volume of sales is the same for both proprietary and standard interface.

Proof**:** It can be easily shown that $\theta_{Ls} - \theta_{Lp} = 0$. This proves that the segments of active buyers is identical under both the interface types, and hence identical sale volume.■

In equilibrium whether buyers own the mixed product P_{ab} or P_{ba} depending on whether $\theta_x < \theta_y$ or $\theta_x > \theta_y$.

Proposition 4**:** The profit under standard interface is strictly higher than that under proprietary interface for both the firms as long as $\alpha_a > \alpha_b$ and $\beta_a > \beta_b$; the increment in profit under standard interface is exactly equal for both the firms.

Proof**:** Using equilibrium prices, we calculate, $\Delta_a = \pi_{sa} - \pi_{sa} = \frac{(\rho_x\delta_y - \rho_y\delta_x)^2}{9(\delta_x+\delta_y)\delta_x\delta_y}$, and $\Delta_b = \pi_{sb} - \pi_{sb} = \frac{(\rho_x\delta_y - \rho_y\delta_x)^2}{9(\delta_x+\delta_y)\delta_x\delta_y}$. Clearly, $\Delta_a = \Delta_b > 0$ if, $\delta_x\delta_y > 0$ or if $\alpha_a > \alpha_b$ and $\beta_a > \beta_b$.■

To test for *ex poste* stability of the solution we need also test the equilibrium outcome by allowing the firms/sellers to pre-bundle their modules with opportunity for discount pricing on the pre-assembled pure product. This would amount to analysing the problem with IMP-strategy. Assuming that in equilibrium the mixed product P_{ab} would be owned by the middle segment of buyers, the profit functions would be as the following (the im in the subscript refers to IMP-strategy):

$$\pi_{aim} = (1-\theta_x)(p_{\mathrm{aa}} - c_{\mathrm{xa}} - c_{\mathrm{ya}}) + (\theta_x - \theta_y)(p_{\mathrm{xa}} - c_{\mathrm{xa}})$$
$$\pi_{bim} = (\theta_x - \theta_y)(p_{\mathrm{yb}} - c_{\mathrm{yb}}) + (\theta_y - \theta_{Ls})(p_{\mathrm{bb}} - c_{\mathrm{yb}} - c_{\mathrm{xb}})$$

Proposition 5**:** The equilibrium outcome with IMP-strategy is identical to MP-strategy: the industry sales as well as prices of modules and assembled products are identical to that of the equilibrium outcome with MP-strategy.

Sketch of Proof**:** Applying FOC we can easily obtain the equilibrium prices and compare those to the prices of MP strategy. It can be verified that the prices are exactly the same.■

Since MP strategy and IMP strategy are equivalent in outcome for both the firms, each can independently decide its own market strategy of how it will sell the products.

Corollary 1**:** When both the firms prefer standard interface, a multiplicity of Nash equilibria may obtain, namely: {MP, MP}, {MP, IMP}, {IMP, MP} and {IMP, IMP}. All the equilibria are payoff equivalent for both the firms.

The equilibrium values obtained are used is the basis for calculating the equilibrium profits of the firms. We use the equilibrium prices and profits in proprietary interface as a benchmark in our analysis to establish the admissibility of standard interface.

Proposition 6**:** The market sizes served by the firms in either type of interface are exactly equal.

Proof**:** The proof is obvious in observing that $\theta_L^s - \theta_L^P = 0$. ■

The above proposition points to the industry gains and consumer welfare under standard interface.

Corollary 2: Social welfare is higher when firms adopt a standard interface.

Proof**:** The prices of the *pure* products are the same under proprietary interface as well as standard interface. The market size is the same under both regimes, however, the profit under standard interface is higher. Under standard interface, the available array of products includes both the pure products available under proprietary interface as well as a mixed product consisting of a module from each manufacturer. Thus consumers, in addition to the mixed product, have all the product choices available to them as under proprietary interface at the same price. Therefore sale of mixed products implies increased consumer surpluses. This proves that adoption of standard interface increases aggregate social welfare. ■

4.2 Divided Quality Leadership (DQL)

In DQL regime each firm is a leader in the quality of *one* module; WLOG here we assume that firm A produces the higher quality X module and firm B produces the higher quality Y module. Firm A remains the Total Quality Leader (TQL), that is its integrated-product, P_{aa} is the higher quality pure product. As noted earlier, under standard interface or when sellers individually price modules and do not sell bundled *pure* products with discounted prices, the equilibrium distribution of integrated-product ownership will result in products of at most three distinct qualities. Of these three products, *two* will be mixed products, P_{ab} and P_{ba} and one will be a pure product, which could be either P_{aa} or P_{bb} but not both. On the range of quality, the mixed products would make the *best* and *worst* quality products, while the pure product would serve as the *neutral* zone between the two. In the rare event when only *two* products are sold, both the products will be *mixed* products. This is illustrated by figures 5 and 6. Note that the two figures describe two different possibilities: in figure 5 the integrated-product owned in equilibrium is P_{aa} while in figure 6 the integrated-product owned in equilibrium is P_{bb}. For clarity of reference, we will refer to the equilibrium outcome with pure product P_{aa} as A-dominant equilibrium and the equilibrium outcome with pure product P_{bb} as B-dominant equilibrium; in general we will refer to outcomes where only one pure product is owned in equilibrium as j-dominant equilibrium, where j refers to whichever of the two sellers or manufacturers whose pure product is owned in equilibrium. It is important to note that in a j-dominant equilibrium, the dominated manufacturer $i\,(\neq j)$ essentially sells its modules to two *separated* markets where no buyer opts to own the pure product of this seller or manufacturer; in a way it operates in two disconnected markets where the price of one module has no *direct* effect on the sale of its other module. This has important implications: firm i cannot strategically price one module to affect the sale of its complementing module. The j-dominant firm, however, addresses a contiguous market for both the modules and is in a position of advantage to secure the most profitable prices since it can transfer prices across the modules if is profitable, or it can dampen the price competitive behavior of the dominated firm. This feature has important consequences in the equilibrium analysis of this section.

Figure 5: Product space comprising P_{ba}, P_{aa} and P_{ab}

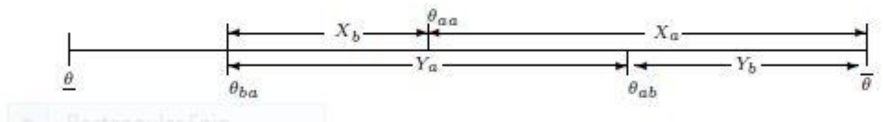
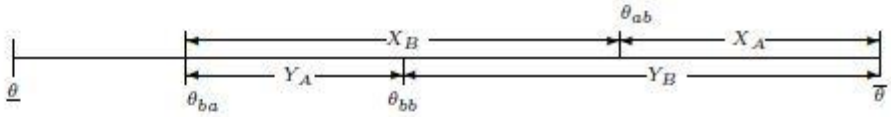
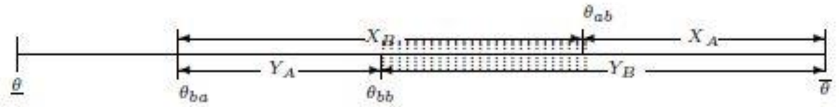


Figure 6: Product space comprising P_{ba}, P_{bb} and P_{ab}



As before, in this section also, we model a simultaneous move game of complete information to analyze for equilibrium strategies with the difference that this time each seller has capability to manufacture one high quality module. As discussed before, the strategy space of each firm or manufacturer includes {MP,IMP,IP}, where **MP**-strategy and **IMP**-strategy assume standard interface.

Figure 7: B-dominant equilibrium; modules of firm A are sold in non-contiguous market segments



4.2.1 Determination of Optimal Strategy

In a standard modular market if both the firms use **MP**-strategy their *effective* profit functions would be as follows:

$\pi_a^{MP} = (1-\theta_y)(p_{xa}-c_{xa}) + (\theta_y-\theta_{aa})(p_{aa}-c_{xa}-c_{ya}) + (\theta_{bb}-\theta_L)((p_{ya}-c_{ya}))$
subject to the constraint: $p_{aa} = p_{xa}+p_{ya}$.

$\pi_b^{MP} = (1-\theta_y)(p_{yb}-c_{yb}) + (\theta_{aa}-\theta_{bb})(p_{bb}-c_{xb}-c_{yb}) + (\theta_x-\theta_L)((p_{xb}-c_{xb}))$
subject to the constraint: $p_{bb} = p_{xb}+p_{yb}$.

The profit function for both the firms using **IMP**-strategy under the assumption that the rival firm is using **MP**-strategy has a relaxed constraint:

$\pi_a^{IMP} = (1-\theta_y)(p_{xa}-c_{xa}) + (\theta_y-\theta_{aa})(p_{aa}-c_{xa}-c_{ya}) + (\theta_{bb}-\theta_L)((p_{ya}-c_{ya}))$
subject to the constraint: $p_{aa} \leq p_{xa}+p_{ya}$.

$\pi_b^{IMP} = (1-\theta_y)(p_{yb}-c_{yb}) + (\theta_{aa}-\theta_{bb})(p_{bb}-c_{xb}-c_{yb}) + (\theta_x-\theta_L)((p_{xb}-c_{xb}))$
subject to the constraint: $p_{bb} \leq p_{xb} + p_{yb}$.

The marginal buyers who are indifferent between the two qualities of modules X and Y are respectively: $\theta_y = \frac{p_{yb}-p_{ya}}{(\beta_b-\beta_a)}$, $\theta_x = \frac{p_{xa}-p_{xb}}{(\alpha_a-\alpha_b)}$, $\theta_{aa} = \frac{p_{yb}+p_{xa}-p_{aa}}{(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}$, and $\theta_{bb} = \frac{p_{aa}-p_{bb}}{(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}$; and the marginal buyer indifferent between buying a product and not buying anything at all is $\theta_L = \frac{p_{bb}-p_{xb}-p_{xa}}{(\alpha_a+\beta_a)-(\alpha_b+\beta_b)}$. Essentially, **MP** stipulates that firms compete on the prices of the corresponding modules only with the overall intention of maximizing their profits. Allowing all possible product combination, the profit maximization process is a optimization problem with the constraint requiring that the price of the bundled pure product be equal to the sum of prices of the modules.

As noted earlier, under the use of standard interface or MP-strategies, any outcome will almost always result in a j-dominant firm outcome. In principle, any of the two firms can be the j-dominant firm; since the relative costs of modules that determine the emerging pure product that would sell in equilibrium. Recall that $\theta_x$is the marginal buyer indifferent between the higher quality X module and the lower quality X module; θ_y is the marginal buyer indifferent between the higher quality Y module and the lower quality Y module. If $\theta_y > \theta_x$, then firm A would be the j-dominant manufacturer. The buyers' distribution in this case would be as follows: buyers above θ_y own P_{ab}, buyers between θ_y and $\theta_x$buy P_{aa} and buyers between θ_x and θ_L buy P_{ba}. If $\theta_x > \theta_y$, then firm B would be the j-dominant firm, and the buyers' distribution would be as follows: buyers above θ_x buy P_{ab}, buyers between θ_x and $\theta_y$buy P_{bb} and buyers between θ_y and $\theta_L$buy P_{ba}. For equilibrium analysis, we need only consider one instance of j-dominance; WLOG we will analyze the case of A-dominance. Note that this choice has no relation to the fact that firm A has been assumed to be OLQ for our study.

Before we proceed with the analysis of equilibrium we will make some observation that is specific to DQL under standard interface as is obvious from the above diagrams. While adoption of **MP**-strategy induces the equilibrium ownership of one pure product, adoption of **IMP**-strategy could change this outcome. Let us consider the case under consideration in this section where the quality ranking of possible fixed products are as follows: $P_{ab} > P_{aa} > P_{bb} > P_{ba}$. When both firms use **MP**-strategy the contiguous distribution of product ownership is as follows: $P_{ab} > P_{aa} > P_{bb} > P_{ba}$, the top segment of buyers owns P_{ab} the middle segment owns P_{aa} and the lowest segment owns P_{ba}; if firm A switches to **IMP**-strategy, the equilibrium product set remains the same, however, the market size and profits change in favor of firm A. If, on the other hand firm B were also to switch to **IMP**-strategy, the distribution of product ownership will switch to $P_{ab} > P_{aa} > P_{bb} > P_{ba}$ with four distinct segments in the market each with a different *full* product. Note that the pure products are owned by the contiguous middle segments of buyers while the peripheral segments own mixed products. We will refer to these segments as AB-segment, AA-segment, BB-segment and BA-segment. It is important to note that segments AB and AA are in the control of firm A; and segments BB and BA are in control of firm B; by ``in control" we mean a contiguous market segment where the firm “in control" sells at least one of its module in each of the segments, while the module of the rival firm selling in one of these segments is disconnected from the segments it (rival firm) controls. We will refer to segments AA and AB as A-enclave; and BB and BA segments as B-enclave. In a non-cooperative game, where the enclaves are in the control of a single firm, each will have an incentive to use proprietary interface as the firm in control would seek to extract rent from the sale of the module of the rival firm selling in its enclave of control. Since there is no agency to enforce a standard interface, it will be difficult to obtain a self-sustaining coordination between the firms in the adoption of **MP**-strategy or standard interface. As we will show here, the preference for **IMP**-strategy is equivalent to the adoption of proprietary interface.

As before, preference for **SI** would be indicated by universal indifference between **MP**-strategy and **IMP**-strategy; if, on the other hand, **IMP**-strategy dominates **MP**-strategy for any of the firms, the equilibrium preference for **SI** would break down.

Lemma 2 The total market served decreases when sellers or manufacturers use **MP** strategy with standard interface.

***Proof*:** It can be easily shown that $\theta_L^s - \theta_L^p > 0$ where θ_L^s and θ_L^p are indexes of marginal buyers in proprietary and standard interfaces respectively, that is buyers that are indifferent between owning a product and not owning a product. ■

In the above proof $\theta_L^s - \theta_L^p$ results in a complex but clearly positive expression can be provided by the author on request. The Lemma is an indirect proof that the industry profits actually increase when firms adopt **MP**-strategy. However, every firm has an incentive to deviate to **IMP**-strategy given that the rival firm is pricing modules without price discounts on its pure product. Note that in case of SQL **IMP**-strategy and **MP**-strategy are pay-off equivalent, but this may not be true in DQL regime.

***Lemma* 3:** In DQL, for any firm it is best response to play **IMP**-strategy when the rival firm plays **MP**-strategy.

***Proof*:** Let us consider firm B (the dominated form). Given firm A playing **MP**-strategy, its profit function with **MP**-strategy is $\pi_b^{MP} = f(p_{yb}, p_{xb}, p_{bb})$ subject to the constraint that $p_{bb} = p_{yb} + p_{xb}$. On the other hand, its profit function using **IMP**-strategy is, $\pi_b^{IMP} = f(p_{yb}, p_{xb}, p_{bb})$ subject to the constraint that, $p_{bb} \leq p_{yb} + p_{xb}$. Obviously, the profit outcome with **IMP**-strategy is higher than the profit obtainable with **MP**-strategy. The same reasoning would apply to firm A, the j-dominant firm. ■

A clear implication of this result is that switching to **IMP**-strategy against its rival's play of **IMP**-strategy increases the firm's profits while decreasing the profit of the rival firm. We can see, the 2x2 game in the DQL involving **MP**- and **IMP**-strategies under standard interface amounts to a game that is a variant of the well-known game of the Prisoner's Dilemma: both firms would be better off playing **MP**-strategy, but if one firm plays **MP**-strategy the other will have incentive to switch to playing **IMP**-strategy.

***Proposition 7*:** In the DQL regime, {IMP, IMP} will constitute a unique pure strategy Nash equilibrium.

***Proof*:** Clearly **MP**-strategy is dominated by **IMP**-strategy for both the *j*-dominant firm as well as the dominated firm, and hence {IMP, IMP} will emerge as the unique Nash equilibrium. ■

As has become obvious, under DQL **IMP**-strategy is not profit equivalent to **MP**-strategy. Hence equilibrium in **IMP**-strategies is a proxy for the adoption of proprietary interface.

***Proposition 8*:** When firms have relative quality advantage in one of the modules, adoption of proprietary interface will be an outcome in Nash equilibrium.

***Proof* :** The proof obtains from the previous results. ■

We should note that when the *j*-dominant firm switches to **IMP**-strategy, the dominated firm playing **IMP**-strategy will certainly earn less profit than it would when both firms played **MP**-strategy; however, it is not clear if its profit would be even less than its profits under proprietary interface. Regardless of how the profits compare, the dominated firm will switch to proprietary interface for clear strategic reasons. In a normative study of equilibrium outcome, it can be easily argued that if the dominated firm fixes itself on playing **MP**-strategy, it will serve as a signal to the *j*-dominant firm that it (dominated firm) is willing to sell its modules as mere quality modifying substitutes for some module of the *j*-dominant firm. Given this signal, the *j*-dominant firm would be induced to employ a proprietary interface to extract further rent from the dominated firm and further marginalize it in the industry. So indeed, there are serious strategic risks for a firm to accept such an outcome. The assumption of "strategic preference" of a firm to sell its own pure product when the rival firm resorts to selling its pure product at a distinct price, is indeed in view of this outcome in competition. Empirically, in the SLR camera industry we observe that the manufacturers of the full SLR camera systems use proprietary interface, while those manufacturers who specialize in components like Tamron, Sigma etc. produce their components fitted with relevant physical interface to be used as quality or feature modifying appendages on the SLR camera body systems of these full system of pure product manufacturers.

Standard interface is welfare enhancing but can only be sustained through regulatory devices. This is an example where proprietary interface emerges as a result of non-cooperative competition and firms are unable to realize the socially optimal outcome; it is clearly an instance of the famed Prisoner's Dilemma game.

5. Conclusion and Discussion

In the preceding, we demonstrated that in a duopoly of vertically differentiated products, the question of standard interface is informed by variety if quality, but more significantly by quality leadership structure in the industry. This is in contrast to the case of an industry of horizontally differentiated products where product variety coordinates between the firms. In the case of quality differentiated firms, individual-rationality driven coordination takes place when the leadership is concentrated in one of the firms, which results in the adoption of a standard interface. If each of the firm is q quality leader with respect to one of the modules, proprietary interface prevails. Use of standard interface generally increases industry profit. With the use of standard interface in SQL, the incremental profit gains of the industry accrue equally to both the firms with no incentive for deviation *ex poste*. However, under DQL the same does not hold true specifically because one of the firms will always have incentive to deviate *ex poste* to create a market *enclave* for itself by selling its pre-assembled or bundled pure product. The use of standard interface in DQL cannot be sustained because of a lack of commitment power or an enforcement mechanism.

We can use our result to argue in reverse as well, that we can anticipate outcomes for industries where proprietary interface is not sustainable, for example where modules communicate using electric signals via copper wire. In industries where proprietary interface is *unenforceable* or a standard interface is current for exogenous reasons, and products are modular, firms will do better by choosing consistent quality ranking for all of their modules, that is they choose the same quality ranking for all their modules as the quality ranking for their pure product. In such industries, mixed products can be obtained no doubt but such products serve to offer transitional-quality levels between two neighboring qualities of pure products. Perhaps a good example of such an industry would be the industry of home-theater systems or audio systems. However, there are industries that correspond more closely to DQL and mixed products are very likely to be seen in those industries as well, but such products are usually sold preassembled by the *j*-dominant firm that uses the mechanism of *products preassembly* as a means of collecting rent from the market of quality-upgrade.

Going back to the market, our analysis here might help explain why in the SLR camera industry Canon and Nikon maintain proprietary interface. Note that in common perception, Nikon lens are superior to Cannon lenses; since Cannon tends to be a leader in optical electronics; its electronic circuitry in the camera body is highly regarded. This appears to be a scenario corresponding to the regime of DQL identified in this paper. In DQL we have seen that proprietary interface emerges as the industry preference for lack of firms' commitment; and the proprietary interface is enforceable. In the home theater industry where proprietary interface is *unenforceable* firms tend to have consistent quality ranking for their modules. In the PC industry where again proprietary interface is *unenforceable* we see DQL for instance between Dell and Sony. Here Dell is the *j*-dominant firm which sells high quality Dell systems but it also sells products equipped with Sony monitors that are pre-assembled by Dell.

In this article we considered a duopoly; however, this research focus can be applied with equal relevance to the case of oligopoly comprising both *full*-product manufacturers as well as modules-*only* manufacturers. We address this in a future research.

Modularity and interface strategy is an important aspect of the modern day manufacturing terrain and will become increasingly important in the current trend towards globalization and decentralized manufacturing paradigm. We addressed this problem using a stylized model and consequently our analysis and results are subject to some limitations. One of the limitation of the research is that we considered a single-period problem with no cost to modularity. In addition we modeled the game as a simultaneous move game. A potential improvement can be achieved by considering two-period game or performing a steady-state analysis. Considering the game in the mold a Stackelberg leadership could be a relevant and insightful undertaking. We would consider these approaches in our follow-up research.

Endnotes

[1] We will exclude the flash unit from our consideration

[2] By system manufacturers we mean those who manufacture both lenses and the camera bodies

References

Economides, N 1989, 'Desirability of Compatibility in the Absence of Network Externalities', *American Economic Review*, Vol. 79, pp. 1165-1181.

Einhorn, M.A. 1992, 'Mix and Match Compatibility with Vertical Product Dimensions', *The Rand Journal of Economics*, Vol. 23, Issue 4, pp 535-547.

Farrell, J. and Saloner, G 1985, 'Standardization, Compatibilities and Innovation', *The Rand Journal of Economics*, Vol. 16, Issue 1 (Spring, 1985), pp 70-83.

Farrell, J, Monroe, K.H and Saloner, G 1998, 'The Vertical Organization of Industry: Systems Competition versus Component Competition', *Journal of Economics & Management Strategy*, Vol. 7, Number 2, pp143-182.

Regibeau, P. and Matutes, M.1988, 'Mix and Match: Product Compatibility without Externalities', *The Rand Journal of Economics*, Vol. 19,Issue 2, pp 221-234.

Sheikh, F. 2014, 'Standard Interface in Modular Products: The Case of Duopoly with a Quality Leader', *Journal of Business and Behavioral Sciences*, Vol. 26, Issue 1, pp 20-32.

Tirole, J.1988, 'The Theory of Industrial Organisation', The MIT Press, Cambridge, Massachussetts