Innovation and Technology Diffusion in Competitive Supply Chains

Ayhan Aydin, Rodney P. Parker

PII: S0377-2217(17)30778-6
DOI: 10.1016/j.ejor.2017.08.047
Reference: EOR 14666

To appear in: *European Journal of Operational Research*

Received date: 19 October 2016
Revised date: 13 June 2017
Accepted date: 25 August 2017

Please cite this article as: Ayhan Aydin, Rodney P. Parker, Innovation and Technology Diffusion in Competitive Supply Chains, *European Journal of Operational Research* (2017), doi: 10.1016/j.ejor.2017.08.047

Highlights

- We consider core technologies that are created by upstream firms in supply chains.
- We model a multi-stage game in a two-tier competitive supply chain.
- We define and describe two elements for the success of a technology.
- We show that consumer market characteristic affect these two elements differently.
- This bifurcation means one or the other may be weak, and policy implications.

Innovation and Technology Diffusion in Competitive Supply Chains

Ayhan Aydin[1]

aaydin2@gmu.edu

Rodney P Parker[2]

rodney.parker@chicagobooth.edu

Abstract

Innovations in consumer products frequently rely on technological advances across multiple tiers in a supply chain. Considering the consumer market demand and downstream investment conditions as input, we model a game in a two-tier supply chain where downstream firms choose to adopt different levels of an upstream technology and an upstream technology leader determines its pricing policy. We identify two necessary but distinct elements for the successful development, adoption, and diffusion of upstream technologies that are sold to lower tiers as components within final products. (1) The level of technology demanded by the market: We develop a measure, Technological Potential, which describes the highest level of an upstream technology demanded by consumer markets. (2) A sufficiently rich return to an upstream innovator, as a function of different levels of technology. From these two elements, we show that the relative magnitudes of two competing sets of consumer market factors determine the Technological Potential whereas the overall magnitude of the factors in both sets determines the return to the upstream developer. We discuss how this difference in consumer market factors' influence on these two elements may determine how different technologies fare in the supply chain. Our results have managerial implications for: investors in research and development project selection in identifying profitable technologies that are also demanded at higher capability levels; and for governments in defining more targeted public policies - for example in choosing the right tier of a supply chain to provide subsidies - to encourage market support for certain technologies.

Keywords: OR in research and development, supply chains, technology, competition, innovation

1. Introduction and Motivation

In addition to technological innovations that are achieved by the producers of final consumer products, technological innovations that improve various observable capabilities of products used by consumers are created in the upper tiers of supply chains. Considering the supply chain of technology starting from basic

[1]George Mason University
[2]University of Chicago

research in natural sciences and extending into final products for consumers, we refer to these as "upstream technologies" in this paper. The computation power of personal computers is determined and limited by the power of microprocessors produced by upstream firms Intel and AMD. Many durable goods rely on chemical and material technologies which are developed through substantial R&D activities by upper-tier chemical firms such as DuPont and BASF. This strongly dependent supply chain relationship is widely recognized in the literature, e.g., Bhaskaran and Krishnan (2009).

Given the necessity of concomitant investments by multiple supply chain tiers, it is not usually clear why certain technological capabilities of consumer products are not improving as quickly as seemingly desired. This is especially true for upstream technologies. Contemporary smart cell-phones with a multitude of capabilities still lack a good battery-life until the next recharge. The battery charge lasts so much less than those available a decade ago that municipalities are coming up with innovative ideas for recharging cell-phones and similar devices in public places, including artificial trees (Curcic, 2014). Consumers are openly demanding cell-phones with battery longevity longer than half-a-day. On the other hand, batteries for electrical cars seem to be developing faster to overcome "range anxiety" (Clark, 2014), and might change the automobile industry rapidly in the next decades. Since these upstream technologies are usually incorporated into consumer products by downstream industries, it is likely that consumer market factors will shed light on the problem of why some technologies "succeed" and others stagnate. Hence, we ask the following research questions: (1) How does the nature of competition and other fundamental factors in the consumer markets influence the successful development of different types of upstream technologies that may improve consumer products' observable capabilities? (2) Why are some technologies that are created by upstream firms never sold to the downstream firms and why do the upstream firms not develop some technological capabilities that are seemingly highly desired in the consumer products fast enough?

The Industrial Organization literature on innovative activity does not typically study vertical relationships between industries. However, industry level factors such as product market demand, technological opportunity, and conditions of appropriation are empirically shown to be behind innovative activity and output, e.g., Schmookler (1962) and Pakes and Schankerman (1984). Hence, our demand model is imbued with these downstream market factors to explain the development and adoption of technologies into a two-tier supply chain model.

From the supply chain perspective, for an upstream technology to become widely used in consumer products (1) upstream firms must foresee a sufficient return from investing in the necessary R&D projects, and (2) some downstream firms (OEMS, integrators) should find it profitable under competition to adopt higher technology levels. These are the two necessary elements for a successful technology. Our results confirm the necessity of these two elements, but more importantly tie them to the consumer market factors that are inputs to the model. Moreover, we show how consumer market factors differently influence these two drivers. Specifically, we show that while the relative magnitudes of two distinct set of downstream factors determine the true level of technology demanded by the consumer markets, the overall magnitude of all the factors determines the financial return to an upstream technology leader. The difference in how consumer market factors influence these two fundamental elements explain a variety of paths for how upstream technology dimensions may be adopted down the supply chain. This distinction is also shown to be useful, for example, for upstream firms to balance their R&D portfolios or for better targeting of government policies to encourage development of socially desirable technologies. Ultimately, we divine the combinations of factors which result in a successful technology: creation of the technology upstream, adoption of the technology downstream by competing firms, and diffusion of the technology-laden product in the market.

Numerous examples of successful technologies are readily observable. However, technology failures are less visible since they may be held up in the upper tier due to limited financial rewards or in the downstream tier due to tepid demand for the technology, but consumer factors are believed to be important (e.g., Douthwaite et al. (2001)). Erat et al. (2013) provide an example where DuPont forced their new Stainmaster carpet technology upon their downstream integrators. Despite the undisputed superior performance of Stainmaster, the adoption of this technology resulted in downstream bankruptcies and DuPont's ability to extract profits from their innovation was limited. Although our model does not perfectly match the DuPont example, we likewise see that diminished competition (of a form) can reduce the financial returns to the upstream innovator. Also, we can provide some insight as to why the Stainmaster technology was not viable, using the Technological Potential metric described below. We shed light into the factors leading to technology successes and failures.

We solve a multi-stage game among upstream technology leaders and competing downstream following firms. We first develop a measure of the true desirability of the level of a technological capability by the consumer markets using downstream market factors; we call this *Technological Potential*. We then investigate the upstream profit return from a technology using these same factors, and hence explain why some financially more viable technologies imply higher returns for their developers - albeit not necessarily demanded at high capability levels by the lower tier. We show that consumer market factors have bifurcating effects on these two elements. Hence, we provide a consumer market based explanation to why some upstream technologies might be developed but held up in the upper tiers whereas some are never developed but are strongly desired in the consumer markets.

In light of these bifurcating effects of consumer market factors on the two elements, we show that certain types of competition in the downstream tier imply an expanding consumer market with respect to the technology in question, which benefits both tiers of the supply chain. In short, more intense (but the right type of) competition can be beneficial for the level of technology demanded and more financially rewarding for both tiers of the supply chain. In this paper, we focus only on upstream technologies that are sold to the lower tier within a component (product), and exclude those that are licensed in technology markets.

2. Literature Review

There are several recent papers in the operations management literature on the development and use of upstream technologies in lower tier industries. The primary research focus of these papers includes price discrimination for maximum return for an upstream technology, the effects of contracting schemes between supply chain tiers, the effects of leadership in the chain, the effect of the level of functionality of upstream components in the consumer products, and vertical collaboration mechanisms to improve the level of technology investments. We will review here several of these papers that have similar supply chain perspectives to ours.

Erat and Kavadias (2006) considers a monopoly supplier of a process or component technology to multiple competing OEMs. The supplier licenses the current technology for a fixed fee in the first period and a possibly enhanced version of it in the second period. They focus on the pricing decision of the supplier in two periods considering the level of enhancement of the technology in the second period, future market size, probability of delay in the launch of the enhanced version, and other strategic factors. They show the conditions under which the supplier does inter-temporal price discrimination and induces partial adoption in the downstream market. Similar to our results, they also find that the supplier's revenue is not endlessly increasing in the level of technology improvement; there is a finite optimal technology level. In contrast to Erat and Kavadias (2006) however, we focus on the downstream market's strategic factors and demand factors which constitute the relationship between downstream products and the upstream technology. We show how these factors may be used to explain different scenarios a technology dimension may face. We use firm-level demand functions in contrast to Erat and Kavadias (2006) where a consumer utility model with fixed market size is employed.

Erat et al. (2013) also looks at a monopoly supplier selling a "subsystem" to two downstream firms. They investigate how the fraction of the end-product functionality included in the upstream subsystem affects both tiers of the supply chain and argue that there is a trade-off between the reduction of cost and the risk of successful adoption from functionality, and the decreasing value appropriation power that results from increasing integration of the upstream subsystem and the downstream end-products. The reduction of the appropriation power in their chain due to increasing functionality is analogous to the negative effects on consumer prices and the total size of the downstream market we observe for some upstream technology capabilities. Unlike the evaluation of a general functionality level of any upstream component (technology) in Erat et al. (2013), we differentiate between different technology dimensions depending on the way they are perceived in consumer markets to provide potential explanations for how different categories of technology dimensions fare in the supply chain.

Motivated by large OEMs trying to encourage the suppliers of their important components to innovate, Wang and Shin (2015) discuss three different types of contracts between an upstream supplier and a downstream firm. They investigate the effect of the type of contract on the level of upstream investment, considering the performance of the upstream component and heterogeneity of the preferences of the consumers. They show that revenue sharing contracts coordinate the chain, especially if the upstream investment costs are high. We consider technology-based wholesale pricing of upstream components and our primary motivation is similar to those of the first two papers: larger upstream firms want to induce the adoption of an upstream technology. However, our focus is not on the type of contracting between the tiers and its effect on technology investments. Therefore, we assume a more general expression for the lower tier's payment to the upper tier.

Krishnan et al. (2015) examine how the diffusion and adoption of innovative and socially desirable products can be enhanced by the deliberate choice and transfer of supply chain leadership at different stages of innovation. We model a two-tier supply chain similar to the rest of the literature. Krishnan et al. (2015) model a three-tier supply chain primarily to investigate a potential new lever, supply chain leadership, in encouraging R&D in supply chains. We do not assume a certain leader in the supply chain. Yet, our model incorporates the pricing strategy of a potential upstream technology leader.

Jain and Ramdas (2005) consider the repositioning/redesigning problem downstream firms face especially when their product's lifecycle is substantially longer than that of an exogenously developed upstream technology. Using a stochastic dynamic model, they show when it is optimal for downstream firms to closely follow an exogenously evolving upstream technology. Jain and Ramdas (2005) focus on a single downstream firm's decision given different upstream technology choices in an inter-temporal setting and solve an internal optimization problem. Hence, the paper considers a similar technology constraint upstream tiers impose on downstream tiers. The primary technical difference is that we use a game to model the *competition* between downstream firms given a superior upstream technology and a laggard one. Although we incorporate the downstream optimal technology choice decision under competition, we investigate how these downstream decisions change depending on the consumer market factors of the upstream technology and eventually how an upstream technology leader responds with its own pricing and technology sale policy.

In addition to the non-cooperative models above, Bhaskaran and Krishnan (2009) look at vertical collaboration possibilities between two firms in developing and marketing a new technology that improves the utility of the downstream product. They emphasize the importance of market and technological characteristics when making product development decisions. In our work, we model these characteristics in detail and examine their effect on the success of an upstream technology. Since collaboration is beyond our scope, we assume a non-cooperative competition game among both downstream players and the upstream firms.

Xiao and Xu (2012) discuss when and how royalty revisions (contract revisions) in a vertical supply chain formed between a primary innovator firm and a marketer are useful. Using principle-agent models, they investigate contingent and non-contingent contracts with respect to the performance of the resulting innovation offered by the marketer (downstream firm). Zhu et al. (2007) similarly discuss a single buyer's problem of stimulating its supplier's adoption of a new technology in an information asymmetry setting, and determine the optimal contract design. In another contracting paper, Gilbert and Cvsa (2003) consider a large supplier's effort to influence the product development decisions of its buyers. They look at the effect of different levels of price commitment prior to sales on such efforts. These three papers look at possible upstream levers beyond pricing to influence downstream technology decisions. In contrast, we are not investigating these alternative upstream levers and instead consider the optimal pricing and technology transfer decision of an upstream technology leader in response to downstream firms' competitive behavior among themselves (in response to consumer market factors that define the nature of competition among them).

In the growing branch of innovation literature with a supply chain perspective discussed above, a common element is the mutual dependency of different tiers' efforts to advance the development and usage of a technology and the general dependence on the market and technology characteristics. Similarly, our primary problem is examining the development of upstream technologies which can truly alter the capabilities of consumer products - with possibly socially desirable attributes (Krishnan et al., 2015) - and their vertical diffusion into consumer markets depending on the nature of the technology, the downstream market structure, and the investment (adoption) cost conditions. We provide some explanation to why some technologies are demanded at higher levels while the consumer markets appear unwilling to pay for these seemingly highly desirable technologies.

While this literature review is limited to papers with a supply chain focus, there is a large OM literature treating a single firm's investment decisions in technology development, technology adoption, upgrade release timing, and product architecture. Krishnan and Ulrich (2001) provide a detailed review of earlier related work. More recently, Ramachandran and Krishnan (2008) and Krishnan and Ramachandran (2011) discuss the benefits of modular upgradability by localizing possible improvement in modules and how to alleviate the design inconsistency that may arise from such an approach. Krankel et al. (2006), Bhaskaran and Ramachandran (2015), Druehl et al. (2009), Klastorin and Tsai (2004), and Huisman and Kort (2003) also present some recent work with a single tier on optimizing the adoption/release of new products with improved technologies. Our paper has a significantly different game theoretical supply chain setting than the optimization and single-firm models used in these papers. On the other hand, similar to these papers we model the optimal behavior of each downstream firm under a similar question of technology adoption (yet in competition with each other and the upstream technology leader within a supply chain).

Finally, the economics literature has considered technological innovations and quality choice, usually within a single market and tier, from the perspective of vertical differentiation, focusing mostly on the effect of competition on the investment levels. This branch of literature emphasizes how firms try to escape intense competition and commoditization by quality differentiation, e.g., Mussa and Rosen (1978), Gabszewicz and Thisse (1979), Donnenfeld and Weber (1992), Sutton (1996), and Lehmann-Grube (1997). Competition is usually interpreted as the number of firms, whereas we model the intensity of competition with sensitivity parameters in the demand function to reflect the consumer market characteristics. Moreover, the ground of competition among the downstream firms in our model is extended to cover detailed consumer market factors since they form the basis for classifying different technology dimensions in question. Upstream technological capability (and limitations) on the downstream firms is another significant difference of our model from these papers in this branch of the economics literature.

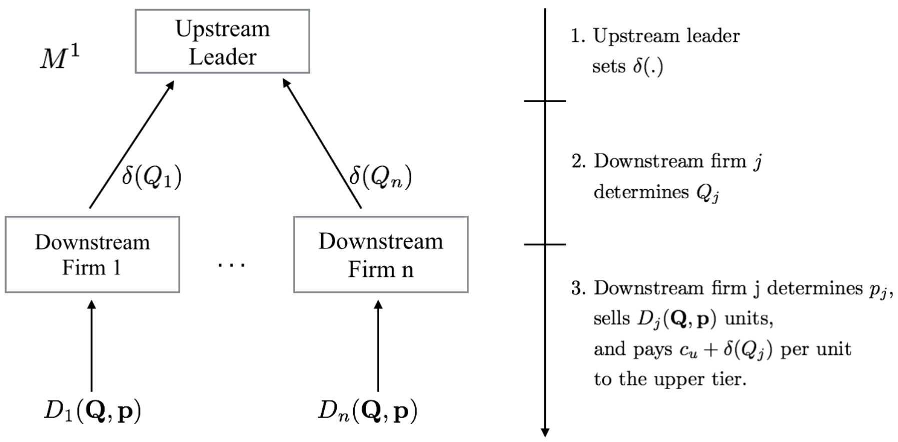
3. Model Setup

Consider a two-tier supply chain where upper tier firms develop upstream technologies which are subsequently sold to downstream firms (OEMs, integrators) within a component or service. Downstream firms invest further to incorporate the upstream technology-laden component into their products, which are then sold to the market. Our model spans three-periods: (1) the upstream firms price the upstream technology; (2) the downstream firms adopt part or all of the available upstream technology, under competition; and (3) the downstream firms price and sell their product to consumers. Pricing decisions following R&D decisions is a common modeling assumption, e.g., Curtat (1992), since these decisions frequently span different time scales. The third period may be interpreted as an appropriation period, representing the product lifetime duration over which any investment is recouped.

3.1. Supply Chain Structure

The upper tier of the supply chain consists of a "technology leader" and other firms which are "technology laggards." There are numerous examples of leaders and laggards in upstream technologies. For example, in personal computer processors Intel is frequently cited as a consistent technology leader over Advanced Micro Devices (Goettler and Gordon, 2011). Another example is Corning Corporation which developed and manufactures the market-leading Gorilla Glass 4 used in smartphones, but has competitors Asahi Glass Co. of Japan (which makes Dragontrail) and Schott AG of Germany (which makes Xensation); Asahi and Schott would be considered technology laggard firms in the upper tier. In our model, the most direct interpretation is that there is a single firm in the upper tier (the technology leader) while the other firms (the technology laggards) offer a second best alternative technology; the laggards play a passive role in the model and can be ignored, as justified below. The supply chain is portrayed in Figure 1.

Figure 1: Supply Chain and Timeline of Decisions



The lower tier of the supply chain consists of n competing firms, which adopt the offered technological product and further invest to incorporate the technology into their own product. For example, Intel's Core i5 processor has been adopted by Hewlett Packard, Dell, Lenovo, Acer, amongst others for usage in their laptop computers. Similarly, Corning's Gorilla Glass 4 has been incorporated into smartphones manufactured by Samsung, Motorola, HTC, Nokia, Google, LG, Lenovo, Sony, and others. However, this thin and durable glass has also been incorporated into tablets, ultrabooks, televisions, cameras, and even interior architecture, marker-boards, and automotive applications.

3.2. Measuring Technology

For our purposes, we take the current technology levels offered by the firms in the upper tier as given, with one firm as the distinct leader, similar to Erat et al. (2013) and others. The technology itself is measured along a technology capability scalar, similar to Bhaskaran and Krishnan (2009), Krishnan and Ramachandran (2011) and others. This technology capability dimension (hereafter "capability") reflects an essential and measurable attribute which is perceived and valued by the final consumers. Many technology-based products have multiple attributes valued by consumers. For example, Gorilla Glass 4 has several measurable aspects which favor its usage in smartphones such as thinness of 0.4mm and Vickers Hardness of 489 kgf/mm^2 (200g load), as well as optical, electrical, viscosity, and durability properties. The thinness of the Gorilla Glass 4 allows Samsung to develop a thinner Galaxy S6 smartphone, and the resulting thinness of the phone is valued by consumers. However, we reduce the capability to a single dimension and this capability attribute offered by the upstream firms is measured on the same scale as the downstream firms' capability adoption choice. Let the upstream technology leader's capability be denoted by M^1 and that of the laggard as M^2 ($M^1 \geq M^2$). (All notation are tabulated in Table 1.) Let Q_j be the capability of downstream firm j's product ($j = 1, ..., n$), limited by the technology offering of the upstream leader, $Q_j \leq M^1$. Corning offers Gorilla Glass 4 at any requested thicknesses from 0.4mm to 1.0mm, for example.

$\mathbf{Q}^0$	Downstream tier's initial technological capability state.
$\mathbf{p}$	Downstream tier price vector.
$\delta(Q)$	Upstream premium tariff.
$\mathbf{Q}^*(\delta(\cdot))$	Downstream equilibrium capability given upstream premium tariff.
$\mathbf{D}(\mathbf{Q},\mathbf{p})$	Downstream tier demand vector.
$\mathbf{p}^*(\mathbf{Q}\vert\ \delta(\cdot))$	Equilibrium price vector given downstream capability state and $\delta(\cdot)$.
$\mathbf{D}^*(\mathbf{Q}\vert\ \delta(\cdot))$	Equilibrium demand vector given downstream capability state and $\delta(\cdot)$.
$\mathbf{p}^*(\delta(\cdot))$	Equilibrium price vector given upstream premium, i.e., $\mathbf{p}^*(\mathbf{Q}^*(\delta(\cdot))\vert\ \delta(\cdot))$.
$\mathbf{D}^*(\delta(\cdot))$	Equilibrium demand given upstream premium, i.e., $\mathbf{D}^*(\mathbf{Q}^*(\delta(\cdot))\vert\ \delta(\cdot))$.
α_j or λ_j	Scale parameter of Downstream Firm j's demand in the linear model.
β_{jk} or ν_{jk}	Sensitivity of Downstream Firm j's demand to the price of Firm k.
γ_{jk} or ϑ_{jk}	Sensitivity of Downstream Firm j's demand to the capability of Firm k.
$K_j(\cdot)$	Cumulative adoption cost function of Downstream Firm j.
κ_j, k_j	Cumulative adoption cost function parameters in (L) and (M).
M^1, M^2	Upstream leader and laggard capabilities.
c_j, c_u	Unit cost of Downstream Firm j and upstream firms.
$w(Q)$	Unit wholesale price of an upstream component with capability level Q.

Table 1: Notation

3.3. Prices and Costs

Our focus is not on designing exchange contracts to enhance coordination in the channel (unlike Wang and Shin 2015, for example), but like Erat and Kavadias (2006) we are convinced of the importance of volume *and* technology-based wholesale pricing. The upstream leader sells her technology-based component to the downstream firms for wholesale price $w(Q) = c_u + \delta(Q)$ for $Q \in (M^2, M^1]$ and $w(Q) = c_u$ for all $Q \leq M^2$. The upstream variable production cost is c_u (assumed constant and symmetrical across upstream firms) and $\delta(Q)$ is the premium margin the upstream leader charges for her superior technology.

Although the upstream leader cannot legally price-discriminate among the downstream firms or refuse to offer a technology level to a downstream firm that it is already marketing it to others, it can price-technology-discriminate by using a common premium tariff, $\delta(\cdot)$. Violations of Robinson-Patman antitrust legislation, however, have become increasingly more common since governmental enforcement has virtually disappeared and civil litigation is rarely successful (see Luchs et al. 2010).

The upstream leader chooses $\delta(\cdot)$, an increasing function. If a downstream firm chooses a technology level below the maximum capability of the laggard upstream firm, $Q \leq M_2$, it is charged c_u for each unit of upstream component and it does not matter which upstream firm is the supplier. In this B2B setting, this arises from Bertrand competition in technology levels shared by laggards. This assumption also allows the revenues from technology leadership to be isolated from the benefits arising from other factors. Upstream laggards collect zero return. The variable cost of downstream firm j is also constant and denoted with c_j.

The initial capability of downstream firm j's product is Q_j^0. This capability can be downgraded at no cost, but increasing it results in a fixed (independent of volume) investment cost of adoption: $(K_j(Q_j) - K_j(Q_j^0))^+$, where $K_j(\cdot)$ is the convex increasing cumulative investment function. Define $\underline{Q}$ as the minimum capability level that can be acquired at no cost, i.e., $K_j(\underline{Q}) = 0, \forall\, j$. Convexity of investment costs (usually in quadratic forms) is a common assumption in the literature (e.g., see Zhu et al. 2007 and Wang and Shin 2015). It is also founded on the premise that in the short run, the marginal cost of advancing technology is increasing given the increasing number of constraints imposed by related fields and technologies.

We also use the cumulative cost function to capture the extant value of the firm's pool of knowledge. As a firm wants to advance further, it incurs the difference between the cumulative value of the technology it wants to reach minus the cumulative value of its current technology. Modeling it in this way allows a fairer treatment of asymmetries among the downstream firms' initial capabilities. Opportunity cost aside, enabling the downstream firms to be able to downgrade the capability of their products without incurring additional investment costs (1) reflects the fact that in the short run they do not lose their already acquired knowledge and adoption capabilities, and (2) captures the freedom of the producers of consumer goods in adjusting different attributes of their products.

3.4. Timing and Decisions

The sub-game perfect equilibrium of the whole game results in the following profits in the three steps of the game:

1. **Upstream Pricing:** Given $\mathbf{M}$, the upstream leader's net contribution is the result of the following optimization problem:

$$R(M^1) = \max_{\delta(\cdot)} \sum_{j=1}^{n} \delta\left(Q_j^*(\delta(\cdot))\right) D_j^*(\delta(\cdot))$$

2. **Downstream Adoption:** Given $\delta(\cdot)$ and $\mathbf{M}$, the downstream firms adopt technology:

$$\pi_j^Q(\delta(\cdot)) = \mathrm{eqm}_{Q_j}\ \pi_j^p(\mathbf{Q}, \delta(\cdot)) - \left(K_j(Q_j) - K_j(Q_j^0)\right)^+ \ \text{ for } j = 1, ..., n$$

3. **Downstream Pricing:** Given $\delta(\cdot)$, $\mathbf{M}$, and $\mathbf{Q}$, the downstream firms price:

$$\pi_j^p(Q, \delta(\cdot)) = \mathrm{eqm}_{p_j}\ (p_j(\mathbf{Q}|\ \delta(\cdot)) - c_j - c_u - \delta(Q_j))\, D_j(\mathbf{p}, \mathbf{Q}|\ \delta(\cdot)) \text{ for } j = 1, ..., n$$

where the "eqm" operator represents the value of the unique pure-strategy Nash equilibrium, if it exists. In each of Steps 2 and 3, the n downstream firms *simultaneously* choose their capability or price, reflecting they cannot perfectly observe their rivals' choices. The model is solved backwards, as shown in §4: The solution (in vector form) of Step 3 are the equilibrium prices and demands, $\mathbf{p}^*(\mathbf{Q}|\ \delta(\cdot))$ and $\mathbf{D}^*(\mathbf{Q}|\ \delta(\cdot))$, which are fed into Step 2. The solution of Step 2 are the equilbrium downstream capability and demands, $\mathbf{Q}^*(\delta(\cdot))$ and $\mathbf{D}^*(\delta(\cdot))$, which are fed into Step 1. In Step 1, the upstream technology leader chooses her premium pricing function, $\delta(\cdot)$.

3.5. Consumer Demands

The consumer demand occurs in the third period and is dependent upon the prices and technology capabilities of the n downstream firms. Firm j faces demand $D_j(\mathbf{Q}, \mathbf{p})$, which is increasing in Q_j and p_k, and decreasing in p_j and Q_k, for $k \neq j \in \{1, ..., n\}$. The primary inputs to the model are the sensitivities of the demands the downstream firms face with respect to each other's prices and capability levels. The effect of the length of the downstream appropriation period and idiosyncratic factors such as design can also be captured in the demand functions. We consider three demand functions: a general demand (G), a linear demand (L), and a multiplicative demand (M). We use the general demand form to keep the discussion of the analysis of the game as general as possible. However, we use particular functional forms ((L) and (M)) to derive further results. Linear and multiplicative models have very different properties. As a robustness precaution we consider them in parallel and focus on results which are common to both demand models.

The general demand function (G) operates under the following convexity assumption:

Assumption 1.

(a) $\dfrac{\partial^2 D_j(\mathbf{Q}, \mathbf{p})}{(\partial p_j)^2} \leq 0.$

(b) $\dfrac{\partial^2 D_j(\mathbf{Q}, \mathbf{p})}{(\partial p_j \partial p_k)} \leq 0.$

(c) $\dfrac{\sum_{k \neq j} \partial D_j(\mathbf{Q}, \mathbf{p})}{\partial p_k} \leq 2 \Big| \dfrac{\partial D_j(\mathbf{Q}, \mathbf{p})}{\partial p_j} \Big|.$

(d) $\dfrac{\sum_{k \neq j} \partial^2 D_j(\mathbf{Q}, \mathbf{p})}{(\partial p_j \partial p_k)} \leq \Big| \dfrac{\partial^2 D_j(\mathbf{Q}, \mathbf{p})}{(\partial p_j)^2} \Big|.$

We define the linear (L) and multiplicative (M) demand functions as follows:

$$(L) \quad D_j(\mathbf{Q}, \mathbf{p}) = \alpha_j + \sum_k \beta_{jk} p_k + \sum_k \gamma_{jk} Q_k, \tag{1}$$

$$(M) \quad D_j(\mathbf{Q}, \mathbf{p}) = \lambda_j (1 - e^{-\vartheta_{jj} Q_j}) e^{-\nu_{jj} p_j} \prod_{k \neq j} e^{-\vartheta_{jk} Q_k} \prod_{k \neq j} (1 - e^{-\nu_{jk} p_k}). \tag{2}$$

The specific demand forms ((L) and (M)) are used to assess the sensitivity of the model outcomes to changes in downstream parameters, although the exact effect is likely to differ somewhat even for corresponding parameters in the two forms (e.g., β_{jk} in (L) and ν_{jk} in (M)). In (L) α_j and in (M) λ_j are the primary (non-negative) scale parameters that capture the idiosyncratic factors about downstream firm j and the effect of the length of its appropriation period. They are also measures of the downstream firm's ability to extend the markets in which they wish to operate. The length of the appropriation period can be constructed as the minimum of the planning period that downstream firms will consider when adopting better technologies and the actual period over which the demand functions will be valid before the technology field is leveled.

In (L) γ_{jj} (≥ 0) and γ_{jk} (≤ 0), and in (M) ϑ_{jj} (≥ 0) and ϑ_{jk} (≥ 0) for $k \neq j$ are the self- and cross-capability sensitivities. They represent the importance of the specific upstream technology in question in isolation. *Ceteris paribus*, these parameters capture the benefit downstream firm j obtains from the upstream technology and the harm it inflicts upon its rivals $(k \neq j)$, respectively. For firms operating in relatively independent industries, cross-capability sensitivities are expected to be smaller. An example is the effect Samsung's usage of Gorilla Glass on HTC (large γ_{jk} or ϑ_{jk}) versus BMW (small γ_{jk} or ϑ_{jk}) [BMW uses Gorilla Glass in its i8 plug-in hybrid vehicle to reduce weight].

In (L) β_{jj} (≤ 0) and β_{jk} (≥ 0), and in (M) ν_{jj} (≥ 0) and ν_{jk} (≥ 0) are the self- and cross-price sensitivities. They capture the intensity of the price competition. We consider only downstream products which are each other's substitutes. As both self- and cross-price sensitivities increase, downstream products become closer to perfect substitutes. As these factors suggest, a smaller sensitivity to both own price and the rivals' prices implies the downstream firms become more independent and closer to monopolists.

The linear demand function form (L) is the first order approximation to the general one: $\partial D_j(\mathbf{Q},\mathbf{p})/\partial Q_k = \gamma_{jk}$, $\partial D_j(\mathbf{Q},\mathbf{p})/\partial p_k = \beta_{jk}$. The sensitivities are captured directly with the parameters. Moreover, Besbes and Zeevi (2015) demonstrate the errors from assuming a linear demand function when the underlying demand is not necessarily linear, are not severe. Linear demand forms are common in the supply chain literature, e.g. Savaskan et al. (2004), Liu et al. (2007), Yue and Liu (2006). In the multiplicative form (M), $\partial D_j(\mathbf{Q},\mathbf{p})/\partial Q_j = \vartheta_{jj}e^{-\vartheta_{jj}Q_j}/(1-e^{-\vartheta_{jj}Q_j})D_j(\mathbf{Q},\mathbf{p})$, $\partial D_j(\mathbf{Q},\mathbf{p})/\partial Q_k = -\vartheta_{jk}D_j(\mathbf{Q},\mathbf{p})$ for $k \neq j$, $\partial D_j(\mathbf{Q},\mathbf{p})/\partial p_j = -\nu_{jj}D_j(\mathbf{Q},\mathbf{p})$, and $\partial D_j(\mathbf{Q},\mathbf{p})/\partial p_k = \nu_{jk}e^{-\nu_{jk}p_k}/(1-e^{-\nu_{jk}p_k})D_j(\mathbf{Q},\mathbf{p})$ for $k \neq j$. Multiplicative forms are also used, especially when the preservation of concavity of the demand function is desirable, e.g., Yue et al. (2006), Cai et al. (2010), Bernstein and Federgruen (2005).

The two functional forms have significant differences. (1) In (L) the sensitivities are represented directly with the chosen parameters. In (M) the sensitivities are not purely determined by the indicating parameters. (2) In (L) self-price and cross-price elasticities of demand are decreasing in the capability level, whereas, they are constant in (M). (3) The linear demand model suggests an unbounded demand with respect to the capability dimension, whereas in the multiplicative model it is bounded. Hence, higher demand sensitivity to the capability in the linear demand model suggests a higher market growth, in the multiplicative model it can suggest also an earlier saturation of the market. Despite these differences, both demand models satisfy Assumption 1. In Section 5 we focus on the results which are common to both demand models.

Corresponding to the demand models, we utilize two different cumulative investment cost functions. For (L) we use the quadratic form, $K_j(Q) = \kappa_j Q^2$ and for (M) we use the exponential form, $K_j(Q) = g_j e^{k_j Q}$.

In the next section, we establish the price and capability equilibrium in the downstream market given the pricing policy of the upstream technology leader and establish the upstream technology leader's pricing problem. We leave the discussion of the properties of the equilibrium of the overall game to Section 5.

4. Analysis

In this section, the model described in §3 is solved backwards in time. In §4.1 (Step 3) the downstream firms simultaneously choose prices; in §4.2 (Step 2) the downstream firms simultaneously choose their capabilities; and in §4.4 (Step 1) the upstream leader chooses her price premium for capabilities above the laggards' capabilities. In addition, in §4.3 further results are shown under certain symmetry assumptions. All proofs appear in the Appendix.

4.1. Price Equilibrium

In this section, the downstream firms choose prices simultaneously to establish the price equilibrium ($\mathbf{p}^*(\mathbf{Q}|\ \delta(\cdot))$, and by extension, the demand equilibrium, $\mathbf{D}^*(\mathbf{Q}|\ \delta(\cdot))$, given the downstream capability state, $\mathbf{Q}$, the upstream capability state $\mathbf{M} = (M^1\ \ M^2)^\top$, and the upstream leader's premium function, $\delta(Q)$. ($\mathbf{Diag}(\beta)$ is the matrix whose only non-zero elements are the diagonal entries of β.)

Proposition 1.

(G) *Under general demand satisfying Assumption 1, a unique price equilibrium, $\mathbf{p}^*(\mathbf{Q}|\ \delta(\cdot))$, exists and is defined by the first order conditions:*

$$p_j = c_j + c_u + \delta(Q_j) - \frac{\partial D_j(\mathbf{Q}, \mathbf{p})/\partial Q_j}{D_j(\mathbf{Q}, \mathbf{p})},\ \forall j. \tag{3}$$

(L) *Under linear demand:*

$$\mathbf{p}^*(\mathbf{Q}|\ \delta(\cdot)) = \tilde{\alpha} + \tilde{\gamma}\mathbf{Q} + \tilde{\epsilon} + \tilde{d}\delta(\mathbf{Q}) \tag{4}$$

where $\tilde{\alpha} = -B^{-1}\alpha$, $\tilde{\gamma} = -B^{-1}\gamma$, $\tilde{\epsilon} = B^{-1}C$, $B = \beta + Diag(\beta) \cdot I$, $C = Diag(\beta) * (\mathbf{c} + c_u \cdot I)$, $\tilde{d} = B^{-1} * [Diag(\beta) * e]^{-1}$

(M) *Under multiplicative demand:*

$$p_j^*(\mathbf{Q}|\ \delta(\cdot)) = c_j + c_u + \delta(Q_j) + \frac{1}{\nu_{jj}}. \tag{5}$$

Given the price equilibrium established in Proposition 1, we can determine the equilibrium demand.

Corollary 1. *The equilibrium demand becomes:*

(L) $\mathbf{D}^*(\mathbf{Q}|\ \delta(\cdot)) = \hat{\alpha} + \hat{\gamma}\mathbf{Q} + \hat{\epsilon} + \hat{d}\delta(\mathbf{Q})$, *where* $\hat{\alpha} = (I - \beta B^{-1})\alpha$, $\hat{\gamma} = (I - \beta B^{-1})\gamma$, $\hat{\epsilon} = \beta B^{-1}C$, $\hat{d} = \beta B^{-1} * [\mathbf{Diag}(\beta) * e]^{-1}$.

(M) $D_j^*(\mathbf{Q}|\ \delta(\cdot)) = \lambda_j(1-e^{-\vartheta_{jj}Q_j})e^{-\nu_{jj}(c_j+c_u+\delta(Q_j))-1}\prod_{k\neq j} e^{-\vartheta_{jk}Q_k}\prod_{k\neq j}(1-e^{-\nu_{jk}(c_k+c_u+\delta(Q_k))-\nu_{jk}/\nu_{kk}})$, $\forall j$.

4.2. Capability Equilibrium

In this section, the downstream firms' capability equilibrium is established, given the upstream leader's capability state $\mathbf{M} = (M^1\ M^2)^\top$ and her premium function, $\delta(Q)$.

Assume $\delta(Q)$ is continuously differentiable for $Q \in [\underline{Q}, M^2)$ and for $Q \in (M^2, \infty)$. We allow non-differentiability at the point M^2 since most practical premium functions are so given the requirement that $\delta(Q) = 0$ for any $Q \le M^2$. Let $\delta(\mathbf{Q}) = (\delta(Q_1)...\delta(Q_n))^\top$, i.e., upstream premiums in vector form. Let $m_j^*(\mathbf{Q}|\ \delta(\cdot))$ denote the equilibrium margin, i.e., $m_j^*(\mathbf{Q}|\ \delta(\cdot)) = p_j^*(\mathbf{Q}|\ \delta(\cdot)) - c_j - c_u - \delta(Q_j)$. We make the following (high-level) assumptions, which are sufficient for the existence of a unique capability equilibrium, for a large enough range for $\mathbf{Q}$.

Assumption 2.

(a) $\partial^2 \left(m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))\right) \Big/ \partial Q_j \partial Q_k \le 0, \forall j,\ k \ne j, \mathbf{Q}$.

(b) $\sum_{k \ne j} \partial^2 \left(m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))\right) \Big/ \partial Q_j \partial Q_k > \partial^2 \left(m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))\right) \Big/ (\partial Q_j)^2,\ \forall j,\ \mathbf{Q}$.

(c) $\partial^2 \left(m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))\right) \Big/ (\partial Q_j)^2 \le 0, \forall j, \mathbf{Q}$.

Assumption 2(a) requires the marginal benefit of a firm from higher capability to be non-increasing in its rivals' capabilities. Assumption 2(b) is a regulatory condition that can be interpreted as the marginal revenue of a firm being more sensitive to that firm's capability level than the rivals'. Assumption 2(c) simply suggests decreasing marginal return with respect to increasing capability of a firm. The multiplicative form satisfies these assumptions for a wide range of values. The linear form violates primarily the condition in (c), which results in convex-concave profit functions. These conditions become less necessary when the cumulative investment function is convex enough. Nevertheless, they tend to hold in general if the demand functions imply that the first and second degree effects of a firm's investment efforts are more influential on its profits than those of its rivals.

For the linear form of the premium function, $\delta(Q) = a(Q - M^2)^+$ where $a \in \Re^+$, $\delta(\cdot)$ is not continuously differentiable at M^2. This can be typical for many possible upstream premium functions. Hence, we define two derivatives at the point M^2: either $\frac{\partial \delta(Q)}{\partial Q}\Big|_{Q=M^2} = 0$ or $\frac{\partial \delta(Q)}{\partial Q}\Big|_{Q=M^2} > 0$, and corresponding two different marginal revenues (which will differ only when $Q_j = M^2$):

$$\rho_j^0(\mathbf{Q}|\ \delta(\cdot)) = \partial m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))/\partial Q_j \Big|_{\partial \delta(Q_j)/\partial Q_j|_{Q_j=M^2}=0}, \tag{6}$$

$$\rho_j(\mathbf{Q}|\ \delta(\cdot)) = \partial m_j^*(\mathbf{Q}|\ \delta(\cdot))D_j^*(\mathbf{Q}|\ \delta(\cdot))/\partial Q_j \Big|_{\partial \delta(Q_j)/\partial Q_j|_{Q_j=M^2}>0}. \tag{7}$$

Let $\mathbf{Q}^*(\delta(\cdot))$ denote the downstream capability equilibrium under the upstream leader's declared premium function (and upstream state $\mathbf{M}$).

Proposition 2. *Under Assumption 2 a unique capability equilibrium, $\mathbf{Q}^*(\delta(\cdot))$, exists such that one of the cases in Table 2 is satisfied for each downstream firm j.*

Table 2: First order conditions for the capability equilibrium

Case	Q_j	Condition
1	$[\underline{Q}, Q_j^0)$	$\rho_j^0(\mathbf{Q}\mid \delta(\cdot)) = 0$
2	Q_j^0	$\rho_j^0(\mathbf{Q}\mid \delta(\cdot)) \leq \partial K_j(Q_j)/\partial Q_j$
3	(Q_j^0, M^2)	$\rho_j^0(\mathbf{Q}\mid \delta(\cdot)) = \partial K_j(Q_j)/\partial Q_j$
4	M^2	$\rho_j^1(\mathbf{Q}\mid \delta(\cdot)) \leq \partial K_j(Q_j)/\partial Q_j \leq \rho_j^0(\mathbf{Q}\mid \delta(\cdot))$
5	(M^2, M^1)	$\rho_j^1(\mathbf{Q}\mid \delta(\cdot)) = \partial K_j(Q_j)/\partial Q_j$
6	M^1	$\rho_j^1(\mathbf{Q}\mid \delta(\cdot)) \geq \partial K_j(Q_j)/\partial Q_j$

Corollary 2. *Under Assumption 2, for any positive premium function, there exists a unique price and demand equilibrium in the downstream market.*

Let $\mathbf{p}^*(\delta(\cdot))$ denote the resulting price equilibrium from the upstream leader's pricing policy, short for $\mathbf{p}^*(\mathbf{Q}^*(\delta(\cdot))\mid \delta(\cdot))$, and $\mathbf{D}^*(\delta(\cdot))$ as the demand equilibrium, short for $\mathbf{D}^*(\mathbf{Q}^*(\delta(\cdot))\mid \delta(\cdot))$.

Two simple direct results of Proposition 2 are Definition 1 and Corollary 3. Definition 1 describes the best capability state the downstream tier is willing to attain even if the upstream premium technology is limitless at no extra cost; this is referred to as as "Technological Potential" (or simply τ) of the downstream tier. Corollary 3 states that if upstream laggards have already attained this level, no upstream firm can collect any positive premium over c_u for any possible technological level.

Definition 1. *For $\delta(Q) = 0$ for all $Q \in [\underline{Q}, \infty)$, the technological potential, τ, of the downstream tier is defined as $\mathbf{Q}^*(\delta(\cdot))$ or in short $\mathbf{Q}^*(0)$.*

Definition 1 (technological potential, TP, τ) and the positive upstream return condition in Corollary 3 are used in §5 when discussing the adoption and financing of different technologies. Assumption 2 is sufficient - yet far from necessary - for its uniqueness.

Corollary 3. *If $Q_j^*(0) \leq M^2$, for all j, then $Q_j^*(\delta(\cdot)) \leq M^2$ for all positive $\delta(\cdot)$.*

Corollary 3 points out an important observation which can be possible for many technological dimensions. If the upstream tier - including the laggard firms - has already acquired a capability level which is beyond the technological potential of the downstream tier, no upstream leader can collect positive return from any technology level. Therefore, all premium tariffs result in the same downstream technology state: the TP of the downstream tier.

For the remainder of our analysis, we assume a linear premium function in the following form: $\delta(Q) = a(Q - M^2)^+$, $a \in \Re^+$. To simplify the notation we use the slope of the premium, a, instead of $\delta(\cdot)$, wherever this linear form is used. Constant unit fees for a given superior technology is common in the literature (e.g., Erat and Kavadias 2006). Considering a linearly increasing form allows discrimination among downstream firms and results in highly non-linear payments to the upstream leader.

4.3. A Symmetrical Downstream Tier

The effects of the major factors we consider such as price/capability cross/self sensitivities can be investigated more closely in a symmetrical downstream tier. Consider n downstream firms all of whose parameters are identical, i.e., in the linear demand model $\alpha_j = \alpha_1$, $\beta_{jj} = \beta_{11}$, $\beta_{jk} = \beta_{12}$, $\gamma_{jj} = \gamma_{11}$, $\gamma_{jk} = \gamma_{12}$, $\kappa_j = \kappa_1$, in the multiplicative demand model $\lambda_j = \lambda_1$, $\vartheta_{jj} = \vartheta_{11}$, $\vartheta_{jk} = \vartheta_{12}$, $\nu_{jj} = \nu_{11}$, $\nu_{jk} = \nu_{12}$, $g_j = g_1$, $k_j = k_1$, and for both models $c_j = c_1$ for all j and $k \neq j$. Hence, the downstream firms are identical in their self-sensitivity parameters, cross-sensitivity parameters, idiosyncratic valuations, and investment cost parameters.

Such a simplification allows us to focus on the relative sensitivity of different kinds of parameters commonly used in the literature, e.g., Erat et al. (2013), Erat and Kavadias (2006), and others. Asymmetry across the downstream firms has further implications, some of which are further discussed in Appendix B.

Corollary 4 to Proposition 2 describes the unique equilibrium when it exists for the (LS) and (MS) cases. Under symmetry the resulting equilibrium is also symmetrical. Hence, we drop the subscript j accordingly in all equilibrium values, primarily $Q^*(a)$, $p^*(a)$, and $D^*(a)$ become the (scalar) equilibrium values for any downstream firm j given a.

Corollary 4. *The unique capability equilibrium, $Q^*(a)$ is one of the 6 cases in Table 2 and satisfies the corresponding condition where:*

$$\begin{aligned}
(\mathbf{LS}) \quad \rho(Q,a) = &\Big(\tilde{\gamma}_{11} + a(\tilde{d}_{11} - 1)\Big) \\
&\Big(\hat{\alpha}_1 + (\hat{\gamma}_{11} + (n-1)\hat{\gamma}_{12})Q + \hat{\epsilon}_1 + (\hat{d}_{11} + (n-1)\hat{d}_{12})a(Q - M^2)\Big) \\
&+ (\hat{\gamma}_{11} + a\hat{d}_{11}) \\
&\Big(\tilde{\alpha}_1 + (\tilde{\gamma}_{11} + (n-1)\tilde{\gamma}_{12})Q + \tilde{\epsilon}_1 - c_1 - c_u + (\tilde{d}_{11} + (n-1)\tilde{d}_{12})a(Q - M^2)\Big). \qquad (8)
\end{aligned}$$

$$\begin{aligned}
(\mathbf{MS}) \quad \rho(Q,a) = &\frac{\lambda_1}{\nu_{11}} e^{-\nu_{11}(c_1 + c_u + a(Q - M^2)) - 1} \left(\vartheta_{11} e^{-\vartheta_{11} Q} - a\nu_{11}(1 - e^{-\vartheta_{11} Q})\right) \\
&\left(e^{-(n-1)\vartheta_{12} Q} \left(1 - e^{-\nu_{12}(c_1 + c_u + a(Q - M^2)) - \nu_{12}/\nu_{11}}\right)^{(n-1)}\right). \qquad (9)
\end{aligned}$$

and $\rho^0(Q, a) = \rho(Q, 0)$.

4.4. Upstream Net Contribution

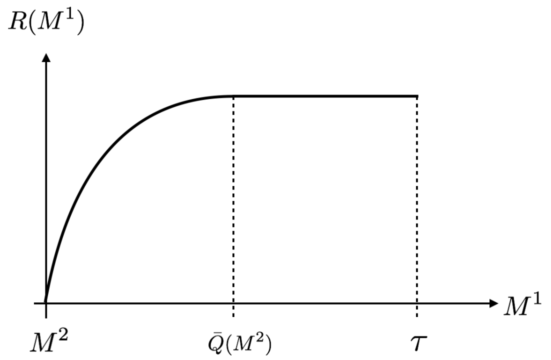
In this section, the upstream leader maximizes the sum of the net contributions from the downstream firms which adopt capabilities between the laggards' technology level, M^2, and the leader's technology level, M^1. This contribution depends both on the unit premium and the equilibrium demand experienced in the lower tier, which are both functions of the capability adopted. In case (L) under the linear premium:

$$R(M^1) = \max_a \sum_{\{j|\ M^2 < Q_j^*(a) \le M^1\}} a(Q_j^*(a) - M^2)D_j^*(a) \tag{10}$$

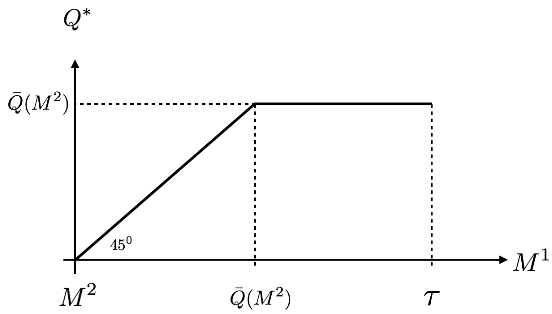
The upstream leader not only tries to maximize its unit price by using a favorable premium, but also induces the adoption of a higher capability and increase the equilibrium demand. The upstream leader can also benefit from the dynamics that arise from asymmetries across downstream firms.

An analytical solution to (10) is impractical and requires solving very high degree polynomials even under linear demand. To investigate the effect of asymmetries among downstream firms, we wrote a numerical procedure (LDCEA) to solve this problem for the linear demand case (with asymmetric downstream firms), which is further discussed in Appendix B. However, symmetrical downstream tiers yield the primary insights more conveniently. In the symmetrical case, $\mathbf{Q}^*(a)$ and τ vectors are also symmetric. Hence, we can represent the upstream return function $R^1(M)$ on a simple graph. A precise stylized description of $R(M^1)$ for any M^1 is intractable even under (L) or (M), yet it has certain properties which we can exploit to explain the behavior of $R(M^1)$ depending on various downstream factors.

Figure 2(a) depicts the typical shape of the upstream leader's return from having a capability level of M^1 over the range $[M^2, \tau]$ over a symmetric downstream tier. $R(M^1)$ is concave increasing in M^1 up to a level - denoted by $\bar{Q}(M^2)$ - and constant for any higher level. The upstream leader cannot obtain more revenue from owning a capability beyond this level and, moreover, chooses not to induce the downstream tier to adopt any further capability - as depicted in Figure 2(b) - since any further capability adopted by the lower tier reduces its revenues. Hence, for any $M^1 \ge \bar{Q}(M^2)$, an upstream leader induces the adoption of only $\bar{Q}(M^2)$; any remaining capability between $\bar{Q}(M^2)$ and M^1 is "held up" in the upper tier and not made available to the lower tier.



(a) Upstream Leader's Revenue



(b) Upstream versus Downstream Capability

Figure 2: Upstream Leader's Revenue and Capability Level Driven to Downstream Tier

Figure 2(a) and Figure 2(b) together explain the economic incentives behind an upstream technology leader has after attaining a technology differential beyond the second-best (laggard) firm. On the one hand, there is already a maximum level the downstream tier is willing to adopt (τ). However, it is not even profitable to sell this maximum demanded level to the downstream tier simply because beyond a smaller hold-up level ($\bar{Q}(M^2)$), upstream return starts decreasing. Hence, if an upstream leader attains a capability between these two important thresholds, it chooses not to sell anything beyond $\bar{Q}(M^2)$ and hence the marginal value of attaining any technology beyond this level is zero.

We can establish $R(M^1)$ using a pseudo return function, $R'(M^1)$, which assumes that the upstream leader charges the maximum premium possible while still inducing the adoption of a specific capability. Let $a'(M^1)$ denote the maximum premium slope that induces the symmetrical downstream firms to adopt a capability level $M^1 \in [M^2, \tau]$, i.e., $a'(M^1) = \{\max a |\ Q^*(a) = M^1\}$. Let $R'(M^1)$ be this pseudo-return curve. $R'(M^1)$ is a continuously differentiable uni-modal function in $[M^2, \tau]$.

If we denote the true revenue maximizing premium slope with $a^*(M^1)$ that leads to the optimal return function $R^1(M^1)$, then $a^*(M^1) \le a'(M^1)$ for any $M^1 < \bar{Q}(M^2)$. However, it is exactly this premium slope for any $M^1 \ge \bar{Q}(M^2)$ ($a^*(M^1) = a'(M^1)$). Hence, $R(M^1) = R'(\bar{Q}(M^2))$ for all $M^1 \ge \bar{Q}(M^2)$, i.e., the pricing (and capability induction) problem of any upstream leader which has a capability level $M^1 \ge \bar{Q}(M^2)$ facing a symmetrical downstream tier can be found by solving:

$$\max_{M^1} R'(M^1) = a'(M^1)(M^1 - M^2)nD^*(M^1 |\ a'(M^1)). \tag{11}$$

The formal treatment of this approximation is provided in Appendix D.1.

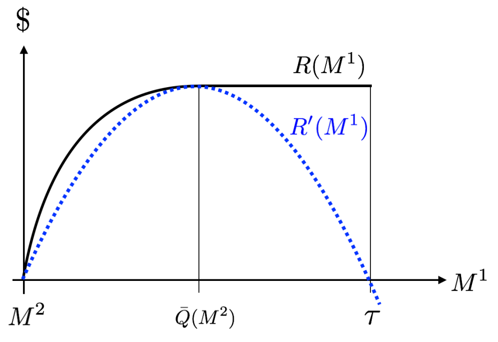


Figure 3: Upstream revenue approximated by the pseudo-revenue curve $R'(M^1)$

The behavior of $R'(M^1)$ with respect to downstream factors is identical to the behavior of $R^1(\bar{Q}(M^2))$, the maximum return an upstream leader can receive from a certain downstream tier, for a given dimension of technology and upstream laggard capability level of M^2 (Figure 3). Hence, $R'(M^1)$ becomes the measure of how a downstream tier is willing to finance a given upstream technology. In §5.2 we use $R'(M^1)$ to demonstrate how downstream tiers with certain types of competition provide higher returns to some technology dimensions.

5. Development and Adoption of Upstream Technology

In this section, we first formalize how downstream market factors influence the level of technology demanded. Then, we explore the effect of the same factors on the supply of the technology - specifically on the returns of a potential upstream leader supplier.

5.1. Technological Potential (τ)

Formally defined in Definition 1, the Technology Potential (τ) is the highest technology state the downstream tier would desire even if the technology is provided at zero premium over marginal cost ($a = 0$). To increase the equilibrium downstream capability state beyond τ, the downstream tier would require subsidies. Hence, τ is a useful upper bound on the technology level demanded by the lower tier. It is not practical to calculate τ exactly in many instances. However, it can be used to understand and explain why some seemingly desirable technologies falter relative to others. In §5.2 we show it is a very good indicator for the true equilibrium technology level demanded. Proposition 3 provides the closed forms of τ for (LS) and (MS).

Proposition 3. *The (scalar) technological potential levels for the linear symmetric tier and multiplicative symmetric downstream tier with n firms are:*

$$(LS) \quad \tau = \frac{-\beta_{11}(\alpha_1 + (c_1 + c_u)\beta^{sum})\Phi}{k_1(2\beta_{11} - \beta_{12})(\beta_{11} + \beta^{sum})^2 + \beta_{11}\gamma^{sum}\Phi} \tag{12}$$

$$(MS) \quad \tau = \frac{\ln\varphi - \ln g_1 - \ln k_1}{(n-1)\gamma_{12} + \gamma_{11} + k_1}. \tag{13}$$

where $\beta^{sum} = \beta_{11} + (n-1)\beta_{12}$, $\gamma^{sum} = \gamma_{11} + (n-1)\gamma_{12}$, $\Phi = 2\beta_{11}\gamma_{11} + \beta_{12}((n-2)\gamma_{11} - (n-1)\gamma_{12})$, *and* $\varphi = \frac{\alpha_1\gamma_{11}}{\beta_{11}} e^{-\beta_{11}(c_1+c_u)-1}\left(1 - e^{-\beta_{12}(c_1+c_u)-\beta_{12}/\beta_{11}}\right)^{(n-1)}$.

Given these closed forms, Proposition 4 characterizes how downstream factors affect technological potential.

Table 3: Comparative statics of technological potential

x	$\partial\tau/\partial x$	x	$\partial\tau/\partial x$	x	$\partial\tau/\partial x$	x	$\partial\tau/\partial x$
α_1	$\nearrow$	λ_1	$\nearrow$	γ_{12}	$\searrow$	ϑ_{12}	$\searrow$
γ_{11}	$\nearrow$	ϑ_{11}	$\nearrow$ & $\searrow$	β_{11}	$\searrow$	ν_{11}	$\searrow$
β_{12}	$\nearrow$	ν_{12}	$\nearrow$	κ_1	$\searrow$	k_1	$\searrow$

Proposition 4. *Downstream demand and investment cost parameters affect the technological potential as described in Table 3.*

For both demand models, the scale/idiosyncratic value parameter (α_1 and λ_1), self-capability sensitivity (γ_{11} and ϑ_{11}), and cross-price sensitivity (β_{12} and ν_{12}) increase the TP, whereas investment cost (κ_1 and k_1), cross-capability sensitivity (γ_{12} and ϑ_{12}), and self-price sensitivity (β_{11} and ν_{11}) reduce the TP. We discuss these effects below.

As expected, technologies which can be differentiated sufficiently across firms and industries, i.e., high self-capability sensitivity and low cross-capability sensitivity, tend be demanded at higher levels. Higher scale factors (α_1, λ_1): if it is versatile for multiple industries with higher volumes (longer appropriation/planning periods) and if it can be adopted at lower costs, a technology dimension tends to be demanded at higher levels by the consumer markets.

The counter-intuitive factor is the cross-price sensitivity (β_{12} and ν_{12}). The case of isolated firms and industries operating in near monopoly conditions is not the most ideal one for the highest downstream demand for a technology. On the contrary, higher levels of technology are demanded when firms are in direct price competition with each other. Sensitivity to rival firms' prices are usually interpreted as firms losing their pricing power against each other. In the case of adoption of upstream technologies, cross-price sensitivities tend to work in the positive direction; firms become willing to adopt more of the technology because this allows them to collectively raise their mark-up in the downstream market relatively more than they could have done if they had been operating in isolation.

By itself, TP does not explain how much of a technology is financed; it describes the span of feasible technology levels the downstream firms may request. The upstream firm providing any technology requires sufficient compensation. TP only provides a limit on the range of capability levels over which a technology leader can collect non-negative returns. In the next section, keeping TP constant, we show that the downstream parameters work differently when it comes to compensating the upstream leader.

5.2. Financing the Upstream Technology: The Right Type of Competition

In order to investigate the return to an upstream technology provider, we design the following numerical study for both the (LS) and (MS) models. We take a base set of values for a downstream tier and find TP. Then, we vary two parameters, one which increases TP and one which decreases it, while keeping the TP constant. We calculate the greatest equilibrium return of the upstream leader (which has a capability $M^1 \geq \bar{Q}(M^2)$, i.e., $R^* \doteq R(\bar{Q}(M^2)))$, by using the pseudo-revenue function $R'(M^1)$. (How this approximation works is explained in §4.4.) We also record the equilibrium price (p^*), capability (Q^*), and demand in the consumer market (D^*), the downstream profits (π^*), and the optimal premium payment to the upstream leader (δ^*). By keeping TP fixed in this experiment's set up, we understand how the downstream market factors influence the upstream return without the bias of changing the technology demanded.

In the (LS) model, α_1, γ_{11}, and β_{12} are the factors in favor of TP, and γ_{12}, β_{11}, and κ_1 are against. In (MS), ϑ_{12}, ν_{11}, k_1, (and similarly g_1) are the factors against TP, and λ_1 and ν_{12} are the factors in favor, whereas ϑ_{11} increases TP at smaller values and reduces it at higher levels. Hence, there are 9 different ways of choosing one variable from each group in the (LS) model and 12 in the (MS) model. We used the base cases in Table 4 to demonstrate our observations.

Table 4: Fixed Technological Potential Experiments Base Cases

(LS)				(MS)			
Variable	Base Value	Variable	Base Value	Variable	Base Value	Variable	Base Value
α_1	40	γ_{12}	-0.2	λ_1	5000	ϑ_{12}	0.05
γ_{11}	2.1	β_{11}	-0.7	ϑ_{11}	0.2	ν_{11}	0.8
β_{12}	0.2	κ_1	2.5	ν_{12}	0.5	k_1, g_1	0.05, 0.01

Let y_1 be the variable chosen from the set of variables in favor of TP and y_2 be the variable from the set which are against ($y_1 \in \{\alpha_1, \gamma_{11}, \beta_{12}\}$ and $y_2 \in \{\gamma_{12}, \beta_{11}, \kappa_1\}$ for (LS); $y_1 \in \{\lambda_1, \vartheta_{11}, \nu_{12}\}$ and $y_2 \in \{\vartheta_{12}, \nu_{11}, k_1, g_1\}$ for (MS)). The tuple (y_1, y_2) was then varied around the values in Table 4 while keeping TP constant and maintaining the regulatory and base assumptions. Denote these lowest and highest values by y_j^l and y_j^h, $j = 1, 2$. Let z^l and z^h be the equilibrium values of each quantity of interest $(Q^*, D^*, p^*, \delta^*, R^*, \pi^*)$ corresponding to y^l and y^h. The ratio of percentage change in z to the percentage change in the euclidean distance of (y_1, y_2) to the origin $(||y||)$ is calculated:

$$\Delta = \frac{\%\text{ change in } z}{\%\text{ change in } ||y||} = \frac{\frac{z^h - z^l}{z_l}}{\frac{||y^h|| - ||y^l||}{||y^l||}}. \tag{14}$$

In all the experiments, along the search directions $\vec{y}$, TP is kept constant. For the (LS) model $\tau = 115.1734$, and for the (MS) model $\tau = 25.5214$.

The details of the measurements are provided in Appendix D.2. From (y_1^l, y_2^l) to (y_1^h, y_2^h), the intensity of the two downstream factors is increasing while TP remains constant. Tables 5 and 6 show the relative effect of increasing the intensity of each pair of downstream factors on the equilibrium values, for (LS) and (MS), respectively.

We now discuss some observations gleaned from Tables 5 and 6.

Observation 1. *For both demand models, if firms are more sensitive to each others' prices and capability levels, both the downstream firms and the upstream leader earn higher profits in equilibrium.*

Observation 1 states that a good direction of competition that increases the upstream leader's return and downstream firms' profits is along the cross-price and cross-capability sensitivities: $(\beta_{12}, \gamma_{12})$ in (L) and $(\nu_{12}, \vartheta_{12})$ in (M).

Table 5: Relative effect of increasing intensity of downstream factor pairs in (LS) model

Factor pairs (LS)	Q^*	D^*	p^*	δ^*	R^*	π^*
(α_1, γ_{12})			$+$	$++$	$++$	$++$
(α_1, β_{11})				$+$	$++$	$++$
(α_1, k_1)			$+$	$++$	$++$	$++$
$(\gamma_{11}, \gamma_{12})$	$+$	$--$	$-$	$+++$	$+$	$---$
$(\gamma_{11}, \beta_{11})$		$+$	$--$	$--$	$--$	$--$
(γ_{11}, k_1)		$++$	$++$	$+$	$++$	$+++$
$(\beta_{12}, \gamma_{12})$			$+$	$++$	$++$	$+$
(β_{12}, β_{11})		$++$	$--$	$--$	$++$	$+++$
(β_{12}, k_1)		$++$	$++$	$++$	$+++$	$+++$

$+++$ if $\Delta \geq 1$,
$++$ if $\Delta \in (0.25, 1)$,
$+$ if $\Delta \in [0.05, 0.25]$,
$-$ if $\Delta \in [-0.25, -0.05]$,
$--$ if $\Delta \in (-1, -0.25)$,
$---$ if $\Delta \leq -1$.

Table 6: Relative effect of increasing intensity of downstream factor pairs in (MS) model

Factor pairs	Q^*	D^*	p^*	δ^*	R^*	π^*
$(\lambda_1, \vartheta_{12})$		$+++$			$+++$	$+++$
(λ_1, ν_{11})						
(λ_1, k_1)		$++$			$++$	$++$
(λ_1, g_1)		$++$			$++$	$++$
$(\vartheta_{11}, \vartheta_{12})$		$+++$	$-$	$---$	$++$	$+++$
$(\vartheta_{11}, \nu_{11})$	$+$	$--$	$--$	$--$	$--$	$--$
(ϑ_{11}, k_1)	$--$	$++$	$--$	$---$	$---$	$++$
(ϑ_{11}, g_1)	$--$	$++$	$--$	$---$	$--$	$++$
$(\nu_{12}, \vartheta_{12})$		$+++$			$+++$	$+++$
(ν_{12}, ν_{11})		$++$	$-$	$-$		
(ν_{12}, k_1)		$+++$			$+++$	$+++$
(ν_{12}, g_1)		$+++$			$+++$	$+++$

$+++$ if $\Delta \geq 1$,
$++$ if $\Delta \in (0.25, 1)$,
$+$ if $\Delta \in [0.05, 0.25]$,
$-$ if $\Delta \in [-0.25, -0.05]$,
$--$ if $\Delta \in (-1, -0.25)$,
$---$ if $\Delta \leq -1$.

Observation 2. *For both demand models, if a technology dimension is versatile (i.e., it can be used by more firms and industries) or if the appropriation period for the technology lengthens, both tiers of the supply chain earn higher profits in equilibrium. This is true even if higher versatility comes at the expense of higher competition in terms of increasing cross-capability sensitivity, cross-price sensitivity or at the expense of higher costs of adoption.*

It is highly intuitive for higher scalability - a technology being used by more firms and industries - to increase the upstream leader's return from it. However, Observation 2 emphasizes a less intuitive version: this is generally true even if the versatility of the technology (α_1 or λ_1) comes at the expense of higher adoption cost (κ_1, k_1), self-price sensitivities (β_{11}, ν_{11}) and cross-capability sensitivities (γ_{12}, ϑ_{12}), three factors which always negatively affect TP.

Observation 1 and 2 point out the two important indicators of a technology that imply higher returns to an upstream leader, and hence its viability to be created in the first place. The main intuition illuminating how they work is the downstream benefit. The exact mechanism behind each should be different, however, in all these directions of changes, the consumer market expands in terms of volume and/or demand.

Observation 3. *The equilibrium technological capability sold to the downstream tier is relatively stable in TP.*

Observation 3 confirms the importance of TP as a good barometer of whether higher levels of a technology are demanded by the supply chain (Q^*). The maximum level that will be passed from the upper tier to the lower tier is primarily a function of the upstream laggard capability (M^2) and downstream TP. Clearly, from Tables 5 and 6, Q^* is mostly stable when τ is constant and the parameters (y^1, y^2) are varied, while the other quantities in the tables vary significantly.

The common denominator of the observations above is: for a given level of technology demanded, if the technology dimension in question is used by industries which have relatively strong factors (greater in magnitude), both for and against TP, it tends to provide a higher return to the upstream leader while increasing the downstream firms' profits through the expansion of consumer markets both in volume and/or consumer prices. This combined observation is especially important for the creation of upstream technologies which have steep associated R&D costs.

6. Discussion

As Bhaskaran and Krishnan (2009) and others emphasize, market characteristics are crucial in explaining the level of development of technologies, especially those that require the participation of multiple supply chain tiers. In this paper, we describe and solve a rich model of market engagement in price and technology wedded to a two-tier competitive supply chain, with a wholesale exchange based on both technology and volume. We show how the market characteristics influence the two related yet different elements behind the creation, adoption, and diffusion of upstream technologies: technological potential and the upstream leader's return.

We demonstrate that technological potential (TP) is a good measure of the level of a technology demanded by consumer markets and that it results from the relative magnitudes of two competing sets of factors. TP is shown to be increasing in the sensitivity of the downstream firms to each other's prices; i.e., a technology being used by isolated industries and firms operating in near monopoly conditions is not the ideal case for it to be demanded at high capability levels. This result is parallel to earlier results in a different branch of literature on the affects of competition on the creation of *cost-reducing* technologies that are licensed in the technology markets (Kamien and Tauman, 2002).

We also demonstrate that an upstream technology is more profitable and hence has a better chance of being financed, if the implied downstream tier has strong market characteristics, both in favor and against TP. That is to say, a technology dimension is more likely to bring a higher return to an upstream technology leader if the two competing sets of market factors - one in favor and one against - both have high magnitudes. Therefore, downstream market characteristics impact the driver behind the financial viability (creation) of a technology differently than they affect the level of technology demanded. Thus, for an upstream technology to be further developed by some upstream firms, adopted by downstream firms, and diffused into the consumer markets, the market characteristics of the downstream tier should be both *balanced* (the sets of factors in favor of technology potential should have relatively higher magnitude than those of the factors that are against the technology potential) and collectively *strong* in magnitude (given the relative magnitudes, both sets of factors should have nominally high magnitudes). Such a case results in greater diffusion either in the form of volume and/or price expansion in the consumer markets.

6.1. Balance versus Strength of Downstream Market Factors

For the technology to be demanded above the upstream laggard capability, TP needs to exceed M^2, too. For it to be supplied, the upstream leader's return should exceed its investment costs. The former is a result of the relative magnitudes of two sets of factors, as discussed in §5.1. The latter is a result of the overall magnitudes of all factors (combined strength) whether they increase or lower TP (§5.2). Hence, the downstream market factors' effect on the two requirements for the development, adoption and diffusion of upstream technologies bifurcates along these two directions.

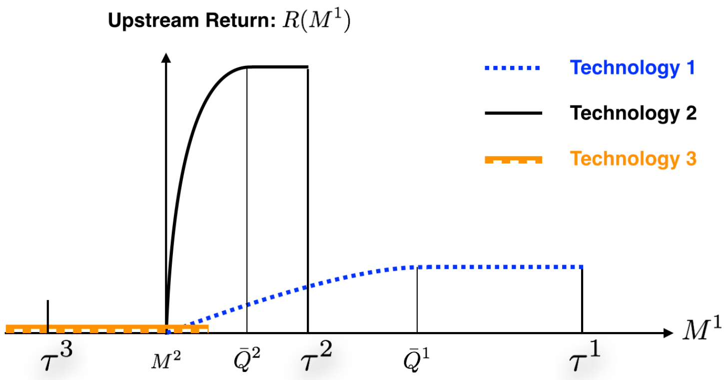


Figure 4: Technology 3 is not demanded beyond laggard cabability. Technology 2 is profitable for the upstream leader, but not demanded at high levels. Technology 1 is highly demanded but profitable.

Figure 4 demonstrates three circumstances an upstream technology may find itself in: "Technology 3" has a TP which is lower than upstream laggard capability ($\tau^3 < M^2$). No extra capability level of Technology 3 is demanded by the consumer markets. "Technology 2" has a TP that is higher than upstream laggard capability ($\tau^2 > M^2$) and provides relatively higher return than that of "Technology 1," which compensates the upper tier much less yet is demanded at higher levels ($\tau^2 < \tau^1$).

In terms of balance of the downstream factors, Technology 1 is the superior case. In terms of total strength of downstream factors, Technology 2 is a better case. The third technology is unfortunate in both senses. We speculate that the DuPont's Stainmaster carpet example discussed in §1 is a scenario where the TP is below the prevailing carpet technologies (i.e., Technology 3), but the technology was imposed upon the downstream firms and the failure became very public. (As discussed in §1, this example applies to a licensed process rather than a wholesaled product but some lessons may be transferable.) The bankruptcies of the integrator firms reduced downstream competition and thus reduced DuPont's upstream returns, as our model also suggests. The reason an upstream technology does not reveal itself in consumer products can be one of these three cases.

Some technologies with high TP levels may suggest downstream tiers with relatively weak market characteristics (small magnitudes of the parameters) such that the resulting return curve from that technology does not encourage investment by any of the upstream firms. In Technology 1, the balance of factors may be very favorable; on the other hand if this is a socially desirable technology the focus should be in increasing the returns for the potential upstream developers. The primary obstacle resides in the upper tier and subsidies directed primarily toward that tier may resolve the problem.

In the case for Technology 2, some technologies may be created in the upper tiers but are held up there because their TP level in the downstream tier is low (which results in lower $\bar{Q}(M^2)$). Providing higher subsidies to the upstream tier only increases their rent but does not advance the technology.

6.2. Speculations about Some Contemporary Technologies

Diagnosing which of the two elements behind the delivery of the technology by the supply chain fails may be helpful both for management practices and governmental policies. Some technologies might have a low TP, and hence are not truly demanded at high levels. We suspect that cell phone battery life may be of this type. Although, consumers frequently complain about the battery lives of new smartphones, which have a myriad of other desirable capabilities, we suspect that the cross-capability sensitivities of cell-phone producers to each others' phones' battery lives is prohibitively high. A smartphone producer which attains a long battery life can significantly increase its demand, but only at the expense of other firms. Hence, in equilibrium the cell-phone industry does not expect a significant market expansion and return from advancing this capability (i.e., high γ_{11} but with high γ_{12}). The true TP level for cell-phone battery life until the next recharge may not be far above the current approximate half-a-day of active usage.

On the other hand, batteries for electrical cars are advancing far more rapidly. Due to the necessary infrastructure investments that will take time, advancing electric car technologies are not an immediate threat to current conventional gasoline powered vehicles. Yet, the benefit to a potentially superior electrical car is still high. Hence, we suspect there is a high γ_{11} and relatively low γ_{12} for the total power level that can be stored in an electric car battery, implying a large TP. Moreover, this relatively new industry might have strong market characteristics, high adoption costs, high cross- and self-price and capability sensitivities, which we show has the potential of a large return to an upstream developer of longer-lasting electric car batteries. Interestingly, Elon Musk, the CEO of electric car manufacturer Tesla Motors, has evangelized battery technologies in transportation, naturally, but also for home storage of solar energy (Smith and Sweet, 2015). Presumably the latter is to foster faster innovation in battery technology, with Musk hoping for a spillover from one burgeoning application (home energy storage) to another (vehicle energy storage). If this is not sufficient, we expect subsidies directed toward the upper tier (the developer of the batteries) should work better. We should note that these are speculations made from the perspective of consumer (downstream) market factors onto different upstream technology dimensions and to explain the markets' true desire for them. An upstream firm eventually has to weigh them against its own investment costs and the uncertainties in R&D for any technology dimension. This upstream investment cost side is beyond the scope of research here. We discuss this point further in §7.

6.3. Implications for Public Policies

In general if a seemingly desirable upstream technology has a low TP and strong consumer market characteristics, public policies should be targeted not toward the upper tier that would develop it, but toward the consumer market to increase its TP. This may be in the form of subsidizing adoption, increasing the appropriation period by further intellectual property (IP) protection or by other means that increase the factors in favor of TP and reduce the ones against it. An example of this would be the U.S. and California governments' rebate to buyers of plug-in electric vehicles.

If a desirable upstream technology has a high TP, yet has not been developed in the upper tier, this may be due to weak market characteristics in the consumer markets resulting in poor potential returns for the developer. Public policies targeted to further protect the lower tier will not help in making this technology more viable and profitable for the upstream leader. The policies should subsidize the upper tier, whether in terms of reducing the risks and investment costs of the upper tier, or increasing IP protection level for the upper tier. A prime example of this is the Research and Experimentation Tax Credit under the Internal Revenue Code section 41, operating since 1981, where companies may tax deduct their R&D expenses. Our results suggest such a tax credit could be more effective if it were targeted to high TP industries.

7. Concluding Remarks

In this paper we study the effects of consumer market factors on upstream technologies, which are themselves implied by the current and potential use of an upstream technology dimension in various consumer products. We demonstrated that these factors can be used to classify different technology dimensions and that they influence the two necessary elements for their success, the technology level demanded (Technology Potential, TP) and the return to the upstream leader who develops them, differently. This difference is then is used to explain multiple ways an upstream technology may fare (or be held up) in the supply chain. Depending on which element is weaker, we suggest public subsidies to be targeted toward different tiers of the supply chain.

An important managerial implication of our results is that TP and the accompanying return function can be used by upstream firms in their R&D project selection. They can choose technology dimensions with sufficiently steep return curves and in those technology dimensions target improvement levels which do not exceed the TP of the consumer markets. Collecting enough data to quantify TP may require more detailed models empirically to find the market parameter values. At the level of abstraction used in this paper, our results might be used in an ordinal way. However, future research to quantify TP (and $R(M^1)$) or a proxy for it may lead to practical tools to support project selection for research-focused firms or venture capitalists seeking viable investment opportunities.

A natural extension of this research is to technologies which are not sold within a component for the consumer products but through licensing in the technology markets. This alters the upstream compensation slightly and hence may change the upstream leader's manipulation strategies of the downstream tier. Comparing the two mechanisms of technology transfers between the tiers of a supply chain may allow us to explain the more appropriate marketing mechanism (e.g., pricing, licensing, contracting) for different types of upstream technologies.

Downstream firms exert significant efforts to adopt upstream technologies and we have modeled their investment costs in our supply chain model when determining the technology level demanded and the upstream leader returns. Moreover, a downstream firm may exert effort to innovate to improve its own product (architecture, design), alter its product significantly to become almost a new product, or even invent a whole new product category to make use of the (potentially) developing upstream technology. In our model, among the consumer market factors, the idiosyncratic factors of downstream firms represent this lower tier firm capability in creating a market for the use of the upstream technology (yet it is an exogenous input parameter to our model and can be endogenized in a future extension). We used this factor to capture this important role of the downstream tier. However, the exact nature of interaction can be richer and itself be improved for the overall supply chain to work better in supporting technological innovations. Downstream firms may lead or operate hand-in-hand with upstream firms to develop both the upstream technology dimension and the consumer products that make use of it. We believe that from a supply chain perspective, there is much to be explored in terms of new levers to push technology, ranging from different cooperation methods between tiers, pricing and reimbursement mechanisms, downstream efforts in creating the consumer market base to eventually finance upper tier technologies, and even leadership choices (e.g., Krishnan et al. (2015) investigates when should the downstream tier and when should the upstream tier lead the supply chain for successful innovation.)

Finally, the investment decisions of upstream firms depends not only on the consumer market factors and the two elements they determine as studied here - in general we can dub these as the market side of the problem - but also on the R&D costs, on the uncertainties of the outcomes, and on the competition among the upstream firms themselves. Therefore, another extension of this paper is a competition model among upstream firms in R&D investments to develop a certain technology dimension with a simplified input of market factors - for example a parameterized upstream leader return/profit function - distilled from this paper.

References

References

Bernstein, F., Federgruen, A., 2005. Decentralized supply chains with competing retailers under demand uncertainty. Management Science 51, 18–29.

Besbes, O., Zeevi, A., 2015. On the (surprising) sufficiency of linear models for dynamic pricing with demand learning. Management Science 61, 723–739.

Bhaskaran, S.R., Krishnan, V., 2009. Effort, revenue, and cost sharing mechanisms for collaborative new product development. Management Science 55, 1152–1169.

Bhaskaran, S.R., Ramachandran, K., 2015. Competitive product introductions in technologically dynamic environments. Working paper.

Cai, X., Chen, J., Xiao, Y., Xu, X., 2010. Optimization and coordination of fresh product supply chains with freshness-keeping effort. Production and Operations Management 19, 261–278.

Clark, P., 2014. New battery aims to transform electric cars. Financial Times.

Curcic, S., 2014. The tree that recharges your phone. Financial Times.

Curtat, L., 1992. Supermodular Stochastic Games: Existence and Characterization of Markov Equilibria. Ph.D. thesis. Stanford University. Stanford, CA.

Donnenfeld, S., Weber, S., 1992. Vertical product differentiation with entry. International Journal of Industrial Organization 10, 449–472.

Douthwaite, B., Keatinge, J., Park, J., 2001. Why promising technologies fail: the neglected role of user innovation during adoption. Research policy 30, 819–836.

Druehl, C.T., Schmidt, G.M., Souza, G.C., 2009. The optimal pace of product updates. European Journal of Operational Research 192, 621–633.

Erat, S., Kavadias, S., 2006. Introduction of new technologies to competing industrial customers. Management Science 52, 1675–1688.

Erat, S., Kavadias, S., Gaimon, C., 2013. The pitfalls of subsystem integration: When less is more. Management Science 59, 659–676.

Gabszewicz, J.J., Thisse, J., 1979. Price competition, quality and income disparities. Journal of Economic Theory 20, 340–359.

Gilbert, S.M., Cvsa, V., 2003. Strategic commitment to price to stimulate downstream innovation in a supply chain. European Journal of Operational Research 150, 617–639.

Goettler, R.L., Gordon, B.R., 2011. Does amd spur intel to innovative more? Journal of Political Economy 119, 1141–1200.

Huisman, K.J.M., Kort, P.M., 2003. Strategic investment in technological innovations. European Journal of Operational Research 144, 209–223.

Jain, S., Ramdas, K., 2005. Up or out - or stay put? product positioning in an evolving technology environment. Production and Operations Management 14, 362–376.

Kamien, M.I., Tauman, Y., 2002. Patent licensing: The inside story. The Manchester School 70, 7–15.

Klastorin, T., Tsai, W., 2004. New product introduction: Timing, design, and pricing. Manufacturing & Service Operations Management 6, 302–320.

Krankel, R.M., Duenyas, I., Kapuscinski, R., 2006. Timing successive product introductions with demand diffusion and stochastic technology improvement. Manufacturing & Service Operations Management 8, 119–135.

Krishnan, V., Mnyshenko, O., Shin, H., 2015. Inclusive innovation: Broader market coverage for innovative products with deliberate supply chain leadership. Working paper.

Krishnan, V., Ramachandran, K., 2011. Integrated product architecture and pricing for managing sequential innovation. Management Science 57, 2040–2053.

Krishnan, V., Ulrich, K.T., 2001. Product development decisions: A review of the literature. Management Science 47, 1–21.

Lehmann-Grube, U., 1997. Strategic choice of quality when quality is costly: the persistence of the high-quality advantage. RAND Journal of Economics 28, 372–384.

Liu, L., Parlar, M., Zhu, S.X., 2007. Pricing and lead time decisions in decentralized supply chains. Management Science 53, 713–725.

Luchs, R., Geylani, T., Dukes, A., Srinivasan, K., 2010. The end of the robinson-patman act? evidence from legal case data. Management Science 56, 2123–2133.

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

Pakes, A., Schankerman, M., 1984. An exploration into the determinants of research intensity, in: R&D, Patents, and Productivity. University of Chicago Press, pp. 209–232.

Ramachandran, K., Krishnan, V., 2008. Design architecture and introduction timing for rapidly improving industrial products. Manufacturing & Service Operations Management 10, 149–171.

Savaskan, R.C., Bhattacharya, S., van Wassenhove, L.N., 2004. Closed-loop supply chain models with product remanufacturing. Management Science 50, 239–252.

Schmookler, J., 1962. Economic sources of inventive activity. Journal of Economic History 22, 1–10.

Smith, R., Sweet, C., 2015. Will tesla's newest battery pan out? The Wall Street Journal.

Sutton, J., 1996. Technology and market structure. European Economic Review 40, 551–530.

Wang, J., Shin, H., 2015. The impact of contracts and competition on upstream innovation in a supply chain. Production and Operations Management 24, 134–146.

Xiao, W., Xu, Y., 2012. The impact of royalty contract revision in a multistage strategic R&D alliance. Management Science 58, 2251–2271.

Yue, J., Austin, J., Wang, M.C., Huang, Z., 2006. Coordination of cooperative advertising in a two-level supply chain when manufacturer offers discount. European Journal of Operational Research 168, 65–68.

Yue, X., Liu, J., 2006. Demand forecast sharing in a dual-channel supply chain. European Journal of Operational Research , 646–667.

Zhu, K., Zhang, R.Q., Tsung, F., 2007. Pushing quality improvement along supply chains. Management Science 53, 421–436.