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Patent Portfolio Management of Sequential Innovations: Theory and Empirics

Jinyoung Kim

The Institute of Economic Research - Korea University
Anam-dong, Sungbuk-ku, Seoul, 136-701, South Korea, Tel: (82-2) 3290-1632, Fax: (82-2) 928-4948

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Korea University

ABSTRACT

This paper develops a model for understanding a firm's decisions regarding the maintenance (renewal) and patenting of sequential innovations and studies how these decisions are affected by the model's parameters such as maintenance fees and filing fees. The model offers a discriminating testable hypothesis, predicated on the cross-price effects, to identify complementarityor substitutability across sequential innovations. Our empirical results show that higher filingfees are associated with lower probability of patent renewal, which corroborates the case of complementarity in sequential innovations.

Keywords: Renewal, Patenting, Sequential innovations, Patent portfolio, Patent maintenance fees, Application filing fees

JEL Classification Numbers: O32, O34

I. Introduction

In the past few decades, technological innovations and inventions have become extremely important to firms for their survival in competitive markets. As a result, the management of intellectual properties has become a high priority for innovating firms in many industries, andit has been reportedthat firms utilize a variety of methods for the management of intellectual properties. For example, via legal protection (patent, trademark or copyright), an innovating firm attempts to prevent competitors from imitating its new products and can thereby protect its market share. Secrecy offers firms an alternative means of securing R&D returns while avoiding both the legal expenses of patent application and infringement prosecution, and the potentially much greater losses from the disclosure of sensitive information to competitors.

Among the various methods of intellectual property management, patentingisconsidered the most effective legal protection from outsiders (competing firms) as well as insiders (departing research personnel)[1], which renders patent portfolio management a critical issue for innovating firms. In general,patent portfolio management involves two activities: the patenting of new innovations and the maintenance (or renewal) of existing patents. Upon the arrival of a new innovation, a firm decides whether to file for a patent or to rely on secrecy. When filing a patent application, it is required to pay application filing fees. Under the current U.S. system, after the examination period (typically 2 years), a patent is granted which guarantees legal protection for 20 years after filing. Every patent grantis subject to payment of maintenance fees, which must be paid to maintain the patent in force. These fees are due at 3½, 7½ and 11½ years

[1] See Kim and Marschke (2005) for the survey of the role of patents.

from the date on which the patent is granted. In this paper, we examine theoretically and empirically how factors such as application filing fees and maintenance fees affectan innovating firm's patenting and renewal decisions onitssequential innovations. In particular, we investigate the own-price effects of those fees on patenting and renewalas well as their cross-price effects, where the latter effects provide us a testable implication to identify complementarityor substitutability across sequential innovations.

Earlier studies onpatent renewal haveprimarily focused on three broad topics. Using records of patents' renewals and expirations, Pakes (1986), Schankerman and Pakes (1986), Lanjouw (1998), Schankerman (1998)have attempted to estimate the private pecuniary values of patents under the premise that a patent will not be renewed unless its value exceeds the cost of maintenance or renewal. Deng (2005) extends this literature by examining the joint determination of patenting and renewal of a given innovation and using information on both dimensions to estimate the innovation's value, but does not take into account sequential innovations within a firm.In contrast to our paper, these studiesdo not consider a firm's renewal decision jointly made with patenting decisions on subsequent innovations and thus ignore, for example, the effect of filing fees for subsequent innovations on renewal of antecedent patents. Furthermore, they assume that the revenue across innovations is independent and identically distributed while our model allows for the possibility that revenues across sequential innovations are correlated and a firm's patenting and renewal decisions on two innovations are therefore jointly made. Liu et al. (2008) has empirically studied whether a firm is more likely to have its patent renewed when the patent belongs to a sequence of complementary innovations identified by the USPTO as parent, divisional, and continuation-in-part patents. This paper, however, does not examine the interrelationship between patenting and renewal decision in the context of sequential innovations of a firm.

The second topic concerns the optimal mechanism issues in the intellectual property protection system: (1) whether and when the patenting-renewal system is optimal with regard to inducing the proper amount of research efforts, and (2) what are the optimal maintenance (renewal) schedule and fees (Gans *et al*., 2004). Although the literature is not generally optimistic regarding the efficiency of the patenting-renewal system (Wright, 1983), some studies have demonstrated the conditions of an economic environment in which the patent-renewal system is optimal (O'Donoghue *et al*., 1998). Cornelli and Schankerman (1999) showed that the renewal system can shift research efforts toward higher-productivity firms in the presence of asymmetric information. Scotchmer (1999) demonstrated that the renewal system is equivalent to direct revelation mechanisms with asymmetric information on research costs and benefits. These theoretical studies presume that patenting and renewal decisions, in addition to R&D, are responsive to changes in patent filing fees and maintenance fees, such that efficiency may be achieved by the patenting-renewal system. The empirical component of this paper attempts to provide direct evidence on how responsive these decisions are with regard to price changes.

The third topic addresses various roles of the patent renewal system. Langinier (2004), Horstmann *et al*. (1985), and Crampes and Langinier (1998) have argued for the strategic utilization of patenting and renewal in order to deter entry. Hall and Ziedonis (2001) stated that firms make patenting decision strategically for a variety of purposes: to keep or establish their position in a technological domain, to block rivals from patenting related inventions, and to expand their portfolio even with lower quality patents, as a defensive strategy. Cohen *et al*. (2000) also claimed that firms manage patent portfolios with patenting and renewal decisions to use them in negotiation with other firms. The main contribution of our paper to this extensive literature is to offer a new *positive* theory regarding the management of a firm's patent portfolio in an environment of sequential innovations.

This paper is organized as follows. Section 2 lays out a formal model of a firm's patenting and renewal decisions in an environment in which firms develop sequential innovations. Section 3 describes the data and explains our empirical specifications. We report our empirical findings in Section 4. Finally, the paper concludes in Section 5, and it includes a discussion of the quantitative importance of our estimates in explaining observed variations in patenting and renewal behaviors.

II. A Dynamic Model of Sequential Innovations

We start with a representative firm that lasts for infinite periods. In each period the firm pursues a fixed number of independent lines of research, and each line of research produces a new patentable innovation per period. Index j for different lines of research is treated as a continuous variable and the total number of research lines is denoted by N. The firm transforms an innovation to a product whose life on the market ends in two periods,[2] and therefore two sequential innovations in the same research line overlap in their lifespans. If a new innovation in

[2] A four-period model may be more realistic since the U.S. patents are renewed at 4th, 8th and 12th years from the grant date. However, this complication would not provideany further intuitionbeyond our two-period model.

research line j in period t is patented at the beginning of its life, the firm earns the revenue, θ^t_{jt} ($\in R^+$). Otherwise, the firm's revenue from the innovation is ν^t_{jt} ($\in R^+$) over period t. We assume that both θ^t_{jt} and ν^t_{jt} are random variables and determined by the intrinsic value of the innovation in its first period of life (θ^t_j), and thus $\theta^t_{jt} = \theta^t_j + \varepsilon_{j1t}$ and $\nu^t_{jt} = \theta^t_j + \varepsilon_{j2t}$ where ε_{j1t} and ε_{j2t} are randomly drawn prior to the making of the patent decision from two time-invariant, independent distributions, respectively, that are known *a priori*.

When an innovation in line j is patented in period t, the firm decides on patent renewal at the beginning of period t+1. If the patent is renewed, the firm earns θ^t_{jt+1} ($\in R^+$) in period t+1, while its revenue is ν^t_{jt+1} ($\in R^+$) if not renewed. Variables θ^t_{jt+1} and ν^t_{jt+1} are each correlated with the innovation's value under patent protection in period t, θ^t_{jt}. More specifically, both variables depend on the depreciated value of θ^t_{jt} with the common depreciation rate ρ ($\in(0,1]$): $\theta^t_{jt+1} = \rho\theta^t_{jt} + \varepsilon_{j3t+1}$ and $\nu^t_{jt+1} = \rho\theta^t_{jt} + \varepsilon_{j4t+1}$ where ε_{j3t+1} and ε_{j4t+1} are random variables with time-invariant, independent distributions that are known *a priori* and are realized prior to the renewal decision.

We assume for simplicity that an innovation not patented in the first period of its lifespan is not worth patent protection in the second period, and that the firm earns the same revenue in the second period from a product under no patent protection (either not patented in the first period or not renewed).

The firm's profit gained from two overlapping innovations in the same research line j in period t depends on its decisions regarding patenting (P_{jt}) of a new innovation and renewal (R_{jt}) of an old innovation and is denoted by $\pi_{jt}(R_{jt}, P_{jt})$. We assume that two overlapping innovations in the same research line are not independent and can be either complements or substitutes in the sense that function π_{jt} is either supermodular for the former case or submodular for the latter case.[3] The relationship between the two overlapping innovations is determined stochastically due to the unpredictability of R&D outcomes and they can be either complements with probability q_{jt} which is exogenously given or substitutes with probability 1- q_{jt}. We assume for simplicity that the nature of their relationship is revealed prior to renewal and patenting decisions and symmetric across all research lines with the same probability, q_t. With N number of research lines, the firm thus has $q_t N$ cases of complements and $(1-q_t)N$ cases of substitutes in period t.

We define V_{jt} and W_{jt} as the value of the firm contributed by research line j at the end of period t-1, when the innovation born in period t-1 was patented and when it was not, respectively. The firm's decisions regarding patenting (P_{jt}) and renewal (R_{jt}) in period t when the innovation was patented in period t-1 depend on the firm's profit for each combination of patenting and renewal decisions, as is described in Table 1. In this table, δ is a time discount factor ($0<\delta<1$), and application filing fees and maintenance (renewal) fees in period t are denoted as c_{at}, and c_{rt}, respectively.[4]

Note that the firm's profit is increased by α_j when the old patent is renewed ($R_{jt} = 1$) and the new innovation is patented ($P_{jt} = 1$) if α_j is positive. We can show that this profit function

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[3] A function f is supermodular and its arguments are complements if the sum of the changes in f when several arguments are increased separately is less than the change resulting from increasing all the arguments together. Put differently, increasing one or more variables in a supermodular function raises the return to increasing other variables. This idea of complementarity is equivalent to Edgeworth-complementarity in production: factors are Edgeworth-complements if having more of one factor increases the return to the other factor. If $-f$ is supermodular, then f is called submodular. For the details of supermodularity and complementarity, see Topkis (1978) and Milgrom and Roberts (1990).

[4] In general, the firm's revenue from a patent not renewed ($v^{t-1}{}_{jt}$) may be affected by whether or not a new innovation is patented. Or, the revenue from a new innovation that is not patented ($v^{t}{}_{jt}$) may be affected by whether or not the patent in the previous period is renewed this period. These possibilities are not crucial to the model's implications and are thus not addressed in our model.

Table 1: Profit to the firm from research line j in period t

Patent renewed	New product patented	Firm's profit, $\pi_{jt}(R_{jt}, P_{jt})$
No ($R_{jt} = 0$)	No ($P_{jt} = 0$)	$\pi_{jt}(0, 0) = \nu^{t-1}_{jt} + \nu^{t}_{jt} + \delta\ W_{jt+1}$
	Yes ($P_{jt} = 1$)	$\pi_{jt}(0, 1) = \nu^{t-1}_{jt} + \theta^{t}_{jt} - c_{at} + \delta\ V_{jt+1}$
Yes ($R_{jt} = 1$)	No ($P_{jt} = 0$)	$\pi_{jt}(1, 0) = \theta^{t-1}_{jt} - c_{rt} + \nu^{t}_{jt} + \delta\ W_{jt+1}$
	Yes ($P_{jt} = 1$)	$\pi_{jt}(1, 1) = \theta^{t-1}_{jt} - c_{rt} + \theta^{t}_{jt} - c_{at} + \alpha_j + \delta\ V_{jt+1}$

with positive α_j is supermodular and its two arguments are complements. In this case, the technology embedded in the succeeding innovation is complementary to that in the preceding innovation, such that having both under patent protection generates additional profits beyond the sum of profits each innovation generates on its own. For example, Athey and Schmutzler (1995) argue that a demand-enhancing (product) innovation and a cost-reducing (process) innovation are complementary.

If the technologies in sequential innovations are substitutable, such that patent protection on one would reduce the profit from the other, α_j assumes a negative value and the profit function is submodular. Sequential innovationsin the process of "creative destruction" are considered in general as substitutes (Schumpeter, 1942; Caballero and Jaffe, 1993).

When the innovation in period t-1 was not patented, the firm's only decision to make in period t is whether or not to patent a new innovation. In this case, the firm's profit will be that shown in the first row of Table 1 (when $R_{jt} = 0$ and $P_{jt} = 0$) or in the second row of that table (when $R_{jt} = 0$ and $P_{jt} = 1$).

We first consider the case of complementary technologies (α_j>0). When the prior innovation is patented, the firm chooses not to renew the patent ($R_{jt} = 0$) and not to patent a new innovation in period t ($P_{jt} = 0$) if and only if profit $\pi_{jt}(0, 0)$ is greater than that from any other choice. The conditions are: $(\theta^{t}_{jt}-\nu^{t}_{jt}) = (\varepsilon_{j1t}-\varepsilon_{j2t}) \equiv \theta_{jt} < c_{at}-\delta\,(V_{jt+1}- W_{jt+1})$, $(\theta^{t-1}_{jt}-\nu^{t-1}_{jt}) = (\varepsilon_{j3t}-\varepsilon_{j4t}) \equiv \varepsilon_{jt} < c_{rt}$, and $\theta_{jt} + \varepsilon_{jt} < c_{rt} + c_{at}-\alpha_j-\delta\,(V_{jt+1}- W_{jt+1})$ where θ_{jt} and ε_{jt} denote net gains from patent protection in the first period and in the second period of the product's life cycle, respectively. The firm does not renew ($R_{jt} = 0$) but patents ($P_{jt} = 1$) if and only if $\theta_{jt} > c_{at}-\delta\,(V_{jt+1}- W_{jt+1})$ and $\varepsilon_{jt} < c_{rt}-\alpha_j$. Or, the choices ($R_{jt} = 1$) and ($P_{jt} = 0$) are made if and only if $\theta_{jt} < c_{at}-\alpha_j-\delta\,(V_{jt+1}- W_{jt+1})$ and $\varepsilon_{jt} > c_{rt}$. Finally, the firm renews and patents if and only if $\theta_{jt} > c_{at}-\alpha_j-\delta\,(V_{jt+1}- W_{jt+1})$, $\varepsilon_{jt} > c_{rt}-\alpha_j$, and $\theta_{jt} + \varepsilon_{jt} > c_{rt} + c_{at}-\alpha_j-\delta\,(V_{jt+1}- W_{jt+1})$. These renewal and patenting decisions of the firm are depicted in Figure 1 on the θ_{jt}-ε_{jt} space. Intuitively, Figure 1 indicates that the firm is more likely to renew the patent the higher is the net gain from patent protection with renewal (ε_{jt}), given θ_{jt} (see quadrants I and II). Also, the firm is more likely to patent a new innovation the higher is the net gain from patent protection with new patent filing (θ_{jt}), given ε_{jt}(see quadrants I and IV).

When sequential innovations reflect substitutable technologies ($\alpha_j < 0$), we can derive the conditions for the firm's patenting and renewal decisions in the same manner as in the case of complements. Figure 2 illustrates the conditions for these choices when the firm has patented the prior innovation.

We can also show that the condition for patenting in the case when the prior innovation was not patented is the same, regardless of whether the technologies are complementary or substitutable: $\theta_{jt} > c_{at}-\delta\,(V_{jt+1}- W_{jt+1})$.

Effects of Patent Filing Fees

Our model shows that an increase in filing fees (c_{at})—either temporarily(i.e. rising only in the current period) or permanently (in the current as well as all periods afterward)—lowers the probability of a firm patenting an innovation (that is, a negative "own-price" effect), regardless of whether the overlapping technologies are complementary or substitutable. The following proposition describes the "cross-price" effect of a change in patent filing fees that generates a discriminating testable implication as to whether sequential innovations are complementary or substitutable.[5]

Proposition 1. A temporary or permanent increase in filing fees(c_{at}) lowers the probability of renewal when the sequential technologies are complementary, but raise the renewal probability when the technologies are substitutable.

Proof: See Appendix A.

Consider a permanent increase in filing fees. The first-order effect is to raise the renewal probability and lower the patenting probability when the firm has substitutable innovations.[6] Renewal becomes more attractive than patenting also in the following period due to higher filing fees in that period, which means that the value of holding a patent in this period increases. However, we can show that the former (first-order) effect is stronger than the latter (second-order) effect, and therefore the net effect of rising filing fees is to raise the renewal probability and

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[5] A number of papers have empirically examined the complementarity of innovations or innovation strategies. Arora and Gambardella (1990) tested whether various research cooperation strategies between large biotech firms and universities or small/medium sized firms are complementary. Miravete and Pernias (2006) showed significant complementarity between product and process innovations.

[6] Note that a temporary change in c_{at} produces only this first-order effect.

lower the patenting probability. When technologies are complementary, the first-order and second-order effects operate in the same direction: lowering both the patenting probability and the renewal probability.

Figures 3a and 3b illustrate the effect of an increase in c_{at} when the technologies are complementary (α_j>0) and substitutable (α_j<0), respectively. The dashed boundaries in these figures result from this change in c_{at}.This change is illustrated to lower the probability of renewal when α_j>0 but raise the renewal probability when α_j<0.

Proposition 1 predicts that the effect of filing fees on renewal at a firm level is more likely to be negative for a firm with more research lines associated with complementary innovations (i.e. a firm with higher q_t).

Effects of Patent Maintenance Fees

We can easily verify that an increase in renewal fees (c_{rt}) temporarily or permanently lowers the probability of the firm renewing a patent in period t, regardless of whether technologies are complementary or substitutable. This "own-price" effect has been analyzed theoretically and empirically in earlier studies like Pakes (1986), Lanjouw (1998), Gans et al. (2004), and Deng (2005). The following two propositions describe the "cross-price" effect of a change in maintenance fees (c_{rt}).

Proposition 2. Suppose that renewal fees (c_{rt}) rise only in period T with c_{rt} intact for t = T+1,…,∞. This temporary increase in renewal feeslowers the probability of patenting in period T when the technologies are complementary but raises the patenting probability when the technologies are substitutable.

Figures 4a and 4b illustrate the effect of a temporary increase in renewal fees when the technologies are complementary (α_j>0) and substitutable (α_j<0), respectively. Note in these figures that only the intercepts on the vertical axis move up with those on the horizontal axis intact because V_{jt+1} and W_{jt+1} are not affected by a temporary change in c_{rt}. These figures show that a temporary increase in renewal fees lowers the probability of patenting when α_j>0 but raise the patenting probability when α_j<0.

Proposition 3. Consider a permanent increase in renewal fees (c_{rt}) where c_{rt} rises for t= T,…,∞. This increase lowers the patenting probability in period T when the technologies are complementary. However, its effect is ambiguous when the technologies are substitutable.

Proof: See Appendix B.

If sequential innovations are substitutable (α_j<0), increasing renewal fees in period T have a direct substitution effect, lowering the renewal probability and raising the patent probability in period T (this pertains to the effect of a temporary change in renewal fees). However, when renewal fees are expected to be higher in the future as well, holding a patent that offers an option of later renewal becomes less attractive. This reduces the patenting probability and consequently favors renewal against patenting. Therefore, the effect of a permanent change in renewal fees on the patenting probability can go either way when sequential innovations are substitutable. Figure 4d illustrates the effect of a permanent increase in c_{rt} when α_j<0. The shift in boundaries with the permanent increase in c_{rt} indicates that the firm will renew only for higher draws of ε than before, which is depicted as the contracting area of renewal in Figure 4d. The reduction in the future value of patenting due to rising renewal fees lowers the likelihood that the firm patents, and Regions A1 and A3 in Figure 4d illustrate this. However, the substitution effect can increase the propensity of patenting in expense of renewal, which is illustrated in Region A2. Note that Regions A1 and A3 do not take place if the increase in c_{rt} is temporary, which leads to Proposition 2.

The effect of a permanent increase in renewal fees when the technologies are complementary (α_j>0) is illustrated in Figure 4c. The shift in boundaries to dashed lines due to this permanent increase demonstrates falling probabilities of both renewal and patenting.

At a firm level, our analysis suggests that the more lines of research which produce complementary innovations a firm has (i.e. q_t is higher), the more likely rising renewal fees have an adverse effect on the patenting probability, at least temporarily.

Effects of Degree of Complementarity or Substitutability

Variations in the degree of complementarity or substitutability across sequential innovations can affect the propensities of patenting and renewal, as is described in the following proposition.

Proposition 4. When technologies are complementary, a higher degree of complementarity (higher α_j where α_j>0) raises both the patenting probability and the renewal probability. When the technologies are substitutable, a higher degree of substitutability (higher $|\alpha_j|$ where α_j<0) lowers the patenting probability and has an ambiguous effect on the renewal probability.

Proof: See Appendix C.

Sequential innovations being more substitutable implies that choice $(R_{jt}, P_{jt}) = (1, 1)$ is less attractive due to the lower profits from the choice, which makes patenting and renewal less likely. Moreover, as the future value of a patent is smaller for innovations with higher substitutability, the propensity to patent falls, which renders the renewal probability higher as the result of substitutability. The net effect of higher substitutability is, therefore, to lower the patenting propensity, but is ambiguous with regard to the renewal probability.

Higher complementarity in sequential innovations causes higher propensities to patent and renew as the profits from choice (R_{jt}, P_{jt}) = (1, 1) are higher. Higher complementarity further raises the probability of patenting, as well as that of renewing, because the future value of a patent is higher, which raises the patenting probability, and hence the renewal probability as innovations are complementary. In the case of complementary innovations, a higher degree of complementarity thus raises both the patent probability and the renewal probability.

III. Empirical Implementation

We test our propositions on renewal and patenting decisions against patent-level and firm-level panel data, respectively. In the estimation of renewal decision, we utilize a logit model with the indicator variable for renewing a patent as the dependent variable. A panel-data regression model is employed for the firm's patenting decision, where the dependent variable is the firm's patent count per R&D dollar. The explanatory variables in both models include patent maintenance fees and application filing fees, in addition to patent-specific and firm-specific regressors.

Data Description

In 1980, new legislation was introduced in the US patent system mandating that maintenance fees be paid to maintain the status of patents in force: all utility patents which issue from applications filed on and after December 12, 1980 are subject to the payment of maintenance fees. These fees are due at 3½, 7½ and 11½ years from the date on which the patent is granted, and the maintenance fees can be paid with a surcharge during the 6-month grace period. If the maintenance fees and any applicable surcharge are not paid, the patent will expire on the anniversary of the date the patent was granted in the 4th, 8th, or 12th year after the grant of the patent. The maintenance fees are subject to reduction for small entities that are independent inventors, small businesses with less than 500 employees, or nonprofit organizations. Table 2 provides the historical data on maintenance fees in current and constant dollars which are collected from the Official Gazettes published by the USPTO in various years. Note in this table that patent applications filed prior to Dec. 12, 1980 were guaranteed full patent life if granted.

Data regarding application filing fees are also collected from the Official Gazettes (see Table 3). As of 2007, application filing fees include basic fees, fees for applications with independent claims in excess of 3, fees for applications with claims in excess of 20, and fees for applications with multiple dependent claims. The last type of fee was initially introduced for patent applications filed in 1983. Application filing fees have been also subject to reduction for small entities since 1983. Note that variations in maintenance and filing fees in our data occur in the cross-sectional dimension (by firm size) as well as in the time-series dimension (by nominal fee changes and inflation).

Data regarding patent renewals and expirations are taken from the work of Jaffe and Trajtenberg (2002). Data are available for patents filed since Dec. 12, 1980 and cover patents renewed until Oct. 29, 1996. Information regarding the number of patents, R&D expenditures, capital-labor ratio, self-citation rate and other characteristics of firms each year are taken from the NBER Patent Citations Data (see Hall, Jaffe and Trajtenberg, 2005, for details), which were created by matching the U.S. patents to their assignees in the Standard and Poor's Compustat database. The Compustat database provides extensive data (including R&D expenditures) for all publicly traded firms. The NBER dataset contains approximately 1,000 firms in an unbalanced panel, extending from 1965 to 1995 in years of application filing. Table 4 reports the definitions and summary statistics of the variables utilized in our analysis while Table 5 shows their correlations.

Model Specification

Our empirical strategy is to estimate "demand" functions (one for renewal and the other for patenting) in a reduced form to find the price effects. The basic specification for our patent renewal analysis is a panel-data logit model with firm-specific random effects:

$$\mathrm{Prob}(R_{ift} = 1) = \Lambda(\alpha + \beta' X_{ift} + u_f + \varepsilon_{ift}),$$

where R_{ift} is a binary variable for the renewal of firm *f*'s patent *i* which is subject to the renewal decision in year *t*, $\Lambda(.)$ indicates the logistic cumulative distribution function, the variable u_f is a random firm-specific constant term, and ε_{ift} is the error component. The vector X_{ift} for patent *i* of firm *f* in year *t* includes variables implicated by our model which are considered exogenous in the renewal decision. Those variables are: maintenance fees (MAINT), application filing fees (FILING)[7], self-citation ratio (SCITE) as a measure of the degree of complementarity or substitutability, and the number of citations received by the patent in 5 years following grant date

[7] In constructing variable FILING, we add basic fees and per-claim fees multiplied by the firm's average number of claims in excess of 20. FILING concerns the filing fees in the year of the decision to renew.

(CRECEIVE). Based on evidence that citations received reflect the economic value of a patent (Trajtenberg, 1990), CRECEIVE is included as a regressor in order to control for patent value. We also include as a regressor the total annual number of a firm's patents that are subject to maintenance fees (RENEW) because a firm may face credit constraints with too many patents to renew. In the benchmark specification, we pool all patents subject to maintenance fees in their 4^{th}, 8^{th}, and 12^{th} years after granting, and include in X_{ift} two indicator variables: 8TH_YR for patents in their 8^{th} year, and 12TH_YR for patents in their 12^{th} year. All variables in X_{ift} are adjusted for inflation and in the logarithmic form, except for all indicator variables, CRECEIVE and SCITE because the latter two variables can take zero values.

The total annual number of a firm's patent applications (APPLI) and the two variables that are commonly used in studies on patenting and renewal—a firm's R&D expenditures (R&D) and capital-labor ratio (K/L)—are included as additional regressors only in the specification for the sensitivity analysis because these three variables may be endogenous in the model of a firm's renewal decision. We include APPLI in order to control for the number of innovations, or research lines.

We cannot adopt the same binary model for the analysis of patenting decisions as we do not observe innovations whichare not patented. For the patenting decision analysis, we employ instead a panel-data regression model with firm-specific random effects:

$$\mathrm{Ln}(PAT_{ft}/R\&D_{ft}) = \gamma_f + \delta' X_{ft} + v_t,$$

where PAT_{ft} is the number of patents granted to firm *f* that were applied for in year *t*, X_{ft} is a vector of filing fees, maintenance fees at the time of patenting decision, and firm *f*'s characteristics in year *t*, as described above, γ_f is a firm-specific constant term, and Ln denotes natural logs. Note that this specification can be interpreted as a linear probability model to the extent that the number of innovations is proportional to the R&D expenditures.

The construct of the maintenance fee variable in this model differs from that in the aforementioned logit model, because we utilize firm-level data for the regression analysis instead of patent-level data for the logit analysis. We use the weighted average of maintenance fees for the 4^{th}, 8^{th}, and 12^{th} year patents, weighted by the share of the firm's patents in their 4^{th}, 8^{th}, or 12^{th} year in all patents subject to maintenance fees (MTFEE).

IV. Empirical Findings

Trends in Renewal Rate

Table 6 reports the annual patent renewal rates between 1986 and 1996. This table shows that the renewal rate for 4^{th}-year patents increased steadily until 1989, at which time the trend reversed itself. The renewal rate fell from 84.99 percent in 1989 to 78.60 percent in 1995. The table shows a surge in the renewal rate from 78.60 percent in 1995 to 80.98 percent in 1996, which may be attributable to a data truncation problem, namely that the renewal data from Jaffe and Trajtenberg (2002) covers only patents renewed until Oct. 29, 1996. As do Schankerman and Pakes (1986), we also find in this table that patents are less likely to be renewed as they become older.

Figure 5 draws the annual expiration rate of the U.S. patents in the 4^{th} year and the real-term maintenance fees for patents in their 4^{th} year for large entities. Note that the maintenance fees for small entities display the same pattern of change over time. This figure shows remarkably synchronized movements between the two time series: both of which fell until the early 1990's and rose afterwards. This finding indicates that renewal decisions are responsive to changes in maintenance fees.

Results from the Logit Analysis of Renewal Decision

Table 7 reports our estimation results on the determinants of the firm's renewal decision. In column 1 which is our benchmark model, we observe that the maintenance fees (MAINT) exert a significantly negative effect on renewal decision, consistent with the implication of our model. This finding is repeated in the other columns of Table 7.

The filing fee variable (FILING) is shown in column 1 to exert a significant and negative effect on renewal. According to Proposition 1, this finding lends support to the notion of complementarity in sequential innovations within a firm on average. Complementarity may be due to the fact that it is not in the best interests of a firm to do research for innovations that readily replace the firm's existing innovations and erode the revenues from the old innovations quickly.

Higher patent filing fees discourage firms from patenting low-valued innovations, assuming that firms know the value before patenting, or at least can make an informed guess about it. This selection implies that patents under the higher-fee regime are more likely to be renewed at any given age, other things equal. Therefore, the estimated negative effect of filing fees on renewal cannot be explained away by the selection effect.

In order to check whether the nature of sequential innovations varies across patent classifications, we introduce in column 2the interaction terms of 36 patent category dummies and the logarithm of filing fee variable (FILING) as regressors. We find that all the interaction terms are associated with significantly negative coefficients, which indicates complementarity in sequential innovations across all patent classifications. We also ran the same specification as in column 1 with a sub-sample for each classification (not reported in Table 7 to save space) and the results indicate complementarity in most industries. We found the interaction term with a significantly negative coefficient for 9 classifications (Organic Compounds, Resins, Miscellaneous-chemical, Drugs, Biotechnology, Measuring & Testing, Power Systems, Semiconductor Devices, and Earth Working & Wells; see classifications in Appendix D), with a significantly positive coefficient for only one classification (Agriculture, Husbandry, Food),[8] and with an insignificant coefficient for the rest. Note that we find innovations are complementary in those technology groups such as Drugs, Biotechnology and Semiconductors that are especially prolific generators of innovations and patents and produce relatively homogenous outputs based on globally standardized technologies. We also found in those regressions with the sub-samples that the maintenance fee variable (MAINT) is associated with a significantly negative coefficient for most classifications (30 out of 36) and with an insignificant negative coefficient for the rest.

We can expect that the renewal probability for a patent can be influenced by how many other patents to renew a firm has due to credit constraints. Column 1 shows that the renewal probability for a single patent is negatively associated with the total number of renewable patents

[8] This may be due to technological revolutions in agriculture during the 1980's and 90's. Agricultural technology experienced a major transformation based on molecular genetics in these two decades (Graff et al., 2003), and as these biotechnologies were replacing old technologies, old innovations and new ones may have become more substitutable.

(RENEW) in the same year. The effect of the number of citation received as a proxy for patent value (CRECEIVE) is strongly significant and positive as anticipated.

We utilize the self-citation ratio (SCITE) as a measure of the degree of complementarity or substitutability in sequential innovations. Regardless of whether the relationship across sequential innovations is complementary or substitutable, a higher self-citation ratio may be reflective of a higher degree of their relatedness. Proposition 4 predicts that higher self-citation ratio (SCITE) will raise the renewal propensity when sequential technologies are complementary, and the result in column 1 shows that its effect is positive and significant.[9] This recapitulates the case of complementarity in sequential innovations for a firm.[10]

As illustrated in Table 6, older patents are less likely to be renewed, which is confirmed by the results in Table 7: the indicator variables 8TH_YR and 12TH_YR are associated with significantly negative coefficients and the coefficient corresponding to 12TH_YR is larger in terms of absolute value than the coefficient corresponding to 8TH_YR.

As part of the sensitivity analysis, we include three additional regressors in column 3 to further control for firm characteristics although they may be endogenous in our model. We find that the renewal probability is positively related with the number of patentable innovations (APPLI). If a firm has more new innovations that complement existing patents, it will have a stronger incentive for renewal. The positive relationship with APPLI is thus consistent with the

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[9] In their study with US pharmaceutical and biotechnology patent data, Liu *et al*. (2008) show that the self-citation ratio exerts a significant and positive effect on renewal decisions.

[10] In the context of patent litigation, Lanjouw and Schankerman (2004) find that self-citation indicates the presence of a "cumulative innovation" by the patentee, and that there is complementarity among technologically related patents in a firm's portfolio that raises the willingness to protect the property rights of the key, early inventions in the chain.

complementarity in sequential innovations.

We included R&D expenditures (R&D) in column 3 as a proxy for the size of the research enterprise to account for scale economies in patent maintenance. Alternatively this variable may pick up systematic variations in patent values by firm size. If the values of patents owned by larger firms are higher in general, we would expect higher renewal probability for larger firms, given other control variables are constant. R&D expenditures are shown to exert a significantly positive effect on renewal decision, in accordance with this prediction.

We include in column 3 the capital labor ratio (K/L) as a regressor for two reasons. According to Cohen et al. (2000) and Parr and Sullivan (1996), a highly capitalized firm may have stronger incentives to patent than less capitalized firms due to strategic patenting behaviors. A patent infringement suit that leads to court injunction and production stoppage will be more destructive for a firm that has made a large capital investment in a state-of-the-art physical plant. Such vulnerability may encourage the firm to develop a diverse portfolio of patents that it can use as a bargaining chip to ward off infringement suits. On one hand, this implies that patents by highly capitalized firms may have lower values and are thus less likely to be renewed. On the other hand, those patents may be maintained in force longer just for the strategic motive. Secondly, Hall and Ziedonis (2001) report that firms in high-tech industries such as semiconductor industry invest in more expensive facilities that were becoming obsolete more quickly. Since the product lifespan in most high tech industries is shorter, the renewal probability may be lower for those firms. The result in column 3 shows that the capital labor ratio exerts a significant and negative effect on renewal decisions.

As the key variables in our estimation may be time-trended, in column 3 of Table 7 we also report the regression estimates with a time trend variable (T) entered as an additional regressor. The results indicate that the effects of maintenance fees and filing fees are still negative and significant with the time trend variable included.

Column 4 reports the marginal effect of a 1% increase of each variable (in its linear form) in column 1 on the probability of renewal where the marginal effects are evaluated at the sample means of the regressors. We note quantitatively strong effects of maintenance fees and the number of backward citations. For example, an increase in maintenance fees by 1% from its mean reduces the probability by 10 percentage points. We can expect that the elasticity of the renewal probability with respect to maintenance fees is higher in magnitude when patent values are lower. To test this implication, we separate our sample to observations with CRECEIVE bigger than or equal to 6 and those with CRECEIVE less than 6 in columns 5 and 6, respectively. The renewal probability is shown to be much more responsive to changes in maintenance or application fees among patents with lower CRECEIVE.

In the last three columns of Table 7, we re-estimate column 1 with the sub-sample of those patents to renew in their 4^{th}, 8^{th}, or 12^{th} years, respectively. We find that the estimated effect of MAINT decreases in magnitude and becomes less significant as the patents get older, and the estimated FILING effect becomes larger in magnitude and more significant, although it is insignificant for patents in their 12^{th} years. Columns 7-9 verify that all other regressors exert the same effects on renewal as in the pooled regression model.

We also assessed the sensitivity of our estimates to the distributional assumption for the probability distribution. The estimated effects of our regressors are as pronounced when we assume the normal distribution and thus employ the probit model (not reported to save space).

Results from the Linear Regression Analysis of Patenting Decision

Table 8 shows our estimation results of the determinants of the firm's patenting decisions, employing the random-effects regression model. The dependent variable is the logarithm of the firm's patent applications in year *t* which were eventually granted per R&D dollar. This model can be interpreted as a linear probability model as the number of innovations is proportional to the R&D expenditures. The explanatory variables include the logarithms of the filing fee measure (FILING), of the maintenance fee measure (MTFEE), of the number of patents to renew (RENEW), the average number of citation (MCRECEIVE) and the self-citation ratio (SCITE). The analysis uses observations after 1980 because patents filed before 1980 are not subject to maintenance fees.

We find in this table that FILING is strongly negatively related with patenting, as predicted. The effect of MCRECEIVE is shown to be significant and negative in all columns of Table 8, which implies that firms that produce more valuable patents tend to have a lower patent propensity possibly due to quality and quantity tradeoff in patentable innovations.

Our model predicts that higher self-citation ratio (SCITE) as a measure for the degree of complementarity or substitutability will raise the patent propensity when sequential technologies are complementary, and lower it when they are substitutable. A significantly positive effect of SCITE reported in Table 8 corroborates the case of complementarity in sequential innovations, which recapitulates the finding in Table 7.

The estimated effect of MTFEE suggests that higher maintenance fees lower the firm's propensity to patent. Since we associate a firm's patenting probability with the maintenance fees of the same year in our specification, the effect of MTFEE is likely to reflect its "temporary" effect as described in Proposition 2. According to this proposition, our finding is consistent with the case of complementarity in sequential innovations, which is also suggested by the effects of FILING in Table 7 and SCITE in Table 8. Not surprising in this light, we determine that RENEW is related negatively with the patenting propensity. In column 2, we report the result from the benchmark specification with firm-level fixed effects instead of random effects, which qualitatively and quantitatively evidences impacts similar to those of our regressors in the random-effects models .

Attempting to check whether the nature of sequential innovations varies across industries, we include as regressors in column 3 the interaction terms of 17 industry dummies and the logarithm of the maintenance fee variable (MTFEE). The result shows that all the interaction terms are associated with negative coefficients, and the coefficients are significant except 3 industries (industry 27, 29, 31 in SIC code numbers; see Appendix E).

As part of the sensitivity analysis, we introduce in model 4 two additional regressors, the capital labor ratio (K/L) and time trend (T), where K/L is not included in the benchmark model because of the endogeneity issue. We find that the estimated effect of K/L on patenting is not supportive of the hypothesis that a highly capitalized firm may have stronger incentives to patent than less capitalized firms, as a firm that has made a large capital investment in a state-of-the-art physical plant may wish to develop a diverse portfolio of patents that it can utilize as a bargaining chip to ward off infringement suits, which can cause production stoppage (Cohen *et al.*, 2000; Parr and Sullivan, 1996). As our key variables in our regression may evidence time trends, we introduce the time trend variable (T). The results show that the effects of all the regressors, including maintenance fees and application fees except RENEW, remain intact in column 4.

We also assessed the sensitivity of our estimates to the construction method of the maintenance fee variable, MTFEE. The estimated effects of maintenance fees, as well as those of the other regressors, were pronounced when we introduced maintenance fees for 4^{th}-year patents (alternatively, fees for 8^{th} or 12^{th}-year patents) as a regressor in place of MTFEE (results not shown).

V. Concluding Remarks

In this paper, we develop a model by which a firm's decisions regarding the renewal and patenting of sequential innovations can be understood. In our model, these decisions can be influenced by the own-price effects as well as the cross-price effects. Our model yields a discriminating testable hypothesis as to whether sequential innovations are complementary or substitutable, based on the cross-price effects.

Our empirical results from the estimation of the reduced-form demand functionsindicate that higher application fees are associated with lower probability of patent renewal, which corroborates the case of complementarity in sequential innovations. Our finding that higher self-citation ratio as a measure for the degree of complementarity or substitutability exerts a positive effect on the patent propensity is also consistent with the notion of complementarity in sequential innovations. Sequential innovations tend to be complements possibly because it is not in the best interests of a firm to do research for innovations that readily substitute the firm's existing innovations and erode the revenues from the old innovations quickly. Our findings are robust to various sensitivity analyses we conducted, including models that took into account time trends in our variables and different distributional assumptions.

Our estimation results are not just statistically significant, but quantitatively significant as well. As is shown in Figure 5, real maintenance fees in 1990 dollars for 4th-year patents rose from 450 (225) in 1990 to 850.36 (425.18) in 1995 for large (small) entities, which represents an 89% increase. During the same period, the renewal rate for 4th-year patents fell from 84.84% in 1990 to 78.61% in 1995, which was a drop of 6.23 percentage points. The result of column 7 in Table 7 predicts a fall in the renewal rate by 5.12 percentage points when real maintenance fees are increased by 89%.[11] We can, therefore, explain approximately 82% (=5.12/6.23) of the actual decrease in the renewal rate.

Our estimation results can also be utilized to project how the USPTO's revenue might change when patent maintenance fees are raised. If the maintenance fees for 4th-year patents were to rise by 100% from the sample mean, our results predict that the revenues from maintenance fees for the USPTO would rise by 84%. The revenues would not rise by 100% because the number of patents renewed will be reduced with higher fees.

While the empirical results generally support the implications of our theoretical model,

[11] This calculation of the predicted renewal rate is based on the estimated coefficients in column 7 of Table 7, assuming that all regressors beside MAINT take the sample means.

we have left a number of issues unaddressed. Our model ignores the research and development process through which an innovation is actually produced. In our empirical specification we include R&D expenditures as a regressor to control for research efforts in innovation.

Second, as we cannot observe all innovations, patented or not, that a firm generates via research, we did not employ a binary choice model in our empirical estimation for patenting decisions. Ideally, we wished to estimate the effects of our regressors by determining which innovation were patented and which were kept secret. We plan to pursue these issues in future studies.

Appendix A: Proof of Proposition 1

When we have complementary technologies, we can show in the same manner as in Appendix B that $\partial\Delta_j/\partial c_a < 0$ (see the definition of Δ_j in Appendix B). This implies that the boundaries in Figure 3a shift from a solid line to a dashed line with an increase in c_a, and thus the probabilities for both renewal and patenting fall.

In the case of substitutable technologies, we can demonstrate that $\partial\Delta_j/\partial c_a > 0$, but $\partial(c_a - \delta\Delta_j)/\partial c_a > 0$. This indicates that the area for patenting ($P_{jt} = 1$) is shrunk, but that for renewing ($R_{jt} = 1$) is expanded, as shown in Figure 3b, as c_a rises, which indicates that the patenting probability falls but the renewal probability rises with an increase in filing fees.

Appendix B: Proof of Proposition 3

(i) Case of complementary technologies ($\alpha_j > 0$): We define $\Delta_j \equiv V_{jt} - W_{jt}$ as the future net benefit of holding a patent instead of having a technology without patent protection. If this net benefit gets larger (smaller) as maintenance fees rise, we can conclude that renewal is less (more) likely. Note that the time subscript for Δ_j is dropped since all the distributions are time-invariant and $c_{at} = c_a$, $c_{rt} = c_r$ for analyzing the permanent effects of prices. We can show that

$$\Delta_j = \int_{c_r}^{\infty}\int_{-\infty}^{c_a-\delta\Delta_j-\alpha_j}(\varepsilon_j - c_r)\,dG(\theta_j,\varepsilon_j) + \int_{-\theta_j+c_a+c_r-\delta\Delta_j-\alpha_j}^{\infty}\int_{c_a-\delta\Delta_j-\alpha_j}^{c_a-\delta\Delta_j}(\varepsilon_j + \theta_j - c_r - c_a + \alpha_j + \delta\Delta_j)\,dG + \int_{c_r-\alpha_j}^{\infty}\int_{c_a-\delta\Delta_j}^{\infty}(\varepsilon_j - c_r + \alpha_j)\,dG\,.$$

Differentiating Δ_j with respect to c_r,

$$\partial\Delta_j/\partial c_r = \left[\frac{\partial A}{\partial \Delta_j}\right]\left[\frac{\partial \Delta_j}{\partial c_r}\right]\int_{c_r}^{\infty}(\varepsilon_j - c_r)\,g(\varepsilon_j)\,d\varepsilon_j \quad - \quad A \int_{c_r}^{\infty} g(\varepsilon_j)\,d\varepsilon_j \quad +$$

$\int_{c_a-\delta\Delta_j-\alpha_j}^{c_a-\delta\Delta_j}\left(\frac{\partial B}{\partial \Delta_j}\cdot\frac{\partial \Delta_j}{\partial c_r}+\frac{\partial B}{\partial c_r}\right)f(\theta_j)d\theta_j - \delta\left[\frac{\partial \Delta_j}{\partial c_r}\right]f(c_a-\delta\Delta_j)\ \int_{c_r-\alpha_j}^{\infty}(\varepsilon_j-c_r+\alpha_j)g(\varepsilon_j)d\varepsilon_j\ +\ \delta\left[\frac{\partial \Delta_j}{\partial c_r}\right]f(c_a-\delta\Delta_j-\alpha_j)\ \int_{c_r}^{\infty}(\varepsilon_j-c_r)g(\varepsilon_j)d\varepsilon_j\ +\ \left[\frac{\partial C}{\partial \Delta_j}\right]\left[\frac{\partial \Delta_j}{\partial c_r}\right]\int_{c_r-\alpha_j}^{\infty}(\varepsilon_j-c_r+\alpha_j)g(\varepsilon_j)d\varepsilon_j - C\ \int_{c_r-\alpha_j}^{\infty}g(\varepsilon_j)d\varepsilon_j$,

where $A = \int_{-\infty}^{c_a-\delta\Delta_j-\alpha_j}f(\theta_j)d\theta_j$, $B = \int_{-\theta_j+c_a+c_r-\delta\Delta_j-\alpha_j}^{\infty}(\varepsilon_j+\theta_j-c_r-c_a+\alpha_j+\delta\Delta_j)g(\varepsilon_j)d\varepsilon_j$, $C = \int_{c_a-\delta\Delta_j}^{\infty}f(\theta_j)d\theta_j$, $\partial A/\partial\Delta_j = -\delta f(c_a-\delta\Delta_j-\alpha_j) < 0$, $\partial B/\partial\Delta_j = \delta\int_{-\theta_j+c_a+c_r-\delta\Delta_j-\alpha_j}^{\infty}g(\varepsilon_j)d\varepsilon_j > 0$, $\partial B/\partial c_r = -\int_{-\theta_j+c_a+c_r-\delta\Delta_j-\alpha_j}^{\infty}g(\varepsilon_j)d\varepsilon_j < 0$, $\partial C/\partial\Delta_j = \delta\ f(c_a-\delta\Delta_j) > 0$.

Rearranging the equation for $\partial\Delta_j/\partial c_r$, we can show that $\partial\Delta_j/\partial c_r < 0$, and hence the renewal probability is lower as c_r rises.

(ii) Case of substitutable technologies ($\alpha_j<0$): In this case, the net benefit becomes

$\Delta_j = \int_{c_r}^{\infty}\int_{-\infty}^{c_a-\delta\Delta_j}(\varepsilon_j-c_r)dG(\theta_j,\varepsilon_j) + \int_{\theta_j-c_a+c_r+\delta\Delta_j}^{\infty}\int_{c_a-\delta\Delta_j}^{c_a-\delta\Delta_j-\alpha_j}(\varepsilon_j-\theta_j-c_r+c_a-\delta\Delta_j)dG + \int_{c_r-\alpha_j}^{\infty}\int_{c_a-\delta\Delta_j-\alpha_j}^{\infty}(\varepsilon_j-c_r+\alpha_j)dG$.

Differentiating Δ_j with respect to c_r,

$\partial\Delta_j/\partial c_r = \left[\frac{\partial D}{\partial \Delta_j}\right]\left[\frac{\partial \Delta_j}{\partial c_r}\right]\int_{c_r}^{\infty}(\varepsilon_j-c_r)g(\varepsilon_j)d\varepsilon_j - D\int_{c_r}^{\infty}g(\varepsilon_j)d\varepsilon_j + \int_{c_a-\delta\Delta_j}^{c_a-\delta\Delta_j-\alpha_j}\left(\frac{\partial E}{\partial \Delta_j}\cdot\frac{\partial \Delta_j}{\partial c_r}+\frac{\partial E}{\partial c_r}\right)f(\theta_j)d\theta_j - \delta\left[\frac{\partial \Delta_j}{\partial c_r}\right]f(c_a-\delta\Delta_j-\alpha_j)\int_{c_r-\alpha_j}^{\infty}(\varepsilon_j-c_r+\alpha_j)g(\varepsilon_j)d\varepsilon_j + \delta\left[\frac{\partial \Delta_j}{\partial c_r}\right]f(c_a-\delta\Delta_j)\int_{c_r}^{\infty}(\varepsilon_j-c_r)g(\varepsilon_j)d\varepsilon_j + \left[\frac{\partial C}{\partial \Delta_j}\right]\left[\frac{\partial \Delta_j}{\partial c_r}\right]\int_{c_r-\alpha_j}^{\infty}(\varepsilon_j-c_r+\alpha_j)g(\varepsilon_j)d\varepsilon_j - F\int_{c_r-\alpha_j}^{\infty}g(\varepsilon_j)d\varepsilon_j$,

where $D = \int_{-\infty}^{c_a-\delta\Delta_j}f(\theta_j)d\theta_j$, $E = \int_{\theta_j-c_a+c_r+\delta\Delta_j}^{\infty}(\varepsilon_j-\theta_j-c_r+c_a-\delta\Delta_j)g(\varepsilon_j)d\varepsilon_j$, $F = \int_{c_a-\delta\Delta_j-\alpha_j}^{\infty}f(\theta_j)d\theta_j$, $\partial D/\partial\Delta_j = -\delta\ f(c_a-\delta\Delta_j) < 0$, $\partial E/\partial\Delta_j = -\delta\int_{\theta_j-c_a+c_r+\delta\Delta_j}^{\infty}g(\varepsilon_j)d\varepsilon_j < 0$, $\partial E/\partial c_r =$

$-\int_{\theta_j - c_a + c_r + \delta\Delta_j}^{\infty} g(\varepsilon_j) d\varepsilon_j < 0$, $\partial F/\partial\Delta_j = \delta\, f(c_a - \delta\Delta_j - \alpha_j) > 0$.

Rearranging the above equation for $\partial\Delta_j/\partial c_r$, we can also show that $\partial\Delta_j/\partial c_r < 0$ and $\partial(c_r + \Delta_j)/\partial c_r > 0$. This change with rising c_r is illustrated in Figures 4c and 4d (see the main text for explanation).

Appendix C: Proof of Proposition 4

When technologies are complementary, we can demonstrate that $\partial\Delta_j/\partial\alpha_j > 0$, which implies that a higher degree of complementarity raises the net benefit of holding a patent. An increase in α_j then can be shown to shift the borders in Figure 1 in such a way that the areas for both patenting and renewal are expanded, thus raising the probabilities of both patenting and renewal.

On the other hand, when technologies are substitutable, we can demonstrate that $\partial\Delta_j/\partial\alpha_j > 0$, and the area for patenting is reduced when we have a higher degree of substitutability (higher absolute value of α_j), which means a reduction in the probability of patenting. Note that the higher absolute value of α_j means a small α_j, as α_j is negative in this case. The effect of α_j on renewal is ambiguous.

Appendix D: Patent Classification, Category and Sub-category Names (NBER Patent Citations Data, Hall, Jaffe and Trajtenberg, 2005)

Category 1: Chemical (Subcategory 11: Agriculture, Food, Textiles; 12: Coating; 13: Gas; 14: Organic Compounds; 15: Resins; 19: Miscellaneous-chemical)

Category 2: Computer & Communication (Subcategory 21: Communications; 22: Computer Hardware & Software; 23: Computer Peripherals; 24: Information Storage)

Category 3 Drug & Medical (Subcategory 31: Drugs; 32: Surgery & Medical Instruments; 33: Biotechnology; 39: Miscellaneous-Drug & Medical)

Category 4: Electrical & Electronic (Subcategory 41: Electrical Device; 42: Electrical Lighting; 43: Measuring & Testing; 44: Nuclear & X-rays; 45: Power Systems; 46: Semiconductor Devices; 49: Miscellaneous-Electronic)

Category 5: Mechanical (Subcategory 51: Materials Processing & Handling; 52: Metal Working; 53: Motors, Engines & Parts; 54: Optics; 55: Transportation; 59: Miscellaneous-Mechanical)

Category 6: Others (Subcategory 61: Agriculture, Husbandry, Food; 62: Amusement Devices; 63: Apparel & Textile; 64: Earth Working & Wells; 65: Furniture, House Fixtures; 66: Heating; 67: Pipes & Joints; 68: Receptacles; 69: Miscellaneous-Others)

Appendix E: SIC Codes

Group 20: Food And Kindred Products; Group 22: Textile Mill Products; Group 25: Furniture And Fixtures; Group 26: Paper And Allied Products; Group 27: Printing, Publishing, And Allied Industries; Group 28: Chemicals And Allied Products; Group 29: Petroleum Refining And Related Industries; Group 30: Rubber And Miscellaneous Plastics Products; Group 31: Leather And Leather Products; Group 32: Stone, Clay, Glass, And Concrete Products; Group 33: Primary Metal Industries; Group 34: Fabricated Metal Products, Except Machinery And Transportation Equipment; Group 35: Industrial And Commercial Machinery And Computer Equipment; Group 36: Electronic And Other Electrical Equipment And Components, Except Computer Equipment; Group 37: Transportation Equipment; Group 38: Measuring, Analyzing, And Controlling Instruments; Photographic, Medical And Optical Goods; Watches And Clocks; Group 39: Miscellaneous Manufacturing Industries.

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Table 2 Patent Maintenance Fee Schedule for Applications Filed after Dec. 12, 1980

Year when renewing patents	Maintenance fees in Current Dollar (Small/ Large entity)			Maintenance fees in 1990 Constant Dollar (Small/ Large entity)		
	4th year	8th year	12th year	4th year	8th year	12th year
1984	200/400	400/800	600/1200	241.2/482.4	482.4/964.7	723.5/1447.1
1985	225/450	445/890	670/1340	263.3/526.7	520.8/1041.7	784.2/1568.4
1986	225/450	445/890	670/1340	257.7/515.3	509.6/1019.2	767.2/1534.5
1987	225/450	445/890	670/1340	250.8/501.6	496.0/992.0	746.8/1493.6
1988	225/450	445/890	670/1340	242.5/485.1	479.7/959.4	722.2/1444.5
1989	225/450	445/890	670/1340	233.7/467.4	462.2/924.3	695.8/1391.7
1990	225/450	445/890	670/1340	225/450	445/890	670/1340
1991	225/450	445/890	670/1340	217.4/434.8	430.0/860.0	647.4/1294.8
1992	415/830	835/1670	1250/2500	391.9/783.9	788.6/1577.2	1180.5/2361.1
1993	415/830	835/1670	1250/2500	383.1/766.2	770.8/1541.7	1154.0/2307.9
1994	465/930	935/1870	1410/2820	420.3/840.7	845.2/1690.4	1274.6/2549.1
1995	480/960	965/1930	1450/2900	425.2/850.4	854.8/1709.6	1284.4/2568.8
1996	495/990	985/1990	1495/2990	430.3/860.7	865.0/1730.0	1299.7/2599.4
1997	510/1020	1025/2050	1540/3080	436.1/872.3	876.5/1753.1	1316.9/2633.9
1998	525/1050	1050/2100	1580/3160	444.0/888.0	888.0/1776.1	1336.3/2672.6
1999	470/940	950/1900	1455/2910	391.8/783.6	792.0/1583.9	1213.0/2425.9
2000	415/830	950/1,900	1,455/2,910	338.6/677.2	775.1/1550.2	1187.1/2374.3
2001	425/850	975/1,950	1,495/2,990	338.6/677.3	776.9/1553.7	1191.2/2382.4
2002	440/880	1,010/2,020	1,550/3,100	344.6/689.1	790.9/1581.8	1213.8/2427.6
2003	445/890	1,025/2,050	1,575/3,150	341.2/682.5	786.0/1572.0	1207.7/2415.5
2004	455/910	1,045/2,090	1,610/3,220	339.2/678.5	779.1/1558.3	1200.4/2400.8

Note: Patent maintenance fees for applications filed by large entities between Dec. 12, 1980 and Aug. 27, 1982 were subject to the fee schedule for small entities.

Table 3　Patent Application Filing Fee Schedule (current dollar)

Filing year	Basic fees (S/L)	Independent claims in excess of 3 (S/L)	Claims in excess of 20 (S/L)	Multiple dependent Claims (S/L)
1965	65	10	2	
1966	65	10	2	
1967	65	10	2	
1968	65	10	2	
1969	65	10	2	
1970	65	10	2	
1971	65	10	2	
1972	65	10	2	
1973	65	10	2	
1974	65	10	2	
1975	65	10	2	
1976	65	10	2	
1977	65	10	2	
1978	65	10	2	
1979	65	10	2	
1980	65	10	2	
1981	65	10	2	
1982	65	10	2	
1983	150/300	15/30	5/10	50/100
1984	150/300	15/30	5/10	50/100
1985	150/300	15/30	5/10	50/100
1986	150/300	15/30	5/10	50/100
1987	170/340	17/34	6/12	55/110
1988	170/340	17/34	6/12	55/110
1989	170/340	17/34	6/12	55/110
1990	170/340	17/34	6/12	55/110
1991	170/340	17/34	6/12	55/110
1992	170/340	17/34	6/12	55/110
1993	185/370	18/36	6/12	60/120
1994	355/710	37/74	11/22	165/230
1995	365/730	38/76	11/22	120/240

Table 4 Variables Used in the Regressions

Variable	Description	Mean [Std. Dev.]
Whether to Renew	Dummy variable for whether a patent is renewed or not	0.85795 [0.3491]
Patents/R&D	Annual number of a firm's patent grants per R&D dollar	1.2342 [4.388]
MAINT	Patent maintenance fees per patent (1990 constant dollar)	959.66 [554.8]
FILING	Application filing fees (basic fees plus firm-average fees for claims in excess of 20 in 1990 constant dollar)	443.47 [152.2]
MTFEE	Average of maintenance fees for 4^{th}, 8^{th}, and 12^{th} year patents, weighted by the shares of patents in 4^{th}, 8^{th}, and 12^{th} year (1990 constant dollar)	393.06 [517.5]
RENEW	Total annual number of a firm's patents which are subject to maintenance fees	314.60 [341.6]
APPLI	Total annual number of a firm's patent applications	279.47 [400.9]
CRECEIVE	Number of citations received by citing patent in 5 years following grant date	8.9203 [11.71]
MCRECEIVE	Firm's per-patent average of the number of citations received in 5 years following grant date	5.4896 [5.109]
R&D	Firm's annual R&D expenditures in real terms	7.35e+8 [1.1e+9]
K/L	Firm's value of plants and equipments (real dollar) per employee	81,642 [105,057]
SCITE	Number of backward citations to a firm's own patents as a fraction of all citations in the firm's patents ($\in[0,1]$)	0.17283 [0.0881]
8TH_YR	Dummy variable for a patent subject to 8^{th}-year maintenance fees	0.29619 [0.4566]
12TH_YR	Dummy variable for a patent subject to 12^{th}-year maintenance fees	0.04128 [0.1989]

Table 5   Simple Correlations between Covariates

	LnMAINT	LnFILING	LnRENEW	CRECEIVE	SCITE	8TH_YR	12TH_YR	LnAPPLI	LnR&D	LnK/L
LnMAINT	1.0000									
LnFILING	0.5082	1.0000								
LnRENEW	0.2547	0.1871	1.0000							
CRECEIVE	0.0107	-0.0088	0.0090	1.0000						
SCITE	0.0489	0.0042	0.4067	0.0274	1.0000					
8TH_YR	0.0652	0.0579	0.8167	0.0793	0.4070	1.0000				
12TH_YR	0.1058	0.0850	0.8016	0.0716	0.2795	0.8513	1.0000			
LnAPPLI	0.0328	0.0182	0.2879	-0.0652	0.2550	0.1903	0.1725	1.0000		
LnR&D	0.6704	0.0765	0.1144	0.0193	0.0262	0.0033	0.0257	0.0250	1.0000	
LnK/L	0.4379	0.2852	0.0766	0.0006	0.0232	0.0074	0.0153	0.0284	-0.1346	1.0000

Note: Simple correlations between covariates in Table 7 are reported, based on 147,791 observations.

Table 6 Renewal Rate

Year	4th-year renewals		8th-year renewals		12th-year renewals	
	A. Patents renewable	B. Renewal rate (%)	A. Patents renewable	B. Renewal rate (%)	A. Patents renewable	B. Renewal rate (%)
1986	10,801	83.26				
1987	41,689	83.39				
1988	63,884	84.09				
1989	68,961	84.99				
1990	71,750	84.84	8,993	75.86		
1991	82,580	83.89	34,765	74.31		
1992	77,809	81.33	53,717	70.13		
1993	95,440	80.07	58,616	67.79		
1994	90,239	79.07	60,873	66.03	6,822	57.26
1995	94,470	78.60	69,280	66.92	25,832	57.58
1996	66,359	80.98	39,485	68.68	24,453	60.08
Total	763,982	81.85	325,729	68.69	57,107	58.61
(Data used in our analysis)	(97,916)	(90.97)	(43,774)	(77.81)	(6,101)	(59.97)

Note: The total number of patents subject to maintenance fees is reported in column A. Column B reports the renewal rate which is the ratio of the number of patents renewed to the number of patents subject to maintenance fees.

Table 7 Renewal Decision

Dependent Variable: Whether to Renew | Random-Effects Logit Model

	(1) Benchmark		(2) Industry variations		(3) Extra controls		(4) Model 1	(5) C≥6	(6) C<6
	Coef.	z	Coef.	z	Coef.	z	dPr/dLnX	dPr/dLnX	dPr/dLnX
LnMAINT	-0.9308	-20.58	-0.9315	-20.56	-0.8228	-14.57	-0.1041	-0.0626	-0.1390
LnFILING	-0.2404	-7.24	#	#	-0.1751	-4.64	-0.0269	-0.0137	-0.0382
LnRENEW	-0.1269	-5.47	-0.1276	-5.50	-0.2664	-9.15	-0.0142	-0.0029	-0.0166
CRECEIVE	0.0477	37.16	0.0467	35.78	0.0475	36.96	0.0053	0.0023	0.0162
SCITE	0.6603	3.87	0.6716	3.93	0.1971	1.13	0.0739	0.0768	0.0596
8TH_YR	-0.3807	-9.75	-0.3862	-9.86	-0.4468	-10.25	-0.0452	-0.0458	-0.0443
12TH_YR	-0.7347	-11.90	-0.7489	-12.07	-0.8484	-12.14	-0.1045	-0.1229	-0.0895
LnAPPLI					0.2217	11.09			
LnR&D					0.2740	9.37			
LnK/L					-0.1941	-3.67			
T					-0.0052	-0.57			
Observations	147,791		147,791		147,791		147,791	72,787	75,004
Log Like.	-50447		-50232		-50257				
χ^2 (d.f.)	9440.57 (7)		9771.53 (42)		9632.52 (10)				
p value	0.00		0.00		0.00				

Note: The z columns report the ratios of the coefficient to its standard error. The p value reported is of the test that all coefficients are jointly zero. #Column 2 includes interaction terms of 36 patent category dummies and LnFILING to incorporate distinct effects of the latter variable across patent categories (see Appendix D). The marginal effects on Pr(Renew) of a 1% increase of the variables (in their linear form) in column 1 are reported in column 4. In column 5 and 6, we separate our sample to observations with CRECEIVE ≥6 (col. 5) and those with CRECEIVE <6 (col. 6), and report the marginal effects of the regressors in column 1, using each subset.

Table 7 Renewal Decision (cont.)

Dependent Variable: Whether to Renew — Random-Effects Logit Model

	(7) 4th Year Renewal		(8) 8th Year Renewal		(9) 12th Year Renewal	
	Coef.	z	Coef.	z	Coef.	z
LnMAINT	-1.0850	-17.29	-0.9193	-13.94	1.4194	1.41
LnFILING	-0.1497	-2.94	-0.3337	-7.40	-0.5606	-0.85
LnRENEW	-0.0876	-3.34	-0.0453	-1.15	-0.1006	-1.65
CRECIEVE	0.0523	24.83	0.0473	25.86	0.0397	10.92
SCITE	0.8212	3.40	0.1633	0.61	0.8866	1.18
Observations	97,916		43,774		6,101	
Log Like.	-25620		-20535		-3746	
χ^2 (d.f.)	1510.52 (5)		1156.62 (5)		122.31 (5)	
p value	0.00		0.00		0.00	

Note: The z columns report the ratios of the coefficient to its standard error. The p value reported is of the test that all coefficients are jointly zero. Columns 7-9 re-estimate column 1 with the sub-sample of those patents to renew in their 4th, 8th, or 12th years, respectively.

Table 8 Patenting Decision

Dependent Variable: Log(Number of Patents/R&D in mil. $) Random-Effects Regression Model

	(1) Benchmark		(2) Fixed effects		(3) Industry variations		(4) Extra controls	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z
LnFILING	-0.1536	-3.43	-0.1209	-2.64	-0.1568	-3.50	-0.1459	-3.26
LnMTFEE	-0.1653	-5.05	-0.1518	-4.54	#	#	-0.1046	-2.36
LnRENEW	-0.0506	-3.79	-0.0577	-3.84	-0.0455	-3.38	-0.0266	-1.74
MCRECEIVE	-0.0121	-4.20	-0.0104	-3.35	-0.0123	-4.25	-0.0136	-4.58
SCITE	0.2715	2.03	0.1113	0.80	0.3148	2.34	0.2824	2.11
LnK/L							-0.1894	-4.82
T							-0.0109	-1.29
Observations	3525 (634 firms)		3525 (634 firms)		3524 (633 firms)		3518 (634 firms)	
R^2	0.0349		0.0249		0.0759		0.0364	

Note: The z columns report the ratios of the coefficient to its standard error. All columns employ firm-level random effects. # Column 3 includes interaction terms of 17 two-digit SIC codes and LnFILING to incorporate distinct effects of the latter variable across industries (see Appendix E for the SIC classification).

Figure 1
Renewal and Patenting Decisions:
Complementary Technologies Case ($\alpha_j > 0$)

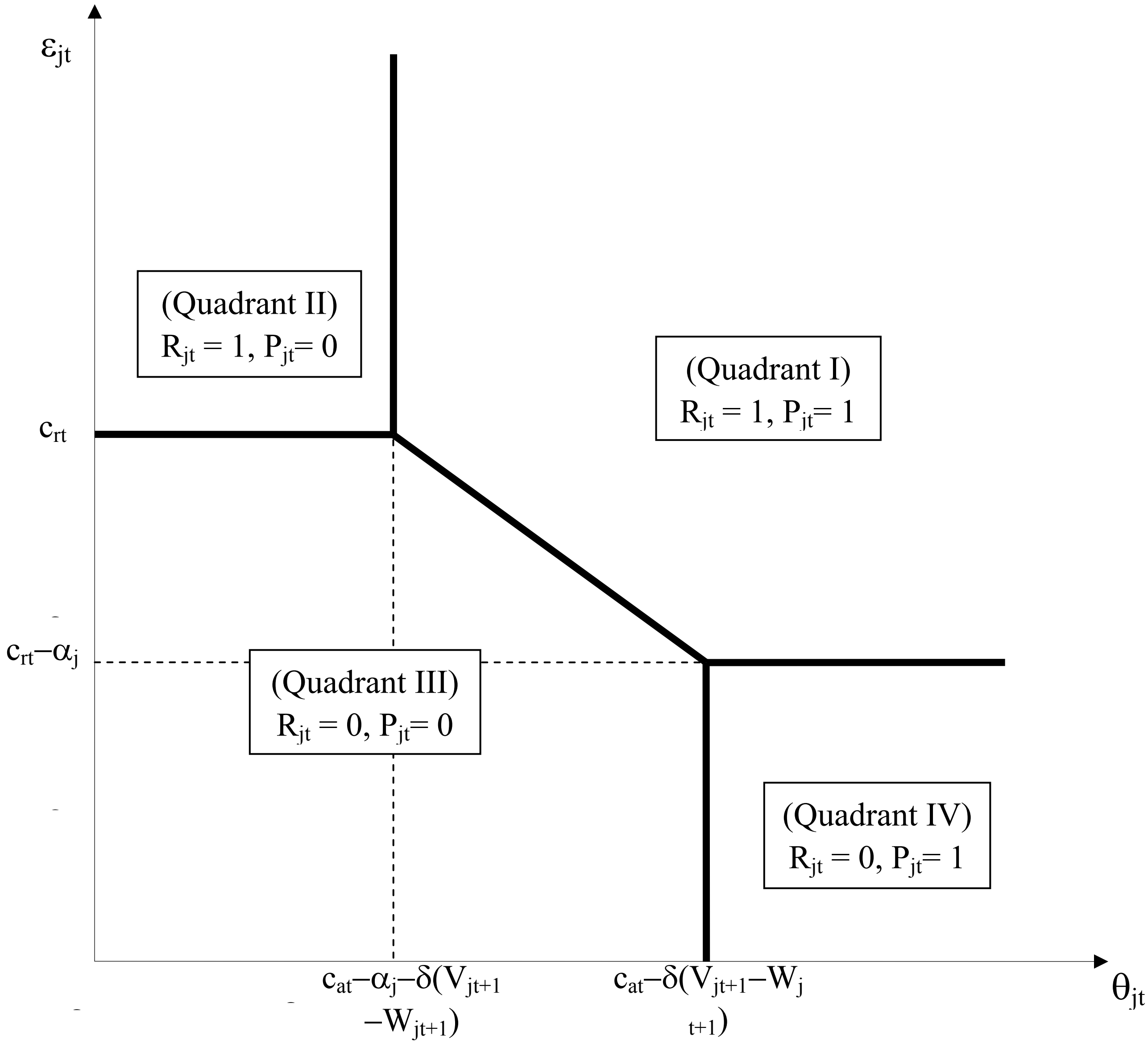

Figure 2
Renewal and Patenting Decisions:
Substitutable Technologies Case (α_j< 0)

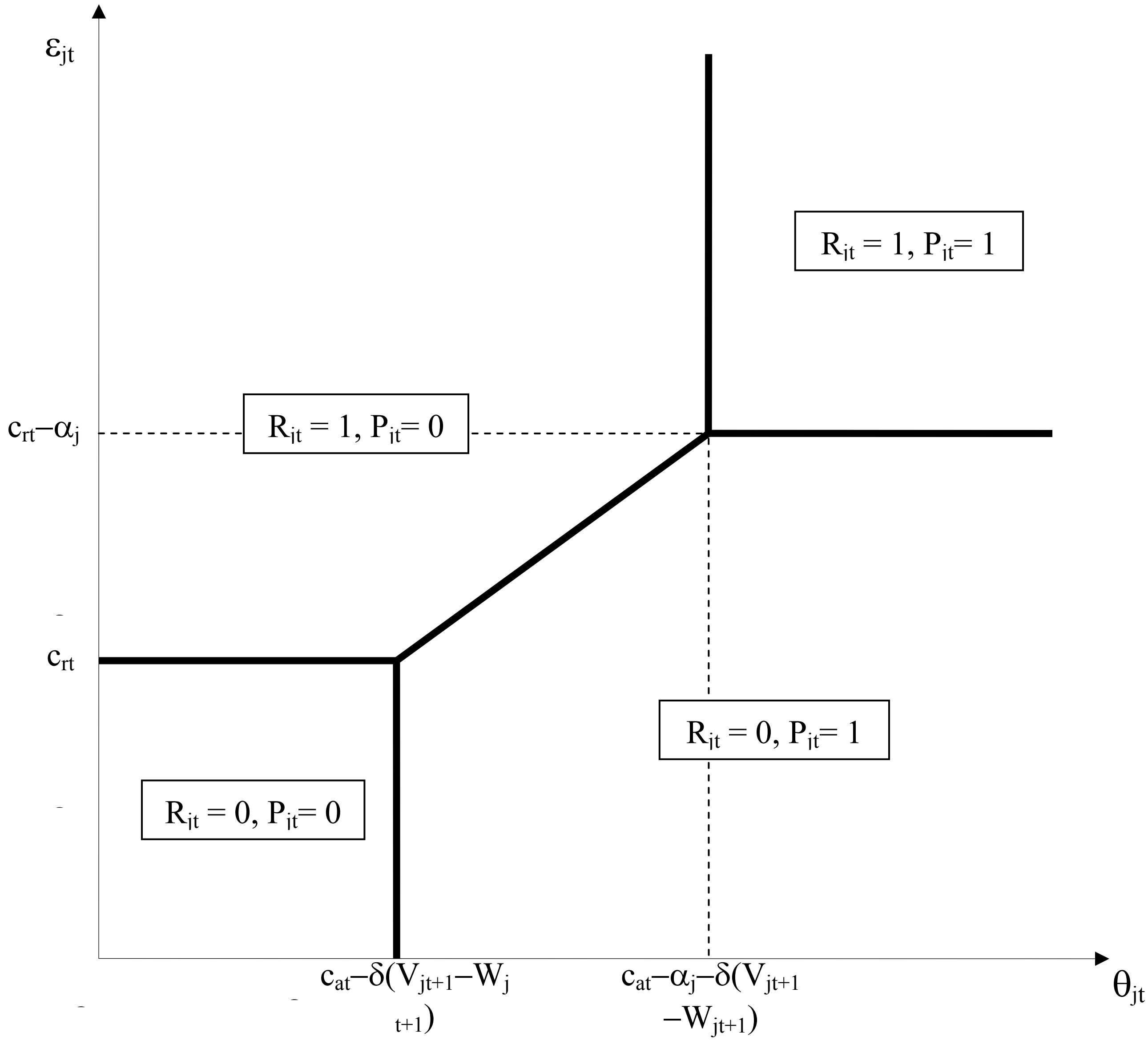

Figure 3a
Effect of a Temporary or Permanent Increase in Filing Fees:
Complementary Technologies Case ($\alpha_j > 0$)

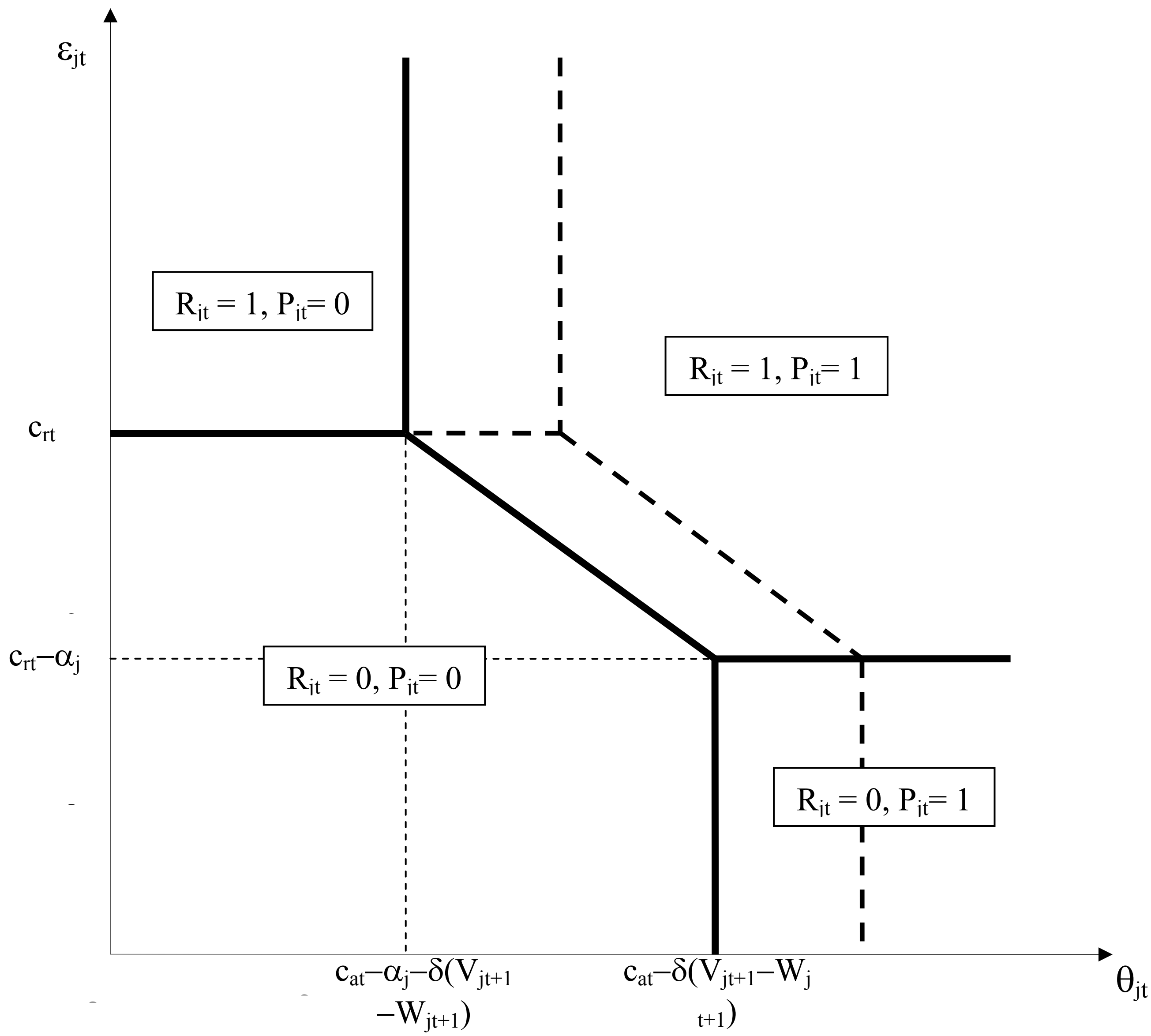

Figure 3b
Effect of a Temporary or Permanent Increase in Filing Fees:
Substitutable Technologies Case (α_j< 0)

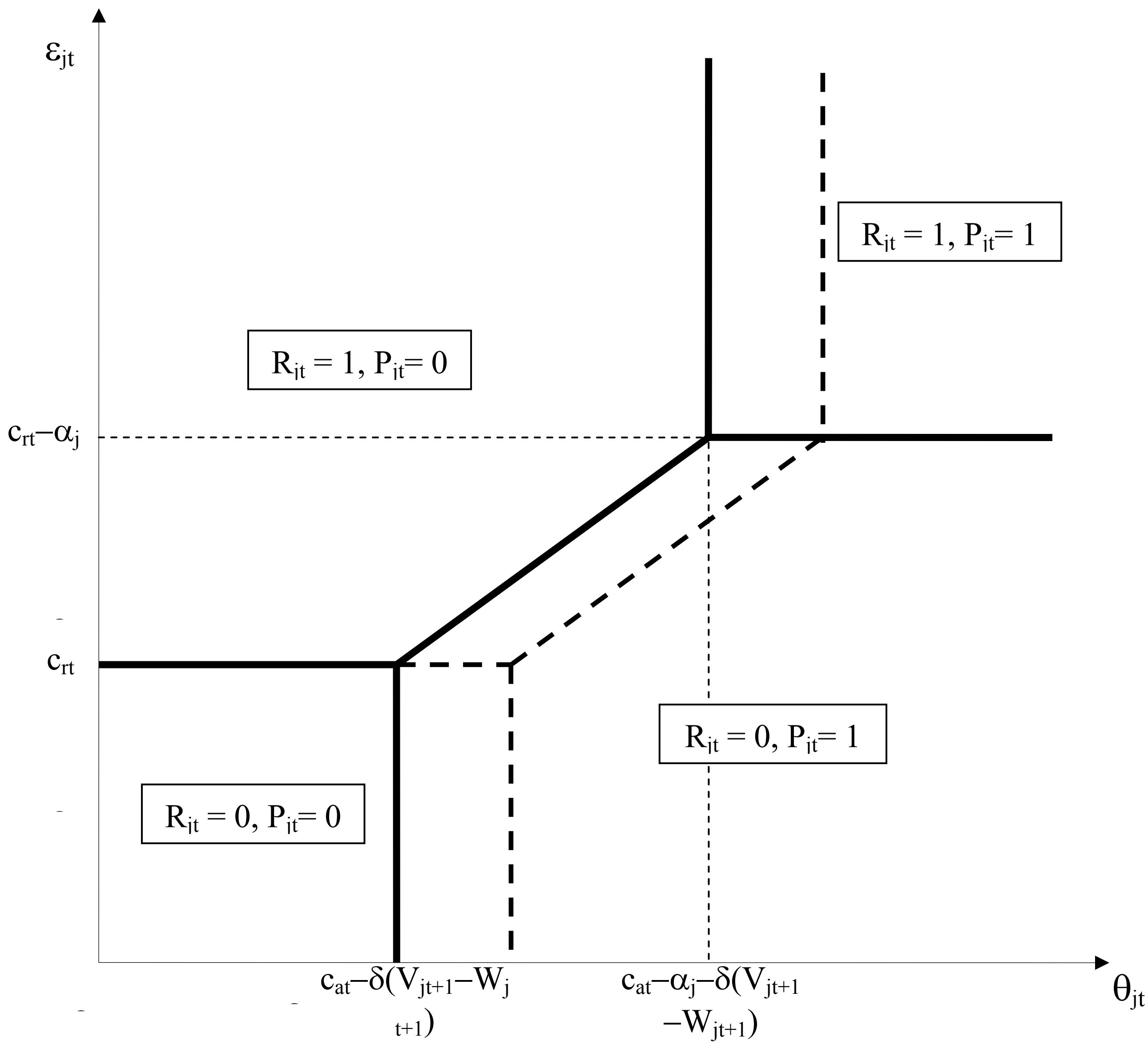

Figure 4a
Effect of a Temporary Increase in Renewal Fees:
Complementary Technologies Case (α_j> 0)

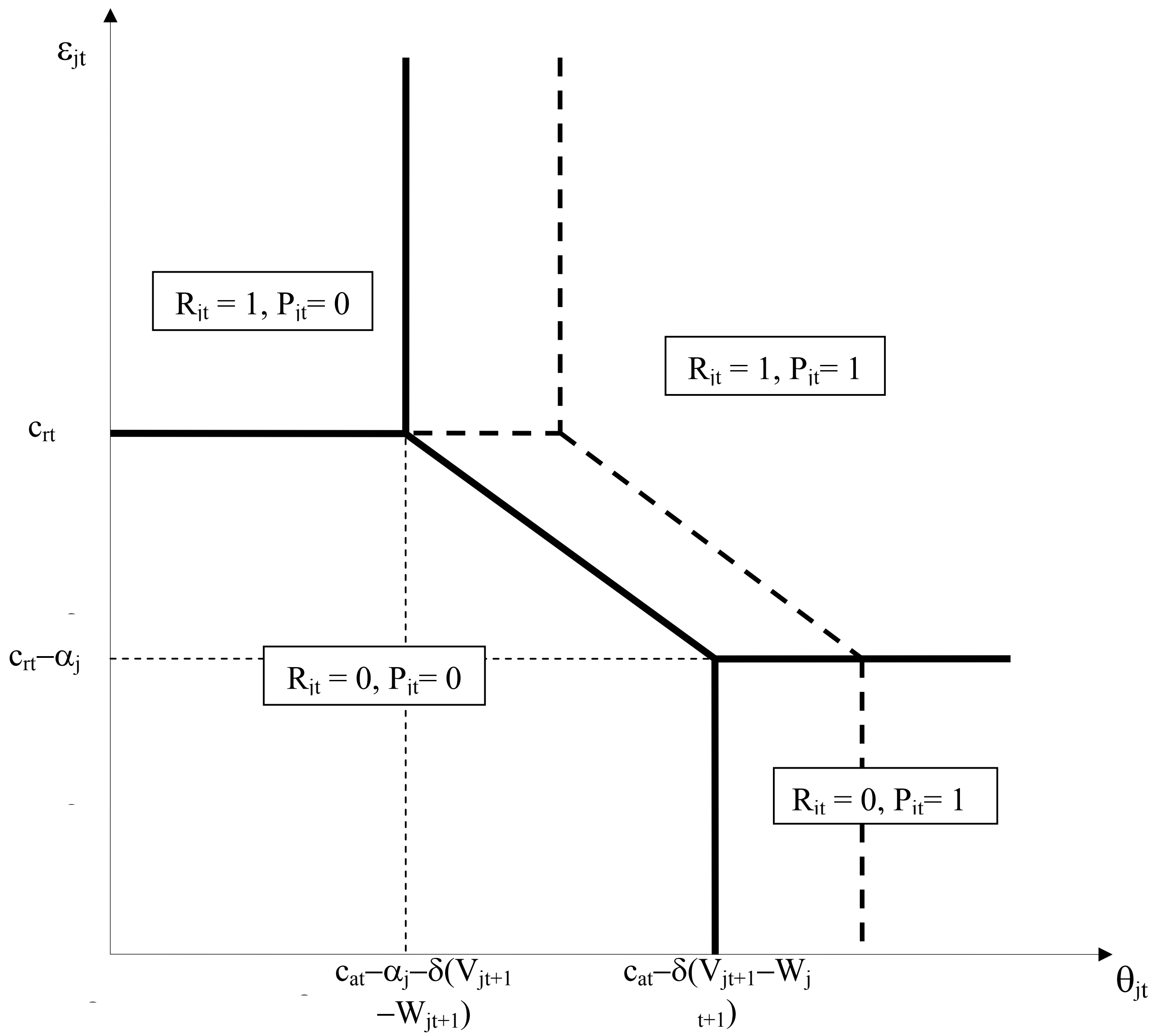

Figure 4b
Effect of a Temporary Increase in Renewal Fees:
Substitutable Technologies Case ($\alpha_j < 0$)

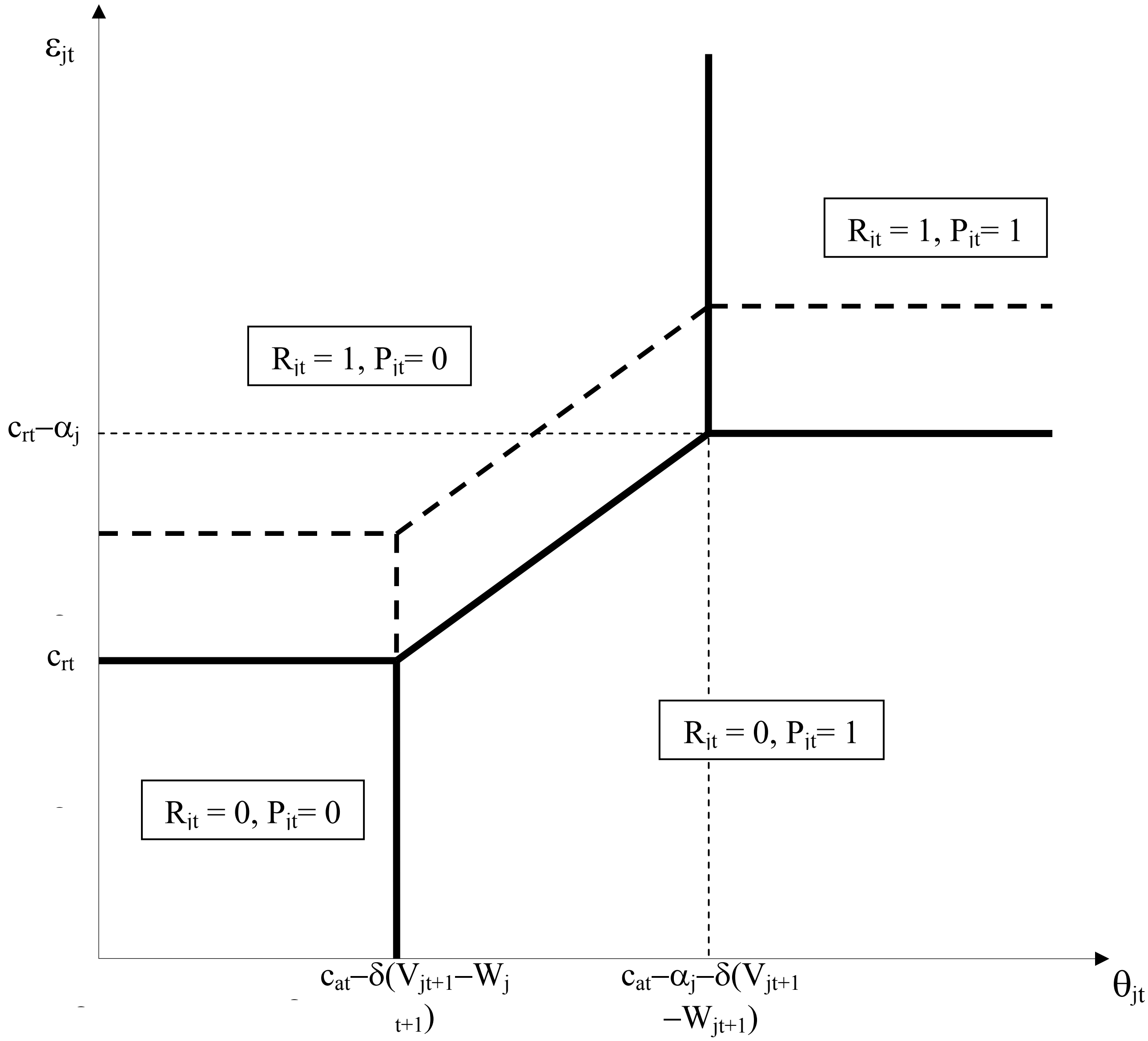

Figure 4c
Effect of a Permanent Increase in Renewal Fees:
Complementary Technologies Case ($\alpha_j > 0$)

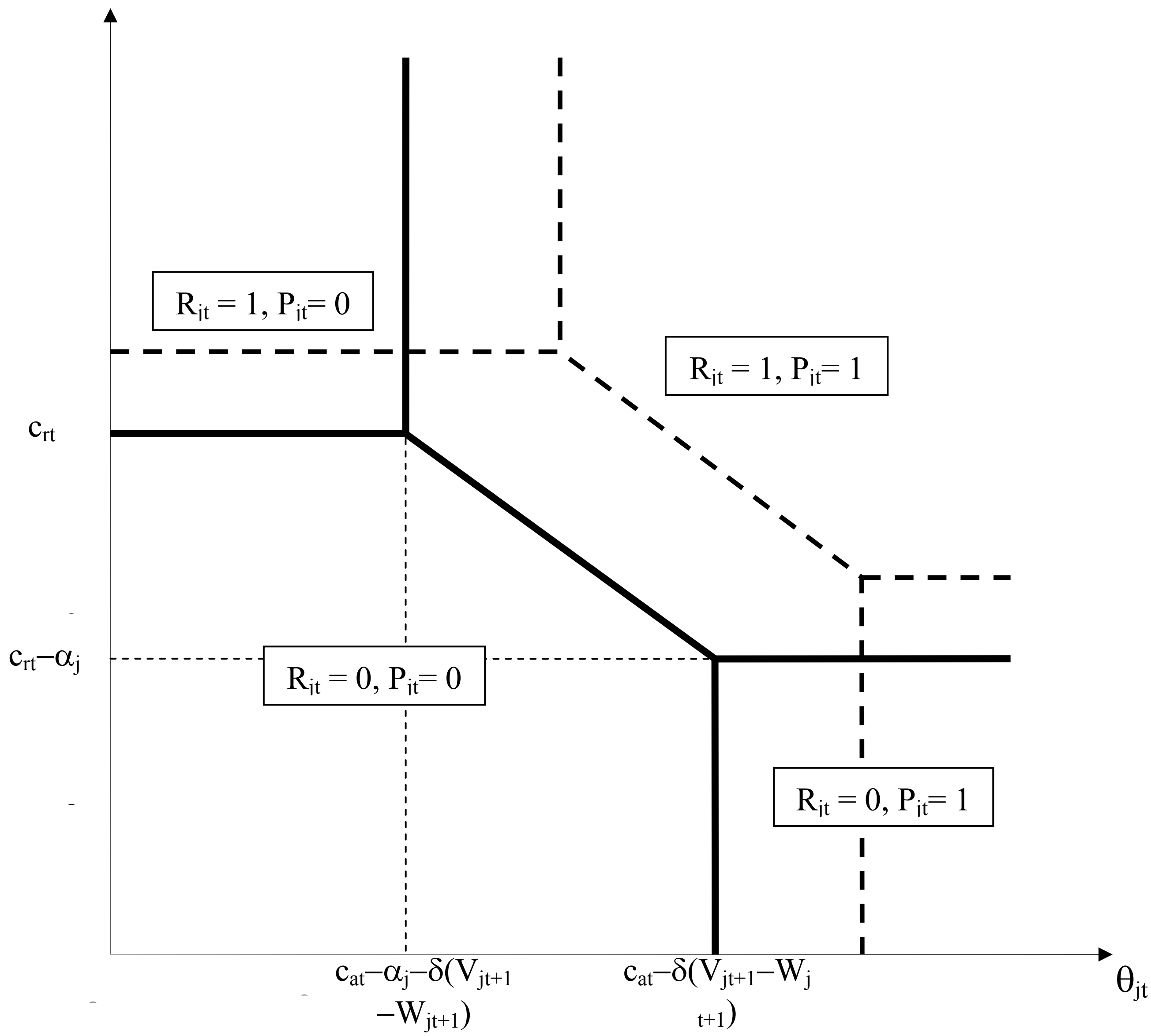

Figure 4d
Effect of a Permanent Increase in Renewal Fees:
Substitutable Technologies Case (α_j< 0)

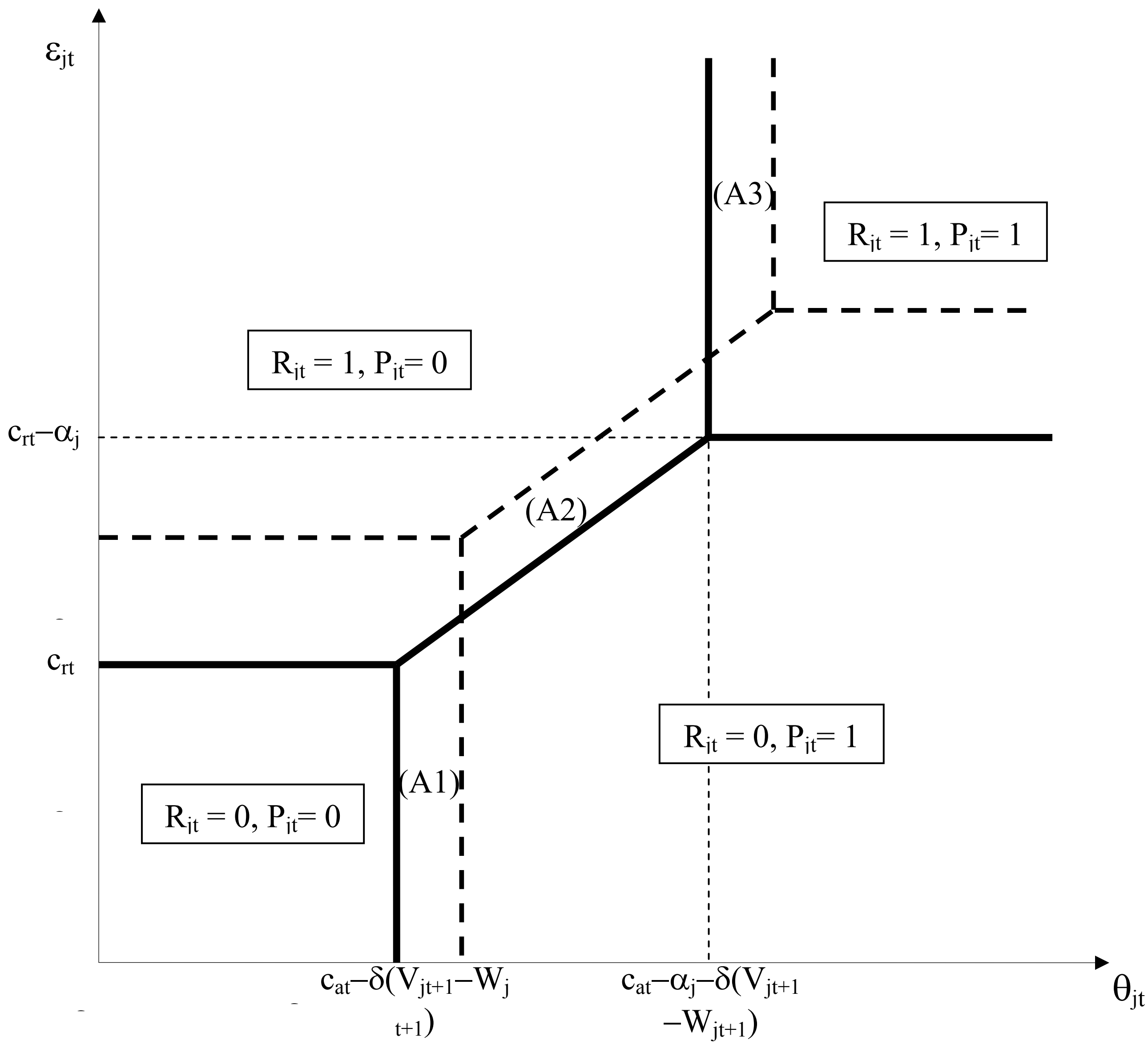

Figure 5
Patent Expirations and Maintenance Fees