

Appropriability and Commercialization: Evidence from MIT Inventions

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The effects of appropriability on invention have been well studied, but there has been little analysis of the effect of appropriability on the commercialization of existing inventions. Exploiting a database of 805 attempts by private firms to commercialize inventions licensed from the Massachusetts Institute of Technology (MIT) between 1980 and 1996, we explore the influence of several appropriability mechanisms on the commercialization and termination of projects to develop products based on university inventions. Our central hypothesis is that the relationship between a licensee's decision to either terminate or commercialize the invention is driven by the current market value of the invention, as well as the option value of delaying its commercialization. We use a competing risks framework that allows for nonparametric heterogeneity and correlated risks. We find that better appropriability in the sense of more effective patent strength and secrecy has a strong negative effect on the hazard of license termination. The effectiveness of learning has a strong positive effect on the hazard of technology commercialization, while lead time has a negative effect.

Key words: competing risks; innovation; optimal stopping problem; patent scope; lead time; learning; university licensing; termination

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1. Introduction

Do strong intellectual property rights enhance the commercialization of new technology? Surprisingly, we do not know the answer to this question (Gallini 2002). Although the role of property rights in innovation has been studied extensively since Arrow (1962) argued that firms underinvest in R&D because they cannot fully appropriate the returns, much of this work focuses on the effect of intellectual property rights, particularly those associated with patents, on inventive activity. Moreover, while there is a rich literature on the determinants of licensing activity (Thursby and Thursby 2007), there has been little analysis of whether licensed inventions are commercialized, and the effects of appropriability mechanisms on these outcomes (Hahn 2003). As firms increasingly rely on externally generated inventions, particularly those invented and patented by universities, this represents an important gap in our understanding (Arora et al. 2001, Santoro and Chakrabarti 2002, Thursby and Thursby 2004).

We examine the effect of various appropriability mechanisms on the commercialization of university inventions by exploring the same population of inventions licensed from the Massachusetts Institute of Technology (MIT) used in Shane's (2002) work on the determinants of licensing. Specifically, we examine the population of 805 attempts by private firms to commercialize patentable inventions licensed from MIT between 1980 and 1996. For these inventions, we relate appropriability mechanisms to the timing of termination and commercialization decisions.

We view the decision of a licensing firm as an optimal stopping problem under uncertainty (see Dixit and Pindyck 1994). This uncertainty stems from the embryonic nature of university technologies and the difficulty in identifying and protecting associated markets (Thursby and Thursby 2002, Shane 2000). Survey evidence from university technology licensing offices (TLO) shows that the majority of inventions licensed are no more than a lab scale prototype at the time of license (Jensen and Thursby 2001, Thursby

et al. 2001). Thus, for most university inventions, further development is needed for commercial application. Survey evidence from businesses that license-in university inventions shows that this development is risky: half of all commercialization efforts fail, and 47% of these failures can be attributed to technical reasons (Thursby and Thursby 2004).

Market uncertainty is an additional source of risk for nascent university technologies. Defining market opportunities for early stage inventions is difficult, so much so that many university inventions end up with applications that are not anticipated at the time of license (Shane 2000, Thursby and Thursby 2002). Further, exclusive licenses such as those we consider, do not necessarily prevent competitors from developing substitutes or inventing around a licensed patent.

In this context, we consider the fact that at every point in time the licensee can decide to either commercialize, drop the license, or keep the license but delay commercialization. This gives rise to a real option in commercialization. Moreover, returns may be appropriated using a variety of mechanisms. While some of these are legal, such as patents or trade secrets, others, such as learning or a first-mover advantage, are consequences of business strategy (Cohen et al. 2000, Kamien and Schwartz 1972, Levin et al. 1987). In our theoretical discussion, we argue that different appropriability mechanisms influence the timing of licensees' decisions by affecting either the current market value of commercializing the invention, the option value of keeping the license without commercialization, or both.

Estimation of the hazard rates of termination of the license and commercialization of the invention reveals that legal mechanisms have a strong and negative effect on the hazard of termination. However, with the exception of patent scope, they have only a weak effect on the hazard of commercialization. The reverse is true for appropriability mechanisms based on business strategy, which primarily affect the hazard of commercialization. These results are consistent with our theoretical arguments, under the assumption that most university technologies are embryonic. They are also in line with the observation that when appropriability mechanisms such as patents and secrecy are effective, firms may be able to appropriate returns from the license without commercializing a product.

By showing that several dimensions of appropriability affect the hazards of license termination and invention commercialization, we contribute to the literature on appropriability and innovation. In particular, our results on patent strength contribute to the extensive literature on patents and innovation (for a survey, see Gallini 2002). By treating the decision to commercialize an invention as an optimal stopping problem, we examine patent scope and innovation

in a way that incorporates the possibility of termination, which, although quite relevant to embryonic technologies licensed to firms, has been ignored in the literature. Thus, our analysis also complements the growing literature on the modeling of strategic decisions as real options (see Ziedonis 2007).

Furthermore, we contribute to the empirical literature on the effectiveness of patents in appropriating the returns from R&D by directly examining the relationship between patent characteristics and the development of products based on newly invented technologies, rather than relying on perceptions of R&D personnel responding to surveys (Taylor and Silberston 1973, Mansfield 1986, Mansfield et al. 1981).

Our analysis also extends the literature on product development and management. For example, Lilien and Yoon (1990) and Bayus et al. (1997) show that it may be optimal for market pioneers to delay product launch depending on demand characteristics, as well as market competition. Our results on commercialization contribute to this literature by relating the hazard of commercialization to appropriability mechanisms. In this regard, we also contribute to the literature on commercialization strategy. For example, Gans et al. (2003) examine whether innovative start-up firms commercialize their innovations independently or by partnering with other firms as a function of patent rights, secrecy, or the litigation environment. Both our theoretical discussion and our empirical results add to this line of inquiry by considering other measures of appropriability and the timing of independent commercialization.

Finally, we contribute to the practice of technology management and strategy by highlighting the fact that the intuitive trade-off between current market value and option value depends strongly on appropriability conditions. An important implication, validated by the empirical analysis, is that in lines of business where learning is an effective means of appropriating returns, the current market value tends to dominate and inventions are brought to market quickly. By contrast, in lines of business where being a first mover is effective, delays in commercialization may occur because of the option value associated with further product development. Given the increasing reliance of firms on externally generated inventions, particularly those developed in universities, this information should be useful to managers in technology-intensive industries.

Section 2 presents our theoretical arguments on the relation of appropriability mechanisms to the timing of a licensee's decisions and the hazards of termination and commercialization. The competing risk-hazard model used in the empirical analysis is described in §3, and details about our data are provided in §4. Section 5 presents the main results, as well as a variety of robustness checks. Section 6 concludes.

2. Appropriability Mechanisms, Termination, and Commercialization

In our analysis, the timing of termination and commercialization is determined by the licensee's optimal decisions when faced with market value uncertainty. Hence, it is natural to consider the conditional probability that either event (commercialization and termination) occurs at time t given that no event has occurred before, that is, the *hazards* of commercialization and termination. Our approach is similar to Pakes's (1986) model of patent renewal decisions, except that we consider both the decisions to terminate and to commercialize. In the simplest formulation of the problem, given that the firm has not yet commercialized, the value of the license to the firm will be a function

$$V_t(\Pi_t, b_t, c_t),$$

where Π_t is the current expected value to the firm of cumulated profits from commercializing the invention (net of licensing fees) or *market value*, b_t is the benefit from holding the license without commercialization, and c_t is the cost of keeping the license for one additional period without commercialization. This cost may include development costs and surely includes the sum of license fees owed to the university, with the exception of royalties based on sales.

Note that b_t may well exceed Π_t . For example, firms may license patented inventions to build "fences" around products they already produce or to increase their bargaining power in obtaining cross-licenses, as well as to earn royalty income (Levin et al. 1987, Cohen et al. 2000, Arora et al. 2007). In fact, university TLO personnel often express concerns over licensee motives and report that the contracts they use in exclusive licensing include due diligence requirements as well as complicated payment terms to discourage firms from shelving the technologies licensed (Dechenaux et al. 2007). Of course, keeping a license without commercialization may not reflect shelving per se. If property rights are weak (e.g., in electronics or mechanical engineering inventions), the licensee might keep a license until critical knowledge is transferred, but then terminate the license and invent around the patent.¹ In this case, a terminated license may indicate neither a lack of technology transfer nor technology failure (Goldfarb and Henrekson 2003).

The market value, other benefits, and the value function all depend on the effectiveness of appropriability mechanisms such as patent strength, scope, and other nonpatent mechanisms. They also depend

on the amount of time the licensee has been able to spend on development, as well as potentially complex aspects of the product life cycle. Thus, the expected value of V_t may be nonmonotonic as a function of time. There may also be significant heterogeneity between licensees facing otherwise identical appropriability conditions. For example, Teece (1986) and Teece et al. (1997) explain how the ability to benefit from an invention depends critically on the firm's prior experience with related technologies, as well as the ownership of complementary assets. Although we do not discuss this issue further in this section, our empirical model accounts for it by controlling for unobserved heterogeneity.

In any period, the licensee will choose not to terminate the license as long as V_t is greater than zero. Note that $V_0 > 0$ must hold for all licenses in the sample because the firms voluntarily obtained the license from the university. However, the licensee's decision regarding commercialization depends on the difference between the expected profits from immediate commercialization and the option value of delaying (Takalo and Kanninen 2000). Our analysis focuses on how various appropriability mechanisms affect this difference. Other things constant, the conditional probability of commercialization increases as the probability of a high market value increases. This is similar to what Takalo and Kanninen (2000) call the *cash-flow effect*. However, other things constant, the probability of commercialization decreases as the value of simply holding the license one more period increases. This is similar to the *option effect* in Takalo and Kanninen (2000), and we refer to it as such. The conditional probability of termination in period t also depends on the cash flow and the option effects. In contrast to commercialization, the two effects reinforce each other and contribute to decreasing the hazard of termination.

For a formal treatment of these effects, the reader is referred to the online appendix, which is provided in the e-companion.² Here we focus on the intuition underlying the role of different appropriability mechanisms in the timing of commercialization and termination. In addition to the distinction between mechanisms that require commercialization and those that do not, we distinguish those that are legal from those related to business strategy.

2.1. Patent Strength, Patent Scope, and Secrecy

These three appropriability mechanisms pertain to legal means of protecting intellectual property. Based on the Mansfield et al. (1981) study of patents and

¹ Katharine Ku, head of the Stanford Office of Technology Licensing, has indicated to the authors that not only does this happen, but it is considered fair play and not at all unethical.

² An electronic companion to this paper is available as part of the online version that can be found at <http://mansci.journals.informs.org/>.

imitation costs, it is natural to think of both patent strength and patent scope as raising the cost of imitating the licensed technology. Secrecy should have the same effect. Hence, an increase in the effectiveness of these mechanisms should result in a higher value for the license, via both the market value and the option of holding the license.

Ceteris paribus, we would expect an increase in patent strength, patent scope, or secrecy to reduce the hazard of termination. This logic should apply whether or not the licensee intends to commercialize the technology; that is, the legal mechanisms of appropriating returns may provide as much or more value from preemption or cross-licensing as they do from discouraging imitation of a newly developed product (Arora et al. 2007, Arora and Ceccagnoli 2006).

The dependence of the hazard of commercialization on the specific appropriability mechanism is not as straightforward to characterize. Each legal mechanism increases imitation costs and therefore decreases the probability of imitation. This increases both the market and option values because the firm has a longer window to continue development without competition (Kamien and Schwartz 1972, Takalo and Kanninen 2000). The increase in market value should increase the hazard of commercialization, while the option effect works against it. We must note that in the model in Matutes et al. (1996), greater scope decreases an innovating firm's incentives to delay the introduction of applications, while a longer patent leads to increased delays. An earlier result by Reinganum (1982) shows that perfect patent protection accelerates development and thus market introduction.

Note further, for firms that have licensed the invention to block rivals, the effect of the option value is, indeed, the only relevant effect. This effect may also be relatively more important when secrecy is effective, particularly if the technology is closely related to existing technology used by the licensee. Indeed, letting a rival firm obtain the license may lead to disclosure of important information because license agreements often include the possibility for the licensee to work closely with the inventor (Jensen and Thursby 2001, Dechenaux et al. 2007).

Finally, for product innovation, commercialization per se is likely to reveal information about the technology, as modeled, for example, by Gallini (1992). This will almost surely affect the timing of commercialization for licensees that rely on secrecy to appropriate returns. Specifically, when secrecy, as opposed to patents, is used as means of appropriability, the level of current cash flow that barely induces the firm to commercialize is likely to be higher because the probability of highly substitutable imitation is higher.

However, the option value of the license need not be lower.

2.2. Learning

Learning allows the licensee to obtain a significant cost advantage in the product market, and thus, makes imitation less profitable. This advantage is achieved by decreasing the cost of producing a given level of quality over time, and thus requires early commercialization. For this reason, we argue that when returns are appropriated through learning, the value of the license derives mainly from the current market value, while the option value of delaying commercialization is low.

How the effectiveness of learning affects termination is ambiguous. If greater effectiveness of learning was simply to reduce the option value of holding the license (all other things being equal), we would expect learning to increase termination. However, Cabral and Riordan (1997) show that it may be rational for a duopolist to rely on learning by doing to quickly move down the learning curve to induce exit by its less efficient rival. This strategy yields higher profits for the surviving firm. Hence, when learning is effective, the licensee is likely to derive a cost advantage in the product market and face a lower probability of successful imitation. The latter effect would decrease the hazard of termination.

In contrast, learning is unlikely to affect the hazard of commercialization unless the licensee intends to commercialize the technology. Therefore, the expected effect of learning on the hazard of commercialization is straightforward. To benefit from learning, the firm must commercialize, therefore, *ceteris paribus*, learning is likely to increase the hazard of commercialization.

2.3. Lead Time

The licensee's lead time, or the amount of time before entry by the first competitor, is likely to be used to appropriate returns differently across inventions. For example, lead time may be used to establish a brand name, or develop and secure beneficial relationships with large customers. Such efforts would lower the impact of future entry on the first-mover's profit. If, however, lead time is used to get a head start on competitors, then its effectiveness depends on the quality of the commercialized product, and thus, the amount of time spent on development. This is precisely the type of trade-off that Pacheco-de-Almeida and Zemsky (2007) identify in their model. They examine the optimal investment in the development of resources used to secure a competitive advantage in the market for a new product. They show that this optimal investment is guided by a trade-off between what they term "time compression diseconomies" and the firm's preference for entering the

market quickly. Along the same lines as Pacheco-de-Almeida and Zemsky (2007), Lilien and Yoon (1990) argue that a firm developing a new product will benefit from first-mover advantage (consumer lock-in, strong bargaining position with suppliers, etc.) only if its product is of sufficiently high quality (see also Bayus et al. 1997, Benoit 1987). Hence, the relationship between lead time, cash flow, and option effects is not straightforward to characterize.

We expect lead time to be important only to those licensees who have licensed the technology with the goal of commercializing it. If lead time is an effective appropriability mechanism simply because exploiting first-mover advantage decreases the probability of imitation, then an increase in lead time should reduce the hazard of termination. However, if lead time is an effective appropriability mechanism only when the licensee manages to capture a significant share of the market as the first mover, the development costs could become too high for the licensee to consider it worthwhile to continue.

Because of the trade-offs discussed above, the effect of lead time on commercialization is also ambiguous. For an invention that is ready for commercialization, then, conditional on no rival having entered yet, the potential first-mover advantage should be reflected in the current market value. However, the first-mover advantage for embryonic inventions will be reflected in the option value of the license, but not necessarily in the market value. Thus, for such inventions, the greater the importance of lead time, the lower the hazard of commercialization.

2.4. Summary of Predictions

Before turning to the empirical analysis of the hazards, we summarize our predictions in Table 1. The table relates appropriability measures to the cash-flow and option effects and provides our predictions for the effect of appropriability mechanisms on the hazards of termination and commercialization.

Table 1 Predictions: Appropriability Measures and Hazards of Termination and Commercialization

Appropriability measures	Cash-flow effect	Option effect	Hazard of	
			Termination	Commercialization
Strength	+	+	-	+/-*
Scope	+	+	-	+/-
Secrecy	+	+	-	+/-
Learning	+	-	-/+	+
Lead time**				
Embryonic	-	+	+/-	-
Late stage	+	-	-/+	+

*a/b indicates that the direction of the overall effect is given by a if the cash-flow effect dominates the option effect and by b otherwise.

**Depends on the stage of development.

3. Empirical Methodology

Although the cash-flow and option effects taken together have ambiguous effects on the hazards, the panel nature of our data allows us to explore which effect dominates, on average, for our data. We observe a set of MIT inventions, their licensees, and termination and commercialization outcomes. We observe each observation until one of these events, or until it is right censored by the closing of our observation window. Our data reflect the two central competing risks about which we theorize, and we need to control for the empirical reality of right censoring. Thus, we adopt a competing-risks framework. As we discuss below, we might expect a significant amount of heterogeneity among MIT inventions, which may be difficult to control for. With this in mind, the framework we adopt allows for nonparametric heterogeneity.

Let T_f be the duration of a patent that is licensed until first sale and T_d be the duration of a license until it is terminated. Define $T = \min(T_f, T_d)$, and let d_f be an indicator that equals one if a patented technology is commercialized (first sale) and zero otherwise. Let d_d be an indicator that equals one if a patented technology is terminated and zero otherwise. Only (T, d_f, d_d) are observed. Because d_f and d_d are observed, exclusion restrictions are not necessary to uncover the latent survival functions, $S(k_f, k_d | x)$, as long as there is sufficient variation in the vector of regressors x (Abbring and van den Berg 2003, Han and Hausman 1990). Since our data are discrete, we employ a grouped data approach (Han and Hausman 1990). Our model follows McCall (1996).

The probability of a license being terminated conditional on no events occurring through period $k - 1$ is

$$\begin{aligned} \Pr(T_d = k | X, T > k - 1) \\ = 1 - \exp(-\theta_d \exp(\alpha_{dk} + \beta'_d x)), \end{aligned} \quad (1)$$

where x is a set of exogenous (possibly) time-varying regressors. Similarly,

$$\begin{aligned} \Pr(T_f = k | X, T > k - 1) \\ = 1 - \exp(-\theta_f \exp(\alpha_{fk} + \beta'_f x)) \end{aligned} \quad (2)$$

is the probability a first sale associated with a patent occurs conditional on no events occurring through period $k - 1$. Period subscripts on x are dropped for readability. Because the theory does not provide us with guidance as to possible exclusion restrictions, we assume that regressors x are identical in both equations.

The joint survivor function conditional on x is

$$\begin{aligned} S(k_s, k_d | x) = \exp \left(-\theta_f \sum_{r=1}^{k_f} \exp(\alpha_{fr} + \beta'_f x) \right. \\ \left. -\theta_d \sum_{r=1}^{k_d} \exp(\alpha_{dr} + \beta'_d x) \right). \end{aligned} \quad (3)$$

In what follows, let $\Theta = \{\theta_f, \theta_d\}$. α_{wk} are the baseline parameters and can be interpreted as

$$\alpha_{wk} = \log\left(\int_{k-1}^k h_w(t) dt\right),$$

where $h_w(t)$ is the underlying baseline hazard function and $w \in \{f, d\}$. α_{dk} and α_{fk} are the respective baseline hazards and are assumed to follow a third-order polynomial. A third-order polynomial is sufficiently flexible to approximate a baseline hazard function of only five periods. Thus,

$$\alpha_{wk} = \alpha_{0k} + \alpha_{1k}k + \alpha_{2k}k^2 + \alpha_{3k}k^3. \quad (4)$$

The vectors of parameters β_w represent the effects of the exogenous variables. Note that all covariates are constant except patent age and year. Define

$$\begin{aligned} P_f(k) &= S(k-1, k-1 | \Theta) - S(k, k-1 | \Theta) \\ &\quad - 0.5[S(k-1, k-1 | \Theta) + S(k, k | \Theta) \\ &\quad - S(k-1, k | \Theta) - S(k, k-1 | \Theta)], \end{aligned}$$

$$\begin{aligned} P_d(k) &= S(k-1, k-1 | \Theta) - S(k-1, k | \Theta) \\ &\quad - 0.5[S(k-1, k-1 | \Theta) + S(k, k | \Theta) \\ &\quad - S(k-1, k | \Theta) - S(k, k-1 | \Theta)], \end{aligned}$$

$$P_c(k) = S(k-1, k-1 | \Theta),$$

where $P_f(k)$ is the unconditional probability of first sale by the beginning of period k , $P_d(k)$ is the unconditional probability of a license being terminated by the beginning of period k , and $P_c(k)$ is the unconditional probability of neither event occurring through the beginning of period k . An adjustment, $0.5[S(k-1, k-1 | \Theta) + S(k, k | \Theta) - S(k-1, k | \Theta) - S(k, k-1 | \Theta)]$, is made because durations are measured in discrete time.

A key problem with competing-risks models identified in the literature is that when the risks are not allowed to correlate, a potential bias may arise. Unobserved determinants of one event (first sale) may be correlated with unobserved determinants of the complementary event (termination) and duration (decision to do neither). We might expect unobserved components, such as quality of the patent and uncertainty associated with success of the technology, to affect both decisions. In our specification, we allow risks to correlate by permitting a three mass-point distribution of location parameter pairs θ_{dj}, θ_{fj} , where $j = 1, 2, 3$. Each pair occurs with probability p_j . The six location parameters and two free probabilities are estimated by the data. Thus,

$$\varphi_w(k) = \sum_{j=1}^3 p_j P_w(k | \Theta_j). \quad (5)$$

The log-likelihood is

$$\begin{aligned} \log L &= \sum_{n=1}^N \sum_{k=1}^{K_n} d_{fk}^n \log \varphi_{fk}^n + d_{dk}^n \log \varphi_{dk}^n \\ &\quad + (1 - d_{fk}^n)(1 - d_{dk}^n) \log \varphi_{ck}^n \end{aligned} \quad (6)$$

for each of the K_n periods of each of the N attempts.

To identify the model, the baseline hazards α_{f0} and α_{d0} are fixed to zero. Because there is no constant in the regression, we use deviations from the means in x .

4. Data

The data used to test the model's predictions were collected from the MIT TLO. Our sample includes all patented inventions made by faculty, staff, and students at MIT that were assigned to the Institute between 1980 and 1996 and subsequently licensed exclusively to at least one private sector firm. Our unit of analysis is the license. There were 805 exclusive licenses and 2,875 periods in which licenses were at risk. While it is plausible that licenses are terminated after commercialization, the MIT TLO reports that this is a rare event, and hence this information was not collected. That is, we only observe the first event that occurs. The analysis below predicts the likelihood of the first event.

Our data set is an unbalanced, right-censored panel. We have yearly data for each attempt from the date of the contractual agreement on the patent until one of three events occurs: it is right censored (in 1996), it is terminated, or it is commercialized. The data include the date of termination if the license is terminated and the date of first sale if an invention is commercialized. An observation begins the year that MIT TLO records indicate that a firm first licensed a patent. We code TERMINATION as zero, except in the year (if any) that MIT TLO records indicate that the licensing agreement by the given firm no longer covered the invention or if the patent expired, thereby negating the license. We code COMMERCIALIZATION as zero, except in the year (if any) that MIT TLO records indicate that the first dollar of sales from a product or service embodying the invention was achieved. Our discussions with MIT personnel indicate that record keeping was quite good, hence we are confident our data is an accurate representation of reality.

Table 2 reports the summary statistics. In our data, only 49 of the inventions were commercialized within the first year of the license, and the overwhelming majority were never commercialized. Roughly 40% of the licenses were terminated during the period.³

³ Note that remaining patent life reflects the mean remaining life of patents at the time of license.

Table 2 Descriptive Statistics

Variables	Mean	Std. dev.	Min.	Max.
LEAD TIME	5.369	0.506	4	6.13
SECRECY	3.923	0.406	3	4.88
LEARNING	5.003	0.435	4	5.75
PATENT STRENGTH	4.108	0.747	1.75	5.32
PATENT SCOPE	1.339	0.639	1	6
START-UP	0.327	0.469	0	1
INDUSTRY FUNDED	0.168	0.374	0	1
DRUG PATENT	0.216	0.412	0	1
CHEMICAL PATENT	0.311	0.463	0	1
ELECTRIC PATENT	0.265	0.441	0	1
MECHANICAL PATENT	0.032	0.177	0	1
OTHER TECHNOLOGY	0.176	0.381	0	1
REMAINING PATENT LIFE (17 years since grant)	12.85	3.54	1	17
REMAINING PATENT LIFE * PATENT STRENGTH	21.29	14.76	2.73	79.80
REMAINING PATENT LIFE * PATENT SCOPE	6.91	6.17	1	60
<i>N</i>		805		

Table 3 Termination, Commercialization, and Right Censoring by Age of License

Age of license	TERMINATION	COMMERCIALIZATION	Right censored	Total
1	74	49	79	805
2	32	26	48	604
3	54	40	98	497
4	49	20	35	305
5	34	11	34	201
6	8	2	10	122
7	10	6	11	103
8	6	2	9	76
9	0	11	8	59
10	1	0	15	39
11	1	1	7	24
12	0	0	2	15
13	0	0	8	13
14	0	0	2	6
15	0	0	2	4
16	0	0	2	2
Total	269	168	370	2,875

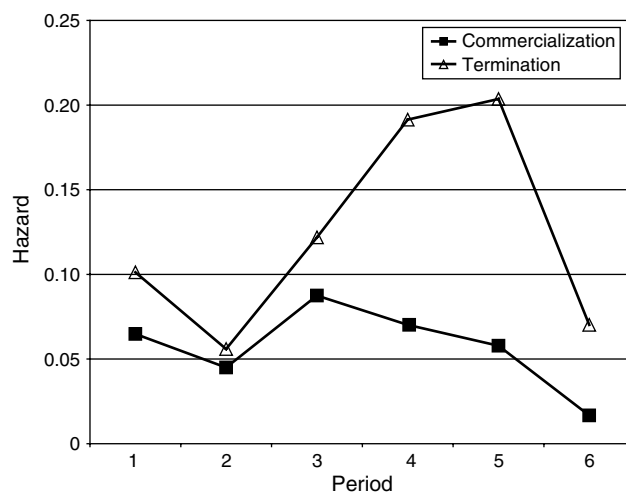
Table 3 reports the unconditional survival rates and the extent of right censoring in the sample. It shows that firms are far more likely to terminate licenses of patents than to successfully commercialize them (323 terminations versus 197 successes). The table also suggests that uncertainty associated with an innovation is generally resolved in the first five years of license because 85% of licenses either lead to commercialization or are terminated by the end of period 5, and 90% of the observed events occur in the first five periods.⁴ The sparseness of this right tail implies that there is little information on which to estimate a baseline hazard. Therefore, we recoded all observations that survived more than five periods as right censored after five periods. The majority (257) are censored during the first four years of the license due to the closing of our observation window in 1996. In addition to the observations that are right censored after 1996, we censored an additional 74 observations. Figure 1 depicts the hazard of each event.

4.1. Measures of Appropriability

As measures of importance of the appropriability mechanisms used in a line of business, we employ four measures from the Yale survey on innovation: patent strength, secrecy, lead time, and learning (Levin et al. 1987). These measures are survey line of business averages. They reflect perceptions of 650 high-level R&D managers in 130 lines of business about central tendencies of the effectiveness of different mechanisms used to appropriate the returns to innovation for process or product R&D in their lines of business. The managers were asked to rate mechanisms on seven-point Likert scales.

To ensure the reliability and validity of their survey, the scholars who conducted the Yale survey pretested their survey with managers from diverse businesses. In addition, to mitigate intraindustry heterogeneity, the respondents were asked to identify major innovations in their industry, and there was not significant variation in responses to this question within industries. Because of their reliability and validity, the measures have been used in several subsequent studies (Cohen and Levinthal 1990, Levin et al. 1987). However, as Griliches pointed out in Levin et al. (1987), the measures for lead time and learning are less objective than those for patent characteristics or secrecy (see the Comments and Discussion section in Levin et al. 1987). Further, Pakes (1986) notes that because of the unusually high level of technical uncertainty inherent in the development of new products and

Figure 1 Unconditional Event Hazards by Period



⁴ We observe only two events after period 10.

processes, the relationship between the outcome of development efforts and expected profits—and thus, to a large extent, appropriability conditions—may be difficult to measure with precision.

The items are constructed from responses to the following question posed both for production processes and products: “In this line of business, how effective is each of the following means of capturing and protecting the competitive advantages of new or improved products (production processes)?” Respondents answered on a seven-point Likert scale from “not at all effective” to “very effective.”

Patent strength is a measure of the effectiveness of patents as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products for two means of appropriability: “patents to prevent competitors from duplicating the product (process)” and “patents to secure royalty income.” Secrecy is a measure of the effectiveness of keeping key information secret as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products to “secrecy” as a means of capturing and protecting the competitive advantages of new or improved production processes (products). Lead time is a measure of the effectiveness of being an early mover as a way to capture and protect competitive advantage in a line of business. It is created from the average response for production processes and products to “lead time (being first with a new process [product]).” Learning is a measure of the effectiveness of moving ahead of competitors on the learning curve as a way to capture and protect the competitive advantages in a line of business. It is created from the average response for production processes and products to “moving quickly down the learning curve.”

Relating our data to the Yale Survey measures of appropriability raises an important empirical issue. Because our sample covers the years 1980–1996, while the survey measures appropriability conditions at a particular point in time, we must assume that the appropriability differences between lines of business are relatively stable throughout our observation period. There is some evidence that cross-industry differences in such factors in appropriability do not vary significantly over time because they are a function of the underlying technology in a line of business (Cohen and Levin 1989). Although one might argue that the absolute strength of patents increased during the period, the intellectual property protection afforded by patents for, say, chemical compounds remains very strong relative to that for electronic devices.

We also employ Lerner’s (1994) measure of patent scope, which is based on the number of international

patent classifications found on the patent. Lerner (1994) finds that this measure is associated with various measures of economic importance: firm valuation, likelihood of patent litigation, and citations. He argues that it represents a broader scope of the monopoly rights covered by the patents. In contrast to the Yale measures, this variable is patent specific.

4.2. Control Variables

The fact that we do not observe many licenses extending beyond five years without a commercialization or termination event does not imply that uncertainty is resolved within five years of issuance of a patent. It is common for licenses to be initiated and survive well into patent life before first sale or termination (Table 4). We measure REMAINING PATENT LIFE as 17 minus the number of years since the patent was issued, conditional on patent issue at time of license. This variation in the remaining life of a patent at the time of license allows us to separately control for the effects of the age of the license and the remaining time of formal patent protection on the hazards of first sale and termination. The former are measured by the baseline hazard estimates, while the latter are measured by the coefficients on REMAINING PATENT LIFE. Some patents were licensed prior to patent grant. We code the REMAINING PATENT LIFE as 17 for these patents until grant—at which time the clock begins. The patent grant clarifies the property right (Gans et al. 2007), and might influence decision making. Indeed, we find that the grant has a significant (negative) effect on termination, although none on commercialization. Controlling for this does not influence the other coefficients. Because this is

Table 4 Termination, Commercialization, and Right Censoring by Patent Age

REMAINING PATENT LIFE	TERMINATION	FIRST SALE	Right censored	Total
17	38	9	2	48
16	38	25	49	112
15	31	15	30	76
14	24	14	36	74
13	37	21	28	85
12	20	8	40	68
11	12	14	26	52
10	15	16	38	69
9	13	14	25	52
8	11	12	21	44
7	12	5	19	36
6	7	7	5	19
5	8	5	4	17
4	3	0	9	12
3	0	1	7	8
2	0	2	15	17
1	0	0	16	16
Total	269	168	370	805

tangential to our analysis, it is omitted from these regressions.

We also include TECHNOLOGY CLASS dummies. Following the Hall et al. (2001) classification of patents, we break the patents into five categories: drugs, electronics (including computers and communications), chemicals, mechanical, and other because we might expect different types of technology to take longer to reach first sale, as is the case for drugs, which need to first obtain FDA approval.

Reduced form hazard ratios suggest that event patterns in the various categories are distinct. For example, licenses of drug patents tend to survive longer than other types of inventions. That said, these technology class controls are relatively crude, and moreover, the Yale appropriability measures are associated with lines of business, which are, in turn, mapped to the patents via their primary three-digit U.S. patent classes. Hence, there is no variation in the Yale appropriability measures within three-digit patent classes. This leads to concerns that the appropriability measures will proxy for technological heterogeneity. While we cannot eliminate this possibility entirely, we explore it in detail in the next section.

We also include a dummy variable that takes the value one if the patent was licensed to a start-up, defined as a firm formed to license the particular technology (33% of the patents in our sample were licensed to start-ups). We also include a dummy variable that indicates whether the research that led to the patented invention was funded by industry. (16.8% of the patents were the result of industry-funded research.) Industry funding does not, however, imply that the firm that funded the research necessarily was the licensee. While research sponsors are not generally afforded special licensing rights, in practice we might expect them to be aware of research results earlier than nonsponsors. We are unable to identify cases in which sponsors licensed the output of research they funded because we do not observe the identity of the research sponsors.

5. Empirical Results

Our results are reported in Table 5. Our unit of observation is a license. In university licensing, several patents may be licensed in a single agreement. If there are many such cases, and they reflect instances in which a single technology is protected through multiple patents, our regressions would overweight these technologies. If such technologies are systematically different than those licensed through single patents, then this pattern would introduce a bias into our analysis. This problem could be mitigated by allowing the error terms to be correlated within each agreement. Unfortunately, we are not aware of a method

to implement this strategy and simultaneously control for unobserved heterogeneity. Because we believe that unobserved heterogeneity is a greater problem than the overweighting of technologies represented by multiple patents, we choose to control for unobserved heterogeneity in our analyses.⁵

We estimate several regressions, and in doing so investigate the general robustness of our results. In all reported models, we include year dummies to control for technology vintage. Our results are generally robust to the omission of vintage controls.

In Model 5(a), we report results of a model that includes all of the appropriability measures. We find that PATENT STRENGTH is negatively related to the hazard of license termination. Although the coefficient on PATENT SCOPE is negative, it is not significant at conventional levels. Thus, we find some support for our prediction that appropriability measures directly related to patents will reduce termination hazards. In contrast, we find that PATENT STRENGTH has no measurable effect on the hazard of commercialization. Recalling Table 1, either the cash-flow and option effects wash each other out, or alternatively, there is no relationship. However, the strong positive relationship between PATENT SCOPE and commercialization hints that the cash-flow effect is dominant. This conclusion is reinforced by the results regarding SECRECY and LEARNING. As predicted by our theory, we find that SECRECY is negatively and significantly related to TERMINATION. We also find that SECRECY is positively and significantly related to COMMERCIALIZATION, which is consistent with the suggestion that cash-flow effects are, on average, dominant. Note that this result is inconsistent with our conjecture in the theory that the threshold for commercialization may be higher when secrecy is used because of the risk that commercialization itself reveals information. While the point estimate for LEARNING is negative in the termination equation, it is not significant at conventional levels. We precisely measure a positive relationship between LEARNING and the hazard of commercialization, as predicted by our theory. This finding complements Cabral and Leiblein's (2001) finding that, for process innovation, adoption of new technology is more likely in firms that have production experience with the previous generation of that technology.

⁵ We might also average patent characteristics within a license. However, this would create a problem as large as the one it was intended to solve. Averaging would leave us unable to accommodate the cases in which one of the licensed patents was either commercialized or terminated separately from the rest of the patents under the license agreement, which we observe in a significant number of cases. Moreover, discussions with the director of the MIT TLO indicate that separate termination is a common occurrence and is represented by several anecdotes in the "lay" theory of technology transfer officers about how to think about these data.

Table 5 Hazard Regressions

Variables	Model (a)		Model (b)		Model (c)		Model (d)		Model (e)	
	TERMINATION	COMMERCIALIZATION	TERMINATION	COMMERCIALIZATION	TERMINATION	COMMERCIALIZATION	TERMINATION	COMMERCIALIZATION	TERMINATION	COMMERCIALIZATION
PATENT STRENGTH	-1.22*** (0.21)	0.06 (0.49)	-1.19*** (0.21)	0.40 (0.48)	-1.29*** (0.35)	1.19** (0.60)	-1.04*** (0.36)	1.31** (0.66)	-0.55 (0.40)	1.55* (0.87)
PATENT SCOPE	-0.17 (0.18)	0.80*** (0.23)	-0.28 (0.20)	0.95*** (0.25)	-0.39* (0.22)	0.79*** (0.27)	-0.49 (0.35)	-0.29 (0.52)	-0.18 (0.38)	-0.35 (0.52)
SECRECY	-1.03** (0.41)	1.57** (0.75)	-1.52*** (0.41)	0.75 (0.73)	-1.68*** (0.45)	1.33* (0.77)	-1.71*** (0.45)	1.37* (0.82)	-1.68*** (0.43)	1.26 (0.82)
LEARNING	-0.46 (0.38)	3.29*** (0.77)	0.32 (0.39)	3.90*** (0.95)	0.06 (0.48)	2.92*** (0.84)	0.26 (0.49)	2.99*** (0.95)	0.21 (0.48)	2.79*** (0.96)
LEAD TIME	0.67* (0.35)	-1.18** (0.54)	-0.04 (0.33)	-1.73*** (0.57)	0.28 (0.45)	-1.51** (0.61)	0.18 (0.44)	-1.53** (0.68)	0.17 (0.43)	-1.46** (0.67)
REMAIN PAT LIFE										
REMAIN PAT LIFE × PATENT STRENGTH							-0.02 (0.02)	-0.05* (0.03)	-0.11** (0.05)	-0.10 (0.09)
REMAIN PAT LIFE × PATENT SCOPE							0.02 (0.05)	0.18** (0.08)	-0.05 (0.06)	0.19** (0.08)
Other control variables										
STARTUP										
INDUSTRY FUNDED										
DRUGS										
ELEC										
MECH										
OTHER										
Year dummies		Yes		Yes		Yes		Yes		Yes
Correlated risks w/ unobserved heterogeneity		Yes		Yes		Yes		Yes		Yes
Log-likelihood		-1,008.93		-997.54		-988.27		-980.55		-977.39

Notes. Standard errors are in parentheses below coefficients. *Significant at the 10% level, **significant at the 5% level, ***significant at the 1% level.

Note that the theory generated ambiguous predictions for two of the three coefficients that empirically we fail to measure with precision (PATENT SCOPE and LEARNING in the termination equation and PATENT STRENGTH in the commercialization equation). We find a positive relationship (at the 10% level) between LEAD TIME and termination and a negative relationship between this measure and commercialization (at the 5% level). The combined termination and commercialization results suggest that, for inventions in lines of business in which LEAD TIME is effective, the current market value is low, most likely because of the need for further development. As per Table 1, in the case of commercialization, assuming that inventions are embryonic, both the cash-flow and option effects reinforce each other.

We explore the robustness of these results in Models 5(b)–5(e). In Model 5(b), we introduce controls for whether the licensee was a start-up and whether the research that generated the patent was funded by industry. A log-likelihood test rejects the null hypothesis that these four coefficients are jointly zero (LR statistic = 11.50). Both STARTUP and INDUSTRY FUNDED are negatively related to termination (the former result is consistent with findings of Lowe and Ziedonis 2006). Our results remain unchanged except that we no longer measure a relationship between LEAD TIME and termination. Further (unreported) analysis indicates that this is due to the inclusion of the STARTUP control, which suggests that our measured positive relationship between LEAD TIME and termination is the result of underlying negative correlation between LEAD TIME and start-ups, who tend to license technologies where LEAD TIME is a less important appropriability mechanism. In Model 5(c), we include four broad technology class dummies. When these dummies are included, PATENT STRENGTH and PATENT SCOPE are significantly related to both termination and commercialization. In this model, PATENT SCOPE becomes significant (and negative) at the 10% level in the termination equation, and PATENT STRENGTH becomes positive and significant in the commercialization equation.

It was not possible to estimate a more parsimonious model that simultaneously excluded class, age, and year controls, included a 3-point mass structure, and a cubic form for the baseline hazard. We suspect such a model is not properly identified due to insufficient variation in the data (see Abbring and van den Berg 2003).

With the exception of PATENT SCOPE, our measures of appropriability vary at the level of line of business, as opposed to the level of the patent. While our results are unaffected, or even strengthened by the inclusion of broad technology class dummies, these dummies are only coarse proxies for technology

class. Thus, as mentioned earlier, our appropriability measures may pick up unobserved heterogeneity across technology classes, and this heterogeneity may drive our results, as opposed to underlying variation in appropriability mechanisms across individual technologies. While controlling nonparametrically for unobserved heterogeneity should alleviate some of these concerns, we conduct further tests to explore this possibility.

If our measures of appropriability are indeed measuring appropriability, their effects should weaken as a patent ages. In Model 5(d), we include the interactions of REMAINING PATENT LIFE with both PATENT STRENGTH and PATENT SCOPE. We no longer measure direct relationships between PATENT SCOPE and either termination and commercialization. However, the interaction of PATENT SCOPE and REMAINING PATENT LIFE is positive and significant, which suggests that the effect that we found in Models 5(a)–5(c)—in which scope is positively related to commercialization—is driven by the younger patents. The main PATENT STRENGTH effect is qualitatively unchanged in both equations. In this model, we also find a marginally significant relationship between the interaction of REMAINING PATENT LIFE and PATENT STRENGTH, however, this result is not robust (see Model 5(e)).

In Model 5(e), we include a measure of REMAINING PATENT LIFE as well as that variable's interactions with PATENT STRENGTH and PATENT SCOPE. REMAINING PATENT LIFE, in itself, should have no effect on termination or commercialization unless the patents are strong. This leads us to expect only the interaction terms to be significant. However, REMAINING PATENT LIFE is also a proxy for the age of the technology (as opposed to the age of the license, which is captured by the baseline hazard rate or vintage of the license, which is captured by the year dummies). Presumably, older technologies have more substitutes which could explain the greater likelihood of termination associated with older patents.

Only the main (positive) patent strength—commercialization finding remains significant. However, we also find that the coefficient on REMAINING PATENT LIFE interacted with PATENT STRENGTH is negative and significant. In addition, as in Model 5(d), we find the coefficient REMAINING PATENT LIFE interacted with PATENT SCOPE to be significant in the commercialization equation. Thus, these results are consistent with the premise that the appropriability measures are indeed measuring differences in appropriability rather than technological heterogeneity.⁶

⁶We also note that if the appropriability measures are picking up unobserved heterogeneity, then these measures should have greater predictive power in a restricted model. In an unreported

We also estimated a model using 24 patent classes as controls. The data do not support this specification fully: only for patent classes in which there are a sufficiently high number of observations can we include patent class dummies, and 86 of the 108 patent classes that our data span perfectly predict outcomes because they are represented in the data by one or two licenses. In general, the results regarding the appropriability measures were weakened. However, due to data limitations, we were unable to estimate this model while simultaneously accounting for unobserved heterogeneity. Hence, it is unclear whether this result is due to the introduction of controls or the failure to control for unobserved heterogeneity (see Footnote 6).

Thus, while the results associated with the interaction of REMAINING PATENT LIFE and PATENT STRENGTH and scope support the general thrust of our arguments, we do not have sufficient within-technology-class variation to conclusively rule out the alternative hypothesis that our appropriability measures are picking up other sources of technological heterogeneity, which would reflect an association between appropriability conditions in line of business and termination and commercialization hazards. To the extent that such a correlation might be associated with other unobserved factors, our results must be qualified.

From our robustness analysis, we conclude that the hazard of termination is decreasing in PATENT STRENGTH and SECRECY. The hazard of commercialization is decreasing in LEAD TIME, and increasing in LEARNING, PATENT SCOPE, and also PATENT STRENGTH. Based on Table 1, these results are consistent with the cash-flow effect dominating the option effect on average for the technologies in the sample. Furthermore, our result for LEAD TIME is consistent with the assumption that these technologies are embryonic inventions for which further development is required.

specification similar to Model 5(e) in which we restricted risks to be independent, and did not allow unobserved heterogeneity, we (i) rejected the hypothesis that there is no unobserved heterogeneity and independent risks, and (ii) found that the explanatory power of the appropriability measures weaken. To understand the intuition behind this result, consider that, in Model 5(c) we found that the hazard of termination decreases if the technology is licensed to a STARTUP, but the hazard of commercialization does not. By contrast, in the restricted model, we found no effect. The sensitivity of the result for STARTUP to controlling for unobserved heterogeneity is what one might expect if start-ups not only differ from well-established firms, but also license inventions that are different from those licensed by established firms. For example, if start-ups license earlier and riskier inventions, but are more reluctant to terminate the license (because terminating the license agreements might imply terminating the start-ups as well), then these two effects would tend to cancel out. However, after controlling for this heterogeneity, then Model 5(c) shows that start-up firms are more likely than other licensees to terminate the development projects.

To get a sense of the magnitude of the effects, and following the literature on these types of competing-risks models, we compute the change in the predicted probabilities of events for the sample. Because the Yale Survey measures are derived from a Likert scale, we look at the effect of a change in one standard deviation from the mean on the predicted probability of events for the sample. Model 5(c) predicts both the mean probability of termination and commercialization for the sample to be 0.12 and 0.10, respectively (all numbers are rounded to two digits). If each manager in a line of business associated with each of the inventions had rated the effectiveness of patents one standard deviation higher, the probability of termination for the sample patents would decrease to 0.10, or 21%, while the probability of commercialization would increase to 0.13. Similarly, if each manager had rated SECRECY one standard deviation higher, the predicted probability of termination decreases 12% to 0.11, while the predicted probability of commercialization increases 16% to 0.11.

We find that each additional international patent class associated with the patent (measured by PATENT SCOPE) decreases the mean predicted probability of termination by 12.5% to 0.11, and increases the mean predicted probability of commercialization to 0.12, which represents an increase of 21%. A one standard deviation change in LEAD TIME is associated with a reduction in the commercialization probability to 0.08, a 17% decline. A one standard deviation increase in the importance of LEARNING increases the probability of commercialization by 25% (the mean predicted probability increases to 0.12).

6. Concluding Remarks

We investigate the role of patents and other appropriability mechanisms in the commercialization of university inventions. An important characteristic of these inventions is that they typically require further development, which is risky for both technical and market reasons. In our theoretical discussion, we view a licensee's decision as an optimal stopping problem in which at every point in time the licensee can decide to either commercialize, drop the license, or keep the license but delay commercialization. This gives rise to a real option in commercialization. How different appropriability mechanisms affect a firm's decisions depends on their impact on the current market value of the license and this real option.

Our empirical analysis applies a competing-risks hazard model which allows for correlated risks and nonparametric unobserved heterogeneity to a data set of 805 exclusive licenses of MIT patents. We find that the hazard of terminating a license is decreasing in the effectiveness of patent strength and secrecy. One

of our most striking results is that, when lead time is important, it appears to be optimal for firms to delay commercialization until the licensee has developed the product. In contrast, we find that patent scope and learning have a positive effect on the hazard of commercialization. These results suggest that, when profiting from embryonic inventions relies heavily on learning, firms should commercialize them as soon as is technically feasible.

This study provides guidance to managers who are increasingly managing the process of commercializing university inventions, which are often embryonic at the time of license. It suggests that companies should manage technology licenses using a real-options framework rather than the static frameworks which are commonly used. Because a licensee can always terminate a license, try to commercialize the technology under license, or simply wait. As emphasized by Ziedonis (2007), licensing creates a much more elaborate set of strategic choices than just simply “the right to commercialize” that is portrayed in the literature. Terminating a license and delaying a commercialization effort are also important strategic choices available to managers. In fact, under certain circumstances, delaying commercialization is a better strategy than trying to commercialize a licensed technology.

Moreover, the “right” strategy for managing a technology license depends on the commercialization environment created by the line of business in which the invention is being applied. Like Gans et al. (2003), we show that the “right” technology strategy is not the same across all lines of business. For example, in lines of business in which learning is an effective way to capture the returns to innovation, quick commercialization is a better strategy than in lines of business in which first-mover advantage matters a great deal, and delaying commercialization offers strategic value. Thus, the “right” commercialization strategy for semiconductors may not be the “right” commercialization strategy for pharmaceuticals.

Finally, in lines of business in which patents are effective, managers may have reason to adopt strategies which are at odds with the goals of public policies. Strong patents provide an incentive to managers not to terminate commercialization efforts because firms may be able to use those patents to appropriate returns from the license even if they cannot commercialize a technology. Thus, patents have a value to companies over and above their value in facilitating technology commercialization, which is ostensibly the goal of policies such as the Bayh Dole Act, which allows university patent licensing for publicly funded inventions.

A few caveats are in order. First, our analysis does not account for the structure of license agreements.

Work by Choi (2001), Jensen and Thursby (2001), Elfenbein (2005), and Dechenaux et al. (2007) has shown that the structure of payment terms can affect development efforts by licensees as well as the inventors themselves. Thus, while considering these effects is beyond our scope, we cannot rule out license structure as a determinant of termination and commercialization. Second, readers are cautioned that MIT is a unique institution and that the results may not generalize to other universities. This suggests the merits of future research based on data from other universities, as well as more fine-grained measures of technology characteristics.

7. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at <http://mansci.journal.informs.org/>.

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