**GLOBAL DIFFUSION OF TECHNOLOGICAL
INNOVATIONS: A COUPLE-HAZARD APPROACH**

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Abstract

The paper proposes a new methodology called the “coupled-hazard approach” to study the global diffusion of technological innovations. This coupled approach addresses several methodological challenges arising from the global nature of the considered diffusion process **and** the intricacies of the type of innovations studied. First, a global diffusion process is typically composed of two conceptually different, yet inter-linked, processes: (1) diffusion across countries, and (2) diffusion within each country. Second, due to network externalities and/or the presence of central decision makers, technological innovations often exhibit diffusion patterns that cannot be captured by traditional models. In particular, within-country adoption often occurs in “blocks” or “packets” of various size (with sometimes the whole country adopting at once), which prevents the use of S-shaped (Bass-type) diffusion models. Finally, technological innovations may complement or substitute existing ones, which raises the issue of how the size of the installed base of the old technology affects the new diffusion process. The “coupled-hazard approach” is well-suited to address all three issues. Beyond the capability of describing discontinuous diffusion patterns, the method explicitly recognizes the conceptual difference between the timing when a country tries or “pilot tests” the new technology, called “the implementation stage” by Rogers (1983) and the timing of when the innovation is adopted on a national or ubiquitous basis within the country (referred to by Rogers as “the confirmation stage”). In addition to testing the separate influence of exogenous and endogenous country characteristics on these two stages, it also allows us to assess their interrelationship. To illustrate the method, and in order to generate substantive insights, we apply the approach to the global diffusion of digital telecommunications networks across over 160 countries.

1. INTRODUCTION

With the increasing globalization of markets, managerial interest in understanding adoption processes across countries has led to calls for more academic research on international diffusion (see e.g. Douglas and Craig 1992). While a number of studies have begun to answer this call, attention has mainly focused on a comparison of *within-country* diffusion patterns of consumer durables across a *limited number* of industrialized countries.¹ This paper is the first to consider the *global* diffusion of a particular type of innovations, those relying extensively on technological advancements (computers, software, telecommunications innovations and alike).

A number of factors make the study of global technology diffusion particularly interesting as well as challenging. In particular, this paper focuses on three key issues: (1) the two-stage nature of the global diffusion process, (2) the potential irregularity of the resulting diffusion pattern due to the presence of network externalities and/or central decision makers, and (3) the role of the installed base of older generation technologies that the innovation replaces.

First, we argue that global adoption is comprised of two stages. Our framework considers the two stages as conceptually different (but related) measures of innovativeness across countries:

- the time between when an innovation first becomes available in the world and the time it first appears in a country, i.e. the *implementation* stage (as defined by Rogers 1983), and
- the time between the initial trial within a country and its full adoption or substitution, i.e. the *confirmation* stage (as defined by Rogers 1983).

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¹ Gatignon, Eliashberg and Robertson (1989) and Mahajan and Muller (1994), for example, compare the Bass diffusion parameters for a number of household appliances across a set of European countries. Takada and Jain (1991) compare these diffusion parameters for four Pacific Rim countries, and Helsen et al. (1993) assess similarities in the diffusion of three consumer durables across 12 industrialized countries. In a recent paper involving 10 European countries and four durable products, Putsis et al. (1997) provide an innovative model of cross-country diffusion describing the "mixing behavior" of heterogeneous populations.

From a managerial perspective, both aspects may influence production and/or marketing planning decisions. For example, the likely adoption (trial) date for some countries may lie well beyond the firm's typical planning horizon. Similarly, once the initial adoption decision has been made, managers become interested in the subsequent speed of diffusion of the new technology within that country, i.e. how long it will take the country to fully replace the old technology. While the implementation and confirmation stages address separate managerial problems and represent two conceptually different diffusion processes (potentially involving different decision makers and word-of-mouth processes) they should not be studied independently. Indeed, these two processes are closely inter-linked, and may influence each other. For example, countries trying the innovation later may reach full confirmation sooner as they can benefit from earlier adopters' experience with the technology.

Second, while all global products diffuse in the manner theorized above, technological innovations such as computers or telecommunications products **tend to** have unique characteristics vis-à-vis other industrial or consumer goods: **they often exhibit** "network externalities" (Katz and Shapiro 1985), where consumers benefit from other consumers using a product based on the same technology. The existence of network externalities requires increased coordination of consumer adoptions as the technology's value depends on the total size of the adopter population. Network externalities often result in a standard or special regulations imposed upon users (Economides 1996). As a result, the diffusion path of the new technology may occur in "blocks" or "packets", which makes the diffusion process discontinuous. The need for increased consumer coordination and the setting of standards or regulations also mean that, beyond individual consumers' adoption decisions, the diffusion process of technological innovations is typically influenced to some extent by central decision makers, especially in the early stages of the diffusion process.² For telecommunications

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² We would like to thank one of the reviewers for drawing our attention to this issue.

innovations, for example, the local PTT or the government (in European countries) or the FCC (in the US) act as key decision makers in setting standards and regulations which in turn influence the product's diffusion path, especially in the implementation stage. As such, heterogeneity across countries in the role, influence and power of these central agencies might result in vastly different diffusion patterns. In some, especially small countries, for example, the central decision making unit might decide to fully replace the old technology with a new one at the trial stage, making the implementation and confirmation stages indistinguishable.

To better illustrate this problem, consider Table 1 which illustrates four diffusion scenarios. For Country **C₁**, the implementation and confirmation stages cannot be distinguished in time. In the case of digital-communication switches, for example, countries like Gabon, Gambia, and Jamaica implemented digital technology on an ubiquitous basis within their first year of adoption. Clearly, this type of adoption behavior (100% penetration in the first year) runs counter to the notion that adoption patterns within a social system follow an S-shaped penetration curve in every single country. While some countries reach full penetration at the moment of adoption, others exhibit a diffusion pattern that resembles the familiar S-shaped adoption pattern (e.g. Country **C₂** in Table 1). Using the same working example, this was the case for countries like France, Finland, Hong Kong and the Dominican Republic, which maintained a mixture of digital and analogue telecommunications networks for several years after their initial trial of the newer digital technology. It should be noted that both forms of within country diffusion (i.e. instantaneous versus gradual substitution) can occur for both innovative (early-trial) and laggard (late-adopter) countries, as illustrated by Countries **C₃** and **C₄** in Table 1. Using again the digitization example, Gabon and Gambia went to immediate full substitution in 1987, while the Maldives did so in 1991. As for the gradual substitution, France started the process in 1981, while Israel initiated the process only eight years later. As such, a global diffusion model for technological innovations needs to simultaneously accommodate and explain a wide variety of (continuous and dis-continuous) within-country diffusion patterns, and should capture

variations in both the starting time of the diffusion process and the subsequent diffusion path.

Insert Table 1 about here

Finally, new technological innovations often complement or modify existing ones which themselves have already undergone, or are still undergoing, a diffusion process. Examples include the substitution of analogue telephone switches by digital ones and the evolution of computer standards over time. As illustrated in Norton and Bass (1987, 1992), both diffusion processes are inter-linked, raising questions (1) whether the old technology will be fully replaced by a newer generation, and (2) how the size of the old technology's installed base will affect the speed of diffusion of the new generation? "Full replacement" is a standard assumption of product substitution models, but previous research has failed to provide empirical tests for this assumption. The second issue raised by the literature is related to the size of the installed base. A proper international diffusion model needs to be able to measure the impact of the old technology's installed base on both stages in the international diffusion process.

In this paper, we develop a coupled-hazard model which can incorporate all the above aspects of the global diffusion process of technological innovations. In particular, in addition to being flexible enough to test various research hypotheses, the proposed approach can clearly distinguish between the different stages of the global diffusion process, and quantify the link between them. Furthermore, it can accommodate irregular diffusion patterns by allowing full adoption in the first year for some countries, and gradual adoption in others. Finally, it allows to test if *all* countries will *fully* adopt the new technology, and estimate the impact of the old technology's installed base on the diffusion process of the new technology. In a next step, we illustrate the method using data on the timing of digital telecommunications network implementation (first digital-system installation) and full substitution (all analogue systems being replaced by digital

systems within a given country) across the global marketplace; over 160 countries are considered which are located across all continents: 51 in Africa, 38 in Asia, 37 in the Americas, 27 in Europe and 9 in Oceania.³ In this context, we generate substantive insights with respect to three general factors of theoretical interest for global diffusion: (1) economic, (2) social/demographic, and (3) installed base. In doing so, we identify characteristics that allow researchers/managers to distinguish between countries along Rogers' (1983) "innovator-laggard" continuum and quantify the differential impact of these characteristics on the subsequent speed of diffusion after initial trial.

In what follows, we first present a theoretical framework and related research hypotheses. Next, we present the "coupled-hazard" modeling approach. Throughout the model presentation, we will refer to the digitization of telecommunications services as a working illustration. Following the model discussion, we then turn to the empirical findings. We conclude with caveats and suggestions for future research.

2. THEORETICAL FRAMEWORK

Based on hundreds of studies in various disciplines (e.g. sociology, education, marketing, and economics), Rogers (1983, p. 10) defines diffusion as the adoption of an innovation "over time among the members of a social system". Each individual within the social system is theoretically thought to go through four stages of adoption: awareness, interest/intention, implementation, and confirmation. We seek to extend diffusion theories to explain the implementation and confirmation stages, when diffusion takes place across the different countries of the world, i.e. when the community of nations is the social system of interest. The awareness and interest stages are difficult to directly measure, and may increasingly become invariant across countries due to the emergence of the "information age". Put differently, all countries/governments can be

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³ Countries are defined broadly, in that they also include territories, protectorates or colonies, and United Nations members which are, however, often represented as being sovereign states in international agencies (e.g. the World Health Organization or the International Olympic Committee). These smaller states are generally autonomous, have disputed sovereignty, or are distant from the parent country (e.g. Puerto Rico).

assumed to know of a given innovation shortly after its discovery or invention. In the telecommunications industry, for example, all countries are members of the International Telecommunications Union, which regularly reports the existence of innovations to governments.

2.1. The Implementation Stage

In contrast to previously-published studies which focus on a comparison of within-country Bass-model (1969) diffusion parameters, we first want to understand the forces driving the start of a country's diffusion process, which logically precedes any subsequent comparison of penetration levels. The great variability in the trial time of digital communication systems, for example, is illustrated in Figure 1. The figure shows both the actual number of countries introducing digital technology in a given year, and the number of adopters predicted by the aggregate diffusion model of Easingwood, Mahajan and Muller (1983). The figure displays the familiar bell-shaped diffusion pattern. While it gives a parsimonious description of how fast the innovation will be accepted across the world, it does not help management to understand why certain countries adopt sooner than others. Indeed, the aggregate diffusion model used to make the forecasts ignores cross-country differences and cannot explain why in a given year some countries have a higher probability of adopting than others.

Insert Figure 1 about here

Micro-level models relax this homogeneity assumption, and allow the probability of adoption to be heterogeneous across potential adopters (Chatterjee and Eliashberg 1990; Sinha and Chandrashekar 1992). Moreover, since the unit of analysis is at the individual level, various causal factors which may affect the individual adoption decision can then be included directly into the model and formally tested. In our context, the adopted individual-level hazard model will help classify countries along Rogers' "innovator"/"laggard" spectrum and answer the question: Does the profile of an

innovative country differ from that of a laggard country and, if so, what are the distinguishing features?

2.2. The Confirmation Stage

As indicated by Rogers (1983), the decision to try a new technology is not necessarily the terminal stage in the innovation-decision process. During the confirmation stage, the decision-making unit seeks additional information or experiences the relative performance of the new technology, after which it may decide to accelerate, discontinue, or even reverse the diffusion process. As discussed earlier, this second stage can also be characterized by a substantial amount of variability across countries. Beyond explaining the trial phase of the diffusion process, the coupled-hazard model allows us to simultaneously understand what forces affect the rate at which different countries reach full confirmation, as reflected in full substitution of the old technology by the new one.

2.3. Diffusion Patterns

For most innovations, the adoption process of each country *starts* with the implementation stage, *followed by* the confirmation stage, each taking up finite time. However, for technological innovations, as a result of network externalities and/or the involvement of central decision makers, within-country “diffusion” might be instantaneous and, as such, the confirmation stage of certain countries may have zero duration.⁴ Thus, we can observe two broad adoption patterns. In one, a country first tries the innovation partially, and subsequently reaches full adoption gradually. In the other, the country reaches full adoption immediately at the time of trial.

To describe the underlying dynamics of the resulting diffusion patterns, it is important to realize that, at any given time, each country will be in one of the following three (exhaustive and mutually exclusive) states (see Figure 2): state [0,0], where each

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⁴ The temporal aggregation of the observed penetration level may be another factor contributing to an instantaneous confirmation stage (i.e. the diffusion process within the first interval is not observed).

country starts, and where they stay as long as they have reached neither trial nor full confirmation; state [1,0] when a country has partially adopted the innovation (i.e. when the confirmation stage is still incomplete); and state [1,1] when the innovation has fully replaced the old technology. *Diffusion occurs when countries move from one state to another*, and the movements between the different states are described through three transition rates: r_1 (from state [0,0] to [1,0]), r_2 from [0,0] to [1,1]), and r_3 (from [1,0] to [1,1]). Each of these rates reflects a conceptually different process, and may be driven by different considerations. For instance, the size of the installed base of the old technology may be an important consideration in the decision to fully replace the old technology, thereby affecting r_2 and r_3 , but could be less of a factor in the decision to try the new technology on a limited scale (r_1). Alternatively, for countries in state [1,0], their *own* experience with the new technology may be an important determinant for the speed with which they will achieve full substitution (r_3), while countries in state [0,0] can only rely on *other* countries' experience for their decision whether and when to move to state [1,0] (rate r_1) or [1,1] (rate r_2).

Insert Figure 2 about here

We will therefore frame the different research hypotheses in terms of the three transition rates in Figure 2. The conceptual linkage between the *two diffusion stages* (the implementation and confirmation stages) and the *three transition rates* in Figure 2 is clarified when realizing that for the implementation stage, we are interested in the arrows *leaving* state [0,0], while for the confirmation stage, we focus on the arrows *entering* state [1,1]. As discussed in more detail below, the *overall* trial or implementation rate is then given by the sum of r_1 and r_2 , while the confirmation rate is allowed to exhibit state dependence, in that the rate at which state [1,1] is entered, can vary depending on the state currently occupied by the country, i.e. state [0,0] or state [1,0].

2.4. Research hypotheses

Given the above conceptualization, our goal is to gain insights into how country characteristics affect the three transitions described above: (i) reach partial adoption, (ii) reach immediate full substitution and (iii) reach full substitution after partial trial. To do so, we extend diffusion theory to the global theater by considering **four** theoretical factors: (1) economic, (2) social/demographic, (3) installed-base and (4) **international-experience** factors. While many of our hypotheses (those related to the first two factors) are applicable to innovations in general, some consider special characteristics of technological innovations, as highlighted in the introduction.

Our first hypothesis is related to a country's **wealth**, and is directly derived from the diffusion literature. Rogers (1983) notes that innovators tend to have higher income (i.e. they can afford greater economic sacrifice to adopt the innovation). Translating this idea to an international context, several authors have argued that a society's adoption timing and subsequent diffusion rate are related to its standard of living and stage of economic development (Antonelli 1993; Gatignon and Robertson 1985; Helsen et al. 1993). Indeed, a country's wealth can allow it to take higher risks (especially financial) in order to (partially or fully) adopt a technology. However, as the risks involved in trying the new technology on a limited scale are smaller than when faced with a full-substitution decision, we hypothesize a smaller effect on r_1 than on the other two transition rates. We therefore hypothesize:

H1a: The three transition rates are positively affected by a country's wealth.

H1b: The impact of a country's wealth is more pronounced on r_2 and r_3 than on r_1 .

Our second hypothesis is related to the **heterogeneity** of a country's social system. Diffusion theory predicts that innovations diffuse slower in heterogeneous social systems (Gatignon and Robertson 1985). **In the presence of a central decision-making unit, this effect still holds as such decision-making unit may**

experience some difficulties to “force” *all* social-system members to adopt the innovation. Hence, industry-wide consensus/coordination remains important to promote the confirmation stage. We therefore expect that countries with heterogeneous social systems, where consensus/coordination is harder to obtain, will tend to reach full confirmation later, and hypothesize a negative impact on r_2 and r_3 . In addition, while the implementation (trial) stage depends more on the autonomous decision of the central decision maker (instead of the coordination of all social-system members), the social system might still be able to exert pressure on the central DMU. Again, such pressure is more likely to be effective in the presence of coordination/consensus between social-system members. Thus, social-system heterogeneity may negatively influence country adoption timing too, which would translate in a negative impact on r_1 and r_2 . In their study on the diffusion of cellular telephone systems, Dekimpe et al. (1996) found support for the latter hypothesis: social heterogeneity tends to delay the implementation stage. Given that the role of social-system members is more pronounced in the confirmation stage, we hypothesize that social -system heterogeneity has a stronger effect on r_2 and r_3 than on r_1 . In summary, we formally test the following hypotheses:

H2a: The three transition rates are negatively related to the heterogeneity of the country’s social system.

H2b: The effect of social system heterogeneity is larger on r_2 and r_3 than on r_1 .

Our third hypothesis is related to the *installed base* of the old technology. Different factors are to be considered, such as the cost associated with the replacement of the old technology and network externalities. As the cost of replacing the old technology increases with the size of its installed base (Antonelli 1993), we hypothesize that full adoption (confirmation) of the new technology takes longer for

countries with a large installed base of the old technology, resulting in a hypothesized negative impact on r_2 and r_3 . The second factor, network externalities, may influence both stages of the adoption process. The economics literature on network externalities (e.g. Katz and Shapiro 1985, 1986, 1992; Shy 1996) argues that technologies with large installed bases tend to persist (become standards) even if better alternatives become available (a classic example being the QWERTY keyboard). The reason is that the incentives for an individual to switch are smaller if the majority of other consumers are still using the old technology, and as a result the benefits of the new technology are significantly reduced. Said differently, the full conversion of a larger installed base requires more coordination effort from the adopter population (or the central decision maker involved). As such, we expect this “technological inertia” to negatively affect all three transition rates.⁵ However, since we expect the cost argument to be much more prevalent in the full-substitution decision, we hypothesize the effect of installed base on r_2 and r_3 to be stronger than for r_1 .

H3a: The three transition rates are negatively related to the installed base of the old technology.

H3b: The installed base’s effect is stronger on r_2 and r_3 than on r_1 .

Until now, our hypotheses considered exogenous factors specific to the country. Our next hypothesis considers a factor which is endogenous, and relates to the whole worldwide diffusion process. It describes the effect of the cumulative *international experience* with the technology on a single country’s diffusion process. Cumulative adoption by other countries may affect a single country in a number of ways. First, it represents a large network for the new technology, and to the extent that network externalities operate across consumers located in different countries (as is the case for telecommunications innovations, for example) the size of the international network

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⁵ While we provide a rational based on network externalities for the negative effect of a large installed base on the speed of diffusion, our hypotheses are also in line with the findings of previous empirical research on the diffusion of new product substitutes (see e.g. Norton and Bass 1987, 1992).

helps the adoption process within a country (Arthur 1996).⁶ It also provides increased incentives for a country that has not yet adopted the innovation to do so. Beyond network externalities, adoption by other countries also represents increased experience from which an individual country can benefit. For later adopters, the uncertainty associated with the new technology's relative advantage is significantly reduced. Furthermore, as the total number of worldwide adopters increases, better management methods and equipment may be available to allow for a "smooth" and less risky transition to the new technology. As such, we expect that later adopters can "free ride" on the experience of earlier adopters with the new technology. Finally, traditional word of mouth processes and peer pressure by other adopting members **may** also operate across countries (Mahajan and Muller 1994; Putsis et al. 1997), and this again promotes both stages of the diffusion process in a single country. Since we expect the cumulative international experience to increase over time, the above effects also mean that countries adopting the innovation later will experience faster within-country diffusion. In their study on the diffusion of consumer durables in the Pacific Rim, Takada and Jain (1991) found that lagged adoption leads to an accelerated subsequent diffusion, a finding confirmed for other countries and product categories by Ganesh et. al. (1996, 1997). Formally:

H4a: The three transition rates are positively related to the cumulative international experience with the technology.

H4b: The trial time of a country has a positive effect on r_3 .

Our next hypothesis is related to the effect of a country's **own experience** with the innovation, for which the total number of adopters within the country is a natural measure. As indicated before, this hypothesis only applies to countries which have

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⁶ In the context of digital telecommunication networks, the new technology allows for higher quality communications and the introduction of new services. In telephony, for example, a digital network substantially increases the quality of many Internet services. As the pool of countries with high quality networks grows, the remaining countries (or regions in a country) benefit more from joining the network.

reached state $[1,0]$, and hence, only affects rate r_3 .

H5: The transition rate r_3 is positively affected by the country's own experience with the technology.

The next section develops a formal statistical model to test the hypotheses outlined above.

3. EMPIRICAL MODEL DEVELOPMENT

We model the time-until-trial and time-until-confirmation through two interdependent failure-time processes, which each have two states: 0 (reflecting, respectively, that no trial has been initiated, or that no confirmation has been reached yet) and 1 (when trial has been initiated for the trial process, or when full substitution has been reached for the confirmation process).

The joint evolution of both processes is modeled through the coupled approach described in Petersen (1995) and Tuma and Hannan (1984, Chapter 9). Conceptually, a bivariate system of dichotomous states results in four possible “coupled” states: $[0,0]$ reflecting the state countries are in when they have not yet initiated trial nor reached full substitution; $[1,0]$, in case of trial without confirmation; $[0,1]$ when full confirmation is reached without trial⁷; and $[1,1]$ when both trial and confirmation have been reached. The dynamics within the system are fully described by the instantaneous transition or hazard rates between the different states, as illustrated by the different arrows in Figure 3.

Insert Figure 3 about here

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⁷ Obviously, this state can never materialize. We will elaborate later on the simplifications arising from conceptually impossible states and/or transitions.

As shown in Figure 3, the number of rates in the general case equals 12 (i.e. $J (J- 1)$, with J the number of coupled states), whose estimation may prove problematic in a global diffusion context, as the sample size for each individual process will be determined by the number of countries (< 200) on which data are available. Fortunately, not all states can be obtained from certain states, which results in the restriction of multiple transition rates to zero (Blossfeld and Hamerle 1989). These restricted transition rates are represented by a “dashed” arrow in Figure 3. For instance, confirmation cannot be reached before trial, resulting in a restriction on the transition rate from state 1 to state 4. Moreover, we never observe a discontinuance of the diffusion process (i.e. that a country rejects the innovation after having tried it), implying that all rates entering state 1 can be set to zero (Petersen 1995). Because of these intricacies of the considered global diffusion process, Figure 3 reduces to Figure 2, in which only the three instantaneous transition rates discussed earlier remain to be estimated. These rates are represented by full arrows in Figure 3, and denoted (as before) by r_1 , r_2 and r_3 . One of these transition rates, r_2 , models explicitly the possibility that some countries replace their entire installed base of the “old” technology at once, and therefore obtain a 100% penetration in their first adoption period.

Obviously, upon arrival of the new technology (i.e. at time t_0), all countries occupy state 1, i.e. the $[0,0]$ state. Depending on the observed transitions during the observation window $[t_0, t_{\text{end}}]$, four scenarios can be distinguished, which will result in different contributions to the likelihood function.

Scenario A: No trial nor full confirmation is obtained, which implies that the country is still in state $[0,0]$ at the end of the observation period. As shown in Vilcassim & Jain (1991) and Petersen (1995), this results in the following contribution to the likelihood function:

$$L_A = [\exp \{- \int_{t_0}^{t_{\text{end}}} r_1(\tau) d\tau\}] [\exp \{- \int_{t_0}^{t_{\text{end}}} r_2(\tau) d\tau\}] = \exp \{- \int_{t_0}^{t_{\text{end}}} [r_1(\tau) + r_2(\tau)] d\tau\} \quad [1]$$

The first term in this expression captures that no transition has occurred from state [0,0] to state [1,0], while the second term precludes an observed transition from state [0,0] to state [1,1]. $r_1 + r_2$ gives the overall exit rate from state [0,0], i.e. the overall trial rate, while r_1 and r_2 are defined as type-specific hazard (exit) rates (Kalbfleisch and Prentice 1980):

$$r_j = \lim_{\Delta t \rightarrow 0} \frac{P(t \leq T_{trial} < t + \Delta t, J = j | T_{trial} \geq t)}{\Delta t}, j = 1, 2 \quad [2]$$

which are defined conditional on *neither* event (exit to [1,0] or exit to [1,1]) happening up to t .

Scenario B: At time t^* ($< t_{end}$), a transition to state [1,1] is observed, implying that a country has reached an instantaneous full confirmation during the observation period. Under this scenario, the following contribution to the likelihood function is obtained:

$$L_B = [r_2(t^*) \exp\{-\int_{t_0}^{t^*} r_2(\tau) d\tau\}] [\exp\{-\int_{t_0}^{t^*} r_1(\tau) d\tau\}] \quad [3]$$

The first term indicates that at time t^* , a transition is observed from state [0,0] to state [1,1] (cf. Vilcassim & Jain 1991; Kalbfleisch and Prentice 1980; Petersen 1995). The second term, on the other hand, ensures that in this same time span, no transition was observed from state [0,0] to state [1,0].

Scenario C: At time t^* , trial is initiated, but during the observation period, no full substitution is obtained. Using a similar logic, it is easy to show that the corresponding likelihood contribution can be written as:

$$L_C = [r_1(t^*) \exp\{-\int_{t_0}^{t^*} r_1(\tau) d\tau\}] [\exp\{-\int_{t_0}^{t^*} r_2(\tau) d\tau\}] [\exp\{-\int_{t^*}^{t_{end}} r_3(\tau) d\tau\}] \quad [4]$$

The first two terms in Equation [4] are conceptually similar to Equation [3]. The final term, however, ensures that in the interval $[t^*, t_{end}]$, no transition from state [1,0] to state

[1,1] is observed.

Scenario D: Finally, one can consider the case where at time t^* the trial phase is started, while only some time later (i.e. at $t^{**} < t_{\text{end}}$), the confirmation stage is obtained. The corresponding likelihood contribution becomes:

$$L_D = [r_1(t^*) \exp\{-\int_{t_0}^{t^*} r_1(\tau) d\tau\}] [\exp\{-\int_{t_0}^{t^*} r_2(\tau) d\tau\}] [r_3(t^{**}) \exp\{-\int_{t^*}^{t^{**}} r_3(\tau) d\tau\}] \quad [5]$$

Compared to Equation (4), only the last term differs, and now indicates the transition from state [1,0] to state [1,1] at time t^{**} . It should be noted that $r_3(\cdot)$ is defined (i.e. is non-zero) from the arrival in state [1,0] onwards, implying that the duration dependence in $r_3(\cdot)$ is capturing the time since a given country's trial, as opposed to the time since the innovation became available (Tuma and Hannan 1984).

The different scenarios can easily be combined into an overall log-likelihood expression for all N countries by defining four mutually exclusive indicator variables $d_{J,i}$:

$$LL = \sum_{i=1}^N d_{A,i} \ln(L_{A,i}) + d_{B,i} \ln(L_{B,i}) + d_{C,i} \ln(L_{C,i}) + d_{D,i} \ln(L_{D,i}) \quad [6]$$

where $d_{J,i}=1$ if country i falls under scenario J ($J=A,B,C,D$) and zero otherwise.

To test the relevant research hypotheses, one still needs to specify a formal relationship between the transition rates and the covariates of interest:

$$r_{i,1}(t) = r_{0,1}(t) \exp[\beta_1 X_{i,1}(t)] \quad [7a]$$

$$r_{i,2}(t) = r_{0,2}(t) \exp[\beta_2 X_{i,2}(t)] \quad [7b]$$

$$r_{i,3}(t) = r_{0,3}(t) \exp[\beta_3 X_{i,3}(t)] \quad [7c]$$

in which the $X_{i,j}(t)$ -s reflect the values (for country i) of the explanatory variables influencing transition rate j ($j=1,\dots,3$), β_j -s are parameter vectors to be estimated, and the $r_{0,j}(t)$ -s reflect the baseline hazards in the respective transition rates. Since few a priori reasons exist to prefer any particular parametric form (see Levin et al. 1987 or

Trajtenberg and Yizhaki 1989 for a more elaborate discussion), we will implement a variety of distributional specifications, i.e. the exponential (used by Hannan & McDowell 1984), Weibull (used in Chandrashekar and Sinha 1995) and quadratic specification (described in Helsen and Schmittlein 1993). Finally, to describe the time-path of the time-varying covariates, we will adopt the common simplifying assumption that they remain constant *within* a time interval (in our case, a year), but are allowed to change *across* intervals. Under this assumption, the expressions in equations (1)-(5) can be substantially simplified (see e.g. Dekimpe et al. 1998; Gupta 1991 or Vanhuele et al. 1995 for a similar assumption and corresponding derivations). For instance, in case of an exponential baseline, equation (1) becomes:

$$LA = [\exp\{-r_{0,1}B_1(t_{end})\}][\exp\{-r_{0,2}B_2(t_{end})\}], \quad [8]$$

in which

$$B_1(t) = \sum_{j=1}^t \exp\{\beta_1 X_1(j)\}, \quad [9a]$$

$$B_2(t) = \sum_{j=1}^t \exp\{\beta_2 X_2(j)\}, \quad [9b]$$

and in which $r_{0,1}(r_{0,2})$ gives the (constant) baseline hazard. In case of a Weibull or quadratic baseline, the **exp{.}** terms in equations [9a] and [9b] are augmented with, respectively, $[\gamma_1 \ln(j)]$ and $[\gamma_1 (j-1) + \gamma_2 (j^2-1)]$, and $r_{0,1}$ and $r_{0,2}$ then indicate the baseline hazards in the first period.⁸ Similar expressions can be derived for equations [3]-[5], and are available from the authors upon request.

The above specification explicitly captures the dependence between the implementation and confirmation stage. First, the relevant rate of change in the confirmation process (i.e. r_2 versus r_3) is a function of the state of the implementation process (0 or 1). This type of dependency is often referred to as a *state dependency* (see e.g. Petersen 1995). Second, the time of arrival into state [1,0] will be entered as a

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⁸ To ensure the non-negativity of $r_{0,j}$, it will be operationalized as $\exp(\gamma_{0j})$.

covariate to explain variations in r_3 . In doing so, we allow for a so-called *lagged duration dependence* (Flinn and Heckman 1982), in that the length of time until the implementation process stays in state [0,0] may determine the exit rate of the confirmation process out of state [1,0].

Parameter estimates will be obtained through full-information maximum likelihood estimation, i.e. by optimizing the joint likelihood function in Equation [6]. However, this expression is separable, and by appropriately re-defining the censoring dummy's, the three transition rates can be estimated separately using standard hazard-rate procedures (see Petersen 1995 for a more detailed discussion): r_1 when treating the observations in scenario *C & D* as completed, and those in scenarios *A & B* as censored, r_2 when treating the observations in Scenario *B* as completed and all others (i.e. *A, C & D*) as censored, and r_3 by only considering the observations in scenarios *C & D*, and treating the former as censored and the latter as completed. *Hence, while the proposed coupled approach explicitly takes the interdependence between the implementation and confirmation stage into account, standard estimation procedures can still be applied.* Both estimation procedures will be implemented (the joint estimation of Equation [6] and the three separate estimations) as validity check against local optima. In addition, different starting values will be used in each instance to assess whether convergence to the same estimates is obtained.

4. EMPIRICAL STUDY

We now turn to an empirical application of the proposed modeling approach to data collected on the trial and confirmation of digital telephony. While the observed differences across countries in this technology's diffusion patterns may also be affected by a variety of *industry-specific* characteristics, we focus in this study on **four general** factors suggested in the extant literature and described in Section 2: (1) economic, (2) social/demographic, (3) installed base, and **(4) international experience**. We will test these hypotheses using covariates collected on 162 countries.

4.1. Duration Data

Data on the relevant durations were collected from the International Telecommunications Union, a United Nations Agency. The starting point for the time until trial is 1979 for every country, and for those countries (12) which had not yet started the adoption process, the common censoring date was 1993. For the time until full substitution **after partial trial**, both the starting date and the potential censoring date varied across countries. The former variability is caused by differences in the trial time (as discussed before), while the variability in the censoring dates is due to the specific characteristics of the data set. In Egypt, for example, 40% of the telephone network was serviced through digital switches in 1992, but no percentage was available for 1993. As such, the end of the observation period for Egypt was taken to be 1992. For Iceland, on the other hand, the percentage substituted in 1993 (66%) was available, and 1993 was taken to be the censoring point for that country. As such, we take a conservative approach in that for those countries for which a 100% substitution rate is not reported, we censor at the last year for which reliable data are available. In doing so, we take all useful information into account, in that the survival function for those countries reveals that in the time span we observe (which may vary from country to country) no full substitution was reached. The relative frequency of the different scenarios described in Section 3 is given in Table 2, where we also give the relative frequencies of censored and completed observations when estimating the three transition rates separately.

Insert Table 2 about here

4.2 Operationalization of the variables

Following Antonelli (1993) and Helsen et al. (1993), among others, we use GNP per capita (expressed in 0,000 \$) to measure a country's wealth, and use the number

of ethnic groups in the country as a measure of its social system's heterogeneity (see Dekimpe et al. 1998 for a similar operationalization). The size of the installed base of the old technology (in millions of lines) is measured differently in the respective transition rates. For r_1 and r_2 , the size of the telephone network at the end of the preceding period is used. For example, the transition rate in period one (i.e. adoption in 1979) is modeled as a function of the number of telephone lines in 1978, in period 2 as a function of the number of lines in 1979, etc. For the confirmation stage (r_3), on the other hand, the number of lines *not yet serviced* through digital switches is computed in every period. In doing so, we account for the fact that, as the confirmation stage progresses, the remaining installed base of the old network technology gradually becomes smaller. The installed base varied greatly across countries, and showed a highly skewed distribution. To reduce the skew in the data, and to avoid having a small number of extreme observations driving our empirical findings (Hamilton 1992), we took the natural log of the installed base as explanatory variable (see Dekimpe et al. 1997 for a similar practice).⁹ Finally, the time of trial (the extra covariate in r_3 to test **H4b**) is measured relative to 1979, the year the technology became available.

Data on these explanatory variables were collected from Euromonitor Ltd. and the *World Factbook* (Central Intelligence Agency, 1993). One of them, the size of the existing telephone network, is time-varying. All other covariates are treated as time-invariant, i.e. we assume that they did not vary in a systematic fashion over the considered time span. Relevant summary statistics are presented in Table 3, and traditional collinearity tests revealed no serious problems between the time-invariant covariates. Ideally, a multi-item scale should be developed for each of the constructs discussed in the theory section. However, as applied international researchers are well aware of, it is very difficult to find globally representative proxies for over 160 countries.

Insert Table 3 about here

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⁹ Similar substantive findings (sign & significance) were obtained when using other skewness-reducing transformations (e.g. the square root), or when working with the untransformed observations.

There are a number of options to operationalize the time-varying construct “cumulative international experience”. We implement three operationalizations. First, as argued in Helsen and Schmittlein (1993), we can operationalize it with the passage of time. In this context, the positive effect of experience on the process is reflected in an increasing base transition rate. For r_3 , the baseline hazard captures the *additional* experience *since arrival* into state [1,0]. However, the extent of international experience *upon arrival* in state [1,0] will be larger for laggards than for early adopters, and therefore, in **H4b**, we hypothesized an additional positive impact on r_3 of the year of trial, implying that countries which try the innovation later will reach full confirmation sooner. A second operationalization of the international experience effect uses the total number of countries that have already tried the technological innovation. This operationalization is in line with the inter-firm diffusion literature (see e.g. Ganesh & Kumar 1996), and measures each country’s adoption as a dichotomous variable (i.e. has or has not adopted, but does not yet take into account the extent of the adoption). Finally, one could also use the total number of innovations (e.g. digital switches) adopted in the world. This approach is consistent with the learning measures proposed by Mahajan and Muller (1994) and Putsis et al. (1997), among others. In this case, the influence of the different countries is not uniform, but weighted by their own accumulated experience.¹⁰

4.3. Analysis

Parameter estimates for the respective transition rates are given in Table 4a. In this table, we operationalize the international-experience effect through the (Weibull) baseline specification (cf. Helsen and Schmittlein 1993). The slope coefficient of the Weibull baseline (i.e. γ_1) is positive and significant in each of the three transition rates,

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¹⁰ Clearly, the three measures (which are all time-varying) will to some extent be correlated, so we cannot include them simultaneously in the model. Hence, when using the second (number of countries adopted) and third (number of lines already replaced) operationalization, we will use the exponential model as baseline specification.

thereby supporting **H4a**. The upward pattern in r_3 supports the notion that the experience (own + others') gained *after* arriving into state [1,0] positively affects the subsequent substitution rate. However, in **H4b**, we also postulated that the time of entry in state [1,0] impacts this transition rate, as later entrants benefit from more accumulated *prior* experience. This hypothesis was also supported by the data, as evidenced by the positive and significant coefficient of the time-of-trial variable, thereby confirming previous research findings by Takada and Jain (1991) and Ganesh and Kumar (1996).

Insert Table 4a about here

We now turn to the other factors which stand to cross-sectionally characterize the three transition rates. **H1a** hypothesizes that all three transition rates are faster for wealthier countries. This hypothesis is supported, implying that richer countries are faster to complete the confirmation as *well* as the implementation stage. A likelihood-ratio test on the equality of **its impact on** the three transition rates could not be rejected, however ($LR = 1.914 < \chi^2_{0.90, 2df}$), i.e. **H1b** is not supported.

H2a argues that the ethnic heterogeneity of a country has a negative impact on all three transition rates. Interestingly, this hypothesis was only partially supported. While ethnic heterogeneity had a negative impact on transition rates r_2 and r_3 , confirming the conjecture by Gatignon and Robertson (1985), it did not affect r_1 (**thereby supporting the differential-effects hypothesis H2b**). This confirms our conjecture that social consensus is not as crucial for the trial phase of the diffusion process as for the confirmation phase.

Similar to ethnic heterogeneity, the impact of the old technology's installed base had a strong negative impact on r_2 and r_3 (partially supporting **H3a**) but no impact on r_1 (supporting **H3b**). This result nicely illustrates the phenomenon of "technological inertia" underlined in the literature: even if the innovation is available in the social system, social system members are reluctant to switch to the new technology. Interestingly, the

partial introduction of the new technology does not depend on the size of the installed base.¹¹ <<MIKLOS: we have two one-sided discussion here, in the hypothesis section, we also had the cost issue, which we don't mention here, and which is at least as appealing>>

4.4. Robustness tests

4.4.1. Sensitivity to the parametric specification of the baseline hazard

In the previous section, the Weibull specification was used to capture the time dependence in the different transition rates. While this specification has been used extensively in previous research (see e.g. Chandrashekar and Sinha 1995; Rose and Joskow 1990), it is not a priori obvious that this distributional form is preferable. Moreover, the choice of an incorrect functional specification has been shown to bias the parameter estimates of the covariates of interest (Meyer 1990). We therefore assessed the sensitivity of our findings to the adopted distributional form for the baseline hazard by also estimating a quadratic baseline specification (see Table 4b). The overall fit of the two models was comparable (with the quadratic model slightly favored on the basis of the AIC criterion, and the Weibull model preferred on the basis of the consistent AIC criterion),¹² and *all parameter estimates were robust*.

Insert Table 4b about here

An important conceptual difference between the Weibull and quadratic specification deals with the potential deficiency of the latter. Indeed, while the Weibull model assumes (imposes) that eventually *all* countries will *fully* substitute the new

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¹¹ This again, might suggest that the central decision makers act somewhat independently from the social system (which nicely illustrates the conceptual difference between the two stages of the diffusion process). In the case of technological innovations, "inertia" could prevent the introduction of innovations. Through regulation, a central decision maker can promote the introduction of the new technology in spite of **the** social system members' **inertia**.

¹² See Wedel and Kamakura (1998, p. 90) for definitions of the AIC & CAIC criteria.

technology (as the survivor function converges to zero for large t), the quadratic specification allows for some countries to either never try the new technology (when the quadratic term in the baseline specification in $r_1 + r_2$ is negative and significant) or to never reach full substitution (when the quadratic term in r_3 is negative and significant).¹³ Our estimation results in Table 4b suggest that eventually all countries will try the new technology (confirming the “Weibull assumption”), but that some of the countries which have reached state [1,0] may not move to state [1,1]. The closeness in fit between both parametric forms for the baseline hazard makes it hard to prefer either one, however, and leads us to interpret the latter finding with some caution (see, however, also Section 4.4.4 below).

4.4.2. Sensitivity to the operationalization of “international experience”

In Tables 4a and 4b, we operationalized the international experience effect through an increasing baseline hazard in the respective transition rates. As a further validation check, we implemented the two other operationalizations discussed in Section 4.2: the number of countries which have adopted the new technology and the number of lines which have been switched.¹⁴ As illustrated in Table 5, in every instance, support for hypothesis **H4a** was still found, as reflected in the significant positive coefficients of the experience coefficients in each of the transition rates. Moreover, the other substantive insights were again comparable to the ones reported in Table 4a (detailed results are available from the authors upon request).¹⁵ When incorporating as separate covariates into r_3 the cumulative number of *foreign* lines already switched and the cumulative number of *own* lines already substituted, the latter coefficient was found to be positive and significant, thereby providing support for hypothesis **H5**.

¹³ See e.g. Helsen and Schmittlein (1993, footnote 14) or Lancaster (1990) for discussions on the deficiency of distributions.

¹⁴ As indicated before, to avoid multi-collinearity problems between the different time-varying covariates we incorporated these other measures of international experience in a model with an exponential baseline hazard. Similarly, both new operationalizations were implemented one at a time.

¹⁵ The only difference being that GNP/capita was no longer significant in r_1 (both new operationalizations) and r_2 (when working with the number of lines switched), even though the signs remained positive.

Insert Table 5 about here

4.4.3. *Can decreasing prices explain the increasing baseline hazard?*

An alternative hypothesis for the increasing baseline hazard in Tables 4a and 4b could be a decreasing price trend for the digital switches, as is often the case for technological innovations. We did not have price data over time for the different countries in our data set, but collected monthly (**inflation adjusted**) US price data for the period Jan. 1986-Dec. 1993. A deterministic trend regression on these data did not reveal a negative price evolution, however [$\beta_{\text{trend}} = +0.03$; $t_{\text{trend}} = 3.26$].

4.4.4. *Relaxation of the full-substitution requirement*

Thus far, we defined confirmation as a 100% substitution rate, which clearly is a fairly stringent criterion. One could also consider the time needed to reach 90 % substitution, which corresponds to the take-over time in Fisher and Pry's (1971) specification. This less stringent definition of confirmation resulted in more observations falling under scenarios *B* & *D*, as described in Panel B of Table 2, and hence, in more completed observations in the estimation of the respective transition rates. Overall, the same substantive conclusions were obtained (see Table 6): (1) richer countries are more innovative, (2) heterogeneity in the social system delays confirmation, (3) the size of the installed base affects the speed of obtaining full confirmation but not the time of trial, (4) cumulative international experience matters for all three transition rates, and (5) later adopters reach full substitution later. The only difference observed was in rate r_3 , where the GNP/capita variable, while still positive, was no longer significant. Finally, the results in Table 6 also provide additional insights into the question whether all countries will eventually reach the confirmation stage. In this case, both the Weibull (by definition) and the quadratic specification (since none of the quadratic terms is significant) indicate that eventually all countries will reach 90% substitution. If one is willing to assume that in the long run, they will also manage to substitute the remaining

10%, the conclusion from the Weibull specification (Table 4a) would be favored over the quadratic specification (Table 4b).

Insert Table 6 about here

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5. Summary and Extensions

Diffusion processes result in the acceptance or penetration of a new idea, behavior or physical innovation over time by a given social system. In a global context, when the “social system” is the community of nations, we theorize that cross-country diffusion takes place in two distinct, although related, phases: the implementation or trial stage and the confirmation stage. This paper proposed a coupled-hazard approach to model this process, and tested research hypotheses generated from the extant literature. Our objective was to understand the diffusion dynamics of a special product category, technological innovations, which requires that diffusion theory and the resulting models be adapted to take into account the effects of network externalities, such as the potential for a non-S-shaped diffusion pattern within some countries (e.g. due to immediate full substitution), and the considerable impact of the old technology’s installed base.

Our empirical results provide interesting theoretical insights and have important managerial implications. First, we find strong international contagion effects: the more countries that have adopted, or the longer the international experience the world has with an innovation, the higher the chances that other countries will also implement the innovation. For the empirical case studied (digital telephony) we also find that innovative countries are wealthier (consistent with Gatignon and Robertson's (1985) observation at the individual level for consumer goods). We also find that countries with homogeneous social systems reach full confirmation faster (as hypothesized by Gatignon and Robertson, 1985), and that laggard countries have faster within-country

diffusion rates (consistent with Takada and Jain 1991). For the rates describing transitions to full substitution (i.e. r_2 and r_3), our data provide strong evidence for a negative installed-base effect. <<Miklos: I took out your extra sentence; again, we cannot only talk about inertia, there is also the cost story>>

Our empirical findings are based on the observed diffusion process of one high-technology industrial product. Still, our modeling approach is general, and with minor modifications it is applicable to the global diffusion of all product innovations. For instance, the globalization process may be the result of what Rogers (1983) calls a *centralized* process whereby the firm (i.e. the change agent) systematically determines where the innovation should be sold next. In other instances, as in this particular application, diffusion is of a *decentralized* nature where the manufacturers themselves do not determine when sales will begin in a specific country, but where foreign governments determine (even though the firms may try to influence that decision) from what point the innovation is, respectively, implemented or fully confirmed. This decentralized nature of the diffusion process is reflected in our choice of covariates, in that they describe characteristics of the countries, rather than that of the technology providers like Alcatel, AT&T, Ericsson, or Siemens.¹⁶ Future research which considers centralized diffusion processes, using the modeling approach presented, may find support for some of the hypotheses presented and lead, therefore, to greater insights into globalization patterns.

On a more technical level, several extensions to the proposed coupled approach could be envisioned. First, we modeled the interdependence between the implementation and confirmation process by means of a *state dependency* (Petersen 1995), i.e. the relevant rate of change in the confirmation process (r_2 versus r_3) was a function of the state of the implementation process (0 or 1). In addition, the rate of full substitution after partial trial (i.e. r_3) was modeled as an explicit function of the time of

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¹⁶ It should be noted that decentralized processes are likely to exist for a wide variety of product categories such as medical products, telecommunications services, energy-supply systems, electronic products which must meet local type approval, cosmetics, or any other packaged consumer goods which require government approval or face non-tariff barriers.

trial, reflecting what Flinn and Heckman (1982) call a lagged duration dependence. In contrast, one could also consider to model the interdependence between both processes as *rate* dependencies, i.e. model the confirmation rate as a function of the implementation rate (and/or vice versa). This would result in a simultaneous or recursive system of hazard rates, as recently explored by Lillard (1993). A third way of modeling the interdependence between the relevant durations would be to combine the respective univariate distributions into a correlated multivariate distribution, as illustrated for the bivariate case in Chintagunta and Haldar (1998). More research on the relative advantages of the different approaches would be useful, but is beyond the scope of the current research. Second, our framework only allowed for interdependence through the observed covariates. No correction for unobserved heterogeneity, possibly correlated across the tree transition rates, was made. A useful extension may be to add such a correction to the proposed model. Finally, we did not allow for a reversal of the diffusion process. While this phenomenon did not occur for the technology at hand, it might well occur for other innovations. The coupled approach given in Figure 3 could still be used in those instances (see e.g. Petersen 1995 or Tuma and Hannan 1984 for a more elaborate discussion), even though Figure 3 would no longer reduce to the simpler Figure 2, and more intricate likelihood expressions would have to be optimized.

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Table 1: Adoption Timing of the New Technology; An Example

Country	t_1	t_2	t_3	t_4
C_1	0	100	100	100
C_2	10	20	40	80
C_3	100	100	100	100
C_4	0	0	10	20

Note: Figures indicate the % of the old technology replaced by the new one. A non-zero number indicates trial (implementation), while full-adoption (confirmation) is reflected by 100%.

Table 2: Number of Observations in Different Scenarios**A. Confirmation = 100 % substitution**

Joint estimation		Separate estimation of the different transition rates		
Scenario A	12	<u>Trans. rate r_1</u>	<u>Trans. rate r_2</u>	<u>Trans. rate r_3</u>
Scenario B	17	Completed: 133 Censored: 29	Completed: 17 Censored: 145	Completed: 10 Censored: 123
Scenario C	123			
Scenario D	10			
Total	162	Total: 162	Total: 162	Total: 133

B. Confirmation = 90 % substitution

Joint estimation		Separate estimation of the different transition rates		
Scenario A	12	<u>Trans. rate r_1</u>	<u>Trans. rate r_2</u>	<u>Trans. rate r_3</u>
Scenario B	23	Completed: 127 Censored: 35	Completed: 23 Censored: 139	Completed: 18 Censored: 109
Scenario C	109			
Scenario D	18			
Total	162	Total: 162	Total: 162	Total: 127

Table 3: Summary Statistics

Covariate (N=162)	Mean	STDV	Minimum	Maximum
GNP/capita (0,000\$)	0.438	0.655	0.007	3.030
Number of ethnic groups	5.1	2.6	1.0	15.0
Number of analogue lines in 1978 (000,000) ^a	1.807	8.726	0.0003	99.449
Year of implementation ^b				
- Scenarios B, C, D (N=150)	1988.2	3.026	1980	1993
- Scenarios C, D (N=133)	1987.9	3.049	1980	1993

Notes: ^a: Summary statistics are given for the year preceding the year of introduction. In the hazard specification, the covariate is included as time-varying.

^b: Summary statistics are based on countries which have completed the implementation stage.

Table 4a: Parameter Estimates: Weibull Baseline

	Transition rate 1: State [0,0] → [1,0]	Transition rate 2: State [0,0] → [1,1]	Transition rate 3: State [1,0] → [1,1]
γ_0	-6.93 ^c	-19.24 ^c	-15.99 ^c
γ_1	2.33 ^a	6.19 ^a	3.28 ^a
GNP/capita	0.26 ^a	1.07 ^b	0.83 ^b
Ethnic Heterogeneity	-0.00	-0.29 ^a	-0.47 ^a
Installed base of old technology	0.19	-0.47 ^a	-0.64 ^a
Time of trial	-	-	0.79 ^a
LL (separate estimation)	-383.98	-61.41	-35.06

Notes: 1. a (b): Significant at $p < 0.05$ (0.1), one-sided tests; c: significant at $p < 0.05$, two-sided test.

2. LL (joint estimation): -480.45 [AIC = 992.90; CAIC = 1042.40].

Table 4b: Parameter Estimates: Quadratic Baseline

	Transition rate 1: State [0,0] → [1,0]	Transition rate 2: State [0,0] → [1,1]	Transition rate 3: State [1,0] → [1,1]
γ_0	-4.90 ^c	-19.60 ^c	-16.36 ^c
γ_1	0.46 ^a	2.59 ^a	2.98 ^a
γ_2	-0.01	-0.09	-0.24 ^c
GNP/capita	0.27 ^a	1.05 ^b	1.02 ^a
Ethnic Heterogeneity	-0.00	-0.28 ^a	-0.48 ^a
Installed base of old technology	0.20	-0.48 ^a	-0.73 ^a
Time of trial	-	-	0.73 ^a
LL (separate estimation)	-382.20	-60.80	-33.66

Notes: 1. a (b): Significant at $p < 0.05$ (0.1), one-sided tests; c: significant at $p < 0.05$, two-sided test.

2. LL (joint estimation): -476.66 [AIC=991.32; CAIC=1050.10]

Table 5: Other Operationalizations of the Experience Effect

	Transition rate 1: State [0,0]→[1,0]	Transition rate 2: State [0,0]→[1,1]	Transition rate 3: State [1,0]→[1,1]
Cum. # of countries which tried at $t-1$	0.022 ^a	0.038 ^a	0.033 ^a
Cum. # of lines switched at $t-1$ (000,000)	0.009 ^a	0.016 ^a	0.012 ^a

Notes: 1. a: significant at $p < 0.05$ (one-sided test).

2. $LL = -496.43$ (operationalization 1); -511.20 (operationalization 2).

Table 6: Parameter Estimates: 90 % Substitution

	Transition rate 1		Transition rate 2		Transition rate 3	
	Weibull	Quadratic	Weibull	Quadratic	Weibull	Quadratic
γ_0	-6.79 ^c	-4.86 ^c	-17.71 ^c	-16.08 ^c	-11.93 ^c	-11.29 ^c
$\gamma_{1,weibull}$	2.25 ^a	-	5.82 ^a	-	2.80 ^a	-
$\gamma_{1,qua}$	-	0.45 ^a	-	2.04 ^a	-	0.79 ^a
$\gamma_{2,qua}$	-	-0.01	-	-0.07	-	-0.01
GNP/capita	0.23 ^b	0.24 ^b	1.00 ^a	0.99 ^a	0.35	0.29
Ethnic Hetero.	0.00	0.00	-0.25 ^a	-0.24 ^a	-0.11	-0.12 ^b
Installed base	0.21	0.21	-0.36 ^a	-0.37 ^a	-0.34 ^a	-0.35 ^a
Time of Trial	-	-	-	-	0.49 ^a	0.57 ^a

Notes: 1. a (b): Significant at $p < 0.05$ (0.1); c: significant at $p < 0.05$, two sided test.

2. LL (joint estimation): Weibull: -522.20; Quadratic: -520.14.

Figure 1: Variability in Trial Time

Note: Predicted values are based on the aggregate diffusion model of Easingwood, Mahajan and Muller (1983)

Figure 2: A Model of Global Diffusion as a Reduced Coupled System

Note: Digits in parenthesis represent the completion (1) or non-completion (0) of the implementation and confirmation stages respectively.
For example, [1, 0] means that the implementation phase is complete while the confirmation phase is incomplete.

Figure 3: The General Coupled System With Four States

Note: Digits in parenthesis represent the completion (1) or non-completion (0) of the implementation and confirmation stages respectively.
For example, [1, 0] means that the implementation phase is complete while the confirmation phase is incomplete.