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# Strategic Adoption of a New Technology under Uncertain Implementation

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Montréal
Décembre 1997

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**ISSN 1198-8177**

# Strategic Adoption of a New Technology under Uncertain Implementation*

*Marcel Boyer*†, *Séverine Clamens*‡

**Résumé / Abstract**

Les entreprises américaines investiront en 1997 quelque 50 milliards de $ dans des projets de réingénierie dont les deux-tiers s'avéreront, semble-t-il, des échecs, à cause principalement de la résistance au changement et du manque de concensus et d'engagement de la part des hauts dirigeants. Or, notre connaissance des différences stratégiques entre l'adoption d'une nouvelle technologie et son implantation réussie reste fort limitée. Nous inspirant d'un modèle proposé par Stenbacka et Tombak (1994), nous considérons les effets de divers facteurs sur les dates d'adoption de la nouvelle technologie choisies par les doupoleurs, tels de meilleurs programmes d'implantation, des gains relatifs plus élevés d'adopter en premier (et en second), et des coûts d'investissements à l'adoption plus faibles.

*American corporations will spend some $50 billion US in 1997 on reengineering projets. It is believed that two thirds of these efforts will end up in failure because of significant resistance to change and a lack of concensus and commitment among senior executives. Very little effort has been exerted to foster our understanding of the strategic differences between adopting and implementing a new technology. Building on a model first proposed by Stenbacka and Tombak (1994), we show how the adoption timing decisions in a sequential duopoly structure are affected by more efficient implementation programs, higher relative gains of being the first (and second) to successfully implement the technology, and lower relative investment costs of adopting the new technology.*

**Mots Clés :** Adoption de technologie, implantation, duopole

**Keywords :** Technology adoption, implementation, duopoly

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We would like to thank participants in the Econometric Society meetings in Pasadena and Hong Kong for discussions and comments. We remain of course solely responsible for the content of this paper. Financial support from FCAR (Québec) and SSHRC (Canada) is gratefully acknowledged.

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## 1 Introduction

It is expected that in 1997, American corporations will spend some 50 billion US$ on reengineering projects with 80% of that figure going into information systems. More than two thirds of those efforts are likely to end up in failure, according to the most prominent reengineering guru Michael Hammer.[1] According to a survey by Arthur D. Little Inc.,[1] only 16% of executives say that they are fully satisfied with the results of their reengineering efforts while 39% said they were totally dissatisfied. Finally, according to a survey of 400 Canadian and American firms by Deloitte and Touche,[1] the main reasons for reengineering failures seem to be the significant resistance to change and the lack of consensus and commitment among senior executives. This state of affairs has led many gurus, both individuals and firms, to propose new buzzwords and reengineering procedures such as "organizational agility" and "value engineering", focusing more on growth potential than on cutting costs through different downsizing variants.[2]

These developments suggest that a fundamental difference exists between adopting a new technology and successfully implementing it. They stress vividly the significant risks and uncertainties in the transformation process from one technology to another. Clearly, inventions and innovations are quite unpredictable and, once available, their adoption and implementation are even more intrinsically risky or uncertain and unpredictable. The fact that many economists consider the processes of selecting, adopting and implementing inventions and innovations, both technological and organizational, as the main engines of economic growth, makes the above observations even more interesting though troublesome. Numerous examples abound to illustrate the difficulty in recognizing the value of inventions [*The Economist*, 1994.06.18]. Consider for example the case of the laser which, besides its uses in measurement, navigation, chemistry, music, surgery and printing, is revolutionizing together with fiber optics the telecommunications industry. Yet, after its invention at Bell Labs, it wasn't at first considered by lawyers to be valuable enough for the telephone industry to warrant even a patent application. Similar stories exist for other major inventions such as the telephone, the radio and the transistor. Western Union turned down the possibility of buying for a cheap price Bell's 1876 telephone patent considering that its long-term interest was to concentrate on the market for telegraphy, its

[1] *Information Week*, 1994.06.22. The figure for 1997 is a prediction made at the time by Computer Economics Inc. and published in its newsletter *Systems Reengineering Economics*.

[2] *Wall Street Journal*, 1996.11.26.

core activity and market. Marconi thought that his invention of radio would be useful only where wire communication was impossible such as in ship to ship or ship to shore communications (a journalist even suggested that its main and possibly only use would be to transmit Sunday sermons). IBM considered leaving the computer business in 1949 because it estimated that the world market for computer would level off at around 15 units. The inventor of the transistor thought that his invention might possibly be useful in improving hearing aids. There is an even larger number of examples where the difficulties in implementing a previously chosen invention, innovation and more generally a previously chosen technology have been misunderstood or miscalculated. All the above examples are in some sense examples of the difficulty of predicting future technological progress, an umbrella concept which must be understood as covering both the adoption (or diffusion) and the implementation of both inventions and innovations in both techniques and organizations.

Remarkably, only very little effort has been exerted to foster our understanding of the (strategic) differences between adopting and implementing a new technology and of the theoretical and practical implications of these differences. This paper is a small step in that direction. The risks and uncertainties involved in the transformation process from one technology to another are different from and come in addition to the output uncertainty that economists have studied. The most relevant and directly related paper is that of Stenbacka and Tombak (1994); we will adopt in fact their basic model which we will review later. There are two strands of the economic literature which are relevant for our research program. One deals with the decisions of firms regarding the adoption of new technologies. In that strand, we will discuss Weiss (1994), Wozniak (1993), Saha, Love and Schwart (1994), Parente (1994) and Riordan (1992). The other relevant strand of the literature can be somewhat more loosely defined as regrouping the contributions to organizational inertia dealing with the existence of significant resistance to change in organizations. As we mentioned earlier, such resistance factors are basic elements of the adoption process and may indeed be the factors which stands between the decision to adopt and the successful implementation of the newly adopted technologies.

Some have advocated also that cultural differences and in particular the human-machine or human-technology relationships as another possible source of problems at the implementation stage. Because of deep rooted unobservable differences in human perceptions, values and related attitudes across societies, populations and organizations, it may be difficult to predict how a new technology will be met in any given organization. Indeed, a new technology or a new organizational form may very well be more successfully implemented (or accepted) in different sectors, plants or national subsidiaries of a given global firm. We will not cover this third group of factors which may influence the fundamental distinction we make here between adopting and successfully implementing a new technology. Suffice it to mention that they may be part of the answer to the questions we raise here.

We use the theoretical construct of Stenbacka and Tombak (1994) whose model fits our objectives. However our results on the adoption timing decision process are different and even sometimes strictly in opposition to theirs. Our paper is organized as follows. We review in the next section some significant contributions to the analysis of the adoption process and to the analysis of the resistance to change. We then proceed with the presentation of Stenbacka and Tombak (1994) model. In section 4, we characterize the open loop equilibria and in section 5, we present comparative statics results which are informative on the adoption and implementation processes and at times somewhat striking. Concluding comments are gathered in section 6.

# 2 The relevant contributions

## 2.1 The literature on the adoption decision

Weiss (1994) derives some interesting conclusions on a firm's decision to postpone adoption of the current best technology to replace its incumbent technology or to suspend the adoption decision process of the current best technology when improvements are expected in the currently available best practice technology. He observes that the adoption process and the abandonment process are both affected but differently by the expectations of future improvements in the current best technology. He provides empirical evidence from the industry of printed circuit boards, where the incumbent technology is that of "Through-Hole Process (THP)" and the best practice technology is that of "Surface-Mount Technology (SMT)": some 90% of the firms in 1993 were using the incumbent technology. From a purely theoretical point of view, uncertainty in future improvements can inhibit or favor the adoption of current best practice. Weiss demonstrates, by assuming that firms do not have full information regarding the value of future improvements in a technology, that the adoption decision, in light of technological expectations, is more complex than that identified in previous models. He concludes in particular that expectation of early improvements does not always inhibit the adoption decision (non monotonicity). His multinomial logit empirical analysis indicates that firms that perceive greater incremental equipment maintenance benefits to SMT are more likely to adopt and less prone to suspend the adoption process once it has started; firms that anticipate a greater pace of improvements are more prone to suspend the adoption process for the current best practice technology but a greater pace of improvements has no significant effect on the decision to adopt or not; firms which hold more certain expectations of improvements are more prone to adopting but also to suspending the adoption process although the latter effect is not significant; finally, firms that face a higher level of product market competition are less prone to suspending the adoption process but a higher level of product market competition has no significant effect on the decision to adopt. We will consider in this paper a duopoly model of technology adoption and implementation in which a firm' decision to adopt or not depends crucially on its competitor's behavior and on the likelihood of being the first to implement successfully the technology. The characteristics of the technologies will be considered as known and we will assume that the investment cost of adopting the technology decreases over time. Finally, our firms are assumed to be symmetrically informed regarding the riskiness of successfully implementing the technology once adopted.

Wozniak (1993) focuses on innovation adoption and diffusion and on the complementary decision to acquire information on the new technology, a factor which is not unrelated to the concept of implementation we develop in the present paper. He considers the joint decision whether or not to adopt a new technology and invest in technical knowledge to "facilitate faster learning about innovations." Although, in Wozniak's model, the acquisition of information is done before adoption, both decisions are made jointly. Innovations are initially unfamiliar and hence characterized by subjective uncertainty. By learning about the new technology, potential users are able to form better expectations of the profitability of adopting. Considering explicitly the existence of different sources of informations and the strategic positions of the firm (early adopters versus late adopters), he performs an empirical analysis on a sample of Iowa farmers. Two innovations are considered: growth hormone implants and feed additive monensin sodium. Four information sources are considered: talking with personnel from and attending demonstrations or meetings sponsored by either a public or a private information provider. He finds that managers with more education are more likely to adopt new technologies and contact the public source of information than less educated operators and that more educated adopters are more likely to make contact with the public information source than with the information officers of private agricultural firms. More generally, he obtains that the adoption and technical information acquisition decisions are made jointly and that the relative influences of the factors explaining those decisions differ with the timing of adoption and the channel of information dissemination. We will develop a model where the delay between adoption and implementation is stochastic and exogenous or outside the control of firms which differ in their strategic positioning.

Saha, Love and Schwart (1994) stress the fundamental role played by the quality of information on the decision to adopt or not and on the intensity of adoption of a new technology in a context where adoption is divisible and significant risks are present. Recognizing that producers' adoption intensity is conditional on their knowledge on the new technology and on their decision to adopt, they found that larger and more educated operators are likely to adopt more intensively. Their model involves an individual producer's decision to adopt a divisible technology in the presence of risk. They look at factors that could affect adoption and intensity of adoption, and consider the concept of incomplete information dissemination among potential adopters. The objective of their paper is to understand the analytical and empirical implications of this incomplete information in the adoption process. They study the adoption of bST (bovine Somatotropin, a yield-enhancing growth hormone) technology. The approval of this technology by the FDA in November 1993 made milk the first genetically engineered food allowed by the US government. For many observers, this decision opened the gates of the biotechnology age. Saha, Love and Schwart stress that the role of information gathering and learning-by-doing are particularly important in the adoption process of new or emerging technologies. They develop a three-phase model explaining first the information acquisition on the existence of the technology, second the decision to adopt or not and third the intensity of adoption. They used a data set from the Texas dairy industry obtained through a telephone survey conducted a year before the FDA decision, in which the respondents where asked first whether they had heard about bST; and if they did, whether they would adopt it or not if and when the FDA approves it; and if so, what percentage of their herd they would expose to bST. About 84% of respondents were aware of bST and 52% of them said they would adopt it; these adopters (44% of the sample) said that on average that they would expose 43% of their herd to bST. Saha, Love and Schwart found, using a maximum likelihood dichotomous-continuous estimation framework, that education and herd size have a positive and generally significant effect in all three phases (education has only a marginally significant impact in phase 2, the adoption phase); that the decision whether or not to adopt is determined only by the producer's perception of bST-induced yield and adoption costs; that risk attitude and perceptions had no influence on the adoption decision while risk factors did influence the intensity of adoption once the producer has decided to adopt. Finally, plans to expand dairy operations and prior adoption experience (of dairy innovations in the past) have a positive and significant influence on adoption intensity. The diffusion of information on a new technology and the different measures that affect that diffusion could have according to them a positive effect on adoption intensity by reducing the uncertainty associated with the new technology. We will analyze a model of technology adoption where information on the new technology is 'limited' in the sense that implementation of the new technology takes a random length of time once adopted. We will analyze the effect of changes in this random implementation delay on the adoption path of the technology in an industry.

Parente (1994) considers an economy-wide growth model with technology adoption and learning-by-doing in using technologies. At each instant of time, a firm chooses whether to continue to use its current technology or to adopt a more advanced one. The firm gains expertise over time in the use of a technology. Hence, learning-by-doing is specific to the technology and the firm and cannot be (fully) transferred to the new technology adopted. So the firm faces a trade-off in its choice of technologies because the more advanced the new technology is relative to the firm's current technology, the greater its productive potential but the smaller the firm's starting level of expertise in that technology. Parente derives that the firm's optimal decision is to continue to use its current technology until it has accumulated a threshold level of expertise in that technology and then switch to a new one, starting a new round of learning-by-doing. Because the firm's production level is lumpy, he finds that the technology adoption timing decisions of firms and the growth rate of per capita output depend importantly on the efficiency of capital markets. We will consider a simple duopoly model in which the learning-by-doing (implementation) is a 0-1 variable: either the firm has been able to implement the technology or it has not and the time lag necessary to implement a new technology once adopted is stochastic. We do not model the role of capital markets. We are interested in setting up expected payoff exhibiting discontinuous experience effects, but without explicit reference to the quantity decisions.

Riordan (1992) aims at understanding how legal restrictions on competition or preemption do influence the timing of adoption of new technologies. He considers a duopoly where the rival firms that must decide if and when to adopt a new technology, knowing how adoption costs decline over time and how profit flows vary with adoption patterns. He states that price and entry regulations often slow technology adoption by making preemption strategies less attractive and therefore have dynamic efficiency effects in addition to the usual static effects. In his model the firms are not symmetric, adoption by one does not implies adoption by the other and adoption costs may differ. He notices that even if regulations unambiguously slow adoption, the normative significance of this effect is generally ambiguous. Each case must be studied separately. His goal is to delimit contexts in which a lower pace of technology adoption is socially beneficial. In our case, the pattern of profit depend on adoption timings and has important impacts on the relative pace of technology adoption but we do not study explicitly the strategic behavior of the duopolists on the product markets. We use reduced forms of profit functions (levels) which depends on to the relative capacity of firms to compete in product markets and this capacity depends on whether the firm has succeeded in implementing the new technology or not. We consider two identical firms (except that one is stated as the first-mover and the other as the second-mover, in the sense that the first-mover will always adopt the innovation earlier than the second-mover), in an unregulated duopoly with no spillover. The main objective of our paper is to provide new results on the strategic adoption timing decision process in a duopoly in the presence of exogenous technological progress. We consider an infinite horizon duopoly facing uncertainty in the length of time required for successful implementation once the technology is adopted.

## 2.2 The literature on organizational resistance to change

The analysis of inertia in broadly defined organizational contexts is relevant to our objective of better understanding the difference between adopting a new technology and successfully implementing it a firm. We successively consider here contributions on the sources of organizational inertia through the dynamic adjustment costs in investment theory, the role of sticky routines and procedures which are almost by definition difficult to change, the role of multiprincipals in organizational structures in disciplining agents and principals but at the same time preventing smooth adjustments to a changing environment, the role of the rational suppression of potentially valuable informations in contexts of arm length relationships, of the separation of ownership and control and of the existence of strict chains of command in corporations in boosting short term efficiency but a the same time introducing impediments to change, the role of informational cascades in promoting social cohesion and imitation but at the same time making it difficult to trigger or start a movement of change, the role of incentives, usually based on successful completion of tasks, in preventing agents from coming forward with bad news about an impending problem, and finally the role of inertia in providing dynamic incentives in contexts of specific investments and asymmetric information.

The theoretical foundations and empirical grounds for dynamic adjustment costs in investment theory has been a concern of both theorists and practitioners at least since the seminal contributions of Lucas (1967a, 1967b) and Rothchild (1971). Ito (1996) provides us with an institutional perspective into the economic understanding of those costs. He conducts an empirical investigation of investment adjustment costs in mainframe computer investments and shows that those costs are rooted into micro-level dynamics and institutional characteristics of adjustment activities. He derives significant non-convexities in those adjustment costs and obtains that they vary with the presence of "on-line business transaction applications" (order-processing, inventory, accounts payable rules and procedures). New investments in mainframe computing hardware are likely to involve complementary changes in work routines and incentive (information) structures. More interestingly, Ito shows that adjustment costs in mainframe computer investments are not significantly affected by the absence or presence of engineering and programming resources. He claims that those resources may possibly be generally available on external competitive markets and therefore do not constitute a constraint on change. On the contrary, internal organizational routines and business practices impose serious impediments to change and are the sources of significant levels of inertia. In our context, those internal organizational routines and business practices may be an important source of difficulties in implementing successfully a newly adopted technology.

It is important to realize that routines and procedures are rationally chosen and implemented by efficiency seeking firms. Boyer and Robert (1997) suggest that those routines may indeed be rooted in the firm's best response to internal informational asymmetries. Gabel and Sinclair-Desgagné (1996) claim that routines and procedures offer a good compromise between achieving efficiency as consistently as possible and economizing on managerial time spent in repeatedly making decisions. They insist on the ambivalent role of routines inside the firm: "The routines which undoubtedly increase an organization's efficiency also reduce its adaptability to changing circumstances." The fact that many such organizational routines and procedures in different sectors and at different levels in the organization must be interrelated and coordinated through organizational compatibility standards, they will generate a significant level of inertia; changing any one of those routines will be difficult in particular because of the coordination process involved. Indeed, casual observation indicates that those changes are typically infrequent, disruptive and costly. In our context, the adoption of a significantly new technology will typically require a coordinated effort in changing the set of routines in the organization. Hence the importance of distinguishing between adoption and implementation of new technologies.

Dewatripont and Tirole (1996) bring a different perspective on the sources of organizational resistance to change. They consider the pervasive nature of multiprincipal structures in different organizational contexts. These structures can be rationalized as a discipline device inducing agents to exert effort in two particularly important contexts: soft budget constraint and public project cost overruns syndromes. Dewatripont and Tirole observe that a commitment to ex post inefficiency, in the form here of "multiple partisan actors", may be required to obtain efficiency ex ante in an organization. They interpret their results as supporting the usefulness of the ex post inefficient multiplicity of shareholders (investors) in firms and the complementary roles of different government departments (Finance and Treasury together with spending departments such as Education, Health, Transports) as an ex post inefficient supervising mechanism in so far as those government entities are given objectives and missions that "differ from social welfare maximization and furthermore are at odds with each other." Interpreted in the context of adopting and implementing new technologies, these results suggest that the maximization ex ante of the firm's performance may trigger conflicting interests ex post and undermine the successful implementation of a newly adopted technology. To multiprincipal structure which may appear ex ante as the optimal organizational structure will make the necessary coordination of the different principals or interest groups if a new technology is to be implemented in the organization, more difficult to achieve.

A major source of organizational inertia in a corporation takes the form of a rational suppression of potentially valuable informations. Let us consider in such a context the contributions of Crémer (1995), Burkart, Gromb and Panunzi (1996), and that of Friebel and Raith (1996). Crémer (1995) considers the possibility for a principal of monitoring an agent's activities or acquiring information on the performance of an agent and more specifically information on the conditions which may explain the agent's performance. He shows that lowering the cost of monitoring by the principal may in fact hurt her because it reduces her commitment to threats, hence reduces the power of incentives that can credibly be given to him, the agent. Such situations are quite prevalent in corporations. In such situations, the principal will in fact make efforts to credibly convey to the agent that there will be no such monitoring ex post and no acquisition of informations about the conditions which may explain ex post his poor performance. To derive those results, Crémer compares two monitoring technology, a first (efficient) technology which allows the principal to observe, at some cost, whether the agent is truly good or bad and a second (inefficient) technology which allows her to observe only the output level realized by the agent, a random function of the agent's quality. Under the former monitoring technology, the agent is fired at outcome time if and only if he is found to be bad by the principal. Under the latter technology, the agent is fired if and only if output is low. A cost reduction of the first monitoring technology has mixed effects on the principal's welfare: the better information about the quality of the agent must be traded off against the loss of power of the incentives.[3] It is quite likely that new technologies have effects on the relative costs of monitoring technologies. In so far as a new production technology reduces the cost of the above 'efficient' monitoring technology, the implementation stage may clearly suffer from the principal's reduced credibility of commitments to the new technology.

In a related framework, Burkart, Gromb and Panunzi (1996) consider the agency problem and costs that the separation of ownership and control in modern corporations creates for ensuring the pursuit of shareholders' interests by managers. Their insight is that dispersed ownership and the resulting management discretion come with benefits as well. Tight control of managers by shareholders may be ex post efficient but it represents a form of expropriation threat that may reduce not only managerial initiatives but also non contractible investments and in so doing may reduce the profitability of the firm. They show that monitoring and performance-based incentive schemes may have opposite effects in so far as the performance of the relationship is concerned. Friebel and Raith (1996) consider along the same lines the existence of strict chains of command in organizations. If middle managers compete with lower managers for higher management positions, the former may be induced to hire lower quality junior managers in order to secure their promotion to higher positions. The net effect of more competition, which should raise the incentives towards superior performance, combined with lower quality recruiting, which is detrimental to the overall performance of the corporation, may be negative. To prevent this potentially quite damaging negative impact of low quality recruiting, firms have put in place strict chains of command and promotion. Although such strict chains

[3] In a similar vein, Segal and Tadelis (1995) show that it may not be in the interest of the principal to receive an informative signal about the state of the world when renegotiation is possible because the fact that a signal has been observed may reduce the credibility of a commitment by the principal.

of command may be a significant source of organizational inertia, the firms may have to introduce them in order to induce middle managers to hire the best available lower managers. By restricting its use of potentially useful ex post information (competition in promotion), a firm can increase its ex ante probability of higher performance through better quality recruiting. For instance, it has been known for a while that tenure in universities has potentially ambiguous effects on the quality of universities. Once tenured, the faculty may not feel the same pressure to perform in teaching and research. But tenure has also positive effects on the quality of junior faculty recruiting because it protects the tenured (older) faculty against the threats newcomers may represent. The tenured faculty, usually in control of recruiting, are then more likely to recruit the best possible candidates in order to improve the quality of their department which is beneficial to them. In our context, the delegation of authority, that is, the separation of ownership and control in modern corporations, due in part to the existence opposite effects of monitoring and performance-based incentive schemes, together with the existence of strict chains of command, due in part to the negative effects a freer flow of information may have on recruiting and long term profitability, may increase the implementation problems new technologies represent by reducing the flow of information from lower level managers to the principal and by reducing in general the adaptability of the organization to the new technology imperatives.

These results may be considered as different illustrations of Rumelt's (1995) paradoxical assertion that change may require the promise of future inertia and different cases of Dewatripont and Tirole's (1996) result that ex ante efficiency may require a commitment to ex post inefficiency.

Boyer and Robert (1997) have shown more explicitly how the 'optimal' probability of change, when such a change would be implemented under full information, will optimally depend on the parameter structure of the problem at hand and in particular on the relative informational rents of the different participants. Their objectives were "to better understand the unavoidable trade-off between incentives and flexibility in dynamic contexts of asymmetric information, and second to determine the appropriate organizational response to this trade-off." They showed that decision and power structures which have negative effects on the flexibility[4] to implement change in an organization may nevertheless be necessary to maximize the overall performance of the organization. Restated in the context of technology adoption and implementation, their

[4]For a discussion of the different definitions of flexibility in the economic and management literature, see Boyer and Moreaux (1989).

results suggest that more flexibility in adopting and successfully implementing a new technology, which may become necessary because of a changing environment or new information, may come at the expense of efforts exerted up front to make the organization more successful. They identified a clear trade-off in such contexts between *ex ante* efforts and *ex post* flexibility of adaptation. They characterizes also the optimal contract between the principal and the agent, expressed in terms of payment profiles and of relative power of the principal and the agent to recommend and initiate change. Those results suggest that the challenge of successfully implementing a new technology may have deeper rational roots in the organization. The factors which are responsible for a firm's ex ante level of profitability may be the same factors that reduce ex post its flexibility to adopt and successfully implement a new technology.

The literature on fads, customs, fashions and cultural change provide us with a different type of organizational conduct which may lead also to the suppression of valuable information and hence to *inertia*. These fads, customs, fashions and in general cultural factors of change appear as examples of imitation strategies or informational cascades. Those informational cascades, characterized by Bikhchandani, Hirshleifer and Welch (1992), occur when imitation is the best reply function of an individual to the actions of those "ahead" of him. In such contexts, an individual find it optimal to hide his own information to follow instead the behavior of the latter, hence generating observed localized conformity. Bikhchandani, Hirshleifer and Welch (1992) analyze a simple probabilistic model to explain the relatively fast convergence of behavior of different individuals in informational cascades, where information is transmitted only through observed behavior or actions, and the systematic relative brittleness of such behavior. Informational cascades are examples of social learning or dynamic social *inertia*. They develop because observing the past behavior of many individuals reduces the weight of one's specific or private information in determining one's actions. In a similar vein, Moscarini, Ottaviani and Smith (1997) show that only temporary informational cascades can develop when the state of the world changes in a stochastic way. They write: "... social learning induces *inertia* ... During an informational cascade on a single action, the same action persists predictable while the environment changes with positive probability ... This simple model of observational learning can explain why common practice can persist more than it should: agents stick to the practice without possibly knowing in an informational cascade whether others have similar contrary information." In our context of technology adoption and implementation, these results suggest that once a technology is adopted by a firm, its successful implementation, which relies on concerted efforts by many individuals, may be understood as a particular form of an informational cascade. The dependence of such concerted efforts on customs, fashions and cultural characteristics is an important aspect of the implementation challenge.

If a firm wants to develop incentive systems in which its individual members will resist the negative impacts of such informational cascades, it must credibly convince them to reveal their private information and align their behavior on the content of that information rather than on the conduct of others in the organization. In a related context, Levitt and Snyder (1996) consider an organization composed of a principal and an agent where the agent have access to early warnings about impending problems in the organization. They consider a situation where the agent has private information not only on his own effort to make the firm (more precisely the project) more profitable but also on a signal of the likelihood of success of the current project. They show that the principal can entice the agent to reveal truthfully his private signal by making explicit in the incentive scheme the existence of rewards for coming forward with bad news. For instance, the principal must reduce punishment for those who admit failure early rather than follow the crowd in trying to hide bad news through some form of tacit collusion or informational cascade. Levitt and Snyder show that if the information revealed by the agent can be used by the principal to make adjustment decisions (for instance to abandon the project), the principal weakens in so doing, that is, in using the information, the link between the agent's initial effort and the project's outcome. Reducing this direct linkage between effort and outcome reduces the agent's incentives to exert high effort. To induce nevertheless a high effort from the agent, the principal will have to offer a larger expected wage and also credibly commit, if possible, not to cancel some projects with ex post negative expected payoffs, a clear form of inertia. This striking result is due to the fact that the ex post cost of continuing the projects are smaller than the beneficial impact of inducing higher effort ex ante. Again, adopting a new technology and successfully implementing it through a suitable organizational change may be made more difficult and uncertain because of the very same factors which the firm put in place earlier to ensure its profitability and survival.

# 3 The model

This paper deals with strategic timing of adoption of new technologies that exhibit exogenous technological progress in a duopoly over an infinite horizon. Adoption decisions are in general rather irreversible and the acquisition or adoption timing of a new technology is a key element for a firm: an early adoption can imply important expenditures, is usually characterized by considerable uncertainty, and could yield significant competitive advantages.[5] The new technology is exogenous and uncertainty is introduced in the time delay between the adoption date and the implementation date, that is the date at which the technology can be considered as fully functional. Hence, when a firm has adopted the new technology, there exists a probability that this firm will have been able to implement it successfully by a given date. This probability is assumed to be a strictly increasing function of time since the adoption date, so the expected payoff can be interpreted as exhibiting experience effects. The purpose of this paper is to show how this uncertainty influence adoption timing decisions of the duopolists based on a theoretical model first proposed by Stenbacka and Tombak (1994).[6]

We consider a duopoly engaged in a dynamic competition over an infinite horizon. Initially, both firms use the same technology. Then they have access to a new technology and must decide when to adopt it. This new technology will improve their equilibrium profits if and when they can implement it successfully. The equilibrium rates of profit (instantaneous profit levels) are given by: $\pi(x,y)$ with $x \in \{s,u\}$, $y \in \{s,u\}$, where $s$ stands for "successful implementation" and $u$ for "unsuccessful implementation"; the first argument of $\pi$ is related to the firm concerned and the second one to its rival. For example $\pi(s,u)$ is the rate of profit of a firm that has successfully implemented the new technology while its rival has not (possibly because the latter has not adopted the new technology yet) and $\pi(u,s)$ is the rate of profit of a firm that has not successfully implemented the new technology while its rival has. It is assumed that the successful implementation of the new technology yields significant competitive advantages:

$$\text{A1}: \ \pi(s,u) > \pi(s,s) > \pi(u,u) > \pi(u,s) > 0.$$

Furthermore, it is by assumption advantageous to be the first to successfully implement the new technology:

$$\text{A2}: \ \pi(s,u) - \pi(u,u) > \pi(s,s) - \pi(u,s) > 0.$$

Adopting the new technology require an investment cost of $K(t)$, which is decreasing over time but at a decreasing rate:

$$\text{A3}: \ K'(t) < 0, \quad K''(t) > 0.$$

Let us denote by $G_i(t|t \geq T_i)$, the cumulative probability that firm $i$ has

[5] For a model of adoption of flexible manufacturing technologies in strategic contexts in which more flexibility may come at the expense of a reduction in credible commitments, see Boyer and Moreaux (1997).

[6] Stenbacka and Tombak (1994) observe that their model and analysis could be interpreted as a model and analysis of the best time to start a R&D project.

successfully implemented the new technology by time t given that it has adopted it at time $T_i$. It is assumed that $G_i(t|t \geq T_i)$ is increasing with t and, more specifically, follows an exponential distribution:

$$\text{A4}: \; G_i(t|t \geq T_i) = 1 - e^{-\lambda_i (t-T_i)}, \quad 0 < \lambda_i < 1.$$

Note that $1/\lambda_i$ is the expected delay from adoption to successful implementation. It is implicitly assumed that there are no spillover effects since the cumulative probability $G_i$ is independent of the adoption timing of the other firm.

Stenbacka and Tombak (1994) studied both the open-loop equilibrium and the feedback equilibrium. We will concentrate here on the open-loop equilibrium. An *open-loop equilibrium* is the proper equilibrium concept in situations in which firms commit to their adoption timings at the beginning of the planing horizon. Although the terms "leader" and "follower" are used by Stenbacka and Tombak to represent the firm which adopts earlier and the firm which adopts later respectively, those terms do not imply a sequential decision process. A *feedback equilibrium* is the proper equilibrium concept in situations characterized by a "leader" who takes explicitly into account the reaction *function* of the "follower" when deciding when to adopt. It is a concept more appropriate for situations characterized by truly sequential decision making by firms.

# 4 The open-loop equilibrium

We will call the first firm to adopt the new technology the "first-mover" and call the second firm to adopt the new technology the "second-mover" but the reader should be warned that these concepts do not correspond to the similar concepts of leader and follower used for Stackelberg market structures. In an open-loop context, firms choose simultaneously at $t = 0$ their adoption date $T_i$ and commit themselves to those dates. The open-loop equilibrium is a pair of adoption dates $(T_1, T_2)$ such that each firm is satisfied with its own decision given the adoption date of its rival, a Nash equilibrium.

From the above, we can write the expected profits of the firms as:[7]

[7] The equation numbered (1) to (9) correspond to the same equations in Stenbacka and Tombak. Their equation (3), not used here, corresponds to the collusive profit function [the sum of (1) and (2)] and is not relevant for our purpose.

$$
\begin{aligned}
EV_1(T_1,T_2) \quad = \quad & \int_0^{T_1} \pi(u,u)e^{-rt}dt \qquad (1)\\
& + \int_{T_1}^{T_2} [G_1(t)\pi(s,u) + (1-G_1(t))\pi(u,u)]e^{-rt}dt \\
& + \int_{T_2}^{\infty} \Big[ G_1(t)G_2(t)\pi(s,s) + (1-G_1(t))G_2(t)\pi(u,s) \\
& \quad + G_1(t)(1-G_2(t))\pi(s,u) \\
& \quad + (1-G_1(t))(1-G_2(t))\pi(u,u) \Big] e^{-rt}dt \\
& - K(T_1)e^{-rT_1}.
\end{aligned}
$$

$$
\begin{aligned}
EV_2(T_1,T_2) \quad = \quad & \int_0^{T_1} \pi(u,u)e^{-rt}dt \qquad (2)\\
& + \int_{T_1}^{T_2} [G_1(t)\pi(u,s) + (1-G_1(t))\pi(u,u)]e^{-rt}dt \\
& + \int_{T_2}^{\infty} \Big[ G_1(t)G_2(t)\pi(s,s) + (1-G_1(t))G_2(t)\pi(s,u) \\
& \quad + G_1(t)(1-G_2(t))\pi(u,s) \\
& \quad + (1-G_1(t))(1-G_2(t))\pi(u,u) \Big] e^{-rt}dt \\
& - K(T_2)e^{-rT_2}.
\end{aligned}
$$

Maximizing (2) with respect to $T_2$, we obtain the second-mover firm's reaction function (in implicit form) $T_2^*(T_1)$:

$$
\begin{aligned}
& e^{-\lambda_1(T_2^*-T_1)} \tfrac{\lambda_2}{\lambda_2+\lambda_1+r} \left\{ [\pi(s,s) - \pi(u,s)] - [\pi(s,u) - \pi(u,u)] \right\} = \qquad (4)\\
& \tfrac{\lambda_2}{\lambda_2+r}[\pi(s,s) - \pi(u,s)] - rK(T_2^*) + K'(T_2^*)
\end{aligned}
$$

The denominator of the RHS of (4) is negative by A2 and the LHS of (4) is positive; so this implies that the following condition must hold:

$$
rK(T_2^*) - K'(T_2^*) \quad > \quad \frac{\lambda_2}{\lambda_2 + r}[\pi(s,s) - \pi(u,s)] \qquad (5)
$$

Moreover, since $T_2^* \geq T_1$, the RHS of (4) must be less than or equal to one. So we find the following condition:

$$
\begin{aligned}
& rK\left(T_2^*\right) - K^{'}\left(T_2^*\right) \geq \qquad (6)\\
& \tfrac{\lambda_2}{\lambda_2+r} \left\{ \tfrac{\lambda_1}{\lambda_2+\lambda_1+r} \left[\pi\left(s,s\right) - \pi\left(u,s\right)\right] + \tfrac{\lambda_2+r}{\lambda_2+\lambda_1+r} \left[\pi\left(s,u\right) - \pi\left(u,u\right)\right] \right\}
\end{aligned}
$$

Similarly, maximizing (1) with respect to $T_1$, we obtain the first-mover firm's reaction function (in implicit form) $T_1^*(T_2)$:

$$e^{-(\lambda_1+r)(T_2-T_1^*)}\frac{\lambda_1\lambda_2}{(\lambda_1+r)(\lambda_2+\lambda_1+r)}\times \tag{7}$$
$$\{[\pi(s,u)-\pi(u,u)]-[\pi(s,s)-\pi(u,s)]\} =$$
$$\frac{\lambda_1}{\lambda_1+r}[\pi(s,u)-\pi(u,u)]-rK(T_1^*)+K'(T_1^*)$$

The denominator of the RHS of (7) is positive by A2; $T_2 \geq T_1^*$ implies then that the RHS of (7) must be less than or equal to 1. So we have the following condition:

$$\frac{\lambda_1+r}{\lambda_2+\lambda_1+r}[\pi(s,u)-\pi(u,u)]+\frac{\lambda_2}{\lambda_2+\lambda_1+r}[\pi(s,s)-\pi(u,s)] \leq \tag{8}$$
$$\frac{\lambda_1}{\lambda_1+r}\,[rK(T_1^*)+K'(T_1^*)] < [\pi(u,u)-\pi(s,u)]$$

The reaction functions (4) and (7) are downward sloping provided that the second order conditions hold. The adoption timings of the firms are strategic substitutes: an earlier adoption date by one firm reduces the profitability of an early adoption by the other firm. We have FIGURE 1.

INSERT FIGURE 1 HERE

Since $T_2 > T_1$ by definition, only the points under the $45^o$-line are feasible. The points on the $45^o$-line correspond to simultaneous adoption timings.[8]

## 4.1 Comparative Statics: A Critique of Stenbacka and Tombak.

Stenbacka and Tombak were interested in characterizing how the degree of dispersion between the equilibrium timings of the first-mover and the second-mover is affected by the levels of uncertainty and the relative magnitude of the payoffs in different states. From conditions (4) and (7) characterizing an open-loop equilibrium, they derived the following condition for $(T_1^*, T_2^*)$:

$$e^{-r(T_2^*-T_1^*)}\frac{\lambda_2}{\lambda_2+r}\,[\pi(s,s)-\pi(u,s)]-rK(T_2^*)+K'(T_2^*) = \tag{9}$$
$$[\pi(u,u)-\pi(s,u)]+\frac{\lambda_1+r}{\lambda_1}\,[rK(T_1^*)-K'(T_1^*)]$$

[8] It is worth noting here that figure 1 of Stenbacka and Tombak is incorrect. The equilibrium illustrated in their figure 1 is not stable. Stenbacka and Tombak must have mixed the reaction functions. The correct figure, based on analytical arguments and numerical examples, is in fact our FIGURE 1. If we consider $T_1' > T_1^*$, we see that the sequence of adjustment converges to the point $(T_2^*, T_1^*)$, which is the proper open-loop equilibrium.

They studied the variations of uncertainty through the parameters $\lambda_1$ and $\lambda_2$. Their argument goes as follows. An increase in $\lambda_1$ yields an increase in the RHS of this equation (9) which implies a decrease in $T_2^* - T_1^*$. They say that if the RHS increases then the LHS must also increase and because the LHS is decreasing with $T_2^* - T_1^*$, they conclude that $T_2^* - T_1^*$ decreases; and similarly, they claim that an increase in $\lambda_2$ would yield a decrease in $T_2^* - T_1^*$. Stenbacka and Tombak conclude as follows: an increase in $\lambda_1$ would decrease the difference $T_2^* - T_1^*$; an increase in $\lambda_2$ would also decrease $T_2^* - T_1^*$. Therefore, an increase in uncertainty will increase the extent of dispersion in the equilibrium adoption timings.

This line of argument is incorrect because both $T_2^*$ and $T_1^*$ appear in the RHS of (9), so Stenbacka and Tombak cannot conclude the way they did. Their analysis of the effects of variations in $[\pi(s,u) - \pi(u,u)]$ and $[\pi(s,s) - \pi(u,s)]$ is similarly flawed. We will perform the right analysis in section 3.2 below.[9]

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[9] Stenbacka and Tombak consider also the feedback equilibrium. In a feedback equilibrium, the second-mover can react to the adoption timing of the first-mover. So the second-mover's problem remains unchanged. However the first-mover takes the second-mover's reaction function into account when deciding on when to adopt and in so doing acts as a Stackelberg leader. The analysis of the first-mover's decision in a feedback context can be performed by substituting the function $T_2^*(T_1)$ implicitly characterized by (4) for $T_2$ in (1). Since $dT_2/dT_1 < 0$, Stenbacka and Tombak claim that this corresponds graphically to having the first-mover's reaction function in figure 1 shifted to the right, whereas the second-mover's one is unaffected; although this is a rather loose and not very rigorous argument, their result is nevertheless correct. Let us define the reaction functions in this context as $T_2^{**}(T_1)$ and $T_1^{**}(T_2)$. This allows a 'direct' comparison between the feedback timings and the open-loop timings. So they find the new first order condition for the first-mover:

$$\begin{aligned}
&\frac{\lambda_1}{\lambda_1 + r}[\pi(u,u) - \pi(s,u)] + \lambda_2 e^{-(\lambda_1+r)(T_2 - T_1^{**})} \\
&\quad \times \left\{ \frac{\lambda_1}{(\lambda_1 + r)(\lambda_2 + \lambda_1 + r)} + \frac{1}{(\lambda_2 + \lambda_1 + r)} \frac{\partial T_2}{\partial T_1} - \frac{e^{-\lambda_1(T_2 - T_1^{**})}}{\lambda_2 + r} \frac{\partial T_2}{\partial T_1} \right\} \\
&\quad \times [\pi(s,s) - \pi(s,u)] + \frac{\lambda_2 e^{-(\lambda_1+r)(T_2 - T_1^{**})}}{(\lambda_1 + r)(\lambda_2 + \lambda_1 + r)} \\
&\quad \times \left[ \lambda_1 - (\lambda_1 + r) \frac{\partial T_2}{\partial T_1} \right] [\pi(u,s) - \pi(u,u)] \\
&\quad + rK(T_1^{**}) - K(T_1^{**}) = 0
\end{aligned}$$

and they conclude as follows:

> *The feedback equilibrium timings are more dispersed than those of the open-loop case, that is:*
> $T_1^{**} < T_1^* < T_2^* < T_2^{**}$.

They offer the following intuitive argument: in the feedback case, there exist strategic benefits to the first-mover as the expected time interval during which it enjoys

Hence their first proposition:

> *In an open-loop equilibrium, the extent of dispersion between adoption timings:*
>
> *(a) will increase if the degree of uncertainty is increased;*
>
> *(b) will increase if the instantaneous gain of being the first to succeed decreases relative to the instantaneous gain of being the second to succeed.*

We will show with the same model that:

> *In an open-loop equilibrium, the extent of dispersion between adoption timings:*
>
> *(a) will increase if the degree of uncertainty the second-mover is facing is increased ($\lambda_2$ decreases);*
>
> *(b) may increase or decrease if the degree of uncertainty the first-mover is facing is increased ($\lambda_1$ decreases);*
>
> *(c) may increase or decrease if the instantaneous gain of being the first to successfully implement the new technology decreases;*
>
> *(d) may increase or decrease if the instantaneous gain of being the second to successfully implement the new technology decreases.*

## 4.2 The Proper Comparative Statics Analysis.

We now study the same basic model with the four assumptions A1 to A4. We use identical expressions for the expected profits of the first-mover and the second-mover, that is (1) and (2), and find identical implicit reaction functions, that is (4) and (7) above. The main part of our analysis is based on comparative statics with respect to three different parameters. Our investigation yields conclusions either in opposition or more complex than the ones of Stenbacka and Tombak.

The reaction functions of the first-mover (7) and of the second-mover (4) cannot be solved explicitly but can be rewritten in implicit forms as follows:

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first-mover advantages increases [since $dT_2/dT_1 < 0$]. But the tendency to adopt earlier is tempered by the increase in investment costs. The second-mover adopts the technology later since its reaction function is downward sloping.

$$L(T_1^*, \alpha) \quad : \quad \frac{\lambda_1 \lambda_2}{(\lambda_1 + r)(\lambda_2 + \lambda_1 + r)} \times \tag{10}$$

$$\{[\pi(s,u) - \pi(u,u)] - [\pi(s,s) - \pi(u,s)]\} \, e^{-(\lambda_1 + r)(T_2 - T_1^*)}$$

$$-\frac{\lambda_1}{\lambda_1 + r}[\pi(s,u) - \pi(u,u)] + rK(T_1^*) - K'(T_1^*) = 0$$

$$F(T_2^*, \alpha) \quad : \quad \frac{\lambda_2}{\lambda_2 + \lambda_1 + r} \times \tag{11}$$

$$\{[\pi(s,s) - \pi(u,s)] - [\pi(s,u) - \pi(u,u)]\} \, e^{-\lambda_1 (T_2^* - T_1)}$$

$$-\frac{\lambda_2}{\lambda_2 + r}[\pi(s,s) - \pi(u,s)] + rK(T_2^*) - K'(T_2^*) = 0.$$

We are looking for the sign of $dT_2/d\alpha$ and $dT_1/d\alpha$, where $\alpha$ is the parameter under consideration. As usual,

$$dF(T_2^*, \alpha) = 0 \Longleftrightarrow \frac{\partial F}{\partial T_2^*} dT_2^* + \frac{\partial F}{\partial \alpha} d\alpha = 0,$$

that is

$$\frac{dT_2^*}{d\alpha} = -\frac{\partial F / \partial \alpha}{\partial F / \partial T_2^*}$$

In this expression we know that the denominator of the RHS is negative from the second order condition. So the sign of $dT_2^*/d\alpha$ is the sign of $\partial F/\partial\alpha$ obtained from (11). Similarly, the sign of $dT_1^*/d\alpha$ is the sign of $\partial L/\partial\alpha$ obtained from (10). We are going to study successively three different $\alpha$: $\alpha = \lambda_2$ or $\lambda_1$; $\alpha = [\pi(s,s) - \pi(u,s)]$ or $[\pi(s,u) - \pi(u,u)]$; $\alpha =$ a parameter of the cost functions.

### 4.2.1 Comparative statics with respect to $\lambda_2$ and $\lambda_1$

We already know that $(1/\lambda_i)$ gives the expected time from adoption to successful implementation. So the larger $(1/\lambda_i)$ is, the longer firm $i$ would have to wait on average for the implementation to be successful once the new technology is adopted.

LET US FIRST CONSIDER $\lambda_1$.

In order to determine the sign of $dT_2^*/d\lambda_1$ and $dT_1^*/d\lambda_1$, we must find $\partial F/\partial\lambda_1$ and $\partial L/\partial\lambda_1$.

a) Consider $\partial F/\partial\lambda_1$.

We have:

$$\frac{\partial F}{\partial \lambda_1} = \underbrace{\Big[[\pi(s,s)-\pi(u,s)]-[\pi(s,u)-\pi(u,u)]\Big]}_{\leq 0} \times \tag{12}$$

$$\left[\underbrace{\frac{-\lambda_2}{(\lambda_2+\lambda_1+r)}e^{-\lambda_1(T_2^*-T_1)}}_{\leq 0} + \underbrace{\frac{\lambda_2}{(\lambda_2+\lambda_1+r)}\left(-(T_2^*-T_1)\right)e^{-\lambda_1(T_2^*-T_1)}}_{\leq 0}\right]$$

That is,

$$\frac{\partial F}{\partial \lambda_1} > 0 \qquad \Longrightarrow \qquad \frac{dT_2^*(T_1)}{d\lambda_1} > 0$$

When $\lambda_1$ increases, the second-mover adopts later for every adoption date of the first-mover. The reaction function of the second-mover shifts to the right. The intuitive explanation of this result can be given as follows. If $\lambda_1$ is larger, the probability that the first-mover will successfully implement the new technology early after adopting it is larger. Hence the incentive for the second-mover to enter the race toward implementation is weaker and the second-mover wants to adopt later. We can represent these results on a graph as in FIGURE 2.

INSERT FIGURE 2 HERE

When $\lambda_1$ increases, $(T_2^*, T_1^*)$ is no more the equilibrium because the expected profits of the second-mover could be improved with a later $T_2$.

If we rewrite as follows the expression of the expected profits, we can derive more explicitly this result. Let $EV_2(T_1,T_2)$ be the expected value of the second-mover firm given the dates of adoption $(T_1,T_2)$. We have:

$$\begin{aligned} EV_2(T_1,T_2) \quad = \quad & \int_0^{T_1} \pi(u,u)e^{-rt}dt \\ & + \int_{T_1}^{T_2} [G_1(t)\pi(u,s) + (1-G_1(t))\pi(u,u)]e^{-rt}dt \\ & + \int_{T_2}^{\infty} \Big[G_1(t)G_2(t)\pi(s,s) + (1-G_1(t))G_2(t)\pi(s,u) \\ & \quad +G_1(t)(1-G_2(t))\pi(u,s) \\ & \quad +(1-G_1(t))(1-G_2(t))\pi(u,u)\Big]e^{-rt}dt \\ & -K(T_2)e^{-rT_2} \end{aligned} \tag{13}$$

that is:

$$
\begin{aligned}
EV_2(T_1, T_2) \quad = \quad & \int_0^{T_1} \pi(u,u) e^{-rt} dt \qquad (14) \\
& + \int_{T_1}^{T_2} [G_1(t)\pi(u,s) + (1 - G_1(t))\pi(u,u)] e^{-rt} dt \\
& + \int_{T_2}^{\infty} \Big[ G_1(t) G_2(t) [\pi(s,s) - \pi(u,s)] \\
& \quad + (1 - G_1(t)) G_2(t) [\pi(s,u) - \pi(u,u)] \\
& \quad + G_1(t)\pi(u,s) + (1 - G_1(t))\pi(u,u) \Big] e^{-rt} dt \\
& - K(T_2) e^{-rT_2}
\end{aligned}
$$

We know that $G_1(t)$ increases and $(1 - G_1(t))$ decreases with $\lambda_1$. So we understand that when $\lambda_1$ increases, the second-mover has a smaller chance to be in situations $\pi(u,u)$ and $\pi(s,u)$ because the first-mover increases his probability of being in situations $\pi(s,u)$ [that is $\pi(u,s)$ for the second-mover] and $\pi(s,s)$. From A1, we know that $\pi(u,s) \leq \pi(u,u)$, and from A2 that $\pi(s,s) - \pi(u,s) < \pi(s,u) - \pi(u,u)$. With the increase in $\lambda_1$, the second-mover has a bigger chance of ending up with $\pi(s,s) - \pi(u,s)$ and a smaller chance of ending up with $\pi(s,u) - \pi(u,u)$. Consequently the marginal benefits of early adoption are reduced (he is less likely to make larger profits by being the first one to implement) and therefore the second-mover is going to adopt later for every adoption time of the first-mover in order to decrease its investment costs. The reaction function of the second-mover shifts to the right.

b) Consider now $\partial L / \partial \lambda_1$.

We have:

$$
\begin{aligned}
\frac{\partial L}{\partial \lambda_1} \quad = \quad & \underbrace{\frac{\overbrace{\lambda_2 (r^2 + r\lambda_2 - \lambda_1^2)}^{\text{sign?}}}{((\lambda_1 + r)(\lambda_1 + \lambda_2 + r))^2}}_{>0} \underbrace{e^{-(\lambda_1 + r)(T_2 - T_1^*)}}_{>0} \qquad (15) \\
& + \Big[ \underbrace{\frac{\lambda_1 \lambda_2}{(\lambda_1 + r)(\lambda_1 + \lambda_2 + r)} (-(T_2 - T_1^*)) e^{-(\lambda_1 + r)(T_2 - T_1^*)}}_{<0} \\
& \quad \times \underbrace{[[\pi(s,u) - \pi(u,u)] - [\pi(s,s) - \pi(u,s)]]}_{>0} \Big] \\
& - \underbrace{[\pi(s,u) - \pi(u,u)]}_{>0} \frac{r}{(\lambda_1 + r)^2}
\end{aligned}
$$

We can find the sign of all the expressions of the above equation (as they are given) except for $r^2 + r\lambda_2 - \lambda_1^2$. If $r$ is small enough, then $r^2 + r\lambda_2 - \lambda_1^2 < 0$ and $\partial T_1 / \partial \lambda_1 < 0$. If $r$ is large enough, the expression eventually becomes positive since as $r \longrightarrow \infty$, and the first term of increases without bounds while the last two terms decrease towards 0. Hence, we cannot determine unambiguously the sign of the above expression, and therefore $T_1^*(T_2)$ can increase (move to the right), decrease (move to the left) or remain unchanged as $\lambda_1$ increases.
When $\lambda_1$ increases then: $T_2^*(T_1)$ always increases, that is moves to the right; $T_1^*(T_2)$ can either increase, decrease or even remain the same. But if r is small enough to make $r^2 + r\lambda_2 - \lambda_1^2 < 0$, then $T_1^*(T_2)$ will decrease or move to the left and so $(T_2^* - T_1^*)$ will increase. This last case is illustrated in FIGURE 3 where one can see that the dispersion in adoption timings $(T_2^* - T_1^*)$ increases.

INSERT FIGURE 3 HERE

When $\lambda_1$ increases and $r^2 + r\lambda_2 - \lambda_1^2 < 0$, the first-mover adopts earlier because its probability of successfully implementing the new technology increases. As for the second-mover, he adopts later because of the reduced likelihood that he will be the first to implement successfully the new technology.

The intuitive explanation of this result (and of the related result when $r$ is large enough to make $\partial L / \partial \lambda_1$ positive) can be better understood by rewriting the expected value of the first-mover firm as follows:

$$\begin{aligned} EV_1(T_1, T_2) \quad = \quad & \int_0^{T_1} \pi(u,u) e^{-rt} dt \\ & + \int_{T_1}^{T_2} [G_1(t)\pi(s,u) + (1 - G_1(t))\pi(u,u)] e^{-rt} dt \\ & + \int_{T_2}^{\infty} \Big[ G_1(t) G_2(t) \pi(s,s) + (1 - G_1(t)) G_2(t) \pi(u,s) \\ & \quad + G_1(t)(1 - G_2(t))\pi(s,u) \\ & \quad + (1 - G_1(t))(1 - G_2(t))\pi(u,u) \Big] e^{-rt} dt \\ & - K(T_1) e^{-rT_1} \end{aligned} \tag{16}$$

that is:

$$
\begin{aligned}
EV_1(T_1,T_2) \quad = \quad & \int_0^{T_1} \pi(u,u)e^{-rt}dt & (17) \\
& + \int_{T_1}^{\infty} [G_1(t)\pi(s,u) + (1-G_1(t))\pi(u,u)]e^{-rt}dt \\
& + \int_{T_2}^{\infty} \Big[G_1(t)G_2(t)\,[\pi(s,s)-\pi(s,u)] \\
& \qquad +(1-G_1(t))G_2(t)\,[\pi(u,s)-\pi(u,u)]\Big]e^{-rt}dt \\
& -K(T_1)e^{-rT_1}
\end{aligned}
$$

We know that $G_1(t)$ increases and $(1-G_1(t))$ decreases with $\lambda_1$. By assumption A1, $\pi(s,u) \geq \pi(u,u)$; by assumption A2, $\pi(s,u)-\pi(u,u) > \pi(s,s)-\pi(u,s)$, and therefore $\pi(s,s)-\pi(s,u) < \pi(u,s)-\pi(u,u)$. Hence, with an increase in $\lambda_1$, the first-mover is more likely to end up with $\pi(s,u)$ rather than $\pi(u,u)$, which is favorable to advancing adoption; but it is also more likely to end up with $[\pi(s,s)-\pi(s,u)]$ rather than $[\pi(u,s)-\pi(u,u)]]$, which is favorable to postponing adoption. Hence, we cannot in general sign the effect of an increase in $\lambda_1$ on $T_1^*(T_2)$.

The relative importance of the two effects (favorable to advancing or postponing adoption) depends on the value of $r$. The effect of a larger $r$ is to reduce both the second and third integral in (17) in proportion to the value of those integrals (note that the second integral is larger than the third one[10]). If $r$ is large enough, the increase in $\lambda_1$ will indeed induce the first-mover firm to postpone adoption (the first-mover's reaction function moves to the right !). Otherwise, the increase in $\lambda_1$ will induce the first-mover firm to advance adoption (the first-mover's reaction function moves to the left).

Let us now consider $\lambda_2$.

We can perform the same analysis for $\lambda_2$ and arrive at the conclusion below. Since

$$
\begin{aligned}
\frac{\partial F}{\partial \lambda_2} \quad = \quad & \frac{\lambda_2 + r}{(\lambda_2+\lambda_1+r)^2} \times & (18) \\
& \{[\pi(s,s)-\pi(u,s)] - [\pi(s,u)-\pi(u,u)]\}\, e^{-\lambda_1(T_2^*-T_1)} \\
& -\frac{r}{(\lambda_2+r)^2}[\pi(s,s)-\pi(u,s)]
\end{aligned}
$$

and since $[\pi(s,s)-\pi(u,s)] \leq [\pi(s,u)-\pi(u,u)]$ and $\pi(s,s) \leq \pi(u,s)$, we

[10]From A1, $\pi(s,u) > \pi(s,s)-\pi(s,u)$; also from A1, $\pi(u,u) > \pi(u,s)-\pi(u,u)$. Since $G_2(t) \leq 1$, then the second integral is larger than the third one.

have immediately that:

$$\frac{\partial F}{\partial \lambda_2} \leq 0 \qquad \Longrightarrow \qquad \frac{dT_2^*(T_1)}{d\lambda_2} \leq 0$$

Also,

$$\begin{aligned}\frac{\partial L}{\partial \lambda_2} &= \frac{\lambda_1(r^2 + 2r\lambda_1 + \lambda_1^2)}{((\lambda_1 + r)(\lambda_2 + \lambda_1 + r))^2} \times \\ &\quad \{[\pi(s,u) - \pi(u,u)] - [\pi(s,s) - \pi(u,s)]\} \, e^{-(\lambda_1 + r)(T_2 - T_1^*)}\end{aligned} \tag{19}$$

Since $[\pi(s,u) - \pi(u,u)] \geq [\pi(s,s) - \pi(u,s)]$, then:

$$\frac{\partial L}{\partial \lambda_2} \geq 0 \qquad \Longrightarrow \qquad \frac{dT_1^*(T_2)}{d\lambda_2} \geq 0$$

Only one case is possible: $T_1^*(T_2)$ increases or moves to the right, $T_2^*(T_1)$ decreases or moves to the left, so that the dispersion between adoption timings $(T_2^* - T_1^*)$ decreases. We see that when $\lambda_1$ increases, the impact on the dispersion of adoption timings $(T_2^* - T_1^*)$ is totally different from that impact when $\lambda_2$ increases.[11]

#### 4.2.2 Comparative statics with $\alpha = [\pi(s,u) - \pi(u,u)]$ and $\alpha = [\pi(s,s) - \pi(u,s)]$

We now analyze how the degree of dispersion between the equilibrium adoption timing of the first-mover and that of the second-mover is affected by the magnitude of payoffs in the different states.

By studying the effects of a variation of $[\pi(s,u) - \pi(u,u)]$ , we consider a change in the gains of being the first to successfully implement the new technology, while with $[\pi(s,s) - \pi(u,s)]$ we introduce a change in the gains of being the second to reach the successful implementation. Stenbacka and Tombak claim that only one case was possible: Increases in either $[\pi(s,s) - \pi(u,s)]$ or $[\pi(s,u) - \pi(u,u)]$ decrease the dispersion in adoption timings $(T_2^* - T_1^*)$. As before, they base their analysis on equation (9) that represents an open-loop equilibrium condition but only one such condition. As we shall see, the analysis is somewhat more complex but at the same time more interesting than their claims suggest. First let us consider $\alpha = [\pi(s,u) - \pi(u,u)]$

[11] Stenbacka and Tombak claim that in equilibrium, the second-mover has greater incentive to adjust its adoption timing because of the cumulative distribution function which is initially convex and then concave. So an increase in uncertainty (decrease in $\lambda_i$) will induce a higher degree of dispersion in adoption timings.

a) Let us look for the sign of $\partial F/\partial([\pi(s,u)-\pi(u,u)])$. We have

$$\frac{\partial F}{\partial([\pi(s,u)-\pi(u,u)])} = -\frac{\lambda_2}{\lambda_2+\lambda_1+r}e^{-\lambda_1(T_2-T_1)} < 0.$$

Therefore

$$\frac{dT_2^*(T_1)}{d([\pi(s,u)-\pi(u,u)])} < 0$$

b) Let us look for the sign of $\partial L/\partial([\pi(s,u)-\pi(u,u)])$. We have

$$\frac{\partial L}{\partial([\pi(s,u)-\pi(u,u)])} = \frac{\lambda_2\lambda_1}{(\lambda_1+r)(\lambda_1+\lambda_2+r)}e^{-(\lambda_1+r)(T_2-T_1)} - \frac{\lambda_1}{\lambda_1+r}$$

which is negative since $T_2 > T_1$, $e^{-(\lambda_1+r)(T_2-T_1)} \leq 1$, and $\lambda_2/(\lambda_2+\lambda_1+r) < 1$. Therefore

$$\frac{dT_1^*(T_2)}{d([\pi(s,u)-\pi(u,u)])} < 0$$

Hence, both reaction functions shift to the left and both $T_2^*$ and $T_1^*$ decrease: both firms advance their adoption date when the benefit of being the first to implement successfully the technology increases. Depending on the relative strength of the effects on $T_2^*(T_1)$ and $T_1^*(T_2)$, the dispersion in adoption timings $(T_2^*-T_1^*)$ may increase, decrease or remain the same.

LET US NOW CONSIDER $\alpha = [\pi(s,s)-\pi(u,s)]$

a) Let us look for the sign of $\partial F/\partial([\pi(s,s)-\pi(u,s)])$. We have

$$\frac{\partial F}{\partial([\pi(s,s)-\pi(u,s)])} = \frac{\lambda_2}{\lambda_2+\lambda_1+r}e^{-\lambda_1(T_2-T_1)} - \frac{\lambda_2}{\lambda_2+r}$$

which is negative since $T_2 > T_1$, $e^{-\lambda_1(T_2-T_1)} \leq 1$, and $\lambda_2/(\lambda_2+\lambda_1+r) < \lambda_2/(\lambda_2+r)$. Therefore

$$\frac{dT_2^*(T_1)}{d([\pi(s,s)-\pi(u,s)])} < 0$$

b) Let us now look for the sign of $\partial L/\partial([\pi(s,s)-\pi(u,s)])$. We have

$$\frac{\partial L}{\partial([\pi(s,s)-\pi(u,s)])} = -\frac{\lambda_2\lambda_1}{(\lambda_1+r)(\lambda_1+\lambda_2+r)}e^{-(\lambda_1+r)(T_2-T_1)} < 0.$$

Therefore:

$$\frac{dT_1^*(T_2)}{d([\pi(s,s)-\pi(u,s)])} < 0.$$

Hence, both reaction functions shift to the left and both $T_2^*$ and $T_1^*$ decrease: both firms advance their adoption date when the benefit of being the second to implement successfully the technology increases. Depending on the relative strength of the effects on $T_2^*(T_1)$ and $T_1^*(T_2)$, the dispersion in adoption timings $(T_2^* - T_1^*)$ may increase, decrease or remain the same. The same three cases as in the previous case are possible.

#### 4.2.3 Comparative statics with respect to cost functions

Let us redefine the cost functions $K^*(t)$ as the sum of a fixed cost parameter ($\gamma$ for the first-mover and $\beta$ for the second-mover) and a function $K(t)$, similar to the cost function used previously. We change one of our initial assumptions stating that the two firms were exactly identical, except for their strategic positioning. Now they have different costs functions.

$$K_1^*(t) = \gamma + K(t) \quad \text{and} \quad K_1^{*\prime}(t) = K'(t)$$

$$K_2^*(t) = \beta + K(t) \quad \text{and} \quad K_2^{*\prime}(t) = K'(t)$$

So we wonder how changes in parameters $\gamma$ and $\beta$ affect the dispersion in adoption timings $(T_2^* - T_1^*)$.

The impact of a decrease in $\gamma$

Clearly, the parameter $\gamma$ has no direct effect on the decision of the second-mover. Regarding the first-mover, we have

$$\frac{\partial L}{\partial \gamma} = r > 0$$

implying

$$\frac{dT_1^*(T_2)}{d\gamma} > 0$$

Hence, when $\gamma$ decreases, the first-mover's reaction function moves to the left while the second-mover's reaction function is unaffected. The first-mover therefore adopts earlier for each adoption date of the second-mover and the second-mover adopts later implying that the dispersion in adoption timings increases.

It is worth noting that when the first-mover's costs are decreasing, the first-mover decides to adopt earlier and the second-mover to adopt later, so it is possible that the mean of adoption timings, defined as $(T_2^* + T_1^*)/2$, increases. This suggests that a subsidy or tax break to the early adopter (the first-mover), generating a drop in $\gamma$, may delay the average adoption timing of a new technology in an industry. In order to find out if $T_1$ decreases relatively more than $T_2$ increases, we must look at the reaction function of the second-mover and more precisely at its slope. As for a simple case of Cournot duopoly, the slope of the reaction function of the second-mover determines whether or not $T_1$ varies more than $T_2$, when $\gamma$ decreases. If the slope of the reaction function of the second-mover, in the neighborhood of the open-loop equilibrium before the decrease in $\gamma$, is larger [smaller] than 1 in absolute value, then $T_1$ decreases relatively less [more] than $T_2$ increases and the mean of adoption timings $(T_2^* + T_1^*)/2$ increases [decreases].

THE IMPACT OF A DECREASE IN $\beta$

We find similar results to those of the previous case:

$$\frac{\partial F}{\partial \beta} > 0$$

implying

$$\frac{dT_2^*(T_1)}{d\beta} > 0$$

Hence when $\beta$ decreases, the second-mover wants to adopt earlier for each adoption date of the first-mover because his costs are decreasing. In equilibrium, the second-mover adopts earlier and the first-mover adopts later than before. Therefore the dispersion in adoption timings is reduced. Again, it is possible that the mean of adoption timings, defined as $(T_2^* + T_1^*)/2$, increases depending now on the value of the slope of the first-mover's reaction function.

# 5 Conclusion

Much remains to be done to reach a good understanding of the difficulties organizations and firms in particular are facing in successfully implementing new technologies they have chosen to adopt. The data shows that literally billions and billions of dollars will be spent, a good part of it unsuccessfully, in trying to implement technological and organizational changes in firms. We have shown here how the uncertainty regarding implementation affect the adoption timings in an open loop strategic context. And we have conducted some comparative statics on the equilibrium conditions that we have characterized.

Building on a model first proposed by Stenbacka and Tombak (1994), we showed that a more efficient implementation program within the market leader firm (increasing the value of $\lambda_1$) induces the market follower firm to postpone the adoption of a new technology but more surprisingly, it may also induce the market leader firm to postpone the adoption of that technology: such a striking result would be obtained if the market interest rate or more precisely the discount rate is relatively high. In that case, On the other hand, if the discount rate is relatively low, that is low enough to make (15) negative, then a more efficient implementation program in the leader firm will induce the market leader to adopt earlier and the market follower to adopt later, and therefore will increase the difference in adoption timings.

A more efficient implementation program within the market follower firm (increasing the value of $\lambda_2$) induces the market follower firm to advance the adoption of a new technology and induces the market leader to postpone the adoption of that technology. Hence, the difference in adoption timings will decrease. The increased efficiency of implementation programs in the market leader firm and the market follower firm have significantly different impacts.

When the relative gain of being the first to successfully implement the technology increases, both the market leader firm and the market follower firm adopt the technology earlier. The difference in adoption timings may increase or decrease but the technology is adopted faster across the industry. Similarly, when the relative gain of being the second to successfully implement the technology increases, both the market leader firm and the market follower firm adopt the technology earlier also. The difference in adoption timings may increase or decrease but the technology is again adopted faster across the industry.

A reduction in the cost of adoption (investment) of the new technology by the market leader firm increases the difference in adoption timings, the leader adopting earlier and the follower adopting later than previously, with the possibility that the mean adoption timing in the industry increases. It will increase if the slope of the market follower firm's best reply function is larger than 1 (in absolute value). A reduction in the cost of adoption (investment) of the new technology by the market follower firm reduces the difference in adoption timings, the leader adopting later and the follower adopting earlier than previously, with again the possibility that the mean adoption timing in the industry increases. It will increase if the slope of the market leader firm's best reply function is larger than 1 (in absolute value). These results suggest that subsidizing the adoption of new technologies in first-mover firms or second-mover firms may have negative impacts on the mean adoption timings in an industry. Such situations are not pathological but likely to be quite common.

Further research should be directed toward better understanding the factors underlying the uncertainty in implementing new technologies, that is the factors underlying the values of the $\lambda_i$. Such factors are likely to be of different nature and we have covered some of them in our review of the literature on organizational inertia. More research on those factors would be most welcome.

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FIGURE 1

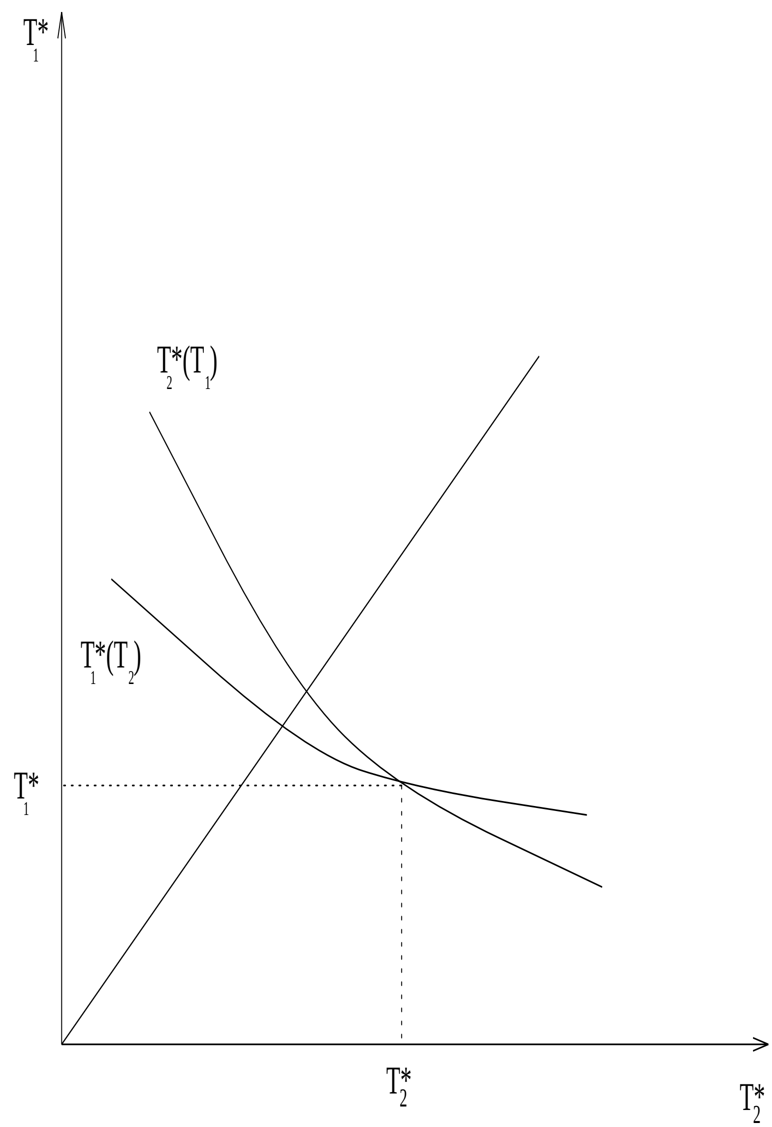


FIGURE 2

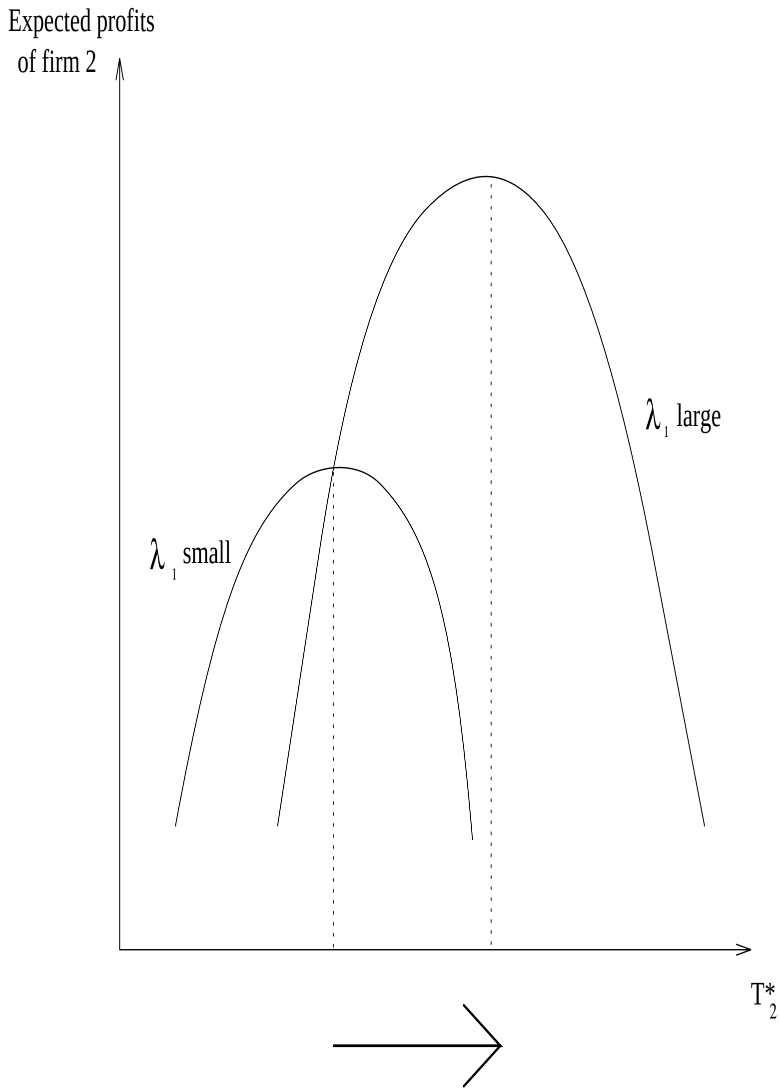
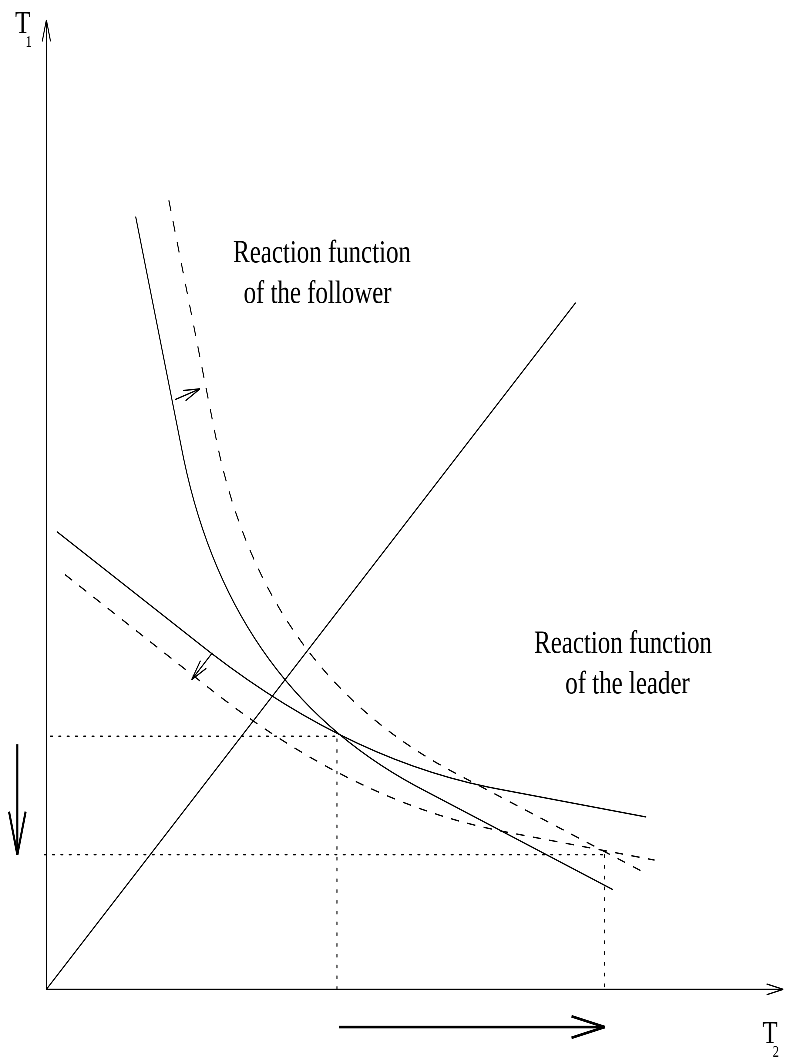


FIGURE 3



$T_1$
Reaction function
of the follower
Reaction function
of the leader
$T_2$

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