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System Dynamics Modeling and the Study of Technological Change

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Resumen

Este artículo discute la posibilidad de analizar el cambio tecnológico a través de los métodos que se derivan de la dinámica de sistemas. En este sentido, la naturaleza del cambio tecnológico como un fenómeno sistémico y complejo hace a los métodos que se derivan de la dinámica de sistemas una herramienta adecuada para su análisis. Por lo mismo, esta posibilidad surge debido a que los métodos que ofrece la dinámica de sistemas permiten tratar con los procesos de retroalimentación y los rezagos en el tiempo que caracterizan muchos de los fenómenos en economía y ciencias de la gestión. Los autores hacen una revisión de alguna literatura importante en relación con la actividad innovadora de las industrias relacionadas con la biotecnología y sugiriendo que el enfoque de la dinámica de sistemas puede ser una herramienta útil para analizar esta actividad en estas industrias.

Palabras clave: dinámica de sistemas; cambio tecnológico; biotecnología.

Abstract

This paper discusses the possibility of studying technological change through applying system dynamics methods. In this sense, the nature of technological change as a systemic and complex phenomenon makes system dynamics methods an adequate tool to this study. However, this possibility emerges because system dynamics methods allow dealing with feedback and time delays characterizing many economic and management phenomena. The authors make an assessment of some important studies in relation to the innovation activity at the biotechnology-related industries and suggesting that the system dynamics approach may be a useful tool to analyze this activity in these industries.

Keywords: system dynamics; technological change; biotechnology.

JEL: O32, B41, O39.

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Introduction

System dynamics (SD) methods have often been employed to study the structure and behavior associated with the management of complex systems. SD is a research method that enhances the understanding of dynamic systems (Sterman, 2000). This methodological approach applies feedback control principles and methods to managerial, organizational and socioeconomic problems (Forrester, 1994). SD methods are concerned to the analysis of the behavior of systems, the behavior of human, physical and technical systems, cognitive and social psychology, economics and other social sciences. In management sciences, SD methods allow studying nonlinear dynamics and feedback control (Roberts, 1978).

In relation to technology management and innovation, SD is a method frequently employed to analyze the diffusion of innovations, because innovation and technology management are highly dynamic and complex phenomena that evolve over time. In this sense, for instance, Maier (1998) has provided a relevant example using SD as a method to study some problems related to technical change and innovation-diffusion phenomena, stressing the idea that the analysis of innovation-diffusion process is a complex phenomenon simultaneously influenced by a large number of variables such as price, advertising, product capabilities, and so on.

This paper reviews some key literature on the use of SD methods in the analysis of technology change. Particularly, some literature on biotechnology-related industries is analyzed as an example of the complexity of technology and innovation phenomena. Actually, this is a promising research field to SD analyses, given that in many emerging economies many unsuccessful biotechnology-related firms frequently appear.

The paper is organized into three sections. Section 2 presents a general overview of how social phenomena can be modeled by the use of SD methods. Section 3 focuses on the analysis of the relationships established between technological change and market structure within the SD literature. Section 4 explains how this approach can be useful to the analysis of management problems in biotechnology-related industries. Sections 5 presents some conclusions from the main ideas discussed in this paper.

System Dynamics Modeling: A General Overview

Statistical and inferential methods are at the core of the analyses related to testing social science theories. In this sense, modeling and simulation are important methods to acquire knowledge in economics and management (Davis et al., 2007; McCarthy et al., 2010; Schwaninger and Grösser, 2008). However, modeling techniques have evolved as they have had to address different problems related to change over time (Cloutier and Rowley, 2000). In this sense, Cloutier and Rowley (2000) point out that in management and economics, the process of development in modeling and simulation techniques have span over three successive periods. In the first period, modeling business cycles was the main task of academic researchers. The modeling construction process in this period attempted to incorporate problems related to causal linkage determination between variables. In the second period, nonlinear models were widely used by academic researchers as they started to be interested on the dynamic properties of economic systems. Finally, in the third period, there was an extensive use of computer hardware and software for simulation purposes.

Although the great effort made to model and simulate in economics and management in the last years, Forrester (1975) has suggested that many empirical models have failed to answer fundamental questions about the behavior that arises from social, economic and environmental interactions. This perspective emphasizes the importance of complexity as a feature characteristic of modern organizations. Moreover, complexity means for the organization a set of feedback interactions and side effects, making traditional experimental methods in social science less flexible. Actually, through this approach, it is possible to know and characterize the underlying structure of an organization. Indeed, the SD approach allows using both quantitative data and qualitative relationships between variables. In so doing, SD models take into account a broader range of information sources and mental models of decision-makers in order to achieve knowledge about changing systems (Forrester, 1975, 1994). Complexity is thus a feature characteristic in business systems, and it has become an important challenge for researchers that require adequate tools for both theoretical and empirical inquiry. In this context, SD is a response to the demands imposed by the complex nature of many social phenomena. In this sense, SD is a way to think about complexity as an explanation of behavioral patterns in the organization that must be firmly linked to its structure (Forrester, 1975; Ford, 1999; Sterman, 2000).

In the same manner, Sterman (2000) suggests that systems and organizations have become increasingly subject to accelerated change and uncertainty. In this sense, this author suggests that structure, complexity and uncertainty are concepts strongly related in SD models, and thus structural change and uncertainty are the most important sources that bring complexity in firm behavior. In the SD approach, systems are treated as dynamic and complex entities. Complexity means that systems are constantly evolving and in disequilibrium. Addition to these principles, Forrester (1975) and Sterman (2000) emphasize that complexity arises because systems are dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent, self-organizing, adaptive, counterintuitive, policy resistant, and characterized by trade-offs.

SD models comprise four elements (Forrester, 1975; Wolstenholme et al., 1993): (1) feedback loops, (2) stock and flow structure, (3) time delays, and (4) nonlinearities. From this perspective, economic and managerial systems are complex multi-loops and interconnected systems, reinforced by feedbacks loops that reveal the actual organization of any structure (Forrester, 1994). In strategy, for instance, this means that symptoms, actions and solutions are not isolated linear cause-to-effect stepping processes (Wolstenholme et al., 1993). Instead, SD considers management and economic systems as circular and interlocked structures (Forrester, 1994). The demand and supply model developed by Whelan and Msefer (1996) is a representative example of how these principles operate within a system. This model equals supply and demand through an adjustment mechanism different from that proposed by the traditional economic theory. In this model, inventory is actually a core variable for achieving a solution. Whether inventory is less than the desired level, the firm indirectly raises the supply level and the price in order to increase the desired rate of production. This study demonstrates though that the availability of a product is the most important variable affecting and regulating market prices and demand. In the Whelan-Msefer's (1996) demand and supply model, feedbacks, stocks and flows, time delays and nonlinearities model and analyze the market in terms of its demand and supply forces.

On the other hand, Sterman (2000) stresses the importance of feedback loops in the SD modeling process. According to this author, the main difference between SD and other techniques does not concern the cause to affect relationships established between variables. This principle is actually "accepted" by all approaches. Instead, SD assumes that cause and effect relationships are generally distant in time and space, and thus policy resistance arises because economic agents are not sensitive to the full range of feedbacks operating in the whole system (bounded rationality). In this regard, Roberts (1978) emphasizes the philosophy underlying SD models and suggests that behavioral patterns in an organization are principally caused by the organization structure itself, and by the fact that an organization should be understood in terms of their common underlying flows instead of separate functions. Wolstenholme et al. (1993) suggests that the structural framework of an organization is characterized to contain sources of amplification, time delays, information feedbacks, and flow diagrams and equations representing modeled relationships. Actually, feedbacks loops can be reinforcing (self-reinforcing) or balancing (self-correcting), and the interaction of both kinds of feedbacks determine jointly the dynamics of the system. Scholars on system dynamics stress the idea that any learning process is actually a feedback process that includes all forms of information, both quantitative and qualitative, to determine the dynamics of the system.

Other important definitions in SD are levels and rates. Technically, the structure of a system in SD is an interconnected set of levels and rates variables (Sterman, 2000). Indeed, SD emphasizes the fact that fundamental processes in managed system must be to convert resources between states using these kinds of relationships. Wolstenholme et al. (1993) define levels as measurable quantities of any resource in a system at any time. Rates represent the speed at which these resources are converted between states. Rates can only depend on levels since these are the only measurable variables of the system. They are usually referred as policy, strategy or decision variables. The behavior of a system is determined using a set of first-order linear difference equations. The innovation process is a good example of how SD methodological principles operating in the analysis of a system (Sterman, 2001). An innovation process is unpredictable and constantly reshapes the market structure. An innovation process depends on many variables, influencing each other at the same time. An innovation process is characterized to be highly complex and uncertain, and thus the key way organizations are able to manage complexity and uncertainty is through knowledge. From this perspective, SD is useful to analyze technological change and innovation.

Accordingly, information and knowledge are the only way to understand decisions. In this sense, what knowledge or what information will be pertinent in order to achieve decisions? The answer to this question concerns the way information is converted into actions through an adequate decision-making process (Forrester, 1994). In this process, creating information about the structure and defining the strategy of the system, it is necessary to specify the state of the system in order to have a casual effect on the rate, and the rules that specify this type of effects (Wolstenholme et al., 1993). Once we have specified qualitative feedbacks loops, structural stock and flow, time delays, and nonlinearities, the simulation process becomes the most important task in order to test any hypothesis in SD. A dynamic hypothesis or influence diagram is defined as a specific language, representing qualitatively the causes and effects of the structure in a system (Cloutier, 2002). However, the process of simulation is at the core of the analysis in SD. The process for constructing a model in SD is specific to this research method (Wolstenholme et al., 1993; Forrester, 1994). It is important to keep in mind that the simulation process reveals underlying relationships in the system. The influence diagram provides the information concerning reinforcing and balancing feedback loops of the system under consideration to capture the structure of the system.

There are five steps in the SD modeling process (Sterman, 2000): (1) the problem definition and articulation (including selection, problem definition, key variables and time horizon); (2) the formulation of dynamic hypotheses, generating initial hypotheses, endogenous focus and mapping; (3) formulation of a simulation model, containing specification, estimation and tests; (4) testing process, containing comparison to reference models, robustness under extreme conditions and sensitivity; and (5) policy design and evaluation, including scenario specification, policy design, sensitivity analysis and interaction of policies.

Forrester (1994) stresses the idea that model simulation is the objective of SD methods. This principle is one way to conduct experimentation in SD. In fact, these authors have also suggested some reasons to believe that simulation and experimentation are at the core of SD analyzing methods, given that SD models are characterized by: (1) dynamic complexity; (2) limited information; (3) ambiguity on variables; (4) limited rationality and unexpected consequences from actions taken; (5) unreliable inferences related to the dynamic of the systems; (6) judgment errors; (7) interpersonal obstacles to learning; and (8) failure taking adequate decisions. Simulation thus gives the possibility to evaluate change and its consequence for a system over time. Simulation improves the ability to understand the results derived from actions or a decision-making process. Forrester (1994) emphasizes that SD simulation is an adequate environment to prototype alternative possibilities in organizations. Lyneis (1999) expresses the same idea suggesting that SD models can play an important role to understand problems, to determine consequences of alternative courses of action and to test alternative solutions under different scenarios.

A feature of the SD method is the relationship between mental models of decision-makers and the structure of a system. If the mental model changes, the structure of the system can be modified, and there exists the possibility to create different decision rules, and thus alternative strategies. New decisions rules and emerging strategies generate other changes in the mental model of decision-makers (Cloutier, 2002). This discussion relates to the problem of bounded rationality in economics and management (Simon, 1982). SD supports the idea that there are not perfect rationality. Indeed, it emphasizes the multi-loop, multi-state and the non-linear character of feedbacks in systems. These characteristics imply the possibility to learn just from a limited perspective and limit the knowledge of the real world. In consequence, there is bounded rationality in economic systems (Sterman, 2000). Finally, it is important to stress the idea that learning in a world of dynamic complexity and imperfect information, decision-makers must develop some kind of insight skills. This idea relates to the possibility to learn and acquire capabilities in order to improve organizational performance. We will continue to analyze this subject in the next section of the paper.

Technological Change and System Dynamics

It is commonly observed that the diffusion and adoption of new products often follows S-shaped or logistic growth pattern. In fact, in the underlying S-shaped behavioral pattern lies the idea that there exist a reinforcing feedback loop generating an initial exponential growth, and then a balancing feedback loop limiting that growth. In a few words, it is possible to say that reinforcing and balancing feedback loops are the result of uncertain innovation processes that affect the whole structure of the market (Sterman, 2000). Moreoever, one way organizations can cope with uncertainty is through learning and knowledge management (Cloutier and Boehlje, 2002). These uncertain situations suggest thus that the SD approach could be an appropriate method to model technological change and innovation, as it implies continuous non-equilibrium positions and evolving market structures. However, technological change is a complex and dynamic process. It is actually a highly uncertain process. Technological change and innovation contain reinforcing and balancing feedback loops that shape the rate of adoption of a new product. From the perspective of the SD approach, an innovation-diffusion process is analogous to an epidemic model (Sterman, 2000). This model can be further developed to obtain a more complete and realistic explanation of how new product innovation-diffusion processes are carried out in markets. The main feature of a more complete model is that it must take into account the fact that at the very beginning there is no explanation of the genesis of initial adopters (Sterman, 2000). For instance, a complete model on innovation-diffusion should give explanations on advertising, media reports, and direct sales efforts, among others.

A more complete model than the one discussed above is the Bass Diffusion Model (Bass, 1969). An important feature differentiating the Bass model is that the former assumes constant the probability that a potential adopter will adopt the new product as a result of external influences at each period. This feature suggests that when an innovation is introduced and the adopting population is zero, the only source of adoption will be external influences such as product advertising (it could also be Beta testing users) (Sterman, 2000).

At the level of markets, the most important consequence resulting from the dynamic features of an innovation-diffusion process is that it constantly reshapes competition and the market structure. Schumpeter and Penrose stressed these principles and the importance of acquiring an adequate research method in order to study innovation and technical change. SD is however a promising approach to deal with technical change and innovation (Maier, 1998). SD emphasizes multi-loop, multi-state and non-linearity trajectories followed by technical change and innovation processes. In this sense, dynamic complexity and limited information are core characteristics that reduce the potential for learning and performing in a system, limiting the acquisition of knowledge about the real world (Sterman, 2000). This problem known as feedback misperception could be explained in terms of a cognitive map of the casual structure (Kleinmuntz, 1993).

The cognitive map is vastly simplified compared to the complexity of actual world. It does not give the possibility to infer correctly the dynamics of the system because misperception and bounded rationality allow just partial knowledge of a system (Simon, 1982). In consequence, complexity, bounded rationality and misperception features are another reason for making SD a framework to analyze technological change. Indeed, SD gives the possibility to learn about the complex functioning of systems, and thus giving organizations the possibility to develop some kind of actions in order to alter or modify their paths over time (Forrester, 1994). If management is the process to convert information into action, namely a decision-making process, thus SD may allow the possibility to implement adequate policies to achieve some specific goals.

Janszen and Degenaars (1998) suggest that technical change and innovation are complex phenomena at least for four reasons: (1) natural resources are fundamental to economic performance; (2) technological knowledge is widely accepted as the most important source of competitive advantage and economic performance; (3) superior technology advantages exist only temporally and are eroded over time; and (4) the decline and up rise of industries in different regions is supported by the idea that the presence of sectoral innovative capabilities in different regions is subject to a dynamic and complex process. This conception about complexity in innovation and technical change can be complemented with the idea that the analysis of technical change and innovation take into account the interactions observed between actors and factors (Janszen and Degenaars, 1998; Levinthal and Myatt, 1994; Nelson, 1995). The underlying assumption is that through this kind of interactions innovation and technological change can be understood as a process resulting in new products. Actually, these new products embody the technological advances developed by the firm, causing markets to evolve constantly. From this perspective, SD makes it easier to understand the relationship between technological change–innovation–competition–market structures as multiple cause-effect interactions driven by the existence of reinforcing feedback loops. Moreover, from an evolutionary perspective, it is clear that the economy is not just characterized as a negative feedback system (a neoclassical balancing of opposing forces view) but a self-reinforcing positive feedback loops system (Lipsey, 2000; Shapiro and Varian, 1999). On the other hand, Anderson et al. (1988), Arthur (1994), and Sanchez (2003) explain how these links between technological change, products and market evolve constantly. However, these principles are useful to explain how new industries and markets emerge and develop continuously. In the analysis of technical change and innovation, these authors stress the idea that it is possible to find some kind of institutions delaying the development of new technologies, and thus causing that products and market structures change constantly through the existence of equilibrating or balancing feedback loops and lock-in effects.

In addition, Cloutier and Boehlje (2002) identify interacting reinforcing and balancing feedback structures in economic and management systems. These feedbacks are amongst the most important factors in an innovation process. Anderson et al. (1988), Arthur (1994), and Janszen and Degenaars (1998) suggest that an innovation process, and the relationships established between the elements in this process, sometimes reinforce (positive feedbacks) and sometimes balance (negative feedbacks) the dynamics of the system. The result is that innovation and technological change is a highly non-linear phenomenon making hazardous any extrapolation of trends, as well as impossible the prediction of the outcome. In short, SD can contribute to the analysis of innovation and technical change. Ford and Sterman (1998), Janszen and Degenaars (1998), Maier (1998), Pardue et al. (1999), and Cloutier and Boehlje (2002) give examples on how innovation research can be conducted using SD tools to get insight on this phenomenon.

Janszen and Degenaars (1998) analyze the dynamics of changes of innovation, new products and markets in the case of the Dutch biotechnology industry. The central idea in this work is that products and markets co-evolve simultaneously. In turn, changes in markets and the development of new products are the result of some kind of innovations supported by specific policies followed by public and private institutions. The SD simulation model developed by these authors contributes to make a comparison between innovative capabilities of a national system of innovation at different moments.

Cloutier and Boehlje (2002) analyze the diffusion of an innovation as a complex process. They demonstrate that the phases in order to develop a new product (R&D activities, commercialization, etc.) involve necessarily technology choices and uncertainty. Therefore, in a dynamic system, it is essential to identify the reinforcing and balancing feedback loops with significant time delays and timing decisions. These authors establish that from the micro perspective, the fundamental problem is to evaluate firm's R&D investment capabilities in order to evaluate expected profits under uncertainty. The problem is thus whether profits generated by new innovation investments are sufficient to cover costs through commercialization. To explore these ideas, these authors study the case of new corn genetics development. They analyze this case under the perspective that the dynamic product competition problem could be better understood with relationships between reinforcing loops between technologies, product strategies, interfirm coordination mechanisms and business environment (Sanchez, 1995).

Maier (1998) analyzes the diffusion of innovations over time. He also emphasizes that this is a highly dynamic and uncertain problem that it is influenced by factors like adequate time to market, pricing, advertising and quality of products. This scheme allows this author to investigate the process of invention, innovation and imitation (or diffusion) under the perspective of the SD approach. He argues that the use of SD methodology allows the development of more complex models to investigate the process of innovation and diffusion. In particular, the attempt of this author is to extend the traditional innovation models to incorporate competition and to map the process of substitution among successive product generations. In short, this model allows the author to evaluate the integration of feedback-decision variables into diffusion models (e.g., what structural elements are necessary to model substitution processes), to evaluate alternative pricing and manufacturing strategies, and to measure the consequence of alternative R&D budgets in order to develop successive product generations.

Pardue *et al.* (1999) analyze the rapidness and effectiveness in commercializing technical advances as critical features to guarantee high-technology industries success. They conduct this analysis for IT companies. The main characteristics they observe in this kind of industries are low inertia, rapid technological change, and swift technological obsolescence, making firms highly innovative. Commercialization, evolution of technical change and the ability of the firms to recognize the value of technical changes in order to assimilate and exploit it is the framework for this analysis. An important conclusion from this analysis is that the ability to recognize the value of technical changes, assimilate and exploit commercially those changes depends heavily on the appropriate investment of R&D carried out by the firm. Using the SD approach, these authors seek to overcome the limits of other approaches for the analysis of the innovation-diffusion process. In particular, they characterize more easily the dynamics of the innovation-diffusion process, the incremental improvement of old technologies as a defensive mean followed by some firms, and the fact that actual a diffusion process develops multiple innovations.

Another interesting analysis is developed by Ford and Sterman (1998). The main idea is that a complete causal dynamic project model must explicitly model and integrate the influence of four basic elements or subsystems: (1) processes structure; (2) resources; (3) targets; and (4) scope. These authors suggest that the development process, resources, scope, and targets of a project interact in complex ways to drive project performance. In this sense, this article is an attempt to demonstrate that traditional or static methods, as it is the case of the Critical Path Model (CPM), are inadequate as they are limited by the use of an indirect project measure and they establish the relationships among scope, resources, and processes into a single duration estimate. Besides, they ignore the way interactions are established between subsystems.

System Dynamics and Biotechnology

Although there are many studies on biotechnology-related industries, there are a few developed under the SD approach (Cloutier and Boehlje, 2002; Janszen and Degenaars, 1998; McMillan et al., 2000; Morecroft and Lane, 1989; Peters et al., 1998; Powell, 1998; Thomassin and Cloutier, 2001; Walsh et al., 1995). This section synthesizes the results achieved in some of these studies with special attention on how SD methods have been employed to analyze technical change and innovation processes as complex and with an uncertain outcome in the case of the biotechnology related-industries.

Janszen and Degenaars (1998) suggest that there are at least four reasons for considering competition and innovation performance quite differently than that in the traditional theoretical approach. These reasons are: (1) technical knowledge is actually an important source of competitive advantage and economic performance for the firm; (2) technical knowledge can be defused to other regions by means of information transfers yielding superior advantage only temporally; (3) competitiveness implies constantly generation and exploitation of new technologies; and (4) the decline-upraise process experimented by many industries is highly supported by the fact that innovative capabilities are subject to a dynamic process. However, the statements listed before are in contrast to the neoclassical propositions about competition and firm behavior.

In the analysis carried out by these authors, there is a demonstration of how institutions, organizations, markets, cultural values and norms, influence innovative activities. However, these variables taken together constitute a system of innovation. The approach proposed in this article is a suggestion on how technologies, products and markets co-evolve simultaneously. The features characterizing biotechnology-related industries can be explained within this theoretical framework. These authors found that co-evolution is the result of some kind of reinforcing and balancing feedback loops sufficient to explain the dynamics of any industrial development process. Moreover, technologies, products and markets co-evolve simultaneously, as they are associated to feedback loops that reinforce this process of evolution. In the same manner, institutional developments delays are associated to balancing feedback loops in the system.

Janszen and Degenaars (1998) also suggest that the most important features to be contained in a model like this would be: (1) presence of a scientific subsystem; (2) presence of technology suppliers; (3) presence of a venture capital market; (4) presence of a favorable home market; (5) presence of fast consumer acceptance of innovative products; (6) existence of consumer aversion of the innovation; (7) governmental subsidies; (8) governmental requirements; and (9) a patent law regime. This model has yielded important results as these hypotheses were empirically examined in the case of the Dutch biotechnology sector. For example, there were favorable conditions, particularly present in the Dutch market pharmaceutical industry, to develop biotechnology innovations. By contrast, the authors found that poor market conditions underlying the Dutch biotechnology agricultural sector prevented for developing new products. In this case, the explanation was that there was not a well-developed venture capital market to start up biotechnology innovation projects in the case of the agricultural sector.

Thomassin and Cloutier (2001) analyzed the case of the Canadian biotechnology that related agricultural and food industries to integrate institutional economics into a modeling framework. These authors also found some important casual relationships or feedback loops characterizing the dynamic behavior of the regulatory process of this sector. They emphasize the importance of some concerns by consumers and investors. For example, ethical considerations and potential environmental risks are the most important concerns for consumers. By the side of the investors, product and process perspectives, as regulatory uncertainty unknown product acceptance and long time delays between R&D and commercialization are mentioned as crucial determinants. The main conclusion achieved in this study is that biotechnology-related agricultural and food industries are characterized to follow a disruptive innovative process. Besides, they found that the participating actors – consumers, investors and regulators – align their strategic transactions and working rules of the regulatory framework that corresponds to a particular efficiency level of the sector.

Powell (1998) examines the importance of interorganizational linkages to knowledge diffusion, learning, and technology development understood as a new logic of organizing many driving technologically advanced industries. This author emphasizes the importance of knowledge-seeking and knowledge-creation for the firm as an adequate way of collaboration. In fact, collaboration can be viewed in two different forms: (1) on the transaction and the mutual exchange of rights; and (2) on the relationship and the mechanisms through which information flows and mutual adjustments take place. Actually, the way firms collaborate with each other can be formal (e.g. joint venture) or informal (e.g. participation in technical communities). Thus, in terms of collaboration among partner firms, there exist two alternative approaches. First, collaboration is viewed as a variant of market mechanisms for exchanging information (industrial organization and strategy approach), and second, collaboration is the result from the needs to combine existing competencies and capabilities with the abilities of others (sociology and organization theory approach). In the case of the biotechnology-related industries, this author suggest they are characterized by high uncertainty, as well as knowledge that is both complex and expanding, and thus the locus of innovation is found in networks of learning rather than in individual firms. The model proposed by Powell (1998) can be synthesized in the following terms. First, firms in technology-intensive fields must rely on collaborative relationships to access, survey, and exploit emerging technological opportunities. Second, this behavior followed by firms implies important changes by the side of the industrial structure. The industrial structure will be shaped by the new interorganizational relations established by firms. Third, the above statements will have four consequences: (1) collaboration will become an important entry barrier (strategic motives); (2) cooperation will accelerate the rate of technological innovation (learning considerations to gain access to new knowledge); (3) collaboration will imply some transformation effects on all participants (connectivity to an inter-organizational network); and (4) collaboration will become a new dimension of competition.

McMillan et al. (2000) analyze biotechnology-related industries focusing on how these industries highly depend on public science. External knowledge is actually a condition to enhance internal innovation efforts. This study is conducted from the perspective of the absorptive capacity model proposed by Cohen and Levinthal (1989, 1990). In this model, absorptive capacity is defined as the ability of a firm to recognize new information, assimilate it, and apply it to commercial ends. Therefore, the exploitation of basic scientific discoveries requires an organization to continuously learn from beyond its boundaries. The argument proposed by McMillan et al. (2000) is that biotechnology-related industries behavior can be widely explain within this framework. Thus, within this framework, biotechnology-related companies play the role of transferring knowledge from public laboratories, universities and public research centers to the marketplace. The study then is an attempt to prove the fact that the longer a company had been public or linked to public knowledge, the more successful innovations it had.

Conclusions

This paper analyzed important issues linked by the principle suggesting that technical change and the innovation process was a complex phenomenon. In this regard, the paper analyzed the SD approach in economics and management. The core idea of this part suggested the SD method was an adequate research approach to examine complex processes like those followed by technological change and innovation processes. An important principle analyzed in this paper suggests that it would be possible to know and characterize the underlying structure of an organization through the SD methodology. We concluded that structure, complexity and uncertainty were concepts strongly related. SD authors suggested that complexity in business systems emerged because those systems are dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent, self-organizing, adaptive, counterintuitive, policy resistant, and characterized by trade-offs. In the same manner, the paper explains how business systems would become increasingly subject to accelerated change and uncertainty. The paper emphasizes the importance of simulation and experimentation in SD works that allows evaluating change in systems over time. Bounded rationality is constantly present in SD models. And so, complexity, bounded rationality and misperception in decision-makers mental models are important reasons to use SD methods as an adequate framework to analyze technological change and innovation processes.

On the other hand, Janszen and Degenaars, for instance, suggested that technical change and innovation were complex phenomena. Cloutier and Boehlje identified reinforcing and balancing feedback structures in economic and management systems. Cloutier and Boehlje found that the diffusion of an innovation was a complex process, involving technology choices and uncertainty. In this sense, other authors like Andersen, and Janszen and Degenaars suggested that an innovation process sometimes would reinforce and sometimes would balance the dynamics of a business system making innovation and technological change a highly non-linear phenomenon. Maier analyzed the diffusion of an innovation over time. This author found that the success of an innovation into the marketplace was influenced by factors like adequate time to market, pricing, advertising and quality of products. In relation to biotechnology and SD, this paper analyzed the works of Cloutier and Boehlje, Janszen and Degenaars, Powell, and Thomassin and Cloutier. Thomassin and Cloutier analyzed the case of the Canadian biotechnology related to agricultural and food industries.

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