Science, Technology and Innovation Policy within RIS: A SD Approach

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\textbf{Resumen} – La dinámica de sistemas (SD) se ha convertido en una herramienta importante para desarrollar nuevas teorías en las ciencias sociales. Este enfoque permite analizar a los sistemas regionales de innovación en términos de los actores, enlaces, y retrasos en el tiempo que los caracterizan. El objetivo de este trabajo es doble. En primer lugar, se analiza la posibilidad de estudiar los sistemas regionales de innovación desde la perspectiva de los métodos que derivan de la DS. En segundo lugar, se evalúa la política de ciencia y tecnología en términos de escenarios alternativos y con el objetivo de apoyar la transferencia de tecnología y las actividades de innovación a nivel regional. En este documento se analiza el caso de la provincia de Michoacán en México.

\textbf{Palabras Clave} – economías emergentes; México; sistemas regionales de innovación; política de ciencia, tecnología e innovación; dinámica de sistemas.

\textbf{Abstract} – System dynamics (SD) has become an important tool to develop new theories in social sciences. It allows analysing regional innovation systems in terms of actors, links, and time delays characterising innovation systems. The aim of this paper is twofold. First, it discusses the relevance of analysing regional innovation systems from the perspective of SD methods. Second, it evaluates alternative science and technology policy scenarios aiming to support technology transfer and innovation activities. The paper analyses the case of the province of Michoacán in Mexico.

\textbf{Keywords} – emerging economies; Mexico; regional innovation systems; science, technology and innovation policy; system dynamics.

\textbf{1. INTRODUCCIÓN}

The results discussed in this paper draw from a larger research project on regional innovation systems, economic growth and competitiveness in emerging economies [1, 2]. In this paper, however, we discuss the possibility to develop key indicators of science, technology and innovation activity within regional innovation systems, as well as a supporting mechanism to design a suitable science, technology and innovation policy in order to improve innovation activities and economic growth at regional level. To achieve this objective, we model a regional innovation system as a complex adaptive system that allows explaining how unexpected results can be achieved from implementing alternative science, technology and innovation policies.

The theoretical approach of innovation developed from the perspective of the innovation systems is not new. In this approach, it is assumed that the innovation process is a systemic phenomenon that follows a not linear trajectory [3, 4]. In addition, it is implied in this approach that innovation is central to competitiveness among firms, and thus that it is pervasive when underpinning economic growth [3]. In this regard, the systemic framework for innovation emphasises the importance of the relationships between sectors as a fundamental explanation to elucidate the performance of innovation systems [4].

Yet, from the perspective of the SD methods, bounded rationality, time delays, and feedback effects in an innovation system could be generating unexpected results when implementing a specific targeting science, technology and innovation policy. In fact, the perspective derived from the SD methods allows analysing institutions, organisations and policies endogenous to an economic system [5]. Furthermore, this approach also allows evaluating the probable evolution of the system resulting from alternative policy scenarios.
To achieve this objective, we developed a regional innovation system from the perspective of system dynamics methods. In so doing, we stress the importance of the SD approach to theory building in social science. In addition, we stress the importance of this approach to develop key indicators of science, technology and innovation activities to sustain a plausible science and technology policy in a regional innovation system. In addition to this introduction, this paper contains four sections. Section two examines the steps required to develop a theory at different levels of analysis [6, 7, 8]. Section three discusses the relation between regional innovation systems and complex adaptive systems stressing the importance of how regional innovation systems in the case of emerging economies emerge and evolve to support regional economic growth through sustaining indigenous firms in the transition to a more innovative and competitive economy, given that in the case of these economies an interactive learning and innovation process may take place at regional level [9]. Section four discusses a causal loop diagram of regional innovation system in the case of emerging economies, exemplifying this discussion with the case of the province of Michoacán in Mexico. Section five presents the main results from the simulation model under alternative policy scenarios. Section six presents some conclusions from the analysis developed in this paper.

2. SD AS A THEORY BUILDING APPROACH IN SOCIAL SCIENCE

SD simulation is a methodological approach that contributes to theory development. It provides a precise means of specifying the assumptions and theoretical logic of a theory [6, 8]. However, this approach of theory development requires to following several steps [6]:

- definition of research questions
- choosing a simulation approach
- definition of a computational representation
- verification of computational representation
- model simulation and experimentation (operationalising constructs, building algorithms, and specifying assumptions)
- model validation.

The SD approach on theory building offers a four theory development at different levels [7]. At the higher level is the claim that the time evolutionary behaviour of social systems is explainable in terms of feedback loops and state variables. Moving down to the next theory, we find the principle of how the concepts of feedback loop and state variables should be used to construct models. A more specific theory is that, unassisted, humans cannot infer the behaviour of systems represented in the above fashion in a way which is logically consistent in that computers are needed to deduce the behaviour. Finally, we come to the idea that each model is a theory.

On the other hand, it is worth saying that simulation models in social sciences may contribute to understanding social phenomena in the real world since they are a significant methodological approach to theory development [6, 8]. Actually, social sciences modelling have generated a great interest among scholars and policy makers as a means to evaluate policy implications resulting from alternative scenarios. In social sciences, the SD approach has proved to be an adequate conceptual and methodological framework that allows systems of innovation theory to become a more formalised and precise approach [5, 10]. The value of SD models when studying innovation systems can be summarised in the following statements [5]:

- they contribute to clarify the underlying causal relationships between variables of the system
- they are useful dealing with time
- they are useful when data are scarce
- they can summarise and simplify the main assumptions and hypothesis of the model
- they uncover data to clarify the importance of different variables
- they explore new possibilities when developing theories.

Consequently, SD simulation models may contribute to theory development when the theoretical focus involves multiple and interacting processes, time delays and other nonlinear effects as they provide an analytically precise means of specifying propositions linking constructs, assumptions, and a coherent theoretical logic underlying the theory [6].

3. REGIONAL INNOVATION SYSTEMS AND COMPLEX ADAPTIVE SYSTEMS

Nowadays, there is a great interest and acceptance among academics and public policy makers to analyse systems of innovation from a systems perspective, given that innovation systems involve many actors, structures and interactions [5, 10, 11, 12, 13, 14, 15]. Actually, this approach allows analysing institutions, organizations, and policies endogenous to the economic system [5], and thus
it allows evaluating the probable evolution of a system that may result from alternative policy scenarios. Therefore, there are at least two reasons to favour a systemic approach when analysing regional innovation systems [14]. First, each particular regional innovation system has its own characteristics. Second, it is necessary to give a dynamic description of the configuration of systems of innovation in order to forecast the probable evolution in the near future. Moreover, from this perspective, many scholars agree with the idea that systems of innovation may be analysed from the viewpoint of the complex adaptive systems [5, 12, 14, 16], given that this approach may contribute to getting insight on the nature of the relationships established between different actors in the process of technology transfer and innovation developments [14, 16, 17]. Certainly, the complex adaptive system approach is based on four dimensions [18]:

- the number of elements that make up the system
- the attributes of the elements
- the number and type of interactions among the elements
- the degree of organisation inherit in the system.

In the case of emerging economies, the main concern about regional innovation systems is how they emerge and evolve to support regional economic growth through sustaining indigenous firms in the transition to a more innovative and competitive economy [9]. Actually, the regional innovation systems approach may allow explaining how learning interactions with other actors may generate some kind of technological spillovers, and hence innovation capability developments among indigenous firms. Nevertheless, in the case of emerging economies, the design of a science, technology and innovation policy at a regional level should be capable to develop a self-containing regional innovation system since in these countries innovation systems are characterised by being highly immature [9].

On the other hand, also in the case of emerging economies, special attention must be paid to the systemic approach when analysing regional innovation systems, given that it is implied an interactive learning and innovation process that takes place at regional level. The reason of this concern is that firms in emerging economies are more dependent on complex and tacit knowledge, and thus less dependent in using codified knowledge [9].

4. A CLD OF A REGIONAL INNOVATION SYSTEM

In this research, we suggest that regional innovation systems are composed by multiple dimensions (variables), each of which is associated with its own rate and direction of change and causally connected to produce patterns of change in the innovation system [19]. From this perspective, we assume that modelling complex systems is an important analytical tool in social science, given that social and economic phenomena can be seen as dynamic systems that commonly exhibit three characteristics [16]:

- they are made up of a large number of elements
- they exhibit significant interactions among these elements
- they can be organised in a system.

In addition, the construction of models based on SD methods have become a mechanism for developing new theories in social sciences, given that this approach stresses the importance of the structure of the system when determining the behaviour and relationships in which the system operates [6, 17, 20, 21, 22]. Furthermore, the SD modelling approach allows establishing cause and effect relationships between variables that define the behaviour of the system [23]. In consequence, models developed under this approach are characterised by a series of feedback loops (reinforcing and balancing) and time delays that describe the complexity of the system [21].

However, the basic concepts making up a system can be classified as resources and information, and levels and rates [24]. The difference between resources and information is essential when building a model from the perspective of SD methods, given that resources should be understood as "physical objects" that become part of the processes that take place within a system, while information is the non-physical means by which control of the resource transformations is exercised [24].

On other hand, levels (stocks) and rates (flows) reveal the true dynamics of the system [24]. The SD approach provides insights on the structure that characterises the systems of innovation, distinguishing between their strategic directions and underlying mechanisms that drive individual actions and govern their interactions with other agents within the system [12, 13]. Indeed, a SD
model should contain a series of feedback loops between causes and effects that explain how actors are interrelated and the nature of these interrelationships. Four basic elements characterise SD models [25]:

- feedback loops
- flows and stocks structure
- time delays
- nonlinearities.

These characteristics reveal the fact that innovation systems can be seen as complex multi-loop systems interconnected within a structure that reinforces multiple feedback processes [26]. In fact, there are two different types of loops: reinforcing (positive) loops and balancing (negative) loops. Reinforcing or positive loops should be understood as a change that is reinforced by generating major changes which are self-reinforcing [21, 27, 28], while balancing or negative loops should be understood as a force which is self-seeking or self-correcting [21, 28, 29]. As a result, the models built from the perspective of the SD methods can be seen as complex systems with a high degree of uncertainty. Moreover, these features characterise the systems of innovation as constantly evolving systems in a disequilibrium, nonlinear, historically dependent, self-regulating, adaptive, and counterintuitive trajectory, making them to be resistant to policy [21]. Indeed, these features mean that symptoms, actions and solutions will not remain isolated as a linear process of cause and effect [24].

Particularly, in the case of the province of Michoacán in Mexico, the first task is to determine the boundaries of the regional innovation system that contains the different actors that in turn generate and use science and technology as a key factor allowing increasing businesses competitiveness in this province. However, each actor must be analysed from the perspective consistent with the role they are playing in the process of generating and using science and technology for achieving higher levels of economic growth. Actually, from the perspective of SD methods, we highlight the role played by the articulation of competencies and skills as attributes of firms within the system that shapes a regional innovation system [13]. In this sense, the SD approach allows analysing the behaviour of the actors within the system, taking into account their strategic direction and underlying mechanisms that drive their actions individually and govern their interactions with other actors [13]. In the case of the innovation system involving different actors who use science and technology in the province of Michoacán, the regional innovation system characterising this province can be analysed through a causal loop diagram (Figure1).

The causal loop diagram (CLD) in Figure 1 explains the production and use of science and technology in this province. The diagram is characterised by eighteen reinforcing (positive) loops, and three balancing (negative) loops. The loop R1 explains how basic research expenditure undertaken by universities generates research results after a time delay. It is assumed an average time delay of two years for successfully acquiring research results. However, once research results have been acquired, they can alternatively be published in academic journals, or transferred to applied research developing projects (research and development projects). Nevertheless, when research results are published in scholarly journals, there will be a positive impact on the province budget to developing new research projects. As in the loop R1, the loop R2 emphasises the same impact on basic science results from the point view of the federal budget for developing new research projects.

The loops R3 and R4 explain how the academic staff and researchers involved in obtaining basic research results may be capable to develop applied research results after a time delay. These loops explain how research results can be evaluated in terms of opportunity and appropriability. However, such an evaluation may result in a more quantity of funding resources from CONACYT and
COECYT in order to support research projects at universities.

The loop R5 shows the relationship between basic and applied research results involving doctoral and master graduate students. When a large number of graduate students are involved in generating basic research results, a more quantity of applied research results will be achieved by means of province government support through COECYT programs. This loop is also characterised by two time delays: the average time to obtain basic research results (two years) plus the average time to obtain applied research results (one year). In the same way, the loop R6 explains how graduate students may publish basic research results. An important feature in this loop is that when academic productivity of graduate students increases, there will be more resources from government agencies such as the COECYT and CONACYT to finance new research projects.

The loops R7 and R8 show the possibility to include graduate students in the generation of applied research results that are evaluated by opportunity and appropriability. These loops explain how companies adopt new technologies knowledge developed at universities by means of hiring graduate students. Particularly, the loop R7 shows the evaluation processes by COECYT, while the loop R8 show this evaluation process taking into account programs launched by CONACYT to foster innovation projects.

The loops R9 and R10 show the relation between applied research expenditure and budget to finance graduate students by COECYT. However, the loop R10 takes into account the fact that applied research results eventually become innovations coming out from industry. This loop reflects the idea that knowledge flows between firms and universities can flow in both directions at the time of developing innovations.

The loops R11 and R12 extend the ideas discussed in the previous loops. In this sense, once applied research results are achieved, firms may develop other innovations by creating incentives for academics and researchers at universities. In practice, the meaning of this process can go alternatively from academics and researchers to applied research results, respectively. In both cases, there is a time delay when generating both basic and applied research results. This relationship can be mediated through some government agencies in charge of accelerating the innovation process in order to generate a greater number of innovations. In fact, this is the case of the loops R13 and R14 that involve COECYT programs of technology transfer.

The loops R15 and R16 reflect the same idea of technology transfer through generating new knowledge at universities, but assessing the degree of opportunity and appropriability of research results. In the same manner, the loops R17 and R18 reflect this idea but taking into account CONACYT programs.

Finally, the balancing loop B1 shows that when an innovation is not ready for the market, companies must seek to gain a greater degree of appropriability through the generation and use of some form of intellectual property, mainly patents. In practice, the use of intellectual property becomes a mechanism by which a company guarantees to obtain economic rents. However, this process involves the support of some government offices to facilitate the process of technology transfer from universities to industry, such as it is the case of COECYT. In other cases, technology transfer goes directly from universities to industry. In these cases, the process of technology transfer may imply a process of re-evaluation for appropriability. This is precisely what explains the balancing loop B2 that may include a government agency in the process of evaluation fror appropriability. In the case of the loop B3, this loop also includes the same idea that previously discussed in the case of the loop B2, but taking into account CONACYT as the government agency in charge of testing for appropriability.

5. SIMULATION RESULTS

The model consists of 111 variables: 21 stock or level variables, 56 flow variables, and 34 parameters. The stock and flow variables allow generating a set of indicators in relation to the scientific, technology and innovation activity in this region. The validation and calibration process of the model was carried out taking into account information generated by some federal and province agencies in charge of science and technology policy in this region. To calibrate the model, other statistic data information from SEP was used. In this case, the indicators presented in this paper are an example on how this model can contribute to design a particular science, technology and innovation policy. The indicators reported in this paper are: number of publications, number of researchers, researchers in the national system of researchers, basic research results,
applied research results, number of innovations, and total number of citations. The model was simulated for the years 2008, 2010, 2015 and 2020.

The simulation results presented in this paper demonstrate how this model can be used to design and evaluate an appropriate science, technology and innovation policy in order to foster innovation capabilities within a regional innovation system. In this regard, it is worthy saying that the results drawn from the simulation of the science, technology and innovation model developed in this research may become a valuable tool to simulate and evaluate alternative science, technology and innovation policy scenarios. Table 1 shows the results of the simulation model developed in this paper.

Table 1. Simulation Results: Indicators of a RIS in México

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<th>Year</th>
<th>Number of Publications</th>
<th>Number of Researchers</th>
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<tr>
<td>2008</td>
<td>108</td>
<td>449</td>
<td>414</td>
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<tr>
<td>2010</td>
<td>172</td>
<td>459</td>
<td>440</td>
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<tr>
<td>2015</td>
<td>273</td>
<td>486</td>
<td>513</td>
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<tr>
<td>2020</td>
<td>359</td>
<td>515</td>
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The results in Table 1 show the behaviour of some selected indicators when generating and using science and technology in the province of Michoacán in Mexico. The results were simulated for the years 2008, 2010, 2015 and 2020 under certain assumptions. These assumptions aim to capture the actual structure of the regional innovation system characterising this province of Mexico. However, this model can generate a greater number of indicators and behaviour for different periods of time. From these results, the behaviour of total number of publications, total number of researchers, researchers in the national system of researchers, basic research results, applied research results, total number of innovations, and total number of citations show a growing trend during in the years of the simulation. However, applied research results and total number of innovations show poor performance in their behaviour.

As an overall explanation to these results, the simulation suggest that there is little interest from researchers in this province to conduct applied research projects in order to develop innovations. In addition, the absence of incentives to commercialise the results of research projects creates a poor development in the number of new projects funded by federal and province agencies in charge of designing science, technology and innovation policies. Finally, the absence of a suitable environment to commercialise applied research results contributes to explain the poor development of new projects and innovations.

6. CONCLUSIONS

This paper discusses the possibility of developing suitable indicators when designing a science, technology and innovation policy. The generation and development of these indicators is drawn using SD methods. In fact, the analysis in this paper concerns the possibility of developing a SD model that may contribute to evaluate innovation activities within a regional innovation system [30, 31].

Another important conclusion in this paper concerns to the fact that the behaviour of these indicators is drawn from the structure characterising this regional innovation system. This conclusion demonstrates how bounded rationality, feedback effects, and time delays may generate unexpected outcomes when a science and technology policy is implemented in a regional innovation system. In addition, these insights demonstrate the usefulness of SD methods to the analysis of complex adaptive systems. Actually, this feature directly draws from the case analysed in this paper, mainly the case of a regional innovation system in the province of Michoacán in Mexico.

In case of this province, the structure characterising its innovation system is determined by the actors involved in the process of generating and transferring knowledge and technology, and thus by the relations established between these actors. Important, this model may allow designing a priori evaluation of alternative science, technology and innovation policies aiming to foster scientific and technological advances to promote innovation activities. Although the number of indicators simulated in this model is too large, this report only presents some of them.

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