A system dynamics model of science, technology and innovation policy to sustain regional innovation systems in emerging economies

José Carlos Rodríguez*
Economic and Business Research Institute,
Universidad Michoacana de San Nicolás de Hidalgo,
Ciudad Universitaria, Edificio ININEE,
Morelia, Mich., 58004, Mexico
and
Institut National de la Recherche Scientifique,
Centre – Urbanisation Culture Société,
385, rue Sherbrooke Est,
Montreal QC, H2X 1E3 Canada
Email: jcrodriguez@umich.mx
*Corresponding author

César L. Navarro-Chávez
Economic and Business Research Institute,
Universidad Michoacana de San Nicolás de Hidalgo,
Ciudad Universitaria, Edificio ININEE,
Morelia, Mich., 58004, Mexico
Email: cnavarro@umich.mx

Abstract: System dynamics (SD) models have become an important tool to develop new theories in social sciences. This approach allows analysing science, technology and innovation (STI) policy within the structure of the system where this process is carried out. In this regard, the main objective of this research is two-fold. First, it aims to develop an SD model of a RIS in the case of emerging economies. Second, it aims to demonstrate how a set of STI indicators can be simulated with this model. In this paper, it is argued that STI indicators are needed to design a timely and accurate STI policy that support innovation activity at a regional level. However, the SD approach provides an adequate framework to integrate into the same analysis key institutions that support the generation and diffusion of technology and new knowledge. The case of the RIS of the province of Michoacán in Mexico is analysed in this paper.

Keywords: regional innovation systems; RISs; science, technology and innovation policy; knowledge and technology transfer; system dynamics; emerging economies.

Introduction

This paper presents results of a larger research project on knowledge transfer and regional innovation system (RIS) in emerging economies (Rodríguez and Gómez, 2012; Rodríguez et al., 2014). System dynamics (SD) methods are applied to simulate a general model of a RIS in the case of emerging economies. In addition, it is also demonstrated how a SD model of a RIS can contribute to simulate a set of science, technology and innovation (STI) indicators to support policy design. The core idea is that simulation models in social sciences are developed to understand the real world given that it is highly complex (Sawyer, 2004). In this sense, SD models may contribute to develop new theories in social sciences since they contribute to get insight on how the structure of a system influences its behaviour and established relationships (Morecroft, 2007; Schwaninger and Grösser, 2008; Sterman, 2000). The value of simulation models to STI developments lies in the possibility of identifying the structure that combines science and technology within the same process where they are carried out.

The objective of this paper is two-fold. First, it aims to develop a SD model of a RIS in the case of emerging economies. Second, it aims to demonstrate how SD methods can be used to develop a set of STI indicators. However, both objectives can be achieved simultaneously given that they result from the dynamics characterising a SD model of an innovation system. An underlying idea in this research is thus that the lack of timely STI indicators might be an obstacle to define an accurate and suitable STI policy that truly supports innovation activity at regional level. In the case of emerging economies, an
accurate and suitable STI policy would be necessary if less-developed regions aim to catch up with other advanced regions. Therefore, the research questions conducting this research are: how SD methods may contribute to model RISs in the case of emerging economies? And how RISs models may contribute to simulate STI indicators to support the evaluation of alternative STI policy scenarios? To answer these questions, a simulation model of the RIS of the province of Michoacán in Mexico is developed. In this case, this model aims to capture the structure of the RIS characterising this province, and thus to get insight on the features characterising knowledge and technology transfer at regional level. The challenge is to demonstrate how the generation, diffusion and use of technology and scientific knowledge determine the structure of RISs in the case of emerging economies. However, some types of system failures may appear at the time of transferring new knowledge and technology from universities to industry (Rodríguez et al., 2014).

Yet, the analysis of STI policy from the perspective of the innovation systems theory provides an adequate framework to integrate into the same analysis key institutions and actors in charge of generating science and technology (Niosi, 2008). This fact reveals the particular role played by the articulation of firms, research institutions and government agencies within a system. The focus of the RISs theory may contribute to analyse the behaviour of actors and institutions in a system, taking into account the strategic direction and underlying mechanisms driving their actions individually, and their interactions with other actors within the same system (Niosi, 2008). In addition, this fact reveals the idea that multiple variables and actors causally linked up with each other may be associated with a distinct rate and direction of change (McCarthy et al., 2010), and thus it allows explaining how some tensions emerge between actors and other stakeholders within the same system at the moment of transferring technology and scientific knowledge to industry (Rodríguez et al., 2014). In fact, each variable is associated with its own rate and direction of change causally connected to other variables and producing patterns of change in each system (McCarthy et al., 2010).

In addition to this introduction, this paper is organised into five sections. Section 2 provides a literature review on RISs and the systemic approach on innovation systems, stressing the case of RISs in emerging economies. Section 3 discusses a SD model of a RIS in the case of emerging economies. The case of the province of Michoacán in Mexico is analysed in this section. Section 4 discusses some important features in relation to model simulation of a RIS in the case of emerging economies. Section 5 presents the main conclusions achieved in this research.

2 Literature review

2.1 RIS and the systemic perspective on innovation systems

The concept of innovation systems has evolved as a useful tool to analyse economic development. Since Freeman (1987), Lundvall (1992) and Nelson (1993), this approach has undergone several changes shifting from national to regional, sectoral/technological, or even global. The innovation systems perspective has taken an increased analytical importance in the technology field due to three factors (OECD, 1997). First, it recognises the importance of knowledge to economic development. Second, the use of the systems approach is increasingly observed in the field of science and technology. Finally, there
are a growing number of institutions involved in the process of knowledge transfer. On the other hand, at regional level, the concept of RISs is relatively new (Cooke, 2001). This concept suggests that regional innovation policies have been also the basis for boosting competitiveness at national level (Cooke, 2001; Cooke and Memedovic, 2003; Porter, 1990, 1998). In this regard, RISs display two important features (Niosi, 2000): they are a combination of public policies, and they are a spontaneous market development of competencies. Certainly, these features have made the RISs approach an appropriate framework to study economic development and competitiveness at regional level.

The RISs approach has gained importance because of the emergence of the knowledge-based economy at least for three reasons (Cooke, 2001; Cooke and Memedovic, 2003). First, at regional level, the RISs approach has revealed the importance of developing a research infrastructure. Second, this approach has also revealed the need to develop a highly qualified workforce. Third, an important component when developing RISs should be to advance an innovative culture. However, the study of STI policy has provided a general theoretical framework to integrate into the same analysis key institutions and actors that produce and use science and technology to support regional economic development (Niosi, 2008). This notion may be useful to describe the behaviour of key actors and institutions in RISs, on the one hand, and the links established between actors and institutions in the innovation process at the time of transferring – generation, diffusion and use – new knowledge and technology within a system, on the other. The RISs approach, therefore, should comprise all actors and institutions underlying the production system that are established, responsible, or related to enhance the innovation process (Edquist and Johnson, 1997).

RISs should be understood as a set of institutions and their related links that can produce, disseminate and adapt regionally new technical knowledge in order to improve firms’ innovative capabilities and competitiveness (Niosi, 2002). The set of institutions and related links that set up a RIS should include firms, universities, research centres and higher education institutions, federal and province agencies in charge of designing STI policies, and the interrelationships established between actors and institutions such as flows of technological, financial and human resources, and regulatory and trade relations, as well (Niosi, 2002). The flows and links comprising a RIS are the flows between government and private organisations, the human flows between universities, companies, public agencies, and governmental regulations emanating from these agencies in order to foster innovation capabilities within organisations, and the flows of scientific and technological knowledge generated from universities and other higher education institutions (Niosi, 2002). In the case of emerging economies, it is not only the creation of new knowledge that accounts for defining a RIS, but the aptitude towards absorbing and transferring new knowledge for innovation purpose (Feria and Hidalgo, 2011). The generation and use of technology and scientific knowledge for innovation purpose have to involve many actors and institutions that set up a RIS. The RISs approach is hence an important tool to analyse economic development at regional level given that, generally, the economic structures characterising a region are composed of only a few sectors that are really innovative (Niosi, 2008). Importantly, in the analysis of RISs, it is essential to distinguish between knowledge production and knowledge diffusion, and thus the way innovation systems operate by means of introducing new knowledge in the economy through interconnected organisations (Lundvall, 1992; Nelson, 1993).
The perspective of RISs suggests that learning interactions between actors in a system can generate technological spillovers that contribute to develop innovation capabilities among firms (Chaminade et al., 2012). This process can be highly complex given that the innovation process is perceived as a systemic phenomenon that is pervasive and central to explain competitiveness among firms (Bergek et al., 2008; Smith, 2000; Woolthuis et al., 2005). The innovation process therefore cannot be longer seen as a process of discovery, but rather as a nonlinear process of learning (Mytelka and Smith, 2002), involving complex interactions between many actors and their environment (Cooke et al., 1997; Niosi, 2010; Smith, 2000; Stamboulis, 2007; Viale and Pozzali, 2010). Moreover, from the systemic perspective, the innovation systems theory allows analysing institutions and organisations to be endogenous to the economic system (Niosi, 2010), and thus as a complex system phenomenon (McCarthy, 2003; Niosi, 2010; Schwaninger and Grösser, 2008; Viale and Pozzali, 2010).

Finally, it is important to mention that there are at least two reasons to favour a systemic approach in the analysis of RISs (Viale and Pozzali, 2010). First, each particular RIS has its own features and characteristics. Second, it is necessary to give a dynamic description of the configuration of each RIS in order to forecast its likely evolution. As already stated before, this perspective implies that RISs are composed by multiple dimensions (variables), each of which is associated with its own rate and direction of change causally connected to produce patterns of change in each system (McCarthy et al., 2010).

2.2 Innovation systems and system dynamics

Simulation models in social sciences contribute to understand social phenomena in the real world (Sawyer, 2004). Indeed, modelling in social science has generated a great interest by many scholars and STI policy makers given that it allows evaluating alternative STI policies. Modelling innovation systems by means of SD methods has acquired great importance as they exhibit three important characteristics (McCarthy, 2003): they are made up of a large number of elements, they exhibit significant interactions among elements, and they can be organised in a system. In fact, SD models have become an important mechanism to develop new theories in social sciences given that this approach stresses the importance of the structure of a system getting insight on the behaviour and relationships in which the system operates (Morecroft, 2007; Sterman, 2000; Schwaninger and Grösser, 2008). In this sense, the model developed in this research demonstrates how the generation of new knowledge depends on the structure where this process is carried out. However, SD methods allow establishing cause and effect relationships between variables that define the behaviour of a system.

SD models are characterised by a set of feedback loops and time delays that describe the complexity of a system (Sterman, 2000). Yet, the basic concepts making up a system can be classified under two categories (Pidd, 2009): resources and information, on the one hand, and levels and rates, on the other. The difference between resources and information is essential when building up a model. Resources should be understood as ‘physical objects’ that become part of the processes that take place within a system, while levels (stocks) and rates (flows) reveal the true dynamics of a system (Pidd, 2009). These characterises allow distinguishing between different innovation systems in terms of their strategic direction and underlying mechanisms that drive individual actions and govern their interactions with other agents (Stamboulis, 2007). By consequence, these
characteristics allow establishing SD simulation models as a set of feedback loops between causes and effects (closed path of actions and information) that explain how actors are interrelated, as well as the nature of these interrelationships.

To develop a SD model, four basic elements must be present (Forrester, 1975): feedback loops, the flows and stocks structure, time delays, and nonlinearities. These elements together contribute to reveal the true nature of innovation systems as a complex multi-loop system interconnected within a structure that reinforces multiple feedback processes (Forrester, 1995). Therefore, it is essential to distinguish between two different types of feedback loops when modelling SD models (Sterman, 2000): reinforcing (positive) feedback loops and balancing (negative) feedback loops. Reinforcing (positive) feedback loops should be understood as a change that reinforces major changes, while balancing (negative) feedback loops should be understood as a force seeking a target (Kirkwood, 1998), and hence SD models can be seen as complex systems with a high degree of uncertainty (Sterman, 2000). In practice, these features imply that systems are constantly evolving in disequilibrium, nonlinear, historically dependent, self-regulating, adaptive, and counterintuitive trajectory, making them policy resistant (Sterman, 2000). In strategic terms, these features mean that symptoms, actions and solutions will not remain isolated as a linear process of cause and effect (Pidd, 2009).

2.3 RISs in emerging economies

Federal states or provinces in Mexico are autonomous political entities that could be understood as independent regions capable of defining their own STI policy. From this perspective, the RISs approach can be seen as an adequate framework to analyse innovation and competitiveness at regional level in this country. In turn, this approach opens up the possibility of developing specific government policies to regionally sustain and stimulate innovation and economic development by means of supporting indigenous small and medium size firms (Cooke and Memedovic, 2003). However, there are some important differences between the two approaches of RISs and national innovation systems (NISs) (Cooke, 2001; Cooke and Memedovic, 2003). First, given that production and innovation processes develop on a global scale and become more science based, regions should take advantage of their specific resources such as a supportive environment for innovative firms (research infrastructure, highly qualified workforce and innovative culture), and therefore from the private actions of the market to interventions of specific government programmes and schemes (Cooke and Memedovic, 2003).

Second, this principle may suggest that the theoretical approach justifying the RISs theory as an adequate framework to analyse innovation at regional level may imply other particularities. Innovation can be focused from a regional perspective given that globalised and national firms can take advantage of specific resources at regional level when they organised their production and innovation processes (Cooke and Memedovic, 2003; Niosi, 2000). In addition, from this perspective, STI policy can be supportive for developing a research infrastructure, a highly qualified workforce, and an innovative culture that may support innovation activity at regional level given that economic growth and competitiveness depend largely on the capacity of indigenous firms to innovate (Cooke and Memedovic, 2003).

Third, from a different perspective, the RISs approach allows including in the same analysis the actors and institutions in charge of developing innovation activity at regional level (e.g., innovative firms, universities and higher education institutions, government
A system dynamics model of STI policy to sustain RISs agencies, and so on), and thus this analysis allows studying government policy actions for enhancing regional innovation by balancing market and public policy relationships (Cooke and Memedovic, 2003). The fact is that regions represent more meaningful communities of economic interest that allow taking advantage of true linkages and synergies among actors (Cooke and Memedovic, 2003).

Finally, in the case of emerging economies, RISs are of particular interest given that this theory has become an adequate approach to explain how some regions are falling behind in relation to other successful regions with highly industrialisation, development and upgrading paths (Padilla-Pérez et al., 2009). Furthermore, analysing and constructing RISs in the case of emerging economies could be a means of facilitating catching-up processes in indigenous firms (Asheim et al., 2007). However, in the case of emerging economies, these differences draw fundamentally from different theoretical challenges as RISs are embedded in different institutional frameworks (Padilla-Pérez et al., 2009). Indeed, RISs in emerging economies are commonly characterised by weak indigenous formal institutions, strong international governance bodies and temporal specificities relying on capital and knowledge that originate nationally in other regions and from abroad (Padilla-Pérez et al., 2009). Companies’ objective in emerging economies is mainly to catching up rather than being first mover, and thus the aim is not only to develop firm-level innovation capabilities but the development of regional capabilities that display high path-dependence and cumulativeness (Padilla-Pérez et al., 2009). However, RISs in the case of emerging economies do not show a high degree of integration and interaction and are more dependent on external flows of knowledge and technology (Padilla-Pérez et al., 2009). Therefore, the analysis of RISs in emerging economies allows raising the following research questions: how SD methods may contribute to model RISs in the case of emerging economies? And how RISs models may contribute to simulate STI indicators to support the evaluation of alternative STI policy scenarios?

3 Empirics

3.1 A CLD of RISs in emerging economies

RISs should include all actors and institutions involved in developing, finding and exploiting technology and scientific knowledge to enhance competitiveness among firms. Particularly, RISs provide an adequate theoretical framework to include in the same analysis key institutions in charge of developing science and technology for economic development. In this regard, RISs reveal the actual dynamics of the relationships established between actors and institutions that set up an innovation system at regional level. However, in this paper, an important task is to determine the boundaries of a RIS in the case of the province of Michoacán in Mexico. Consequently, it is necessary to determine the main actors that use and produce scientific knowledge and technology advances in order to increase competitiveness among indigenous firms. These actors are universities and higher education institutions, province and federal government agencies in charge of supporting STI, and innovative firms. Yet, each actor in this innovation system should be analysed from the perspective of the role they play at the moment of generating, transferring and using science and technology for innovation purpose.
The possibility of developing a mature RIS in the province of Michoacán in Mexico might be influenced by some important features (Rodríguez et al., 2014). First, a mature RIS should include the possibility of developing venture capital markets to support knowledge and technology transfer from universities to industry. In addition, a mature RIS should also include adequate mechanisms that facilitate the process of transferring knowledge and technology from other regions and abroad. Second, the possibility of finding new actors contribute to develop other important links between actors and institutions in a region, resulting in a more complex RIS in terms of its mechanisms for technology transfer and innovation developments. Importantly, from the perspective of the RISs theory, SD modelling and simulation may contribute to evaluate alternative policy scenarios in order to define a STI policy that support the development of innovation capabilities among indigenous firms at regional level (Rodríguez and Gómez, 2012; Rodríguez et al., 2014). However, the analysis of alternative scenarios for evaluating STI policies at regional level in emerging economies is out of scope of this paper. Therefore, SD methods may contribute to reveal the true nature of the articulation of competencies and skills of the companies and other actors that make an innovation system (Stamboulis, 2007). In this regard, SD methods allow analysing the behaviour of the actors in a RIS taking into account their strategic direction and underlying mechanisms that drive their actions individually and govern their interactions with other actors (Stamboulis, 2007).

The causal loop diagram (CLD) in this section adapted from Rodríguez and Gómez (2012) discusses from a general perspective how the generation, diffusion and use of technology and scientific knowledge are carried out in the province of Michoacán in Mexico. Figure 1 shows a CLD of actors, institutions and links setting up a RIS in the case of this province. It comprises twenty-two reinforcing feedback loops and three balancing feedback loops. The loop R1 (R&D expenditure-research results-publication of research results-province budget for R&D-R&D expenditure) shows how expenditure on basic research projects performed by researchers at universities generates research results after a time delay. It is assumed that the average time delay to obtain research results is two years. However, this assumption opens up the possibility of evaluating other alternative scenarios. Once basic research results are achieved, they can be either published in academic journals or transferred to develop applied research projects. When basic research results are published in academic journals, there is a positive impact on the province budget for research granted by the Province Council for Science, Technology
and Innovation (CECTI) to researchers, and thus allowing them allocating more resources to basic research projects. The loop R2 (R&D expenditure-research results-publication of research results-federal budget for R&D-R&D expenditure) explains the same effects as the loop R1, but taking into account the federal research budget granted by the National Council for Science and Technology (CONACYT) to finance basic research projects.

**Figure 1** A CLD of a RIS in Mexico: the case of Michoacán

The loop R3 (R&D expenditure-research results-applied research results-CECTI-province budget for R&D-R&D expenditure) and the loop R4 (R&D expenditure-research results-applied research results-CONACYT-federal budget for R&D-R&D expenditure) explain how researchers developing basic research results can in turn develop applied research projects after a time delay. These loops explain how basic research results can be alternatively funded by province or federal government agencies.
in charge of managing programs to support technology transfer and innovation programs. Interesting, the inclusion of province and federal government agencies in charge of managing programs to support technology transfer and innovation developments is carried out through the inclusion of two additional actors in these loops: CECTI and CONACYT. This fact demonstrates the importance of CECTI and CONACYT to carry out technology transfer processes at universities in Mexico, given that there are only a few universities in this country with technology transfer offices (TTOs). In this regard, the loop R3 evaluates CECTI programs to develop applied research projects as innovations, while the loop R4 evaluates CONACYT programs to develop applied research projects as innovations.

The loop R5 (doctoral and masters graduated students-research results-applied research results-CECTI-doctoral and masters graduated students) and the loop R6 (doctoral and masters graduated students-research results-applied research results-CONACYT-doctoral and masters graduated students) show how students graduated from master and doctoral programs might be involved in developing basic and applied research projects. Typically, the engagement of graduated doctoral students may contribute to develop applied research projects at firms. Such policies concern financing innovation and technology transfer programs through hiring graduated doctoral and master students by firms. If there are students involved in developing applied research projects, CECTI and CONACYT will finance basic and applied research projects. In each feedback loop, it is assumed a time delay of two years before achieving basic research results, and one year before achieving applied research results.

The loop R7 (doctoral and master postgraduate students-research results-publication of research results-province budget for R&D-doctoral and master postgraduate students) and the loop R8 (doctoral and master postgraduate students-research results-publication of research results-federal budget for R&D-doctoral and master postgraduate students) explain the contribution of graduated doctoral students publishing basic research results. Importantly, a key feature in these loops is that higher academic productivity of graduated students may increase the amount of founds granted by CECTI and CONACYT to postgraduate programs.

The loop R9 (appropriability/opportunity evaluation-CECTI-doctoral and master postgraduate students-applied research results-appropriability/opportunity evaluation) and the loop R10 (appropriability/opportunity evaluation-CONACYT-doctoral and master postgraduate students-applied research results-appropriability/opportunity evaluation) show the importance of doctoral and master postgraduate students to generate applied research results. However, research results achieved from these projects are evaluated for technological opportunity and appropriability. Particularly, the loop R9 stresses the idea that graduated master and doctoral students engaged in applied research projects may favour the adoption of new technologies by firms. Yet, the loop R9 includes technological opportunity and appropriability evaluation of applied research projects undertaken by CECTI with a time delay of one year, while the loop R10 includes technological opportunity and appropriability evaluation of applied research projects undertaken by CONACYT with a time delay of one year.

The loop R11 (doctoral and master postgraduate students-appropriability and opportunity evaluation-CECTI-doctoral and master postgraduate students) and the loop R12 (doctoral and master postgraduate students-appropriability and opportunity evaluation-CONACYT-doctoral and master postgraduate students) reinforce the idea that
the expenditure to finance applied research projects is strongly related to basic research developments through financing doctoral and masters programs by CECTI and CONACYT.

The loop R13 (researchers and academic staff-research results-appropriability/opportunity evaluation-companies-innovations in markets-researchers and academic staff) and loop R14 (researchers and academic staff-applied research results-appropriability/opportunity evaluation-companies-innovations in markets-researchers and academic staff) extend the possibility of transferring knowledge from universities to industry. In these loops, once applied results have been achieved, firms may contribute financing innovation developments. In practice, this process can go firstly from developing basic research results and then applied research results (R13), or directly through applied research results (R14). In both cases, a time delay of two years characterises the possibility of generating applied research results and innovations.

The loop R15 (researchers and academic staff-research results-appropriability/opportunity evaluation-CECTI-companies-innovations in markets-researchers and academic staff) and the loop R16 (researchers and academic staff-research results-appropriability/opportunity evaluation-CONACYT-companies-innovations in markets-researchers and academic staff) develop the same idea than the loop R13, but taking into account CECTI and CONACYT funding programs for successfully develop innovations and patents.

The loop R17 (researchers and academic staff-applied research results-appropriability/opportunity evaluation-CECTI-companies-innovations in markets-researchers and academic staff) and the loop R18 (researchers and academic staff-applied research results-appropriability/opportunity evaluation-CONACYT-companies-innovations in markets-researchers and academic staff) reflect the same idea than the loop R14, but taking into account CECTI and CONACYT funding programs for successful developing patents and innovations.

Finally, researchers contribute publishing research results, and transferring technology and new knowledge to industry, as well. In this case, the loop R19 (researchers and academic staff-research results-publication of research results-province budget for R&D-researchers and academic staff) and the loop R20 (researchers and academic staff-research results-publication of research results-federal budget for R&D-researchers and academic staff) demonstrate how research projects (and research results ready for publication) are financed by CECTI and CONACYT. On the other hand, the loops R21 (researchers and academic staff-research results-appropriability/opportunity evaluation-CECTI-province budget for R&D-researchers and academic staff) and R22 (researchers and academic staff-research results-appropriability/opportunity evaluation-CONACYT-federal budget for R&D-researchers and academic staff) demonstrate how research results developed by researchers (and applied research results) can be exploited for commercial purpose.

On the other hand, the balancing feedback loop B1 (companies-appropriability/opportunity evaluation-companies) reflects the idea that when an innovation is not ready to the market, companies should re-evaluate their inventions by technological opportunity and appropriability. This idea implies that using intellectual property protection, it is an important mechanism to obtain economic rents. However, this process may involve the support from CECTI to facilitate the process of technology transfer. In addition, in some cases, the process of re-evaluation goes directly from universities to industry. This is the
case of the balancing loop B2 (companies-propriety/opportunity evaluation-CECTI-companies). The loop B3 (companies-propriety/opportunity evaluation-CONACYT-companies) shows the same idea than the loop R2 but taking into account the opportunity and appropriability re-evaluation process supported by CONACYT.

3.2 Equations and model indicators

However, when applying SD methods, the next step after defining a CLD (dynamic hypothesis) is to develop a simulation model. In the case of RISs, a simulation model might be composed of several equations representing the behaviour of actors and institutions that set up an innovation system. In the model developed in this research, actors and institutions are aggregated at a meso level, namely universities and higher education institutions (through research projects, basic and applied research results, patents granted, graduated students from master and doctoral programs, and so forth), government agencies in charge of designing STI policies (through funding basic and applied research projects by CONACYT and CECTI, technological opportunity and appropriability evaluation, and so on), and innovative firms (through technology and new knowledge transfer from universities, innovations and patents, hiring graduated students from master and doctoral programs, and so forth). The main equations characterising this model are discussed in this section. Particularly, these equations are primarily used to calibrate the model in term of their actual and simulation trends. Table 1 summarises the variables, definitions and units of measure of the equations discussed in this paper. Appendix A in this paper contains a list of all variables and indicators that can be simulated with this model. It is important to keep in mind that the indicators and variables discussed in this paper were simulated only in the case of a reference scenario aiming to demonstrate how SD methods can be used to simulate the dynamics of a RIS in the case of emerging economies. However, the complete model developed in this research contains 116 variables: 21 stock or level variables, 58 flow or rate variables, and 37 parameters.

Table 1 Selected STI indicators

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Definition</th>
<th>Measuring unit</th>
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<tbody>
<tr>
<td>Total research budget</td>
<td>Research financing from federal and state government agencies</td>
<td>Pesos/year</td>
</tr>
<tr>
<td>Basic research projects</td>
<td>Number of basic research projects developed at universities and higher education institutions</td>
<td>Number of projects/year</td>
</tr>
<tr>
<td>Total researchers</td>
<td>Total number of researchers developing basic and applied research projects at universities and higher education institutions</td>
<td>Total researchers</td>
</tr>
<tr>
<td>Graduated doctoral students</td>
<td>Number of doctoral graduated students from universities and higher education institutions</td>
<td>Graduated doctoral students/year</td>
</tr>
<tr>
<td>SNI members</td>
<td>Researchers in the National System of Researchers (SNI)</td>
<td>Researchers with membership in SNI/year</td>
</tr>
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Following Rahmandad and Sterman (2012), the selected variables and indicators analysed in this paper are discussed in terms of their equations. Equation (1), total research budget \((TRB)\), is computed summing up all sources of funding for research projects: a percentage \((k_1)\) of funds from federal and province sources, \(CECTI\) and \(CONACYT\) funds for research projects, and other funds from the Ministry for Education \((SEP)\):

\[
TRB(t) = k_1 \left[ FRB(t) + PRB(t) \right] + CECTI(t) + CONACYT(t) + SEP(t)
\]

where:

- \(TRB\): total research budget
- \(FRB\): federal research budget
- \(PRB\): province research budget
- \(k_1\): research budget factor.

Equation (2), basic research projects \((BRP)\), is computed as a quotient between total research budget \((TRB)\) and total researchers \((TR)\) with a time delay of two years, and a constant research project average cost \((RPAC)\). It is assumed that the average time to obtain successful research results from research projects is two years. Nevertheless, the time delay to obtain successful research results in every case could be quite different depending on the discipline of each research project, namely social sciences, engineering, biotechnology, and so forth. To determine the number of successful research projects, a Poisson distribution function of the type \(Pr(Y = k | \mu) = \frac{e^{-\mu} \mu^k}{k!}\) is used (Rodriguez, 2010):

\[
BRP(t) = \left( \frac{TRB(t-2)}{TR(t-2)} \right) \left( \frac{e^{-\mu} \mu^k}{k!} \right) \quad \text{for } k = 0, 1, 2, \ldots
\]
where

- **BRP** basic research projects
- **TRB** total research budget
- **TR** total researchers
- **RPAC** research projects average cost.

Equation (3), total researchers (**TR**), is computed summing up researchers initial value, a percentage (**k₂**) of recently graduated doctoral students (**GDS**) that are engaged as new researchers at universities and higher education institutions in this province, and external graduated doctoral students (**EGDS**) graduated from outside universities and universities from abroad that are also engaged as researchers at universities and higher education institutions in this province:

\[
TR(t) = RIV(0) + k_2 \cdot GDS(t) + EGDS(t)
\]

Equation (4), graduated doctoral students (**GDS**), incorporates doctoral students that graduated after four years from enrolling. The time delay of four years assumed in this equation corresponds to the average time for graduating at doctoral programs in Mexico. This equation also incorportates a desertion factor (**k₃**), corresponding to those students that do not complete their doctoral programs:

\[
GDS(t) = EDS(t-4) - k_3 \cdot EDS(t-4)
\]

Equation (5), SNI members (**SNI**), is computed using a pulse or dirac delta function, \( \delta(t) \) (Sterman, 2000). This function determines the current number of researchers in the National System of Researchers (SNI) of CONACYT as a point in time when researchers are evaluated to newly enter, re-enter, or remain as researchers in SNI (once in a year). Importantly, each researcher is re-evaluated to remain as member of SNI every three/four years depending on their merits and academic achievements. To remain as member of SNI, researchers must demonstrate high quality research outcomes through publishing in top journals, patenting research results, and so forth. In this model, it is assumed that every year 20% of the researchers will not be capable to remain as members of SNI, and
thus they must be re-evaluated in the next year to re-entering into SNI. Therefore, the SNI equation includes three components: a percentage ($k_2$) of recently graduated doctoral students ($GDS$) engaged as new researchers at universities and higher education institutions, a percentage ($k_4$) of researchers re-evaluated to remain as members of SNI, and a percentage ($k_5$) of researchers out of SNI re-entering into SNI:

$$ SNI(t) = \delta(T, t) \ast [k_2 \ast GDS(t) + k_4 \ast TR(t) + k_5 \ast SNI\ Out(t)] $$

where

- $SNI$ SNI members
- $GDS$ graduated doctoral students
- $TR$ total researchers
- $SNI\ Out$ researchers already out of SNI

$\delta(T, t) = \lim_{W \to 0} (t, T, W) = \begin{cases} 
0 & \text{for } t \leq T \\
\frac{1}{W} & \text{for } T < t \leq T + W \\
0 & \text{for } t > T + W
\end{cases}$

- $k_2$ entering researchers factor
- $k_4$ re-evaluation researchers factor
- $k_5$ re-entering researchers factor.

Equation (6), publications ($PUB$), measures the number of both basic and applied research results for publication in academic journals. This variable is computed by the number of basic and applied research results that will not be developed as R&D projects for commercial purpose. Therefore, this equation uses research results and a publication factor ($k_6$) to compute the number of total publications each year in academic journals.

$$ PUB(t) = k_6 \ast RR(t) $$

where

- $PUB$ publications
- $RR$ research results (basic and applied research results)
- $k_6$ publication factor.

Equation (7), R&D projects ($R&D$), measures the number of research results that are not published in academic journals but are developed as applied research projects. Research results developed as R&D projects are evaluated both for technological opportunity and appropriability with a time delay of one year. However, some R&D projects must be re-evaluated for technological opportunity and appropriability until they are ready to the market.

$$ R&D(t) = (1 - k_6) \ast RR(t) + R&D\ Reev(t-1) $$
where

$R&D$ research and development projects

$RR$ research results (basic and applied research results)

$R&DReev$ R&D re-evaluation for opportunity and appropriability

$k_6$ publication factor.

Importantly, the re-evaluation process for technological opportunity and appropriability involves an equation that in turn requires re-evaluating technological and market conditions in order to develop suitable innovations ready to the market. In this model, the process of re-evaluating for technological opportunity and appropriability is as follows:

$$R&DReev(t) = \begin{cases} 
PTO(t) - InnP(t), & \text{if } InnP(t) - PTO(t) < 0 \\
InnP(t) - PTO(t), & \text{if } InnP(t) - PTO(t) > 0 \\
0, & \text{otherwise}
\end{cases}$$

where

$R&DReev$ R&D re-evaluation for opportunity and appropriability

$PTO$ projects with technological opportunity

$InnP$ innovation projects.

Equation (8), projects with technological opportunity ($PTO$), is computed as a probabilistic normal distribution of R&D adjusted by a technological opportunity factor ($k_7$). Importantly, the probabilistic normal distribution in this equation may allow evaluating alternative scenarios in terms of technological vocations at regional level that in turn may improve the development of regional innovation capabilities:

$$PTO(t) = k_7 \times R&D(t) \times Pr(R&D)$$

where

$PTO$ projects with technological opportunity

$R&D$ research and development projects

$Pr(R&D) \sim N(\mu_{R&D}, \sigma_{R&D}^2)$

$k_7$ technological opportunity factor.

Equation (9), active patents (AP), is computed as the difference between the total number of patents granted minus the total number of patents already expired at a point in time.

$$AP(t) = TP(t) - EP(t)$$

where

$AP$ active patents

$TP$ total patents

$EP$ expiry patents.
Equation (10), total financing innovation ($T_{FI}$), is also computed as a pulse or dirac delta function, $\delta(t)$ (Sterman, 2000). The volume component in this equation corresponds to various conditional variables. This equation seeks to capture all funding sources for developing innovation projects taking into account intellectual property mechanisms that may contribute to guarantee financing sources for successful innovations. Actually, intellectual property (patents) guarantees financial support by federal and province sources, namely CECTI and CONACYT. In addition, some master and doctoral graduated students are engaged at innovative firms allowing technology and knowledge transfer flows from universities to industry:

$$
T_{FI}(t) = \delta(T, t) \left( \begin{array}{l}
FF(t) + \left\{ \begin{array}{ll}
CECTI(t) + CONACYT(t), & \text{if } AP(t) > 0 \\
0, & \text{otherwise}
\end{array} \right. \\
+ \left\{ \begin{array}{ll}
DIP(t) \times GDS(t) \times MW(t) \times 12.5, & \text{if } GDS(t) > 0 \\
0, & \text{otherwise}
\end{array} \right. \\
+ \left\{ \begin{array}{ll}
DIP(t) \times GMS(t) \times MG(t) \times 9.0, & \text{if } GMS > 0 \\
0, & \text{otherwise}
\end{array} \right.
\right)
$$

where

$$
\delta(T, t) = \lim_{W \to 0} \left( \begin{array}{l}
0 & \text{for } t \leq T \\
W & \text{for } T < t \leq T + W \\
0 & \text{for } t > T + W
\end{array} \right)
$$

$T_{FI}$ total financing innovation

$FF$ financing firms

$AP$ active patents

$DIP$ developed innovation projects

$GDS$ graduated doctoral students

$GMS$ graduated master students

$MW$ minimum wage.

It is important to mention that equation (10) seeks to capture the concern in many emerging economies about searching better mechanism to regionally transfer new knowledge and technology developments from universities to industry. However, there might be many other mechanisms that improve technology and knowledge transfer in order to advance regional economic development in the case of emerging economies.

4 Discussion

4.1 Model evaluation for validation

The model evaluation problem concerns the fact that model simulation should be an approximation of the actual system (Martis, 2006). However, model validation resides in
decisions between modellers and users in that when both perspectives are satisfied, the model is valid (Barlas, 1996; Goldberg et al., 1990; Saysel and Barlas, 2004). In this paper, model validation was developed taking into account opinions from scholars involved in studying STI. In turn, the model was calibrated using data generated by province and national government agencies in charge of designing STI policy in the province of Michoacán. In this regard, STI indicators discussed in this paper are an example of how SD simulation models can be useful to design and evaluate alternative STI policy scenarios that support innovation activity at regional level. Yet, in this paper, only simulation results from a reference scenario are discussed as a means to exemplify how SD methods can be applied to model RISs in emerging economies.

4.2 Model simulation

The SD model of the RIS of the province of Michoacán in Mexico was simulated for the period of 2010 to 2020. In this paper, only ten indicators are discussed: total research budget (TRB), basic research projects (BRP), total researchers (TR), graduated doctoral students (GDS), SNI members (SNI), publications (PUB), R&D projects (R&D), projects with technological opportunity (PTO), active patents (AP) and total financing innovation (TFI). Appendix A shows other indicators that can be simulated with this model, and Appendix B contains simulation results of some derived STI indicators simulated with this model.

Importantly, uncertainty appears as a core feature characterising RISs derived from business and innovation developments (Lindqvist et al., 2010). This characteristic shows the need of capturing the actual structure of the RIS in this province and its behaviour in terms of selected indicators. In other words, the simulated model ought to capture the structure and behaviour of the actors involved in generating, using and transferring science and technology for innovation purpose. Figure 2 shows the simulation results of indicators of the RIS of this province. However, from these results, some important features are worthy to mention. First, the low rate of patent activity in this province may suggest the absence of entrepreneurial capabilities and culture among firms, scientists, and other actors in this innovation system (Rodríguez et al., 2014). The promotion of an entrepreneurial culture among researchers and other actors in this RIS could make it easier to develop applied research results and innovations, expanding and creating new markets in order to make more competitive indigenous firms. The lack of incentives to commercialise new knowledge is reflected in the poor number of R&D research projects and patents.

Second, province and national government agencies in charge of STI policy continue to be extremely important to generate and disseminate new knowledge and technology. Third, CONACYT and CECTI are extremely important for the funding of basic and applied research projects. Fourth, CONACYT is a strategic actor in financing master and doctoral programs, as well as supporting and encouraging researchers’ activities. Finally, this model demonstrates that there are no adequate mechanisms to transfer technology from universities to industry in this province. In this sense, many other tools are needed to finance innovation and commercially develop innovation projects.
An important issue from these results should be how to improve the rate of innovation through developing an entrepreneurial culture by means of consolidating an entrepreneurial innovation system (Ács et al., 2014; Gustafsson and Autio, 2011; Hung and Whittington, 2011; Radošević, 2007). In this regard, innovation activity should be the result of both knowledge application and exploitation, on the one hand, and knowledge exchange (generation, diffusion and use), on the other. This perspective may imply thus that innovation activity directly draws from the concept of innovation system at regional level.
5 Conclusions

In relation to using SD methods to model RISs in emerging economies, this paper discussed the possibility of developing a SD simulation model to capture the dynamics of a RIS in these economies. The simulation process was developed by means of SD methods, mainly defining the problem articulation (boundary selection), establishing a CLD (dynamic hypothesis) that explain the qualitative characteristics of an innovation system (e.g. relations between structure and actors and institutions in an innovation system), formulating the equations that capture the structure and behaviour of actors and institutions that carry out STI activities, testing the model through validation and calibration (comparing the simulation model in relation to the actual model), and eventually formulating and evaluating alternative policy scenarios (Sterman, 2000).

However, this paper focused on developing a SD model of a RIS in the case of the province of Michoacán in Mexico. This analysis was carried out by means of developing a CLD characterising the RIS of this province. This case was analysed in terms of the actors, institutions and links established in the system. Simulation results revealed the importance of some actors and institutions in order to advance the development of the RIS in this province. This is the case of province and federal agencies in charge of designing STI policies, the development of venture capital markets, implementing adequate mechanisms to facilitate knowledge transfer from abroad, and so forth. In this regard, the importance of developing adequate transfer mechanisms to assist knowledge and technology transfer from universities to firms was stressed.

On the other hand, it was discussed the possibility of developing a simulation model of the RIS of this province and a set of STI indicators that may support STI policy design. However, the evaluation of alternative STI policy scenarios is out of scope of this analysis. Ten indicators and their corresponding equations were discussed in this paper. The validation and calibration process demonstrated that the dynamics of these indicators corresponds to conditions of the actual innovation system.

Finally, simulation results also reveal the importance of accounting for an entrepreneurial culture among scientists and other stakeholders that set up the system. Further research should be done in relation to how the development of an entrepreneurial culture and capabilities may contribute to improve innovation activity and competitiveness among indigenous firms through an innovation system of entrepreneurship where individual-level opportunity and country-specific institutional characteristics explain resource allocation to develop new ventures (Ács et al., 2014). In the same way, further research should be done in relation to evaluating alternative STI policy scenarios at regional level in the case of emerging economies.

Acknowledgments

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References


A system dynamics model of STI policy to sustain RISs


Appendix A

List of STI indicators from the RIS model of the province of Michoacán

<table>
<thead>
<tr>
<th>STI indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active patents</td>
</tr>
<tr>
<td>Active patents**</td>
</tr>
<tr>
<td>Average citations*</td>
</tr>
<tr>
<td>Average profit rate</td>
</tr>
<tr>
<td>Average rents</td>
</tr>
<tr>
<td>Basic research projects**</td>
</tr>
<tr>
<td>CECTI budget</td>
</tr>
<tr>
<td>CECTI financing</td>
</tr>
<tr>
<td>Citations/researcher*</td>
</tr>
<tr>
<td>CONACYT budget</td>
</tr>
<tr>
<td>CONACYT financing</td>
</tr>
<tr>
<td>Developed innovation projects</td>
</tr>
<tr>
<td>Doctoral programs budget</td>
</tr>
<tr>
<td>Employment</td>
</tr>
<tr>
<td>Federal budget</td>
</tr>
<tr>
<td>Federal graduate programs budget</td>
</tr>
<tr>
<td>Firms financing</td>
</tr>
<tr>
<td>Graduated doctoral students**</td>
</tr>
<tr>
<td>Graduated masters students</td>
</tr>
<tr>
<td>Graduate students/researcher*</td>
</tr>
<tr>
<td>Higher education federal budget</td>
</tr>
<tr>
<td>Higher education province budget</td>
</tr>
<tr>
<td>Innovation projects</td>
</tr>
</tbody>
</table>

Notes: *Other derived indicators simulated with this model (Appendix B).  
**Variables and equations reported in this paper.
Appendix B

Derived STI indicators from the RIS model of the province of Michoacán

<table>
<thead>
<tr>
<th>Derived indicators</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average citations</td>
<td>2.75</td>
<td>2.84</td>
<td>1.92</td>
</tr>
<tr>
<td>Citations/researcher</td>
<td>0.80</td>
<td>1.27</td>
<td>1.09</td>
</tr>
<tr>
<td>Graduate students/researcher</td>
<td>1.27</td>
<td>1.34</td>
<td>1.42</td>
</tr>
<tr>
<td>Patents/researcher</td>
<td>0.04</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>Publications/researcher</td>
<td>0.29</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>Research budget/researcher (000)</td>
<td>115.31</td>
<td>124.26</td>
<td>134.59</td>
</tr>
<tr>
<td>SNI members/total researchers</td>
<td>0.85</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>Total citations</td>
<td>414</td>
<td>686</td>
<td>619</td>
</tr>
</tbody>
</table>