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The Mexican innovation system: A system's dynamics perspective

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ABSTRACT

There is no doubt that technological component is fundamental in the growth and development of the countries. The use of the theory of technology,in its tangible or intangible dimensions (), represents an opportunity toimprove proposed solutions to economical, health, social, or business problematic situations faced inMexico. Mexico's performance in technological development has been insufficient to enhance the well-being of its population. This article presents the design of a model based on systemic thinking (system dynamics) and national models of innovation and knowledge, intending improve governance in Mexico in terms of technology. A quantitative-correlational research method was used in this study presenting four sections: Introduction, methods, results, and discussion. A system dynamics (SD) model is proposed. This work is one of the first ones thatuse system dynamicsand studies interactions between the structural elements of science and technology (S&T) in Mexico.
Keywords: Model, system dynamics, Mexico, Technological innovation, science, and technology.

1. Introduction

1.1 Description of science and technology (S&T) in Mexico

The National Council for Science and Technology (CONACyT) publishes a General Report about the National Status of Science, Technology, and Innovation (IGECTI), which describes the most representative indicators regarding science, technology, and innovation activities performed in the country [1]. Some of them stand out, for example: National budget **spent on scientific research and experimental development, relative to GDP(GIDE / GDP),Human Resources collaborating in Science and Technology (ARHCyT)**, the **National database System of Researchers (SNI)**, among others. These reports show researchers' performance represented by their scientific and technological production by some indicators as: **spread of scientific publications, patents, technology balance of payments (BPT), foreign trade of Hitech goods (BAT),** and**budget spent on Innovation (GI).**

1.2 S&T in Mexico national innovation systems' approach

An effort to outline the components related to science and technology (S&T) in Mexico has been the national innovation systems' approach. The main contribution was presented by Dutrénit*et al.* [two]. The following figures (facts) intend to make visible the problematic situation scientific and technological activitiesfacedin Mexico.

Main components

The Mexican innovation system (MIS) integrates components observed in national innovation systems (NIS) in other countries [3], [4]. The most important components are **government agencies and institutions, public research centers and institutes, higher education institutions (HEIs), companies, intermediate institutions, and financial or support institutions** [2]. Mexican government controls centrally the MIS,affecting the environment where the elements perform. **The National Council of Science and Technology (CONACyT)** [5] is undoubtedly the most relevant institution [6].

Interactions between agents

The MISprincipal characteristicsare the productive sector is highly isolated. There are no essential links with financial institutions nor with HEIs [2]. Links between private companies are scarce (8.2%). 85% of innovative products and processes offered in the market, companies have innovated without collaboration. HEIs have collaborated only with 1.8% of private companies forprocessesinnovation, and only 2.6% of collaborations resulted in products and services innovation [7].

Problematic situation

Evidence suggests that the MIS is incomplete. There are shortages of resources (personnel, capital, and infrastructure) and deficiencies in their operation (involvement of the different agents). Market performance failures such as: Limited capital to finance innovation, incipient critical mass of human resources in S&T, among others; regulatory failures originated by the government like: scarce resources, lack of incentives for promoting interactionsamog different sectors, etc.; and systemic failures as insufficient provision of physical infrastructure, institutional failures, dispersion of resources, little cooperation and networking, slow learning and low development capacity [2], [8], [9]. However, interactions and actions among different system elements lead to characterize an emerging MIS [10].

1.3 Theory

Economic growth and production function

Economic growthis constant over time and maybe the most critical determinant of population's economic well-being. The current growth proposals indicate that savings, population growth, and technological progress, together, are the determinants of economic growth. Improving technological progress is the most important goal of economic policy [11], [12].

Technological innovation

Literature identifies three dimensions of technological innovation [13].The economic dimension: Schumpeter [14] is one of the representatives of this trend. It is founded that capitalism results from "creative destruction" or technological innovation, where innovative entrepreneursare also essential. In addition, Schmookler [15], shows that technological progress is related to demand or market. The sociological dimension of innovation: Several researchers contributed to this approach: Bell [16], Marx [17], Durkheim [18], Parsons [19], Weber [20], North [21], Rosenau [22], among others, explain the importance of technology in society and its changes. And the dimension of technological innovationmanagement (*Management of Technology, MOT*) Pavitt and Damanpour [23],[24] and Betz and Khalil [25], [26], are considered the parents of *MOT*.

Innovation activities have taken different forms in different historical periods [27]. Traditionally, technological innovation process consists of three stages: invention (new products are developed), innovation (introduction of new products to the market), and diffusion (spreadof new products in the market). Toturn an invention into an innovation, a company usually needs to combine different types of knowledge, capabilities, skills, and resources [28],[29].

A chronological review of national technological innovation models

The world of technological innovation, from the national point of view, has been abundant. Various approaches and interpretations do exist: Economics of services [30], Sabato's triangle. [31], Determinants of national competitive advantage [32], national innovation systems (NIS) [33], [4], [3], triple helix model [34], industrial clusters [35], social innovation systems and production (SSIP) [36], profession theory [37], development innovation systems (SID) [38], national learning systems (SNA) [39], national innovative capacity [40], [41], creation of suitable spaces for innovation [42], knowledge intensive business services (KIBS) [43], [44], alternative social models. [45], mode 1 and mode 2 of knowledge generation [46], research environments (centers of excellence) [47], mode 3 of knowledge generation [48, 49], quintuple helix [50], social capacity [51], [52], absorption capacity [53], technological capacity [54], [55], Milieu Innovateur, industrial district, new industrial spaces, local production systems and learning region [56].

Systems dynamics

In the 1950s, at the Massachusetts Institute of Technology (*MIT*), systems dynamics (SD) was born. Forrester [57], [58], an electronics engineer, moved from servomechanisms (he invented magnetic memories) to coordinating defense projects. In his work, he identified the importance of systemic approach to design and control complexity. This methodology was also applied to urban and industrial planning problems, and later, itsapplication was generalized for any continuous system. Currently, DS is a subject of debate [59]. SD has been labeled as a theory [60], [61], a method

[62]-[65], a methodology [66], a field of study [67], a tool [68], [69] and a paradigm [70]. Forrester's workbecamethe natural starting point, because SD is a rigorous, scientific, and consistent modeling approach to understand behavior patterns of complex systems [63], [71], [72]. A complex system is defined as a higher-order structure in DS terminology, with multiple loops and non-linear feedback (great variety of behaviors) [73]. In this sense, SD uses conceptual structures to show the causal links of the variables of a model and then translate these relationships into a simulation model that reproduces the behavior of a system over time [74]. SD helps to conceptualize the causes of an existing behavior and improve a system's behavior through a model [63], [75].

Systems' dynamics and technology

Innovation incorporates interactive processes (including couplings and flows) [76]. Then, technological innovation is the result of complexity of actors and institutions [77]. The complex and social nature of the NIS justifies the use of a systems' dynamics approach and the viable systems model (VSM)for proposing a viable model for technological innovation.

Literature review

Several studies show innovation has become an increasingly frequent topic in social and economic analysis. Fagerberg's [28] findings in the catalog *ISI Citation Index show* that articles dedicated to innovation analysis increased much faster than the total published titles in all other areas of knowledge. Another study [78] confirms this increasing trend. Collaborations of List [79], Schumpeter [14], and Hippel [80] formulated the bases associated with technological progress. Later, during the 70s of the 20th century, Freeman's [33]andNelson & Winter's [81] research results predominated And theiranalyses originated a group of concepts and approaches, such as those of Lundvall [4]and Nelson [3], which reflected an effort to explain the complex process of nations' technological progress.

In Latin America, the Economic Commission for Latin America (ECLAC) has published a large amount of literature; for example, Pérez' work [82],besides ECLAC [83],other international organization, the United Nations Educational, Scientific and Cultural Organization (UNESCO), has contributed with some ideas [84].Other authors like Sabato [31] and Sagasti [85]have provided important work on this topic.

Literature review method

A formal literature review was performed, based on the methods of Hart [86] and Jesson*et al.* [87], following Walker's selection criteria [88]. Search for scientific documents was carried out from 1980 to 2021 in the database *Web of Science*. Particular attention was paid to articles showing a significantly related to the viable systems model (*VSM*). A brief description of each of them has been made. The quality of the information on the subject fulfills the validity attribute [89], which means that the number of written documents and citations is increasing.

Result of the literature review

Application of system dynamics in the technological component isbroad [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109] , [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133]. The high number of search resultsfound on *Web of Science (WoS)*, used as main searching database, makes evident thatthe use of system dynamicsapproach has raised. However,these results suggest that no studies nor proposals using system dynamics approach have been used for analyzing technological and scientific development situation in Mexico, a model focused on technology has neither been designed.Thus, this important scarcity brings opportunities for further research.

Justification

After analyzing the main national proposals for technology and knowledge development, regardless the existence of different perspectives, a common denominator was found: Technological and innovation performance depend on the interrelationships between different agents who create, store and transfer knowledge, skills, and artifacts. Then, there is a line of research that will requiresoonfurther attention from researchers: Experimentation of strategies or public policies regarding technology and innovation [134]. According to several authors [121], [136]-[139], public policies' experimentation is related, among other techniques, to modeling, simulation, and dynamics of systems [100]-[135].

Objective

This work aims to design a model based on systemic thinking (system dynamics) and to formulate national proposals for technology, innovation, and knowledge, intending to improve governance in Mexico regarding technology.

Hypotheses
Proposed working hypothesis are mentioned bellow.

1. Technological innovation can contribute to Mexico's economic growth.
2. It is possible to find a methodology structure based on SD for integrating modeling of complex systems and economic analysis.
3. Simulation's results will eventually show innovation's dynamic behavior in Mexico.

2. Methodology

This work used qualitative research, with a descriptive scope (as it is a proposal for a structural model) and correlational (since it describes causal relationships among the components that form the Mexican technological system). Research design was carried out following Creswell's proposal [140]. Methodology incorporates two approaches, one from the philosophy of science and the other from systemic thinking. Thus, thisresearch work is defined as quantitative-correlational [140], [141]. According to Polonsky and Waller [142], this methodology describes three main moments: Theoretical, methodological, and practical. Problem description was addressed following the method proposed by Shannon [143]. Sterman's methodology [63] was applied as system dynamics methodology. Selection of our systemic method (from the complex systems approach) is based onthe Critical Systems Thinking (*CST*) approach, that inspired Jackson [144], who proposed his*System of Systems Methodologies* (*SOSM*).

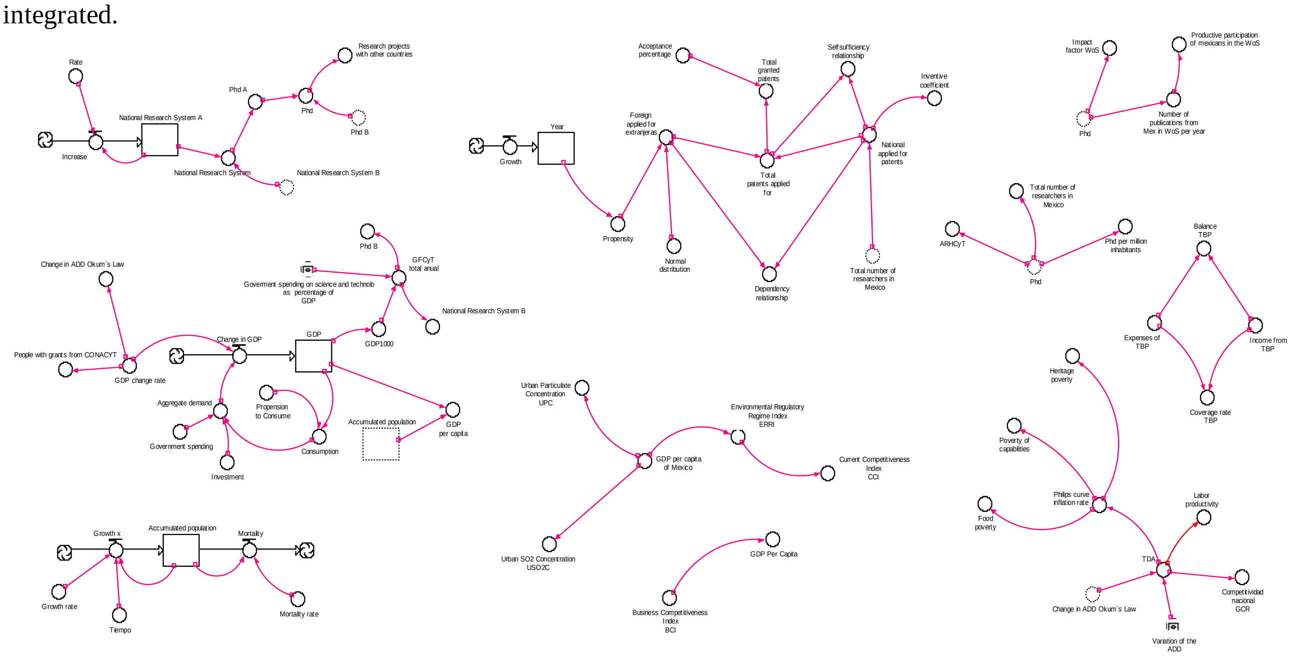
3. Results

Diagnosis of the Mexican science and technology system
The diagnosis of science and technology system in Mexico was carried out using the Viable Systems Model (*VSM*) for building a structure showing actors and their interrelationships, previously identified by Dutrénit*et all.* [2], Cimoli [145], Latin American developing countries, a Lundvall *et al.* [10] and by the OECD [77],[146]. The same stakeholders and their relationshipsare mentioned as well in the current version of the Mexican Law of Science and Technology [147]. The *SOSM*, regarding the characteristics of the technology's problematic situation in Mexicowas characterized as unitary (according to the participants involved);and its system's dynamics as simple-unitary [144].
Proposed model
A series of models were developed following the SD approach, with the software, *I think 8.0*. They intend to model the Mexican economy and simulate its behavior in the short term (4 years). Being inspired by the project *Synco* or *Cybersyn* [148], [149],results obtained allow to reflecton different scenarios and facilitate decision-making processes. Models can provide insights into dynamics of the innovation process, so it is possible to study the impact of innovative policies on Mexico's performance in.
Fifteen models were designed, integrated (Figure 1), and stratified in three cathegories: national, technological change, and science &technology. The first category: national level models include: Innovative capacity, competitiveness-inflation-open unemployment rate, gross domestic product (GDP), total tacit knowledge, environment, technology-based companies (EBT), and population size. For the second category: technological change, proposed topics are: Patents (inventions), diffusion, and innovation. the third category: science &technology, elements included were: Articles in the *WoS* (written by researchers collaborating with Mexican institutions), national system of researchers database, high technology goods (BAT), balance of payments technology related (BPT), and ARHCyT.
In the he first category: national models, Mexican innovative capacity was estimated, considering four aspects proposed by Furman *et al.* [150]. In the second category Phillips' curve [151] of inflation and unemployment and Okum's Law [152] of employment and economic growth were applied for estimating and relating three indicators: competitiveness, inflation, and open unemployment rate (TDA. The third model describes the links among variables involved in GDP and federal spending on science and technology (GFCyT) [11], [153]. Model four:Total tacit knowledge, estimates the knowledge contained in the ARHCyT researchers' group [154], [155]. Model five: environment, correlatesGDP per capita urban particles concentration of (UPC), concentration of SO_2 (USO2C), current Mexico's competitiveness index (CCI) of, environmental regulatory regimeindex (ERRI), and business competitiveness index (BCI) [156], [157]. The sixth model addresses calculation of technology-based companies (EBT), based on three variables proposed by Corona [158]: Research centers, industrial corridors, and business incubators. Finally, in this stratum, a model was designed for estimating the population size required as input for other models, balancingnew births and deaths trough the time.
For the second stratum: technological change, the first model estimates total patents (inventions) granted coming from total patents' applications. Data were obtained from CONACyT [1]. The second technological change model: technological diffusion has as input the EBT calculation and its main variables are: adoption rate obtained from contact

rate and fraction of adopters [63], [159]. The third model: innovation, provides estimated number of innovations (economic success) in Mexico from the EBT. The logic of these links has been proposed by Maier [160].

Regarding the category science &technology, the first model estimates the number of articles in *WoS*, written by researchers collaborating in a Mexican institution, impact factor and percentage of world participation in *WoS*can be onserved as well in this model. Data for the five models of this category "science & technology" were, the obtained from CONACyT [1]. A second model estimates number of researchers who belong to the national researchers' system. [1]. Estimation of high technology goods (BAT) is part of the third model. In fourth model: balance of technology payments (BPT). The balance and the coverage rate were calculated. Finally, in this category, figure x shows an estimate of the ARHCyT.Also total number of researchers and doctoral graduates per million inhabitants was estimated. Data were obtained as well from CONACyT [1].

The integrated model is shown in Figure 1. This SD model is based on fundamental principles introduced by Lee and Tunzelmann [109]. In this model in Figure 1, macroeconomic conditions wereconstituted as additional structural elements to the system, as in Samara *et al.*work [129]. Regarding the innovation process, Utterback and Abernathy work [94] could cover mutual relationships among stages of a product's life cycle of, production process stages of development, and the competitive strategy. The endogenous definition of S&T is consideredfollowing the Milling and Stumpfe'sapproach [104]. Finally, Niosi [161], and Rivera et al. [162] proposals,about a NIS dynamic structure were integrated.



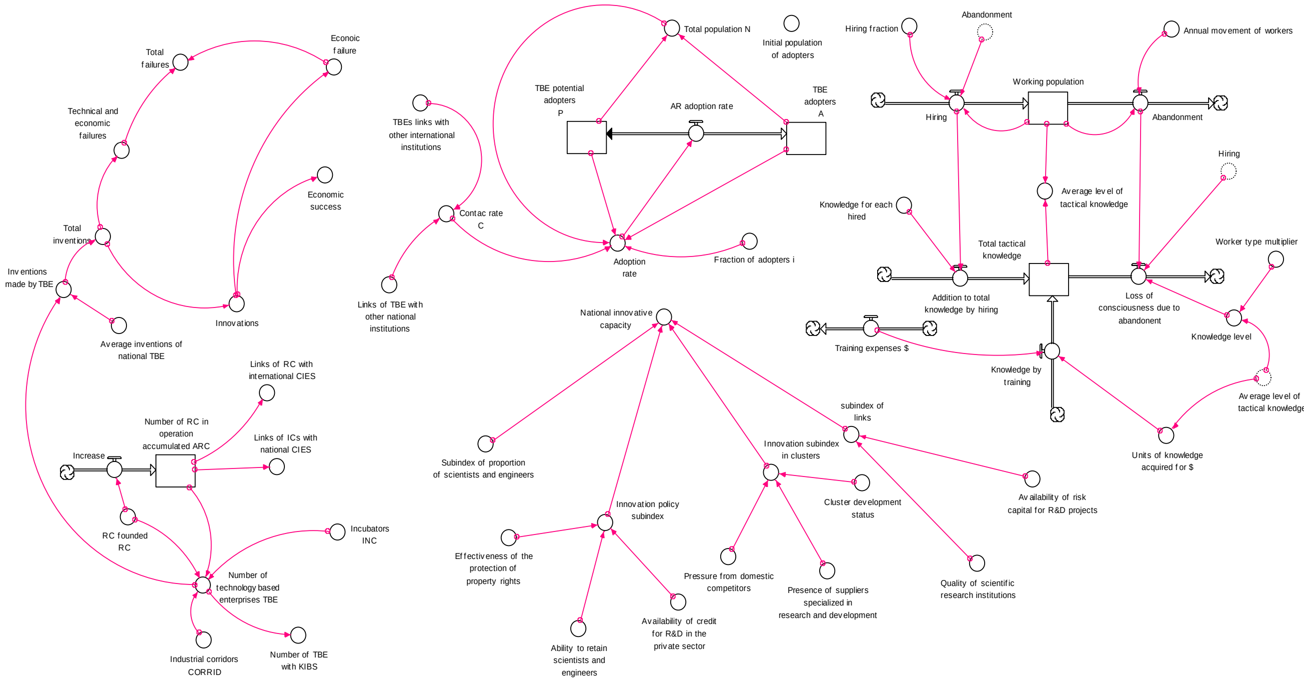


Figure1. Proposal of the Mexican science and technology model.
Own elaboration based on, I think, 8.0.

4. Discussion

1. *4.1 Conclusions*

The model can be described as a conglomeration of institutions, grouped or separated, that contributefor designing and dissemination of new technologies. These institutions constitute the Mexican framework wherepolicies can be created and appliedfor influencing the National innovation process. From this perspective, innovative Mexican performance depends not only on each isolated institution's performance,but also on their interactionsfor creating knowledge and use it dynamically. Understanding these dynamics is one of the main research topics. Understanding links between the components is the key for improving Mexico's innovative performance. From this perspective, all elements in the model are producing, distributing, and applying different types of tangible and intangible knowledge.

The complex and social nature of these interactions justifies the use of the SD approach as an appropriate methodology to model the innovation process. Dynamic behavior arises from interactions among the agents during time. Complexity is caused by the subsystems' dynamicnature, which are closely linked, governed by feedback, non-linear, and depend on history, are self-organizing, adaptive, counterintuitive, political resistant, and characterized by exchanges.

2. *4.2 New research needs*

Popper [163], being part of falsificationism, used to say"observe, think and observe again". In other words, multiple further investigations always followevery investigation. Inside any of them, it is possible to integrate, theoretically, Mandelbrot fractal approach [164] and Hoverstadt'sproposal [165] to reinforce the concept of "resourcefullness". Another practical and methodological option isto use Viplan methodology by Espejo and Reyes [166] to align and enhance participants' efforts facilitating organizational viability.

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