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Scientific and Technological Research Article

# Technological innovation from a system dynamics approach

# La innovación tecnológica desde un enfoque de dinámica de sistema

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**ABSTRACT**

Technological development and innovation models have evolved over time and in an increasingly globalized context. Their implementation results in the strengthening of competitiveness through the strategic development of human and technical capabilities. This research aims to design a model for the management of technological innovation with a system dynamics (SD) approach. The construction of the SD model is based on the analysis of the models found in the literature on the subject; the methodology applied includes the definition of the problem, the causal loop diagram, the flow diagram, the summary of the main equations, and the validation of the model. The main variables identified were capital available for investment in innovation, capital invested for high-level human resources training, human resources with high-level training, capital invested in innovation projects, innovation service contracts, profits from innovation service contracts, and initial capital for investment in innovation.

**Keywords:** system dynamics, innovation management, technological innovation, management models.

**JEL Classification:** C61; O31; O32

**RESUMEN**

Los modelos de desarrollo tecnológico e innovación han evolucionado con el paso del tiempo y en un contexto cada vez más globalizado. Su implementación redunda en el fortalecimiento de la competitividad a partir del desarrollo estratégico de sus capacidades humanas y técnicas. La presente investigación tiene como objetivo diseñar un modelo para la gestión de la innovación tecnológica con un enfoque de dinámica de sistemas (SD). La construcción del modelo SD tiene como referencia el análisis de los modelos encontrados en la literatura sobre la temática; la metodología aplicada plantea la definición del problema, el diagrama de bucle causal, el diagrama de flujos, el resumen de las principales ecuaciones y la validación del modelo. Se identificaron como variables principales: capital disponible para inversión en innovación, capital invertido para formación del recurso humano en alto nivel, recurso humano con formación en alto nivel, capital invertido en proyectos de innovación, contratos de servicio de innovación, utilidades de contratos de servicio de innovación y capital inicial para inversión en innovación.

**Palabras clave:** dinámica de sistemas, gestión de la innovación, innovación tecnológica, modelos de gestión.

**Clasificación JEL:** C61; O31; O32

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## INTRODUCTION

Human development in itself demands increasingly better living conditions based on the search for innovative solutions for their development in society. In the current global, competitive, and changing environment that organizations face, innovation is emerging as a tool that generates competitive advantages (Huang et al., 2023). There is a growing international consensus on the importance of knowledge and learning as a central axis of economic development (Gortari & de Santos, 2006; Jiménez & Palácio, 2010). In this sense, Briede and Rebolledo (2010) recognize that the process of innovating products and services is increasingly difficult in a globalized world with a wide variety of offers.

The development of societies, especially in Latin America, implies generating governmental strategies that increasingly increase access to science and technology (Khan et al., 2021; Lillford & Hermansson, 2021), through incentives to increase their production and socialization. Several investigations show how the development of innovation capabilities influences the creation of competitive advantages (Sossa et al., 2012). For Morales et al. (2012), innovation is present in the different economic and social changes achieved over time since the contributions of the classical and neoclassical schools of economics. He also recognizes economist Joseph Schumpeter as the author of the first formal approach to the concept.

Subsequently, concepts such as "innovation management" appeared; innovation systems derived from the emergence and development of industry and production processes; the need to formalize the R&D process and understand the environment in which innovations are developed and applied (Geissinger et al., 2023). In an increasingly globalized world dominated by free trade, teamwork and the integration of strategies between different science and technology centers, both public and private, that promote technological innovation in the design of production processes and services are of great importance (Abello, 2007).

There are many meanings for the types of innovation, but no classification integrates them in their totality. Some of the classifications are: product innovations, process innovations (those directly related to the concept of technological innovation), and marketing and organizational innovations; on the other hand, the conception of change or degree of novelty in the product (Mera & Paredes, 2014).

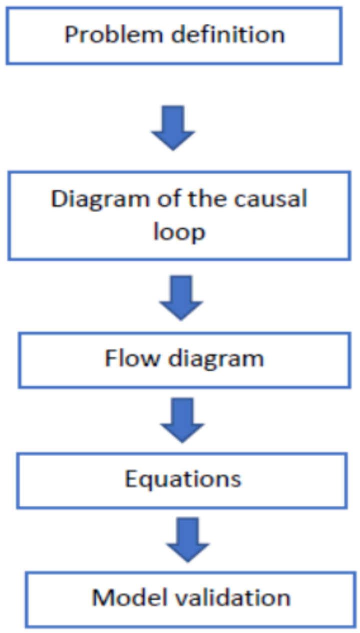
In this documentary research, first of all, a conceptual review of management, innovation, technology, and centers of innovation and technological development was made. Secondly, the way in which the innovation process has evolved was reviewed, and subsequently, the different models for the management of the innovation process within institutions were observed. This document's main purpose is to create a model from a system dynamics (SD) approach for the management of technological innovation as a descriptive and analytical tool that allows better planning and direction of efforts in the sector.

The document's structure, in principle, contains a review of the relevant literature on innovation and SD. Finally, conclusions, contributions, and acknowledgments are outlined.

## METHODOLOGY

A quantitative descriptive research was developed, based on the application of the concepts of system dynamics, to determine causal relationships between different variables that influence innovation management. The research is structured in two main phases; the first is a systematic review with the objective of clarifying the main concepts related to the management of technological innovation. The descriptors used in the search were: innovation, innovation management, technological management, and innovation management models. The second one, where an SD model is developed based on the analysis of the models found in the literature.

**Figure 1.**
*Proposed procedure for the development of the research*




**Source:** own elaboration

The procedure is structured in five stages:

**Stage 1. Definition of the problem**. The work team must be sufficiently exhaustive in the identification of the different variables that influence the proper functioning of the process; this will allow the goals and objectives of the mathematical model to be clear. Teamwork meetings can be held to confront criteria, the participative observation of processes, or individual and collective photographs.

**Stage 2. Causal loop diagram**. The causal loop diagram is constructed based on the influence-dependence relationships found in the previous step. An analysis of their interactions is carried out, and the modeling should not lose sight of the objectives of the problem, its components, and variables.

**Step 3. Flow diagram**. For the structuring of the flow model, the causal model, the identification of the level variables, the input and output flows of each level, and the input-output relationships for each auxiliary variable must be taken into account. In this research, the Vensim PLE software was used to represent the stocks and the flow diagram.

**Stage 4. Equations**. The interaction of various factors in the causality diagram of the system dynamics model is actually a mathematical relationship, and the structure flow diagram is specific to this mathematical relationship between the variables. According to the feedback loop of the interaction between each module of the system, as well as the factual data and related research theory, the quantitative equation between the variables is established (Xue & Xu, 2017).

**Stage 5. Model validation**. It consists of testing the proposed model to assess whether it is consistent with the stated purpose. An analysis of the behavior of the significant variables of the model must be performed once the modeling has been carried out with the established parameters.

## RESULTS AND DISCUSSION

A large group of researchers and international cooperation organizations have made many contributions that have helped us to understand the concepts of research, development, and innovation in R&D&I (de Normalización and AENOR, 2006). Innovation management is strategically a very important management tool for its contribution to the success and development of the organization (Asociación de la Industria Navarra, 2008).

### Innovation management

It accounts for the organization and management of the different resources available to the company, aimed at increasing the creation of new knowledge and technical ideas that, through their application or use, make it possible to produce new products, processes, and services, improve existing ones, or contribute to the improvement of the distribution or marketing phase. They also consider that innovation management is crystallized through the execution of the following eight phases: 1) Innovation as a strategy, 2) Creativity and Innovation, 3) Strategic Surveillance, Benchmarking and Competitive Intelligence, 4) Project Management, 5) Innovation Financing, 6) Innovation Assurance, 7) Innovation Exploitation and 8) Knowledge Management.

### Technology Management

Technology management is the process of planning, organizing, directing, and controlling the activities related to the technology necessary to execute the processes developed in the company. In addition, Solleiro (2009) conceives it as the set of techniques that allow an organization to develop and execute its innovation and improvement plans to maintain or increase its competitive position. Therefore, it can be concluded that technological management is the optimal way to combine human, technical and financial resources for the fulfillment of the organization's objectives, which is materialized in the technological strategy and in the strategic plan for technological development (Gallego, 2005), through the development of the functions of: a) Inventorying, b) Monitoring, c) Evaluating, d) Enriching, e) Optimizing and f) Protecting.

### Technological innovation management models

Innovation management is not unified in the development of a single model, but there is a wide variety of approaches and levels of complexity. Table 1 provides an analysis of some innovation management models. Among the relevant concepts that help to reinforce the proper understanding of what concerns R&D&I, we have: research, technological development, and innovation, among others.

**Table 1.**
*Analysis of Technological Innovation Management Models*

| Innovation management model | Author | Characteristics |
|---|---|---|
| Basic Functions Innovation Management | (Saren, 1984) | The sustainability of the company is ensured by implementing the basic functions: inventory, evaluate, monitor, optimize and protect. |
| Technology innovation management model (COTEC) | (Cotec, 2001) | Dynamic model. It proposes five functions: monitor, focus, train, implement and learn. |
| Generalitat de Catalunya | (CIDEM, 2002) | Innovation management is consolidated in four functions: generation of new concepts, product development, reengineering of production processes, reengineering of commercialization processes; supported by knowledge and technology management. |
| Kaplan y Norton | (Kaplan y Norton, 2004) | It is based on an innovative strategy at the operational level, which is part of the company's general innovation strategy as a way to achieve competitiveness. It is perceived from the four fundamental perspectives of the Balanced Scorecard. |
| R&D&I Management Systems (Standard UNE 166.002) | (de Normalización y AENOR, 2006) | It addresses the responsibility of managers in the innovation management process as a key process, the support processes, with the description of management tools, resources, measurement and system improvement actions. |
| Innovation in SMEs | (Arzola y Mejías, 2007) | R&D&I activities are based on: management responsibility, resource management, process development and the measurement and improvement of results. |
| Innovation in the Services Sector | (Salazar et al., 2010) | It is structured in seven fundamental functions: leadership, strategic planning, processes, customer satisfaction, organization, human resource competence and social responsibility. |

**Source:** Own elaboration based on Arzola and Mejías (2007).

## Application of the proposed procedure

### *Stage 1. Problem definition*

The model's objective was defined as relating the technological innovation management variables with the decisions to train high-level human resources and the development of innovation projects to improve the company's products and processes. In addition, the generation of income through the execution of innovation service contracts, whose profit - once dividends are deducted - becomes the permanent source of financing for the innovation process.

The human resource with high-level training is a decisive variable because it generates man-hours with innovative capacity that directly impacts both innovation projects and innovation service contracts.

The main variables identified are: capital available for investment in innovation; capital invested for high-level training of human resources; human resources with high-level training; capital invested in innovation projects; innovation service contracts; profits from innovation service contracts and initial capital for investment in innovation.

Table 2 shows a reference framework by topic, of research works carried out under the system dynamics approach and related to innovation processes.

**Table 2**.
*Themes of system dynamics in relation to innovation*

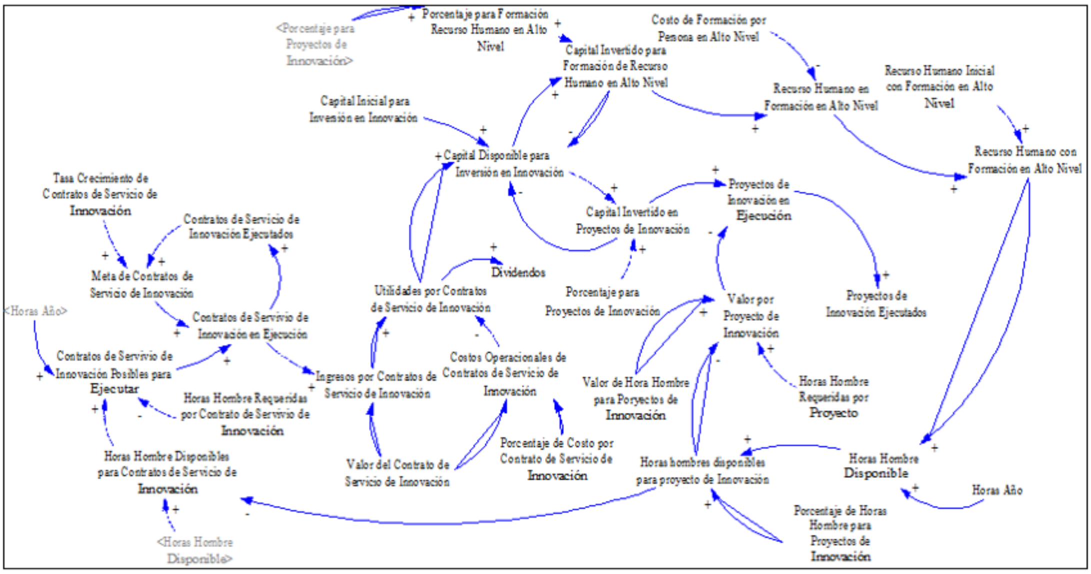
| Theme | Authors | Important aspects |
|---|---|---|
| Coevolution of innovation | (Castellacci, 2018; Luna Reyes & Gil Garcia, 2014) | • Interactions between all these variables in the development of digitalization in government.<br>• Main dimensions: physical capital, R&D and innovation, human capital and population dynamics. |
| | (Chen & Wakeland, 2016; Choi et al., 2016; Nieuwenhuijsen et al., 2018; Timma et al., 2015; Tsai & Hung, 2014) | • Examines the system from a functional perspective and operationalizes the link between forecasting and planning.<br>• Combines empirical study with system dynamics modeling<br>• Integrated multi-generation diffusion model (market and product)<br>• Future technology planning and strategic deployment<br>• Diffusion of cloud computing is affected by quality of service, infrastructure maturity, price, technological maturity<br>• Identification of critical technologies<br>• Product and innovation processes are carried out in parallel, rather than sequentially. |
| Foresight and dissemination of technological innovation | (Musango et al., 2012; Walrave & Raven, 2016) | • Interaction between competing technologies<br>• Integrates the concept of “innovation drivers” with the notion of “transition pathways,” which was developed as part of multilevel framework thinking<br>• Technology is seen as an outcome of innovation<br>• Emerging technological innovation |
| Technological innovation systems | (Grüneisen et al., 2015; Hsieh & Chou, 2018; Kasperek et al., 2014) | • Mechanisms for assessing the impact of innovation processes.<br>• Analysis and forecasting of the impact of cyclical changes within innovation processes.<br>• Types of cycles: Internal cycles (engineering change, manufacturing resources and team-building processes) and external environmental cycles (dependencies and demands related to government and customers). |
| | (Xu et al., 2012; Xue & Xu, 2017) | • Analysis of IT innovation capability: University-industry cooperation, IT personnel and business R&D investment, organizational arrangements, reasonable strategy and an innovative culture.<br>• Synergy between technological and marketing innovation is of great importance for the internalization of introduced technologies and resources. |
| Impact of innovation processes | (Gu et al., 2011; Zaim et al., 2013) | • Components of knowledge: creation or generation, storage or retrieval, transfer or exchange, and utilization.<br>• Development of computer simulation models that portray accumulation and feedback processes. |
| | (Qian et al., 2012; Wu et al., 2010) | • Identification of the differences between risk-based decision making for technological innovation from the point of view of the entrepreneurial team and the traditional problem of individual decision making.<br>• Incident response capability analysis to control the severity of incidents.<br>• Sustainability assessment of technologies |
| Innovation capacity | (Ramírez, 2017; Robledo & Ceballos, 2008) | • Integrating concepts from the sustainable livelihoods framework and technology management.<br>• Evolution of the process of introducing new technologies.<br>• Recognizing the role of R&D within SMEs.<br>• Balanced Scorecard for small and medium-sized enterprises based on the management of technological innovation.<br>• The dynamics of a logistics network is analyzed from the use of technologies for the redesign of any of its nodes. |

**Source:** own elaboration

*Stage 2. Causal loop diagram*

Figure 2 shows the causal loop diagram; the model shows the percentage of capital available for investment in innovation, such as the distribution made, on the one hand, for the training of high-level human resources and, on the other, the investment earmarked for innovation projects.

**Figure 2.**
*Causal loop diagram: summary of main feedback loops*

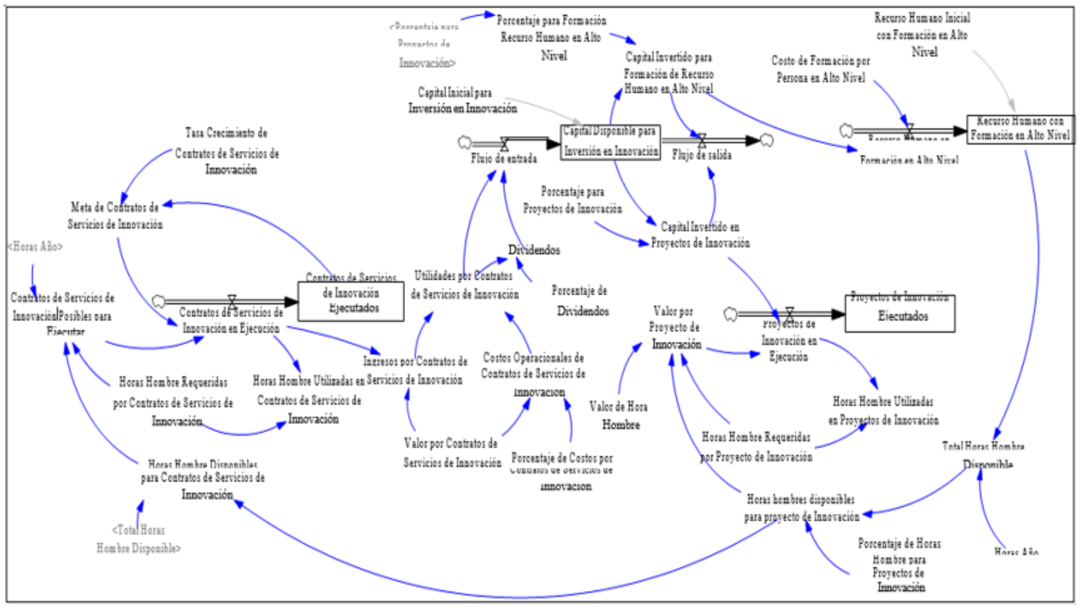



**Source:** own elaboration
Note: the figure appears in its original language

*Stage 3. Flowchart*

Figure 3 shows the flow diagram, and was constructed based on the causal loop diagram. Four state variables are identified: capital available for investment in innovation, human resources with high-level training, investment projects executed, and innovation service contracts executed. The inflow in the variable Capital available for investment in innovation corresponds to profits, after deducting dividends, while the outflow corresponds to the capital invested in training of high-level human resources, plus the capital invested in innovation projects.

**Figure 3.**
*Flowchart of the innovation management process*




**Source:** own elaboration
Note: the figure appears in its original language

The input flows of the other state variables are human resources in high-level training, innovation projects in execution and innovation service contracts in execution. The other variables are auxiliary, constant, and related by means of the arcs or arrows.

*Stage 4. Equations*

**Table 3.**
*System of equations of the model*

| No | Variables | Type | Unit | Formula |
|---|---|---|---|---|
| 1 | Capital Available for Innovation Investment | Level | pesos | INTEG (Inflow-Outflow, Initial Capital for Investment in Innovation) |
| 2 | Seed Capital for Investment in Innovation | Constant | pesos | |
| 3 | Capital Invested in Innovation Projects | Auxiliary | pesos | Capital Available for Investment in Innovation*Percentage for Innovation Projects |
| 4 | Capital Invested for Training of High Level Human Resources | Auxiliary | pesos | Capital Available for Investment in Innovation*Percentage for Training High Level Human Resources |
| 5 | Innovation Services Contracts Executed | Level | contracts | INTEG (Innovation Services Contracts in Execution, 0) |
| 6 | Innovation Services Contracts in Execution | Auxiliary | contracts | IF THEN ELSE(Innovation Services Contracts Target<=Innovation Services Contracts Possible to Execute, Innovation Services Contracts Target, Innovation Services Contracts Possible to Execute) |
| 7 | Innovation Services Contracts Possible to Execute | Auxiliary | contracts | IF THEN ELSE (Man Hours Required for Innovation Services Contracts <=Man Hours Available for Innovation Services Contracts, INTEGER (Yearly Hours / Man Hours Required for Innovation Services Contracts), 0) |
| 8 | Training Cost per Person in High Level | Auxiliary | pesos/ person | RANDOM UNIFORM( 7.5e+07, 1.5e+08, 0) |
| 9 | Operating Costs of Innovation Services Contracts | Auxiliary | pesos | Value of Innovation Services Contracts*Percentage of Innovation Services Contract Costs |
| 10 | Dividends | Auxiliary | pesos | Profit from Innovation Services Contracts*Percentage of Dividends |
| 11 | Inflow | Auxiliary | pesos | Profits from Innovation Services Contracts-Dividends |

**Source:** own elaboration

*Stage 5. Model validation*

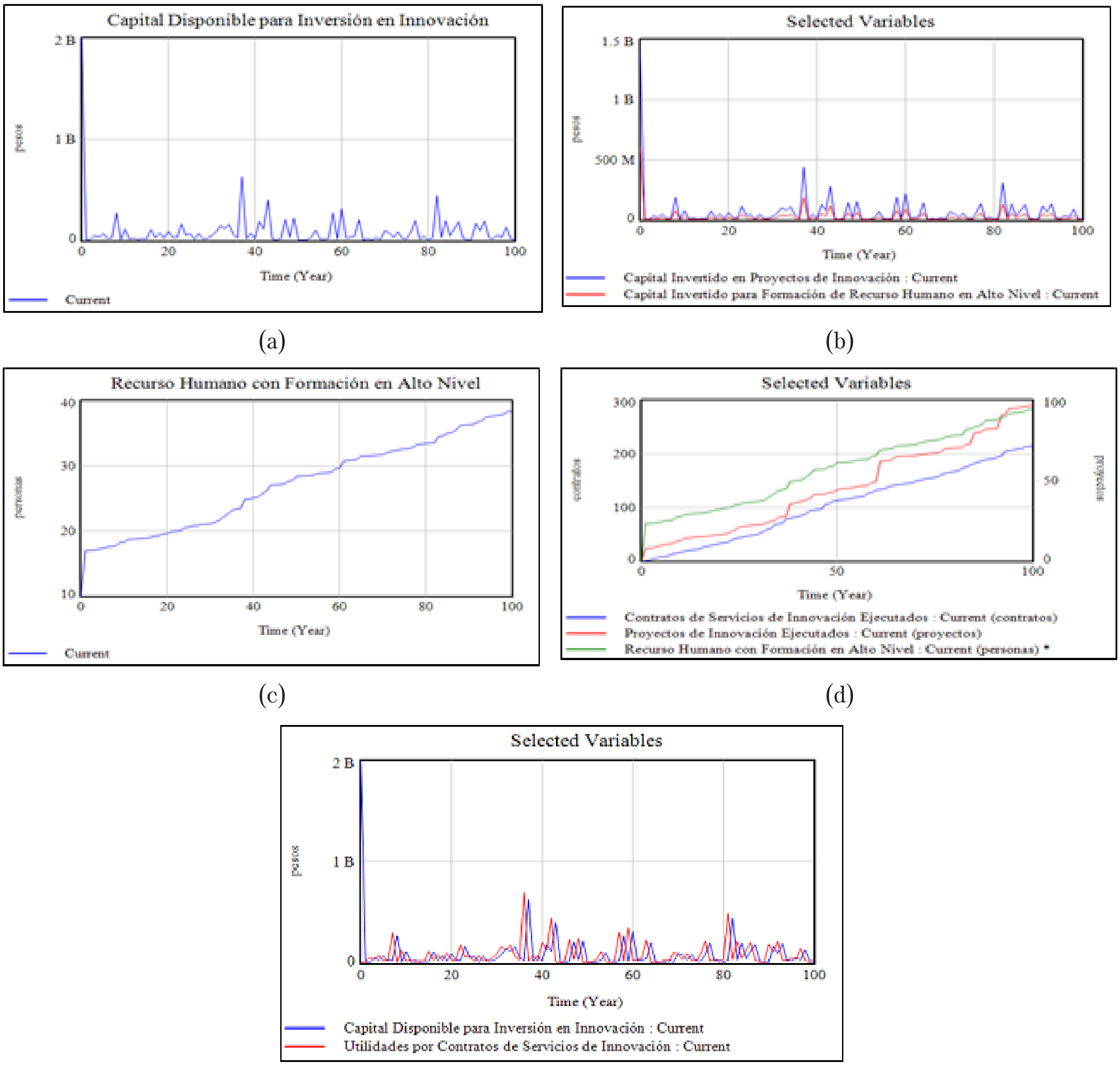
**Table 4**.
*Parameters established for model validation*

| Parameters | Initial value | Unit |
|---|---|---|
| Seed Capital for Investment in Innovation | 2000.000.000 | pesos |
| Innovation Services Contracts Executed | 0 | contracts |
| Training Cost per Person at a High Level | 75.000.000 Msc. 150.000.000 PhD | pesos/person |
| Hours Year | Constant | hours |
| Man Hours Required for Innovation Services Contracts | 240 a 2880 | hours |
| Man Hours Required per Innovation Project | 240 a 2880 | hours |
| Percentage of Costs for Innovation Services Contracts | 0.6 | percentage |

| | | |
|---|---|---|
| Dividend Percentage | 0.1 | percentage |
| Percentage of Man Hours for Innovation Projects | 0.5 | percentage |
| Percentage for Innovation Projects | 0.7 | percentage |
| Innovation Projects Implemented | 0 | project |
| Initial Human Resources with High Level Training | 10 | people |
| Innovation Services Contracts Growth Rate | 0.1 | percentage |
| Value of Man Hour | 55.000 MSc<br>65.000 PhD | pesos |
| Value of Innovation Services Contracts | 20.000.000 a 100.000.000 | pesos |

**Source:** own elaboration

**Figure 4.**
*Behavior of the significant variables of the model*




(e)

**Source:** own elaboration
Note: the figures appears in its original language

Figure 4 (a) shows the behavior of the capital available for investment, which, at the beginning, presents a high level due to the effect produced by the initial capital. Subsequently, its trend decreases, because it depends only on the level of profits. Figure 4 (b) shows the behavior of the capital invested in innovation projects versus the capital allocated for high-level human resource training, where the former shows a higher investment due to the higher percentage allocated to it. Figure 4 (c) shows the behavior of human resources with high-level training, which starts at 10 because it is the human resource with high-level training that exists initially.

Then, Figure 4 (d) shows that, as the human resource with high-level training grows, so do the innovation service contracts executed and the innovation projects executed; this is due to the increase in available man-hours with innovation capacity, which have a direct impact on their growth. Finally, Figure 4 (e) shows the behavior of the capital available for investment in innovation, compared to the profits per innovation service contract, where, at the beginning, there is a higher level of capital available for investment due to the effect of the initial capital, but from now on the behavior is practically the same, because the capital for investment corresponds to the profits.

## CONCLUSIONS

A model based on system dynamics has been developed, which provides an integral perspective to analyze the complex interactions between several key variables in the technological innovation process. This model focuses mainly on three fundamental aspects: the competence of human resources in generating innovation, investment in innovation projects, and income generation through the provision of innovative services.

This model focuses on the company's internal innovation and does not take into account the transfer of innovation from external sources. In other words, it concentrates on how the organization uses its internal resources and capabilities to drive innovation. However, it is relevant to recognize that innovation can also come from external sources, such as strategic alliances, collaborations with other companies, or the acquisition of proprietary technologies. This opens the door to future research that could expand the model to address the innovation transfer from the outside and assess its impact on the technological innovation process.

In summary, this system dynamics model provides a valuable tool for understanding and managing the complex dynamics related to technological innovation in the business environment. Although it has been limited to analyzing internal innovation, its flexibility allows for an expansion to incorporate elements of external innovation in subsequent research, which would further enrich our understanding of this process in the business environment..

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