A Systemic Analysis of the Effects of Public Investment on Innovation Ecosystems Using System Dynamics

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Abstract

Introduction: Public investment policies in science, technology and innovation (STI) generate dynamic, non-linear effects on innovation ecosystems. Understanding how investment decisions shape capacity accumulation and innovation outputs over time is critical for evidence-based policymaking, yet few studies apply formal simulation methods to this problem in the Brazilian context.

Approach: A System Dynamics model was built in STELLA® using historical data from Brazil's FNDCT fund (2010–2024). The model represents infrastructure and human capacity stocks, interconnected through investment flows and structural delays, feeding a sequential innovation pipeline. Three policy scenarios were simulated: status quo, investment increase, and investment cut. No empirical calibration was performed; the focus is on relative behavioral patterns.

Results: Investment effects materialize with a structural delay of approximately three years. Increased investment leads to progressive capacity expansion and higher patent output over the medium term. Investment cuts produce temporary inertia sustained by accumulated stocks, followed by systemic stagnation. The minimum capacity constraint between infrastructure and human capital consistently acts as the binding bottleneck across all scenarios.

Discussion: Findings suggest that STI policies require long-horizon planning, as short-term cuts may mask structural erosion of innovation capacity. The complementarity between infrastructure and human capital implies that unbalanced allocation reduces system effectiveness. The study contributes by formalizing the complementarity between infrastructure and human capital as a limiting mechanism of innovation within a simulation structure, offering a replicable framework for the analysis of STI public policies.

Keywords: System Modeling; Innovation Ecosystems; Public Investment; Capacity Constraints; Policy Simulation

1. Introduction

Innovation has been widely recognized as a central driver of economic and social development, particularly in knowledge-based economies. In the Brazilian context, public funding policies — such as investments channeled through sectoral funds — play a fundamental role in structuring and sustaining innovation ecosystems. However, the relationship between public investment, installed capacity, and innovation outcomes exhibits dynamic behavior, characterized by temporal delays, stock accumulation, and non-linear effects.

In this context, System Dynamics proves to be a suitable approach for understanding and analyzing complex systems, in which public policy decisions generate effects over time and are mediated by interdependent stocks and flows. In particular, dynamic modeling enables the exploration of prospective scenarios, assessing how different investment strategies may influence the evolution of infrastructure and human capacities and the generation of innovation outputs.

The objective of this paper is to propose and analyze a System Dynamics model to simulate the effects of public investment policies on an innovation ecosystem, considering the formation of infrastructure and human capacities, as well as the project and patent pipeline and the comparison of different public resource allocation strategies. The justification lies in the need for analytical tools that support the formulation and evaluation of public policies, enabling an understanding not only of the immediate effects of investments, but also their medium- and long-term impacts.

The research question guiding this study is: how do different public investment policies influence, over time, the formation of infrastructure and human capacities and the generation of innovation outputs in an innovation ecosystem? To address it, this paper offers two main contributions: (i) a methodological contribution, by applying System Dynamics modeling and simulation to the context of STI public policies in Brazil; and (ii) an analytical contribution, by exploring, through prospective scenarios, the dynamic implications of different public investment strategies on the infrastructure, human capacities, and innovation output of an ecosystem.

Despite the relevance of the topic, existing studies on public investment in innovation tend to rely on static or econometric approaches that are ill-suited to capture the temporal dynamics, feedback structures, and non-linearities that characterize innovation ecosystems (GOMES et al., 2018; STERMAN, 2000). System Dynamics models applied specifically to the analysis of STI policies in emerging economies remain scarce, and no study has formally modeled the complementarity between infrastructure and human capital stocks as a binding constraint on innovation pipeline throughput in the Brazilian FNDCT context. This paper addresses that gap.

This paper presents a System Dynamics model developed to analyze how public investment policy decisions shape the evolution of infrastructure, human capacities, and innovation output over time, with findings grounded in the simulation of three contrasting investment scenarios. In doing so, the study advances the literature by explicitly integrating capacity complementarity and structural delays into a simulation framework applied to the Brazilian context.

2. Theoretical Background

System Dynamics (SD) was established by Jay W. Forrester at MIT in the late 1950s and formally introduced in his seminal work Industrial Dynamics (1961). Forrester conceived SD as a methodology to model complex sociotechnical systems through stocks, flows, feedback loops, and time delays, enabling the analysis of how a system's internal structure — rather than external shocks — generates its characteristic patterns of behavior over time. The central insight of the approach is that many counterintuitive outcomes in management and policy arise from the structure of feedback loops and delays within the system itself: reinforcing loops (positive feedback) amplify change and drive growth or collapse, while balancing loops (negative feedback) create goal-seeking and self-correcting behavior. These structures interact with time delays to produce oscillations, overshoot, and stagnation that are difficult to anticipate through linear, static analysis.

Sterman (2000) extended Forrester's foundations by demonstrating that complex systems are characterized by dynamic complexity — a condition in which cause and effect are distant in time and space, feedback is nonlinear, and decision-makers operate with limited visibility into system structure. In this context, SD modeling serves as a "management flight simulator": a structured laboratory in which policies can be tested and their dynamic consequences explored before implementation. Sterman particularly emphasized the role of policy resistance, whereby well-intentioned interventions are undermined by the system's endogenous response — a phenomenon directly relevant to public investment in innovation, where short-term cuts may appear benign due to stock inertia while generating structural deterioration only visible in the medium term.

Hussain and De Vries (2025) conducted a systematic literature review of SD applications in Enterprise Engineering (EE), analyzing 30 peer-reviewed publications and mapping the combined use of both disciplines. Their findings reveal that SD has become widely accepted in EE as a tool for modeling the complex interdependencies and feedback loops within organizational systems, offering structured support for decision-making under uncertainty. The review identified that SD is particularly effective during the problem analysis phase of enterprise design, where understanding the dynamic behavior of a system is critical before proposing interventions. Crucially, the authors highlight that SD's "what-if" analysis capabilities allow decision-makers to evaluate the broader consequences of policy modifications in a way that methods with shorter predictive horizons cannot, establishing SD as a fitting tool for the exploration of public investment policy scenarios modeled in the present study.

In the field of innovation ecosystems, Gomes et al. (2018) provide a foundational theoretical contribution through a systematic literature review covering the evolution of the innovation ecosystem construct from 1993 to 2016. Their work maps the transition from the earlier business ecosystem concept — centered on value capture — to the innovation ecosystem concept, which is centered on value creation through the complementarity between actors, assets, and capabilities. The authors identify six research streams within the field, among which the dynamics of innovation ecosystem lifecycle and the management of interdependent actors stand out as directly relevant to the present model. Their core finding — that innovation ecosystems are characterized by multilateral interdependence and non-generic complementarities — provides the conceptual rationale for modeling infrastructure and human capacity as co-dependent stocks whose joint sufficiency determines innovation output, rather than treating them as independent variables.

Marcon (2023) advances this perspective by examining the dynamics of startup innovation within innovation ecosystems, highlighting how innovation outputs emerge not from isolated organizational efforts but from the dynamic interaction between ecosystem participants and available resources over time. The study underscores that capacity accumulation — particularly human capital and institutional knowledge — is a path-dependent process: the ecosystem's current state constrains its future trajectory, and disruptions to investment flows produce effects that persist well beyond the moment of intervention. This reinforces the theoretical justification for representing infrastructure and human capacities as stocks subject to inertia, and for using SD simulation to trace how investment decisions propagate through the ecosystem over a multi-year horizon. Taken together, the literature reviewed here establishes the three theoretical pillars of the present model: SD as the methodological framework for capturing dynamic complexity; innovation ecosystem theory as the conceptual structure for representing actors and capacity stocks; and the complementarity of infrastructure and human capital as the binding mechanism that determines system throughput.

These theoretical foundations jointly support the design choices made in the present model: the use of stocks and conveyors to represent capacity accumulation and innovation pipeline delays; the incorporation of reinforcing and balancing feedback loops to capture the "Limits to Growth" archetype; and the adoption of scenario simulation as the primary analytical tool for evaluating the dynamic consequences of different public investment policies on the innovation ecosystem. The approach is further supported by applied SD studies demonstrating the method's effectiveness in analyzing systems where structural viability depends on the balance between interdependent components (MARTINS et al., 2020) and where business model innovation unfolds through dynamic feedback between investment, capabilities, and outputs (YUANA et al., 2021) — both structural parallels to the innovation ecosystem modeled here.

3. Methodological Procedures

This study is characterized as an exploratory investigation based on System Dynamics modeling and simulation, adopting a quantitative approach following the principles established by Forrester (1961). The method was applied in four main stages: (i) problem definition and system scope; (ii) construction of the conceptual model; (iii) development of the dynamic model; and (iv) scenario simulation and analysis of results.

The model was developed using STELLA® software (version 10.0.6), which enables the explicit representation of stocks, flows, converters, and time delays. The structural parameters were defined based on the innovation ecosystem literature and reference values adopted for exploratory purposes.

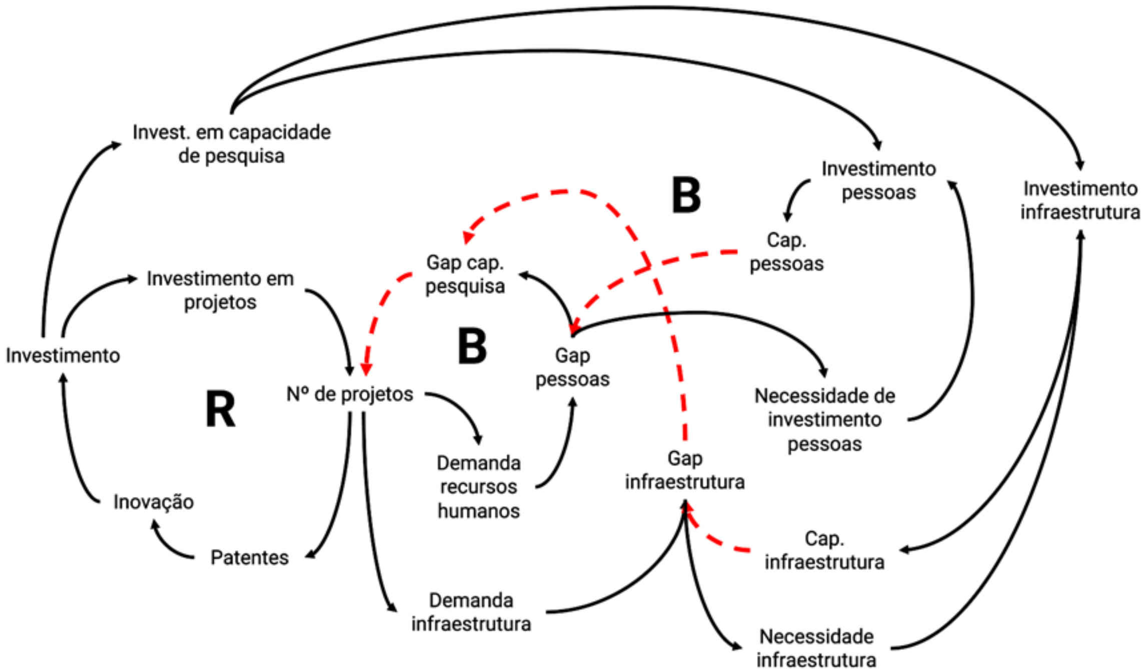
Historical public investment data were incorporated into the model through a graphical function (GRAPH), representing annual investment from 2010 to 2024. From this base, prospective scenarios were simulated in which the investment policy acts as a control variable, enabling the evaluation of different strategies of continuity, expansion, or reduction of investments.

The simulation time horizon was set at 15 periods, interpreted as years, enabling the analysis of medium-term effects of investment policies. Each time step represents one year, which is consistent with the nature of the processes analyzed in the innovation ecosystem. No empirical calibration was performed, since the objective of the study is the exploratory analysis of behavioral patterns and trends under different policy scenarios.

4. Conceptual Model

Figure 1 presents the developed causal diagram, highlighting the structural interaction between investments, capacity formation, and the emergence of gaps that constrain growth.

Figure 1 – Conceptual model of the innovation ecosystem, highlighting the investment, capacity formation, and innovation output subsystems.



The conceptual model represents an innovation ecosystem structured around three main subsystems: investment, capacity formation, and innovation outputs. Public investment acts as an exogenous variable, influenced by an investment policy, and is allocated between infrastructure and people. Reading Figure 1 begins at the central node of public investment, which branches into two allocation flows: one directed to infrastructure capacity and another to human capacity. These two stocks, represented by accumulation nodes, are the foundation that determines the volume of innovation projects the system can execute simultaneously, bounded by the minimum between infrastructure and human capacity. From the project stock, sequential flows feed the innovation pipeline, culminating in the generation of completed patents and available technological information. The feedback arrows close the structural loops of the model, indicating how generated outputs indirectly influence the perceived need for new investments.

The formation of infrastructure and human capacities occurs through the accumulation of infrastructure capacity and human capacity stocks, which determine the number of innovation projects that can be initiated. These projects feed a sequential innovation pipeline, ranging from ongoing projects through to the generation of completed patents and available technological information.

The model incorporates feedback loops and temporal delays, particularly in the maturation process of projects and patents, reflecting the non-immediate nature of innovation outputs. Thus, the conceptual model enables analysis of how investment decisions impact the system over time, even after changes or interruptions in the adopted policy.

Furthermore, the conceptual model incorporates feedback mechanisms that influence system behavior over time. Increased investment contributes to the expansion of infrastructure and human capacities, which broadens the potential number of innovation projects. Conversely, when either capacity — whether infrastructure or human — falls short of system demand, a structural gap emerges: the number of projects that can be initiated becomes constrained by the minimum available capacity between the two dimensions, creating a bottleneck that reduces the entry flow into the innovation pipeline. This mutual restriction mechanism reflects the complementary nature of capacities in innovation ecosystems, in which insufficiency in either dimension — whether physical infrastructure or human capital — compromises overall system performance. These mechanisms configure feedback loops that explain both system growth and stagnation, depending on the investment policy adopted.

From a systemic perspective, the structure represented in the conceptual model aligns with the "Limits to Growth" archetype, in which the initial expansion of the system is constrained by structural capacity restrictions. This archetype is particularly suited to represent innovation ecosystems, in which additional investments do not automatically yield continuous growth without strengthening the underlying capacities.

The main feedback mechanisms can be described by two central loops. The reinforcing loop (R1) represents capacity expansion, in which increased investment raises infrastructure and human capacity, broadening the number of innovation projects. The balancing loop (B1) represents capacity restriction, in which structural limitations generate gaps that constrain the execution of new projects, reducing system growth.

5. System Dynamics Model

The dynamic model was implemented from the conceptual model, using stocks to represent accumulated capacities and flows to describe investment, obsolescence, and project execution processes. Total investment is defined as the product of base investment and the investment policy variable, distributed between infrastructure and people according to allocation parameters. The investment policy variable operates as a dimensionless multiplier applied to the historical FNDCT base investment, enabling the simulation of relative variations in the level of public investment. In the three simulated scenarios, it takes the following values: (i) status quo — multiplier of 1.0, maintaining the historical investment level; (ii) investment increase — multiplier of 1.5, representing a 50% increase over the base investment; and (iii) investment cut — multiplier of 0, fully interrupting the entry of new resources into the system. These values were defined for exploratory purposes, without empirical calibration, with the aim of capturing the qualitative behavioral patterns of the system under different policy regimes.

Table 1 – Main model parameters

Parameter	Description	Value
Simulation horizon	analyzed period	15 years
Maturation time	project pipeline delay	3 years
Patent analysis time	analysis process delay	2 years
Conversion rate	projects → patents	0.2
People percentage	investment allocation	0.5

Innovation projects are constrained by the minimum available capacity between infrastructure and people, reflecting real resource restrictions. The innovation pipeline is modeled through conveyors, which introduce delays associated with project execution, patent analysis, and technological maturation.

Table 2 – Main model stocks and flows

Type	Variable
Stock	Infrastructure capacity
Stock	Human capacity
Conveyor	Innovation projects in execution (pipeline)
Conveyor	Patents under analysis (patent pipeline)
Inflow	Infrastructure investment (fraction of total investment)
Inflow	Human capacity formation (complementary fraction of total investment)
Outflow	Infrastructure and human obsolescence (stock depreciation)
Auxiliary variable	Minimum available capacity = MIN(infrastructure capacity; human capacity)
Auxiliary variable	Total investment = base investment × investment policy

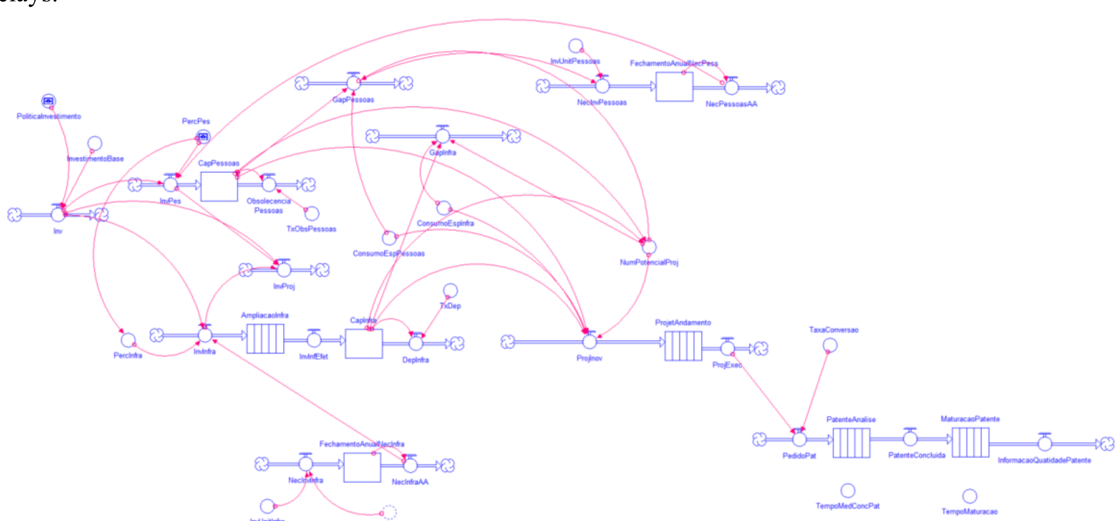
The structural equations governing model behavior can be described as follows. Infrastructure capacity accumulates the investment allocated to infrastructure (defined as the product of total investment by the complement of the people percentage) and depreciates at an obsolescence rate proportional to the current stock. Symmetrically, human capacity accumulates the investment allocated to human capital formation (product of total investment by the people percentage) and depreciates by the same logic. The number of projects initiated each period corresponds to the minimum available capacity between the two dimensions \u2014 expressed by the MIN function \u2014 and feeds the first pipeline conveyor, whose transit time is the project maturation parameter (3 years). Completed projects feed a second patent analysis conveyor (2 years), whose output is multiplied by the conversion rate (0.2) to generate the completed patent flow.

The main model parameters were made available in the simulation interface, enabling direct control of investment policies, conversion rates, and average processing times. This structure allows the analysis of different scenarios without requiring changes to the model structure.

The simulation interface was structured to allow direct manipulation of the main policy and structural model parameters. Controllable parameters include the investment policy, the percentage allocation between people and infrastructure, the project-to-patent conversion rate, and the average times associated with the innovation pipeline. This approach facilitates the analysis of prospective scenarios without requiring modifications to the internal model structure.

The developed model is exploratory and non-predictive in nature, functioning as a public policy laboratory rather than a forecasting tool. Its value lies in capturing qualitative behavioral patterns and the directional effects of different investment regimes, rather than predicting precise absolute values. The focus of analysis therefore lies on the relative trajectories and structural dynamics that emerge across scenarios, which are sufficient to draw policy-relevant conclusions about the timing, magnitude, and complementarity effects of public STI investment. Model validity was assessed through face validity and structural validity: the causal structure and parameter logic were reviewed against the theoretical literature on innovation ecosystems (Gomes et al., 2018; Marcon, 2023) and against established SD modeling principles (Sterman, 2000), and the behavioral patterns produced by the model under each scenario were found to be consistent with theoretical expectations regarding stock accumulation, delay-driven inertia, and capacity-constrained growth.

Figure 2 – System Dynamics model implemented in STELLA® software, with stocks, flows, and temporal delays.



6. Results

Results were obtained from the simulation of three distinct scenarios: (i) investment maintenance (status quo), (ii) investment increase, and (iii) investment cut. In the status quo scenario, a gradual and stable growth of infrastructure and human capacities and innovation output is observed, with continuous generation of projects and patents over the time horizon.

In the investment increase scenario, results indicate an accelerated expansion of capacity and innovation output, but with a delay of several years between the investment increase and the materialization of results, evidencing the presence of structural delays in the system.

In the investment cut scenario, the model reveals behavior characterized by system inertia: despite the interruption of investment, innovation outputs do not cease immediately, being temporarily sustained by accumulated capacities. However, in the medium term, system stagnation is observed, indicating a strong dependence on the continuity of public investment for maintaining innovation performance.

The comparison between the three scenarios shows that the effects of investment policies do not manifest immediately, being strongly influenced by delays and accumulated capacities in the system. Thus, both investment expansion and cuts produce differentiated impacts over time, reinforcing the importance of dynamic analyses for the evaluation of innovation public policies. Graphs present time in years on the horizontal axis and capacity and innovation output variables in relative units on the vertical axis. This behavior is consistent with the System Dynamics literature, which emphasizes the role of delays and stocks in generating non-immediate responses to policy changes (STERMAN, 2000).

6.1 Scenario 1 – Status Quo

In this scenario, the investment policy is kept constant throughout the simulation horizon. Results indicate a gradual growth of infrastructure and human capacity, sustaining a stable flow of projects and patents. The observed behavior reflects a dynamic equilibrium regime, in which the system maintains its innovation output and accumulated capacities without acceleration or collapse.

Figure 3 – Evolution of infrastructure and human capacities and innovation output in the status quo scenario.

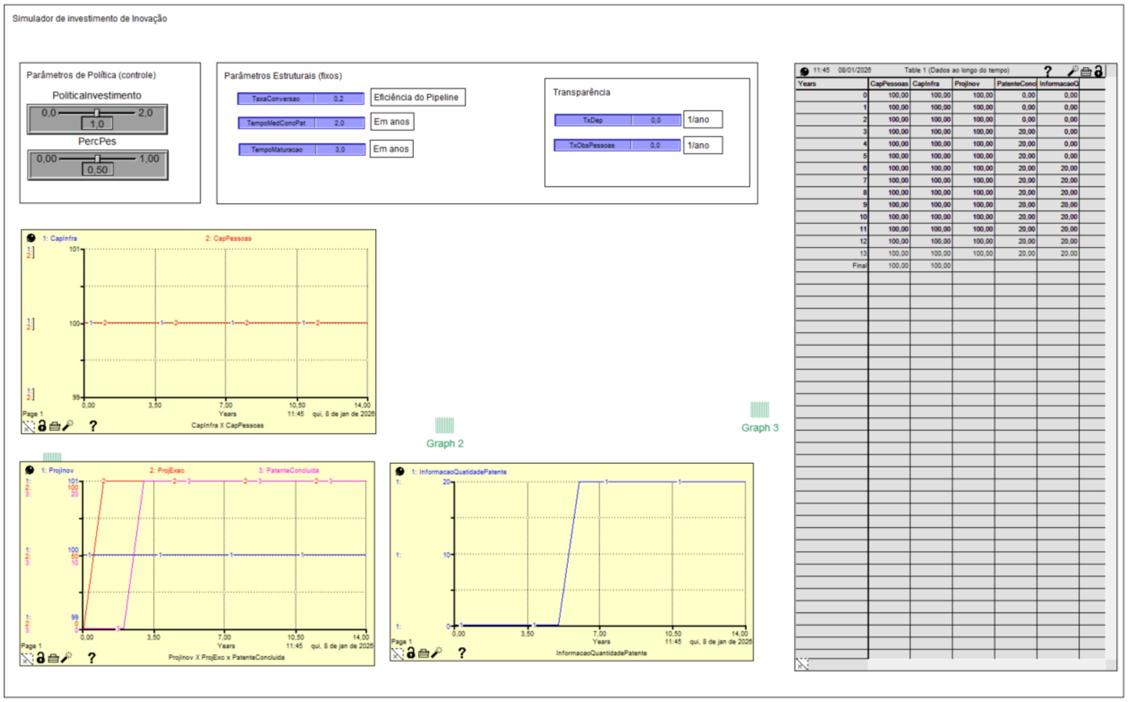
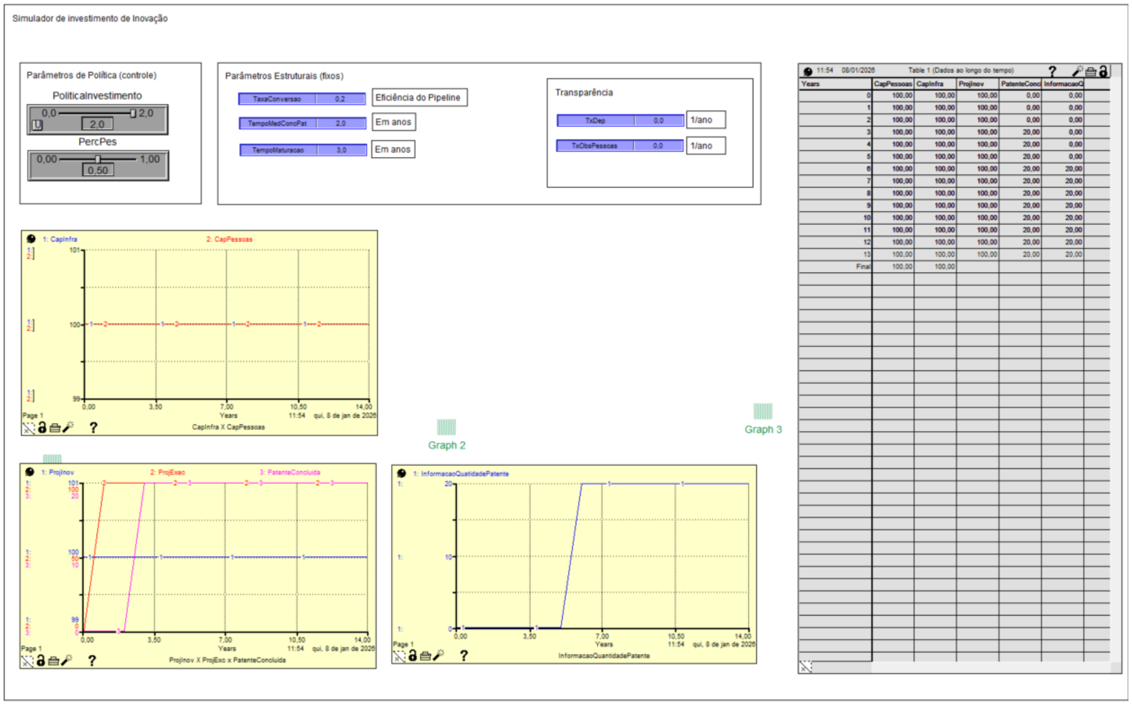


Figure 3 illustrates the evolution of infrastructure capacity, human capacity, and innovation output in the status quo scenario, evidencing stable behavior over time.

6.2 Scenario 2 – Investment Increase

In this scenario, the investment policy is intensified, simulating a sustained increase in public investment throughout the simulation horizon. As illustrated in Figure 4, the impact on infrastructure and human capacities and patent generation occurs with a temporal delay, reflecting the maturation times of the innovation pipeline. This behavior suggests that investment increase policies tend to produce more relevant effects in the medium term.

Figure 4 – Evolution of capacities and innovation output in the public investment increase scenario.



6.3 Scenario 3 – Investment Cut

In the investment cut scenario, the investment policy is reduced to zero, interrupting the entry of new resources into the system. Innovation outputs do not cease immediately, being temporarily sustained by previously accumulated capacities. This behavior evidences the presence of structural inertia and delays in the system. However, in the medium term, the absence of investment leads to innovation stagnation, reinforcing the dependence on continuous public investment.

Figure 5 – Evolution of innovation output in the investment cut scenario, evidencing temporary persistence followed by structural stagnation.

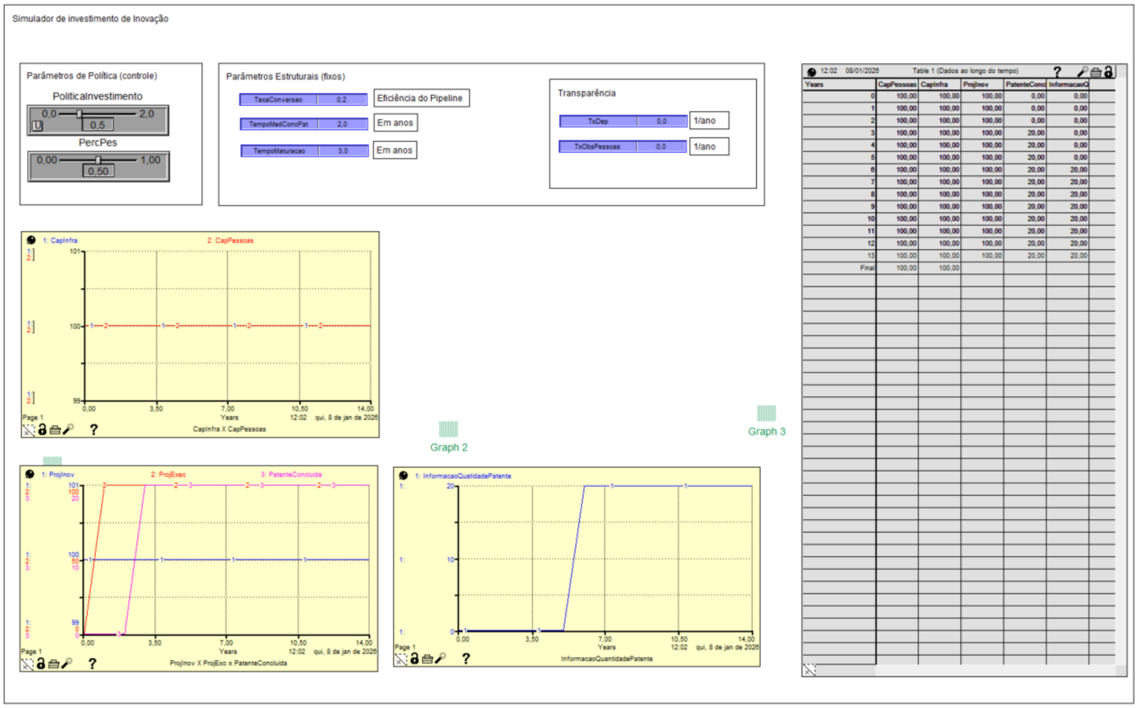


Figure 5 presents the evolution of the system in the investment cut scenario, highlighting the temporary persistence of innovation outputs even in the absence of new financial contributions, followed by a stagnation regime in the medium term.

The investment increase scenario presents greater accumulated growth of infrastructure and human capacities over time, while the cut scenario results in stagnation after an initial period of inertia. Compared to the status quo, differences become more evident from the intermediate periods of the simulation onward.

From a quantitative perspective, the comparison between scenarios reveals significant differences across three dimensions. Regarding the accumulated patent level at the end of the simulation horizon, the investment increase scenario produces a substantially higher volume than the status quo, while the cut scenario results in a lower volume, with a sharp decline from the midpoint. Regarding maturation time, all three scenarios present the same three-year structural delay between project initiation and completion, but the magnitude of results generated after this period diverges increasingly as the time horizon extends. Regarding the capacity trajectories, the status quo scenario maintains stable infrastructure and human capacity levels, the increase scenario shows progressive expansion, and the cut scenario exhibits a gradual decline in accumulated capacities, with a direct impact on the reduction of pipeline entry flows.

In terms of public policy implications, the results suggest three key orientations. First, policies of expanding public investment in science, technology and innovation yield returns that materialize with a delay, requiring continuity and medium- to long-term planning horizons from policymakers. Second, abrupt investment cuts do not result in an immediate decline in innovation outputs — due to the inertia of accumulated stocks — which may induce a misleading perception of system robustness in the short term, followed by structural stagnation in the medium term. Third, the complementarity between infrastructure and human capacities suggests that balanced allocation policies between the two dimensions tend to be more effective than concentrating resources on only one, since the bottleneck will always be determined by the minimum available capacity.

7. Discussion and Conclusions

The results of this study offer a structured basis for discussing the dynamic implications of public investment decisions on innovation ecosystems. Three cross-cutting findings emerge from the scenario analysis that are consistent with the theoretical frameworks reviewed. First, the dominance of structural delays: across all scenarios, the three-year project maturation delay and the two-year patent analysis delay act as persistent buffers that decouple investment decisions from their observable outcomes. This temporal decoupling is a defining feature of innovation systems identified by Sterman (2000) as a primary source of policy resistance, and it implies that policymakers assessing the effects of past investment decisions are inevitably looking at a lagged signal. Second, the binding role of complementary capacities: the MIN-function constraint operating between infrastructure and human capacity means that asymmetric allocation of investment — even when total investment is constant — reduces innovation throughput. This finding extends Gomes et al.'s (2018) complementarity argument into a dynamic simulation context, demonstrating that imbalance between the two capacity dimensions becomes self-reinforcing over time as one stock decelerates and constrains the other. Third, the asymmetry of inertia: the investment cut scenario reveals that innovation outputs are more resilient to downward shocks in the short run than they are to upward ones, due to the buffering effect of accumulated stocks. This asymmetry, theoretically grounded in the path-dependency emphasized by Marcon (2023), creates a systematic risk: decision-makers may underestimate the structural damage caused by investment cuts precisely because the ecosystem appears robust in the period immediately following the cut.

These results indicate that public policy interventions should be evaluated not only in terms of investment magnitude, but also regarding their temporal consistency and structural alignment with the existing capacities in the system.

These findings carry concrete implications for STI policy design. The persistent structural delay in the system suggests that the planning horizon for public investment in innovation should be anchored to medium-term cycles of at least five to seven years, not to annual budget windows. The bottleneck dynamics produced by the complementarity constraint suggest that investment allocation frameworks should treat infrastructure and human capital as joint inputs requiring co-investment, rather than substitutable alternatives. And the asymmetry of inertia suggests that continuity of funding is structurally more important than the absolute funding level in any given year: irregular stop-and-go investment patterns are particularly damaging because they interrupt capacity accumulation at a stage when stocks have not yet reached a self-sustaining level.

This study has several limitations that bound the scope of the conclusions. The model parameters were defined for exploratory purposes without empirical calibration against observed innovation output data, which means the results reflect structural behavioral logic rather than quantitative forecasts. The investment policy multiplier was modeled as a step change, whereas real-world policy shifts are typically gradual and subject to institutional inertia not captured in the current formulation. Additionally, the model abstracts away sectoral heterogeneity within the Brazilian STI system, treating the FNDCT fund as a unified investment stream. Future work should address these limitations through: (i) empirical calibration using longitudinal data on FNDCT disbursements and patent output; (ii) disaggregation of the model by sector or technology area; and (iii) inclusion of additional feedback loops capturing the influence of innovation outputs on future investment decisions through economic productivity gains.

In conclusion, this paper demonstrates that System Dynamics simulation is a productive methodological vehicle for analyzing the dynamic complexity of STI policy. The model developed here reproduces core theoretical predictions from the innovation ecosystem literature — capacity complementarity, path dependency, and delay-driven policy resistance — in a computable structure that allows scenario-based reasoning about policy alternatives. The original contribution to the SD field lies specifically in the formalization of the complementarity constraint between infrastructure and human capital as a MIN-function bottleneck within an innovation pipeline conveyor structure — a causal mechanism not previously modeled in the context of Brazilian public STI investment in the FNDCT context. The application contributes an empirically grounded reference case for the dynamic analysis of public investment in innovation in emerging economies. It also provides a replicable model structure for future SD studies connecting investment flows to measurable innovation performance indicators.

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