Proceedings of the 8th European Conference on Industrial Engineering and Operations Management
Paris, France, July 2-4, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/EU08.20250218
Published: July 2, 2025

Systems Thinking of Innovation Dynamic Framework to Analyze the Progression of Innovation Systems

Michelle Smit
Department of Industrial Engineering
Stellenbosch University
Stellenbosch, South Africa
michellesmit@sun.ac.za

Sara S Grobbelaar
Department of Industrial Engineering
Stellenbosch University
Stellenbosch, South Africa
and DSI-NRF, Centre of Excellence
Scientometrics and Science, Technology, and Innovation Policy (SciSTIP)
South Africa
ssgrobbelaar@sun.ac.za

Abstract

Researchers often employ the event history analysis method to understand the progression and resilience of innovation systems, as this method explores the sequence and timing of key events influencing the innovation system. However, the traditional event history analysis method may not fully explore the cumulative influence of events, trace and identify innovation actors, or capture the dynamics driving the actions of the innovation actors. To address these limitations, we recommend a systems thinking innovation dynamic framework to analyze the progression of innovation systems. This framework offers a novel combination of three existing artifacts: the innovation system framework, the event history analysis method, and the theory on systems thinking. This integrated approach allows for a comprehensive analysis of the development of innovation systems, focusing on how the different components of an innovation system interact and influence one another as a whole rather than examining the individual parts in isolation. This approach will enable authors to create comprehensive case studies on innovation systems, allowing them to a) analyze how technology has evolved, b) identify key events that led to significant breakthroughs or challenges, c) understand the influences of delays on systemic progress and challenges, d) understand the dynamics and resources affecting development, e) pinpoint high-leverage points where interventions can effectively tackle systemic issues causing major challenges, and f) consider whether the designed interventions might lead to unintended consequences in the near future.

Keywords
Innovation system framework, innovation system functions, functional dynamics, systems thinking, and event history analysis

1. Introduction
A technology innovation system (TIS) is a dynamic network of agents, including businesses, research institutions, and government entities, interacting within a specific economic and industrial context, supported by a particular institutional framework that develops, disseminates, and utilizes technology (Maarsingh et al., 2023). This system

creates an environment that encourages knowledge exchange, learning, and collaboration, which can significantly improve productivity, competitiveness, and overall economic growth.

The TIS framework, conversely, is a conceptual and analytical tool that offers a means to understand and analyze TISs. Moreover, event history analysis is an advanced method employed alongside the TIS framework to examine TISs, as it allows researchers to trace the development of innovation events and create a dynamic, temporal understanding of how these technology systems evolve.

Furthermore, integrating tools from systems thinking literature with the analysis of a TIS, using the TIS framework and an evolutionary method such as event history analysis, provides TIS authors with the means to analyze and map various interrelationships among TIS components. This enables a deeper understanding of the system's emergent behaviors. Additionally, it aids authors in conducting root cause analysis of systemic issues while considering the long-term effects that solutions may have on both the system and the surrounding environment of the TIS.

1.1 Objectives

This study aims to develop a comprehensive analytical framework for examining the innovation dynamics and progression of innovation systems by utilizing concepts from systems thinking. Design through the design science research methodology, the framework seeks to enhance the analysis of innovation systems through the event history analysis method. Although some innovation authors have employed mapping concepts from systems thinking, no study has applied systems thinking principles to analyze technology innovation systems. Furthermore, systems thinking principles have not been used alongside the event history analysis method as a framework to investigate the dynamics and progression of technology innovation systems. Implementing such a framework will assist innovation authors in developing in-depth case studies on innovation systems, allowing them to analyze comprehensively how a specific technology has evolved, identify key events that led to major breakthroughs or challenges, and understand the dynamics and resources that shaped development.

2. Literature Review

2.1 Technology innovation systems and event history analysis

An innovation system can be defined as a network of public or private institutes whose activities and interactions initiate, modify, and diffuse innovation (Maarsingh et al., 2023). A technological innovation system (TIS) represents a specific manifestation of the interconnectedness of social and technical aspects within a system focused on a technological innovation or field (Smit et al., 2024). It includes interrelated sectors and firms, a set of institutions and regulations that characterize the rules of behavior, and the knowledge infrastructure linked to a specific technology. TISs are analyzed in terms of their structural components, such as actors, networks, and institutions (as seen in Table 1), as well as their functions, which are the key processes for building an innovation system. Seven key functions, as seen in Table 2, are often identified: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of search, market formation, resource mobilization, and creation of legitimacy (McClelland et al., 2023b).

Table 1. Structural components of TISs
(McClelland et al., 2023a)

IS structures	**Subcategories**
Actors	• Companies, knowledge institutes (including universities, technology institutes, and research centres), government agencies, legal organizations, financial organizations/banks
Networks	• At the level of individual contacts and networks
Institutions	• Rules, laws, regulations, instructions, customs, established practices, traditions, ways of conduct, norms, expectations
Infrastructure	• Physical: instruments, machines, tools, buildings • Knowledge: knowledge, expertise, strategic information • Financial: subsidies, financial support programs, grants

Table 2. Indicators of functional fulfilment of the TIS functions (Maarsingh et al., 2023; McClelland et al., 2023a; Smit et al., 2024)

Function	**Description**
F1: Entrepreneurial Activity	The transformation of knowledge, interaction networks and infrastructure into beneficial business opportunities
F2: Knowledge Development	All activities associated with learning and the obtainment of information
F3: Knowledge Diffusion	All activities, channels, and networks through which knowledge is shared among actors
F4: Guidance of Search	The direction of people and resources towards appropriate opportunities and the provision of clarity, visibility and understanding
F5: Market Formation	All factors influencing the market adoption of an innovation
F6: Resource Mobilization	The alignment of resources to enable the development, diffusion, and use of innovations
F7: Creation of Legitimacy	The creation of institutional compliance and support of social acceptance for innovations to overcome the obstacles associated with `newness' within a market

The TIS literature highlights the importance of path dependency and cumulative causation for understanding long-term innovative development (Maarsingh et al., 2023). Event history analysis (EHA) is an evolutionary method that allows researchers to track the evolution of TIS functions and structural components over time to comprehend how systemic issues are created or resolved during TIS development. The steps involved in the EHA method are presented in Figure 1. Unlike more static analyses, EHA focuses on the sequence of events and their effects on the TIS. It explores how forces originate as events, how they spread through subsequent events, and how combinations of events lead to the growth or decline of the system. By understanding the historical development and the interaction of functions and actors, this combined approach can help identify when, how, and why systemic inadequacies occurred. Merging the TIS framework with EHA is particularly advantageous as it enables a dynamic and temporal understanding of how innovation systems evolve. While the TIS framework provides a structure for understanding a system's key components and functions supporting a specific technology, EHA offers an essential process-oriented perspective (Smit et al., 2024).

Figure 1. The event history analysis steps

The standard EHA method, while valuable for tracing the development of innovation systems over time, has certain limitations (McClelland et al., 2022). While generic EHA focuses on the sequence of events and their impact on innovation system functions, it may not adequately capture the specific circumstances or context in which these events occur. McClelland, Grobbelaar and Sacks (2022) suggested that the CIMO framework explicitly incorporates the definition of the system boundary, the phase of development, the objective of the innovation system, and the identification of its structures as part of the context. This contextual definition is crucial for understanding why specific interventions lead to particular mechanisms and outcomes. Furthermore, EHA focuses on identifying a sequence of events but does not define or suggest methods or tools to guide authors in developing interventions to address specific issues (Maarsingh et al., 2023). While EHA can identify patterns in the development of innovation system functions, it might not fully uncover the systemic structures or perceptions from different system actors that cause these patterns, ultimately leading to specific system outcomes. EHA may not systematically capture the roles and contributions of individual actors within the innovation system (Van Der Merwe and Grobbelaar, 2017). Authors have also argued that EHA may define system outputs in general terms or focus on fulfilling innovation system functions. Still, it might lack a structured approach to defining and analyzing outcomes, including broader development capitals.

In essence, EHA offers a valuable temporal perspective on the evolution of innovation systems by tracking events. However, its analytical usefulness will improve by incorporating systems thinking into its analysis steps, which adds crucial layers of contextual understanding, process specification, structural comprehension, and stakeholder perspective. Systems thinking lessens the tendency for EHA to be merely a descriptive account of events, moving instead toward a deeper, more explanatory, and action-oriented analysis.

2.2 Systems thinking

Systems thinking is a holistic approach to analysis that emphasizes how different parts of a system interact and influence one another as a whole, rather than examining the individual parts in isolation (Rubenstein-Montano et al., 2001). It serves as a conceptual framework for decision-making and problem-solving that considers issues in their entirety and seeks to understand the behaviors that emerge from the interaction of a system's components over time (Crabolu et al., 2024). It moves beyond simple linear cause-and-effect thinking to consider systems' interconnected, dynamic, and purposeful nature.

Systems thinking may be employed alongside IS, as innovation is not linear. Innovation arises from the intricate interactions among various actors, institutions, and other components that make up an innovation system (Galanakis, 2006). Therefore, adopting a systemic perspective is crucial to genuinely understanding how innovation happens and how to influence it. Samara et al. (2024) apply systems thinking in the context of regional IS. The authors emphasize the benefits of systems thinking in improving the analysis of ISs, as innovation is more effectively understood by examining systems. They note that innovation systems, being social systems, are particularly well-suited for system dynamics analysis. Furthermore, Midgley and Lindhult (2021) emphasize how systems thinking can redefine innovation process analysis by highlighting thinking in systems. The resulting innovation processes benefit from enhanced stakeholder dialogue, social learning, and a holistic understanding of change dynamics.

By combining the theory of systems thinking and its core principles with TISs, the benefits can be manifold. Systems thinking equips TIS authors with tools to analyze many interrelationships among TIS components and understand the emergent behaviors of the system as a whole (Galanakis, 2006). This fosters a deeper understanding of how different actors (such as firms, universities, and government bodies) and institutions (like regulations and norms) interact and influence the innovation process. Furthermore, adopting a holistic view allows systems thinking to identify the underlying or root causes of problems within an innovation system, rather than merely addressing surface-level symptoms (Ortt and Kamp, 2022). Additionally, systems thinking aids in developing more comprehensive and effective strategies to tackle systemic problems instead of isolated interventions, thereby reducing unintended negative consequences on the environment where the TIS operates and enhancing overall sustainability (McClelland, Grobbelaar and Sacks, 2023). In essence, integrating systems thinking and innovation systems creates a robust analytical framework for understanding the complexities, dynamics, and interconnectedness inherent in innovation processes, leading to more informed strategies and policies, and a greater potential for fostering innovation and addressing societal challenges.

2.3 Previous studies on systems thinking and innovation systems

Several authors have combined systems thinking tools and ISs. Linnéusson et al. (2022) applied systems thinking modeling to understand how to nurture an innovative culture within healthcare organizations to develop their ISs. They used the system dynamics methodology and causal loop diagrams (CLDs) to model the innovation processes in a healthcare unit that successfully transitioned to generating innovations. The context here is healthcare innovation systems, and the aim was to provide a holistic view, identify dynamics of inertia, delays in change processes, and system relationships to accelerate innovative work. They argue that this approach supports both individual and organizational learning in complex healthcare phenomena.

Furthermore, Arthur, Moizer, and Lean (2023) use systems thinking CLDs to understand regional innovation ecosystems. They aimed to uncover structural drivers and actor inter-relationships that can inform effective regional policy and economic growth strategies.

Similar to Linnéusson et al. (2022), McClelland, Grobbelaar and Sacks (2023), along with Maarsingh et al. (2023) utilized CLD as a systems-thinking tool. Both groups drew from system dynamics literature to support the identification of interaction patterns and causality between IS functions, particularly in the context of EHA. While McClelland, Grobbelaar and Sacks (2023) applied it within TIS analysis, Maarsingh et al. (2023) used it in the context of inclusive IS. While these authors employed systems thinking's CLD to map the ISs, they did not apply the core principles of systems thinking. Consequently, the gap in EHA of IS studies risks being merely a descriptive account of events instead of a more profound, explanatory, and action-oriented analysis. The following section delves into the design science research methodology, a method frequently used by innovation authors to develop frameworks and tools.

3. Methods

This study follows the design science research (DSR) methodology, which is a research approach focused on creating innovative artifacts, such as frameworks, models, methods, or instantiations, to solve identified problems and improve the application environment (Peffers et al., 2007). It aims to enrich both technology and scientific knowledge (vom Brocke et al., 2020). A commonly accepted framework for conducting DSR is the methodology proposed by Peffers et al. (2007), which consists of six activities.

The first activity of the DSR focuses on identifying problems and motivating solutions. It involves defining the research problem and justifying the significance of a solution. This activity occurs in section 2, the literature review, where literature on TISs, event history analysis, and systems thinking is examined.

Activity two involves defining the objectives for a solution (Peffers et al., 2007). The objectives for the solution artifact should be derived from the problem definition and specify what a successful artifact would accomplish. These objectives should be measurable and achievable. This study explored and analyzed existing literature, as presented in Section 2, to identify research gaps, extract relevant theoretical concepts, and derive framework objectives.

Activity three focuses on designing and developing the framework artifact. It involves identifying the artifact's intended functionality and architecture and the actual development process. This usually involves leveraging existing knowledge and theories (Ruyobeza et al., 2023). This activity is detailed in the remainder of this paper, specifically in section 4.

Activity four involves artifact demonstrations. Once the framework artifact is developed, it needs to be demonstrated in a suitable context, in this case applied to a case study, to show its functionality and how it can be used to solve the identified problem. This step is not performed in the paper, but in subsequent case studies by Grobbelaar and Smit.

The fifth activity is evaluation. The artifact's ability to address and solve the identified problem is observed and measured in this activity. The results obtained during the fourth activity are compared to the objectives defined in activity two to evaluate the artifact's effectiveness. This evaluation can involve various methods, including case studies and expert interviews (vom Brocke, Hevner, and Maedche, 2020). Any necessary changes to improve the artifact's effectiveness and efficiency should be communicated back to activity three regarding design and development.

Finally, in activity six, the evaluated artifact should be communicated. The final activity involves presenting the research results, including the problem, the designed artifact, its development process, its demonstration, and its evaluation, to the relevant audiences (Ruyobeza et al., 2T. This study is part of the communication activity. Applying the framework to future case studies will also enhance the communication of the framework artifact developed in this paper.

4. Results and Discussion

Considering the limitations of generic EHA outlined in Section 2, this section introduces the STID framework that addresses these shortcomings.

4.1 From Generic EHA to a Systems-Thinking Paradigm

Figure 2 presents the integration of the event history analysis (EHA) method and the technology innovation system (TIS) framework with systems-thinking theory. The EHA method occupies the innermost circle as it serves as the tool through which the narrative of what occurs in a system over time is identified and conveyed. It answers the question of "*What happened and in what sequence?*" within a system. Next, the second ring presents the TIS framework as it is an analytical tool through which the system actors and the innovation activities they perform are explored. Ultimately, the TIS framework builds on the "What happened and in what sequence?" question in the system by looking at "*Who does what?*" within the system. Finally, the outer ring represents the systems-thinking theory. The systems-thinking theory presents multiple concepts or tools through which the dynamics of the system can be explored and understood. Therefore, the systems-thinking circle answers the question, "*Why does the system behave that way?*"

Figure 2. Integrating the EHA method and TIS framework with systems-thinking theory

The STID framework differs from previous EHA-based approaches in the existing literature in the following five respects:

i. The framework adopts both telescopic and microscopic lenses to define the TIS boundaries. It combines the perspectives of individual innovation actors and a holistic system-level view, ensuring that boundaries are grounded in empirical evidence rather than being predetermined.
ii. Unlike traditional approaches that rely solely on causal loop diagrams, the STID framework utilizes both causal loop and feedback loop diagrams. This dual representation captures the full range of system behaviors, including balancing and information-based dynamics.
iii. The improved classification of system patterns allows for the identification of dynamics that should be reinforced, halted, or avoided to promote effective innovation system progression.
iv. STID explicitly accounts for system delays and incorporates a mechanism to identify system traps, thereby enhancing the framework's diagnostic capability in identifying systemic bottlenecks or failures.
v. It includes a built-in leverage point locator that identifies strategic points within the system where interventions can produce the most significant improvements in system performance.

4.2 Overview of the Systems-Thinking Innovation Dynamic Framework

Table 3 presents the high-level systems thinking innovation dynamic (STID) framework for analyzing the progression of innovation systems. It outlines the framework's steps and the theoretical foundations upon which each step is based, including the TIS framework, event history analysis (EHA), and systems thinking theory. Additionally, Table 3 details the concepts from these frameworks that should be applied during each step of the framework to ensure a comprehensive analysis of the TIS being studied.

4.2.1 Defining system boundaries

Before any event-history analysis can commence, the innovation system's boundary needs to be determined to define which IS is being studied. Clear system boundaries decide whether the focus is a TIS, regional IS, or national IS (McClelland et al., 2023b). In turn, the boundary determines which actors, interactions, events, and external influences the researcher will observe, measure, and explain (Rubenstein-Montano et al., 2001). McClelland, Grobbelaar and Sacks (2022) emphasize that once a boundary is set, it must be re-evaluated throughout the analysis. Van Der Merwe and Grobbelaar (2017) also propose extending boundaries later in the analysis process when a greater understanding of the systems is gained.

The STID framework employs Midgley and Lindhult's (2021) "lenses" concept and the systems thinking concept of holism to define systemic boundaries. A lens serves as a metaphor for a deliberately chosen perspective, such as the viewpoint of entrepreneurs, researchers, and other innovation actors, to study a particular aspect of a system. Utilizing

Table 3. Systems thinking innovation dynamic framework to analyze the progression of innovation systems

Framework steps	Theoretical framework	Concepts to utilize
1. Define the system boundary	Systems thinking	Lenses • Perspective of each innovation actor • Holistic view of the system
2. Data collection **3. Event database construction**	Event History Analysis	
4. Allocating events to IS functions	EHA and TIS	TIS functions • Entrepreneurial Activity; Knowledge Development; Knowledge Diffusion; Guidance of Search; Market Formation; Resource Mobilization; Creation of Legitimacy
5. Narrative construction **6. Data summary**	Event History Analysis	

7. Pattern identification	Systems thinking	1. Use mapping tools to map the order in which the functions occur to identify patterns
		• Causal loop diagrams
		• Feedback loop diagrams
		  • Balancing feedback
		  • Reinforcing feedback

	TIS and Systems thinking	2. Identify systemic structures associated with patterns using the TIS structures and Iceberg model • Identify the structure, influence and hierarchy of the TIS components • Actors; Networks; Institutions; Infrastructure • Identify cases of emergence due to the structure of the TIS components 3. Identify systemic problems • Identify the influence of delays within these loop diagrams • Identify mental models and institutions of innovation actors that contribute to systemic problems 4. Interventions for systemic problems • Identify leverage points for improvement • Design interventions and solutions targeting leverage points and systemic problems • Be aware of system traps
8. Data verification **9. Case study comparison**	Event History Analysis	

different lenses are beneficial as they make the observer-dependence of boundaries explicit, involve considering the systemic boundary from each viewpoint to reveal aspects that might otherwise remain concealed, and legitimizes subsequent boundary extensions if a new lens uncovers important dynamics beyond the original scope. Although innovation systems are typically viewed in terms of lenses related to the innovation types framework, such as the national innovation system (NIS), sectoral innovation system (SIS), or technology innovation system (TIS), within a TIS, lenses represent the perspectives of the TIS actors.

Furthermore, incorporating the concept of holism contributes to the comprehensive analysis of a TIS as it reminds the innovation authors to consider the perspective of all innovation actors associated with a TIS, both those included within the system boundary and those within the external environment (Midgley and Lindhult, 2021; Wicki and Hansen, 2017).

Thus, to identify a system boundary, researchers should start with the most obvious perspective for the study's purpose (e.g., the technology-developer lens). They should list the actors and interactions that the chosen lens identifies as core to the system and record external influences separately. Next, researchers can introduce additional perspectives (e.g., regulator and user) to capture the missing elements and adjust the boundary accordingly. Finally, they should iterate the process to ensure that a comprehensive view of the system is obtained.

4.2.2 Collecting event data and assigning events to IS functions

As mentioned in Figure 2, the TIS framework answers the question of "*Who does what?"*. This is due to the TIS framework identifying the innovation authors in a system (Table 1) and the activities they perform in a system (the TIS functions, as described in Table 2). In innovation literature, the TIS framework presents a framework through which innovation activities can be classified and therefore analyzed. In the STID framework, the collection of event data and classification of events to IS functions are done similarly to the traditional combined EHA-TIS frameworks of McClelland et al. (2023b) and Suurs (2009).

4.2.3 Identifying patterns

Use mapping tools to map the order in which the functions occur to identify patterns

The first step to pattern identification is to use mapping tools to map the order in which the functions occur. TIS functional analysis is important because it provides a structured lens for diagnosing how the core functions of a TIS interact over time, revealing patterns of cumulative causation that either accelerate or stall technology diffusion and market formation. By tracing how the performance of one function (for example, knowledge development) shapes and is shaped by others (such as resource mobilization or market creation), analysts can identify virtuous circles that deserve reinforcement and vicious circles that call for corrective intervention (Maarsingh et al., 2023). In practice, this functional perspective makes it possible to pinpoint leverage points for policy or managerial action, compare the maturity of parallel systems, and explain historical trajectories that would remain opaque if the functions were examined in isolation. Because these insights rest on empirical sequences of events (e.g., pilot projects, investments, regulations) and their causal interdependencies, functional analysis delivers an evidence-based narrative of system dynamics, helping decision-makers move from description to prescription with confidence (McClelland et al., 2022).

Complementary systems-thinking concepts, such as causality, emergence, and feedback, along with their visual representation in feedback and causal loop diagrams, serve as powerful tools for mapping, analyzing, and ultimately understanding the chains of innovation events that characterize TISs. Causality focuses attention on how each event partially conditions subsequent events, creating linear or non-linear linkages that accumulate into complex pathways (Schlüter et al., 2023; Wicki and Hansen, 2017). The notion of emergence comprises the idea that the innovative behavior of the whole system cannot be inferred by summing its parts. The behavior of the whole system surfaces only through interaction, making the identification of cross-functional synergies and unintended consequences essential (Skjølsvik and Kaloudis, 2023).

Feedback loops then reveal whether those interactions are stabilizing (balancing the system) or accelerating (reinforcing growth in a specific direction, both positive or negative) (Wicki and Hansen, 2017), clarifying why some technologies tip into self-sustaining growth while others stagnate (Kim, 2011). Finally, causal-loop diagrams translate this conceptual arsenal into an intuitive visual map that displays nodes (TIS functions), arrows (direction of influence), and closed feedback loops, allowing TIS system analysts to spot leverage points, lock-ins, and potential tipping points at a glance. Together, these systems-thinking tools transform a chronological list of events into a coherent explanation of TIS behavior.

The systems-thinking concepts above can be applied in four practical steps. First, define system boundaries and compile a time-stamped event history; second, assign each event to the relevant TIS function(s) to make functional interdependencies explicit; third, draw a causal-loop diagram that links events and functions according to observed or theorized cause-and-effect relations, distinguishing reinforcing from balancing feedback; and fourth, interrogate the resulting diagram to identify dominant loops, emergent properties, and leverage points for policy or strategy. Iterating through these steps enables analysts to refine the causal story as new evidence emerges and to test "what-if" interventions before they are implemented in the real system.

Apply the systems-thinking concepts outlined above within the STID framework by first constructing a causal-loop diagram. Map the observed functions in the order they occur to make cause-and-effect relationships explicit. Use arrows to indicate the direction of influence and mark each link with a plus to denote a reinforcing loop or a minus to denote a denting balancing loop. Once the core structure is visible, trace the closed chains of influence to identify feedback loops. Assign a short, descriptive name to every loop so TIS analysts can cite it unambiguously. Next, analyze the completed diagram to determine which loops dominate system behavior, how balancing loops suppress desired change, and where a small intervention could flip a reinforcing loop from vicious to virtuous.

Identify systemic structures associated with patterns
Following the mapping of functional patterns, the underlying elements of the TIS can be interrogated with the Iceberg Model. At the event level, each observed TIS function is associated with the patterns and trends identified during systems mapping (see Section 4.2.3). One layer deeper (see Figure 3), the systemic-structure level is examined to establish which TIS actors participate in each stage of the process, how they are interconnected, and whether formal or informal hierarchies influence the direction and pace of activities (Al-Homery et al., 2019). This structural analysis identifies points at which the expected sequence of events is delayed, accelerated, or diverted.

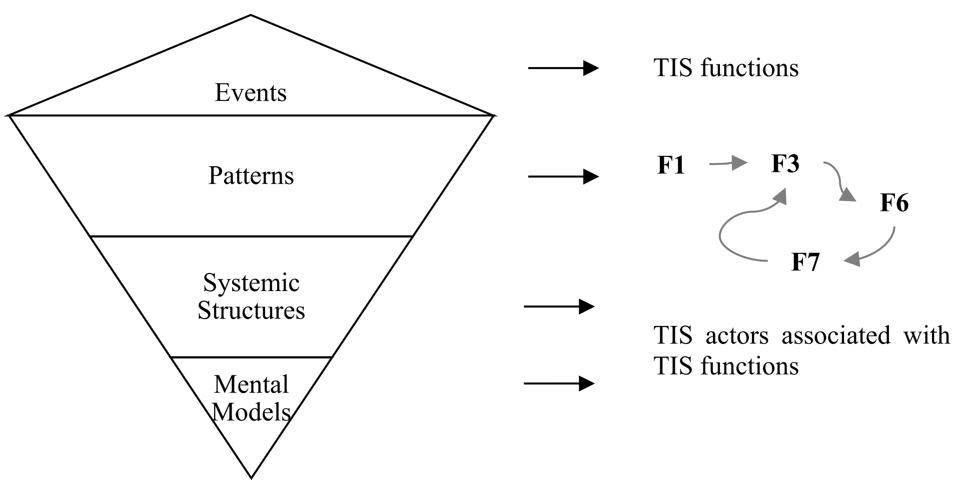

Figure 3. Iceberg model used in systems thinking and its relation to the TIS

Identify systemic problems
Following the identification of the TIS actors at the systemic structures level of the Iceberg model, the hierarchy and structures of the TIS actors can be analyzed to identify systemic problems. Building on this structural scan, the deepest layer of the Iceberg model, namely the mental models level, can be analyzed as it encompasses the shared beliefs, values, and assumptions that reinforce those structures and often contribute to persistent misalignments or ambiguous expectations. Although mental models are among the most intractable components of a TIS, they also exert the greatest leverage on collective behavior (Meadows, 1997). Taken together, the structural and cognitive layers therefore provide

a rigorous explanatory bridge between observable TIS functions and the mechanisms that produce them (Al-Homery et al., 2019; Liu et al., 2021).

This multilevel view also foregrounds the concept of emergence. Examining the individual TIS structures and their mental models in isolation presents a limited view. However, considering how the combinations of these structural components and their mental models influence patterns of events and the system's overall performance reveals aspects of the system that might otherwise have remained hidden. This is due to the interconnected and holistic nature of systems thinking.

A second systemic property that must be explicitly accounted for is delay. Delays refer to the time it takes for a change in one part of a system to affect another part of the same system. Every connection within a system has a delay that can be either imperceptibly short or significantly long. There are various types of delays, including physical, transactional, informational, and perceptual. In system dynamics, understanding delay effects is essential, as almost all relationships in a system have an implied delay (Arthur et al., 2023). Recognizing delays is crucial because they can render a system's behavior unpredictable. Consequently, mapping delays in parallel with structures and mental models helps identify leverage points and informs the design of timely, effective interventions.

Interventions for systemic problems

Having established how structural hierarchies, mental models, emergent properties, and temporal delays interact within the TIS, the analytical focus now shifts from diagnosis to remediation. Translating insight into action begins with the identification of leverage points, which are locations in a complex system where a modest, well-timed adjustment can cascade into disproportionately large effects (Meadows, 1997). Due to the preceding causal-loop diagrams and actor mappings already specifying where reinforcing and balancing feedback loops converge, they provide a clear map of where such points reside and which stakeholders are best positioned to influence them.

Once candidate leverage points are located, they must be interrogated along the same feedback pathways and delay structures outlined in the previous section. Tracing causal chains in reverse ensures that the apparent symptom arises upstream of the proposed intervention site, thereby avoiding the common error of treating surface-level manifestations rather than root causes. The delay parameters uncovered earlier remain critical at this stage: they dictate not only how soon an intervention's effects will be felt, but also the temporal window within which monitoring and course-correction must occur.

Designing the intervention itself demands thoughtfulness. The most effective solutions target the smallest set of variables capable of tipping the relevant loops, and they do so in a manner consistent with prevailing mental models and power hierarchies. Interventions that disregard these cognitive and structural constraints risk rapid rejection and unintended amplification of the problem, known as system traps. Prior to implementation, each proposed change should therefore be screened for well-documented system traps such as Shifting the Burden or Fixes that Fail, archetypal failure modes that emerge when reinforcing and balancing loops interact in particular configurations (Kim, 2011).

Finally, delay-aware monitoring must be embedded from the outset. Because leverage points are sensitive nodes, even a small mis-specification can propagate unpredictably once system lags take effect. Continuous observation calibrated to the expected delay profile enables timely recalibration, preserving both the efficacy and adaptability of the TIS. In this way, the analytic sequence, namely the structures and mental models, emergence, delays, and leverage-point design, forms a coherent pipeline from explanation to intervention, ensuring that corrective actions are both theoretically grounded and practically viable within the living system.

5. Conclusion

This study contributes a comprehensive analytical framework for examining the innovation dynamics and progression of innovation systems by utilizing concepts from systems thinking. This paper builds on the literature regarding the analysis of innovation systems through the event history analysis method. This paper argues that a holistic approach to analysis should be adopted, focusing on how different components of a TIS interact and influence one another as a whole, rather than examining the individual parts in isolation. This approach will enable authors to develop comprehensive case studies on innovation systems, allowing them to: a) analyze how a technology has evolved; b) identify key events that led to significant breakthroughs or challenges; c) understand the dynamics and resources impacting development; d) identify high-leverage points where interventions can effectively address systemic problems causing major challenges; and e) consider whether the designed interventions may lead to unintended consequences somewhere in the near future. The subsequent steps of this study include applying this framework to innovation case studies to complete the final stages of the design science research methodology.

Acknowledgments

Generative AI: In the documentation of this study, the author(s) utilized Grammarly to edit and improve sections for improved readability. After using this tool/service, the author(s) reviewed and modified the content as necessary, taking full responsibility for the publication's content.

References

Al-Homery, H. A., Ashari, H., and Ahmad, A.: The Application of System Thinking for Firm Supply Chain Sustainability: The Conceptual Study of the Development of the Iceberg Problem Solving Tool (IPST), Int. J Sup. Chain. Mgt, 2019.

Arthur, D., Moizer, J., and Lean, J.: A systems approach to mapping UK regional innovation ecosystems for policy insight, Industry and Higher Education, 37, 193–207, https://doi.org/10.1177/09504222221115977, 2023.

vom Brocke, J., Hevner, A., and Maedche, A.: Introduction to Design Science Research, 1–13, https://doi.org/10.1007/978-3-030-46781-4_1, 2020.

Crabolu, G., Font, X., and Miller, G.: The Hidden Power of Sustainable Tourism Indicator Schemes: Have We Been Measuring Their Effectiveness All Wrong?, J Travel Res, 63, 1741–1760, https://doi.org/10.1177/00472875231195736, 2024.

Galanakis, K.: Innovation process. Make sense using systems thinking, Technovation, 26, 1222–1232, https://doi.org/10.1016/j.technovation.2005.07.002, 2006.

Kim, D. H.: Introduction to Systems Thinking, n.d.

Linnéusson, G., Andersson, T., Kjellsdotter, A., and Holmén, M.: Using systems thinking to increase understanding of the innovation system of healthcare organisations, J Health Organ Manag, 36, 179–195, https://doi.org/10.1108/JHOM-01-2022-0004, 2022.

Liu, T., Yang, X., and Guo, Y.: Research on Influencing Factors of Technological Independent Innovation of Equipment Manufacturing Enterprises from the Perspective of Iceberg Theory, Complexity, 2021, https://doi.org/10.1155/2021/2551680, 2021.

Maarsingh, B., Grobbelaar, S. S., Uriona-Maldonado, M., and Herselman, M.: Exploring functional dynamics of innovation for inclusive development: event history analysis of an ICT4D project, Innovation and Development, 13, 243–273, https://doi.org/10.1080/2157930X.2021.1956712, 2023.

McClelland, M., Grobbelaar, S. S., and Sacks, N.: Towards an analytical framework to analyse the evolution of innovation systems, in: 2022 IEEE 28th International Conference on Engineering, Technology and Innovation (ICE/ITMC) & 31st International Association For Management of Technology (IAMOT) Joint Conference, 1–9, https://doi.org/10.1109/ICE/ITMC-IAMOT55089.2022.10033208, 2022.

McClelland, M., Grobbelaar, S., and Sacks, N.: Evaluating Sectoral Innovation System Functional Performance in the additive manufacturing sector: Cemented tungsten carbides case studies, PhD, Stellenbosch University, Stellenbosch, 2023a.

McClelland, M., Grobbelaar, S., and Sacks, N.: Exploring innovation system dynamics: event history analysis of the evolution of the South African additive manufacturing industry, Rapid Prototyp J, 29, 2109–2133, https://doi.org/10.1108/RPJ-04-2023-0143, 2023b.

Meadows, D.: Leverage Points: Places to Intervene in a System, The Sustainability Institute, Hartland, 1–2 pp., 1997.

Van Der Merwe, E. and Grobbelaar, S. S. S.: Evaluating inclusive innovative performance: The case of the eHealth system of the Western Cape Region, South Africa, in: PICMET 2016 - Portland International Conference on Management of Engineering and Technology: Technology Management For Social Innovation, Proceedings, 344–358, https://doi.org/10.1109/PICMET.2016.7806775, 2017.

Midgley, G. and Lindhult, E.: A systems perspective on systemic innovation, Syst Res Behav Sci, 38, 635–670, https://doi.org/10.1002/sres.2819, 2021.

Ortt, J. R. and Kamp, L. M.: A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion, Technol Forecast Soc Change, 180, https://doi.org/10.1016/j.techfore.2022.121671, 2022.

Peffers, K., Tuunanen, T., Rothenberger, M. A., and Chatterjee, S.: A Design Science Research Methodology for Information Systems Research, Journal of Management Information Systems, 24, 45–77, https://doi.org/10.2753/MIS0742-1222240302, 2007.
Rubenstein-Montano, B., Liebowitz, J., Buchwalter, J., Mccaw, D., Newman, B., and Rebeck, K.: A systems thinking framework for knowledge management, Decision Support Systems, 5–16 pp., 2001.
Ruyobeza, B., Grobbelaar, S. S., and Botha, A.: Integrated Remote Primary Care Infrastructure: A Framework for Adoption and Scaling of Remote Patient Management Tools and Systems, 797–817, https://doi.org/10.1007/978-981-19-1607-6_71, 2023.
Samara, E., Kilintzis, P., Katsoras, E., Martnidis, G., and Kosti, P.: A system dynamics approach for the development of a Regional Innovation System, J Innov Entrep, 13, https://doi.org/10.1186/s13731-024-00385-5, 2024.
Schlüter, L., Kørnøv, L., Mortensen, L., Løkke, S., Storrs, K., Lyhne, I., and Nors, B.: Sustainable business model innovation: Design guidelines for integrating systems thinking principles in tools for early-stage sustainability assessment, J Clean Prod, 387, https://doi.org/10.1016/j.jclepro.2022.135776, 2023.
Skjølsvik, K. O. and Kaloudis, A.: Innovating the Innovation System Thinking: a Systemism Model, Journal of the Knowledge Economy, https://doi.org/10.1007/s13132-023-01561-w, 2023.
Smit, M., Grobbelaar, S. S., and Sacks, N.: Innovation system functions: Survey data of additive manufacturing enterprises in South Africa, Data Brief, 57, 110943, https://doi.org/10.1016/j.dib.2024.110943, 2024.
Suurs, R. A. A.: Towards a theory on the dynamics of technological innovation systems Motors of Sustainable Innovation, n.d.
Wicki, S. and Hansen, E. G.: Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage, J Clean Prod, 162, 1118–1134, https://doi.org/10.1016/j.jclepro.2017.05.132, 2017.

Biographies

Michelle Smit (PhD) earned her Ph.D. in innovation and technology management from Stellenbosch University in South Africa in 2023. As Dr Smit's MEng proved to be novel, her MEng was upgraded to a PhD. She completed her Bachelor of Engineering (Industrial) at Stellenbosch University in 2019. She is a lecturer in the Department of Industrial Engineering at Stellenbosch University. Dr Smit is a candidate engineer registered with the Engineering Council of South Africa. Her research focuses on innovation and technology development, commercialization, and adoption, with recent publications examining the progression of innovations through the Valley of Death. Between 2022 and 2024, she and her co-authors published 3 journal articles and 3 conference papers in the proceedings of global conferences.

Sara S Grobbelaar (PhD) received the M.Phil. degree in technology policy from the University of Cambridge, Cambridge, UK (2011). the B.Eng. (electronic) (UP) (2000), the M.Eng. (with distinction) degree in computer (UP) in 2001 and the Ph.D. degree in engineering (UP)(2007), and Post Graduate Diploma (with distinction) in M&E methods (SU) (2013). She is a Professor at the Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa. She is also a registered Professional Engineer at the Engineering Council of South Africa. Prof Grobbelaar is a dynamic scientist with a highly productive research output trajectory. Between 2015 and 2024, she and her co-authors published 78 journal articles and 90 conference papers in proceedings of global and regional conferences. She publishes in the area of innovation for inclusive development, with applications in healthcare, education, agriculture, and manufacturing. Recent publications explore the development of innovation platforms and the evaluation of mhealth projects.