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Research Article

Logic of Scientific Readiness: Constraints, Conflicts, and Pathways of Transformation

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ABSTRACT

Existing models of scientific maturity and readiness help position research systems on a developmental scale, but they often remain descriptive and provide limited insight into the structural causes of stagnation and uneven advancement. This study proposes the TOC-SRL integrative model, combining the logical trees of the Theory of Constraints (TOC) with the level-based framework of Scientific Readiness Levels (SRL). The study is based on the conceptual adaptation of five TOC trees-the Current Reality Tree, Conflict Cloud, Future Reality Tree, Prerequisite Tree, and Transition Tree-to the logic of SRL. The analysis relies on conceptual reconstruction, documentary analysis, and case-based interpretation, using material from Kazakhstan's national science system and the digital transformation of science and higher education. The TOC-SRL model makes it possible to move from descriptive accounts of science policy to a more systemic analysis of constraints, institutional conflicts, maturity conditions, and transition pathways within research ecosystems. The findings suggest that scientific readiness can be interpreted not only as a position on a scale, but also as a causally structured condition shaped by deeper institutional and developmental limitations. The proposed approach extends SRL from a static maturity scale into a dynamic framework for causal diagnosis and transformation-oriented analysis. It offers a structured way to connect readiness assessment with the identification of constraints, conflict resolution, and developmental sequencing in scientific systems.

Keywords: Causal modeling, Kazakhstan, Scientific maturity, Scientific readiness levels, Theory of constraints, TOC logical trees.

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INTRODUCTION

The accelerating complexity of contemporary research ecosystems has fundamentally changed the conditions under which scientific knowledge is produced, verified, and institutionalized. In both developed and developing countries, scientific systems face a characteristic combination of structural fragmentation, epistemic uncertainty, institutional inertia, and uneven organizational maturity. Under such conditions, the ability of institutions to ensure scientific coherence, sustain methodological rigor, and accumulate research capacity depends not only on the volume of resources or the availability of talent but also on the systemic readiness of the scientific environment. This recognition has naturally given rise to readiness-based approaches-most notably the concept of Scientific Readiness Levels (SRL) (Knar, 2025; Zhumashov, 2023), which treats scientific activity as a hierarchical trajectory of maturity, coordination, methodological depth, and epistemic resilience.

However, despite their conceptual value, existing readiness models-and SRL in particular-remain primarily descriptive rather than transformational. They record where a system is located, but they do not explain why it is stuck at a given level, which constraints create the barrier to growth, or how an organization can systematically move toward higher levels of maturity. In other words, SRL offers a taxonomy of scientific capabilities but not a toolkit for diagnosis and intervention. This is a significant limitation, given that scientific stagnation often arises not from isolated weaknesses but from the interaction of multiple constraints, hidden conflicts of incentives, and systemic misalignments (Azoulay *et al*., 2011; Barber, 1986), all of which require structural causal analysis.

Moreover, the Theory of Constraints (TOC), developed within operations research and systems thinking, provides a powerful and formalized methodology for identifying constraints in complex systems (Goldratt, 1990). The TOC logical trees-the Current Reality Tree (CRT), conflict cloud, Future Reality Tree (FRT), prerequisite tree, and transition tree-were specifically designed to reveal causal structures, diagnose root constraints, analyze institutional conflicts, and design coherent pathways of

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transformation. Despite their extensive use in manufacturing, supply chains, project management, and organizational development, TOC tools have, to the best of our knowledge, not been applied to the analysis of research systems, models of scientific maturity, or science policy.

Accordingly, this article addresses that gap by proposing the first integration of TOC logical trees with the scientific readiness level model. In doing so, it seeks to build a unified analytical and intervention-oriented framework for assessing and advancing the maturity of scientific ecosystems. We argue that the combination of SRL and TOC makes it possible to move from static diagnosis to dynamic transformation: SRL provides the topology of maturity, whereas TOC reveals the constraints that determine its trajectory. We contend that this approach enables organizations, research groups, and national systems to do the following:

1) Determine the structural and epistemic barriers to scientific development.

2) Analyze conflicts between competing institutional logics.

3) formulate an empirically grounded vision of the target state of the scientific system.

4) Design transition steps between readiness levels.

Accordingly, first, we introduce the concept of the SRL Constraint System as the causal architecture of limitations that impede the growth of scientific maturity.

Second, we formulate the SRL conflict architecture model, which shows how intersecting institutional incentives and contradictions generate stagnation.

Third, we develop SRL transition pathways as logically validated trajectories of development grounded in TOC transition mechanisms.

Taken together, these elements transform SRL from a static scale into a more comprehensive theory of scientific evolution.

In this way, our study enters the contemporary discourse on science governance, organizational learning, and systemic transformation by offering a theoretically grounded and practically applicable toolkit for universities, research centers, national agencies, and interdisciplinary clusters. It also resonates with the growing interest in modeling scientific productivity, methodological culture, and epistemic integrity (Fortunato *et al.*, 2018). Ultimately, the article shows that scientific maturity should be understood not as a byproduct of individual excellence but as the outcome of systematically managing constraints-constraints that can now be visualized, analyzed and transformed through an integrated TOC-SRL methodology.

Conceptual Framework

The development of contemporary research systems unfolds under conditions of growing systemic complexity, characterized by multilayered institutional structures, high uncertainty, heterogeneous incentives, and dynamic change in the global scientific environment (OECD, 2021; UNESCO, 2021). At the intersection of these factors arises the need for theoretical frameworks capable not only of describing the state of scientific organizations but also of explaining the mechanisms of their development, the constraints on their growth, and the structural conflicts that shape them.

Maturity models are widely used in engineering and organizational sciences-from Technology Readiness Levels (TRL) in the space industry to process maturity models (CMMI) and clinical infrastructure frameworks such as HIMSS. However, the domain of scientific research has long remained outside the scope of such level-based approaches, which has resulted in the absence of a universal language for assessing the quality of scientific processes, methodological culture, and institutional readiness for complex projects.

As a concept, SRL seeks to fill this gap by defining scientific activity as a progressive movement through levels of readiness. These levels encompass the depth of the methodological apparatus, the culture of evidence, the systemic character of research design, the maturity of institutions and practices, integration with educational and innovation environments, and the capacity for reproducibility, scaling, and international cooperation.

However, despite its analytical usefulness, SRL remains primarily diagnostic rather than intervention oriented. It indicates the level of maturity, but it does not reveal the causal mechanisms that determine proximity to that level, identify fundamental constraints, analyze institutional conflicts, or describe transition trajectories. In this sense, SRL resembles descriptive typologies of scientific development but lacks the tools of causal modeling.

This highlights the key conceptual gap, which may be formulated as follows: SRL tells us "where we are," but it does not explain "why we are there" or "how to move forward."

The theory of constraints, proposed by Eliyahu Goldratt, views every system as a set of interconnected elements whose functioning is determined by constraints-that is, structural bottlenecks that suppress performance or development. Unlike statistical or indicator-based models, TOCs focus on causal structure rather than quantitative metrics. This makes it especially valuable for analyzing complex systems in which the central problems are latent, systemic, and nonlinear.

At the core of the TOC are the logical trees:

- The Current Reality Tree (CRT) identifies undesirable effects and their root causes.
- The Conflict Cloud describes fundamental institutional contradictions.

- The Future Reality Tree (FRT) articulates the desired state of the system and tests it for internal contradictions.
- The prerequisite tree defines the necessary preconditions for overcoming barriers.
- The transition tree describes the step-by-step logic of transformation, moving the system from its current state to the desired state.

In short, logical TOC trees provide precisely what level-based maturity models lack not only a description of levels but also a causal map explaining how those levels are reached.

Notably, although TOCs have gained broad recognition in project management, logistics, education, and organizational development (Cox and Schleier, 2010), their application to research systems remains virtually absent. The scientific sector is rarely treated as a system of constraints, largely because of its high level of cognitive and institutional complexity. We regard this as an important theoretical lacuna that the present study seeks to address.

Empirical research shows that scientific organizations develop unevenly. Within the same ecosystem, high methodological standards may coexist with a weak data culture, high-quality research may coexist with persistent institutional barriers, and innovative projects may coexist with administrative conflicts of interest. Such heterogeneity makes a simple linear logic of "level" inadequate and points to the need for causal modeling.

Moreover, SRL captures differences in maturity level but does not explain the structure of constraints that produces those differences. TOC, by contrast, makes it possible to uncover institutional and cultural bottlenecks, conflicts of incentives, logical incompatibilities between strategy and practice, systemic distortions within the scientific ecosystem, and hidden links between local problems and global mechanisms.

We therefore argue that the synthesis of SRL and TOC creates what neither framework can provide on its own: a level-based model of development embedded within a causal architecture of constraints and conflicts.

This integration allows us to transform SRL from a static scale into a dynamic theory of scientific maturity while adapting TOC to one of the most complex classes of systems-research ecosystems.

To clarify the analytical logic of the proposed framework, Figure 1 presents the conceptual architecture of the SRL-TOC integration. The scheme shows how readiness levels are combined with TOC-based causal analysis to move from observed symptoms to root constraints, systemic conflicts, target conditions, and transition pathways.

Figure 1 presents the conceptual architecture of the SRL-TOC integration. The scheme shows that scientific readiness levels provide the vertical logic of maturity, whereas the theory of constraints supplies the causal logic required to identify root constraints, systemic conflicts, maturity conditions, and transition steps. Within this framework, readiness is interpreted not only as a merely descriptive scale but also as a dynamic analytical structure that links symptoms, constraints, and pathways of transformation.

Overall, Figure 1 clarifies the core novelty of the proposed model. Conventional readiness approaches usually indicate the position of a scientific system, but they do not adequately explain why stagnation emerges or how transition to a more mature state becomes possible. Integrating SRL with TOC logic turns readiness assessment into a causal-diagnostic and transformation-oriented instrument. As a result, scientific readiness becomes analytically interpretable through visible constraints, conflicts, conditions, and pathways of change.

METHODOLOGY

The development of our integrated TOC-SRL methodological approach is grounded in the need to combine two complementary epistemological tools: the level-based model of scientific maturity (SRL), which captures the topology of scientific development, and the logical trees of the Theory of Constraints (TOC), which provide causal analysis, constraint identification, and the construction of transformation pathways.

Methodologically, the study is oriented toward moving from static assessment to the dynamic reconfiguration of the scientific system, taking into account institutional, cognitive, and organizational interdependencies.

Our methodological synthesis of SRL and TOC rests on the complementarity of their epistemological functions. SRL provides a hierarchical map of maturity but does not explain the mechanisms by which that maturity is formed. TOC, by contrast, offers a causal apparatus but does not contain structured maturity criteria.

Their combination, we argue, makes it possible to interpret each SRL level through the prism of structural constraints, conflict nodes, causal chains, necessary conditions of development, and transition steps.

In this way, we formulate the SRL Constraint System as a new analytical unit that defines what constrains the growth of scientific maturity and why a system becomes locked at a particular level.

In the present study, the integration process is built around five TOC logical trees, each reconfigured into an SRL-oriented form.

SRL Current Reality Tree (CRT-SRL)

CRT is used to identify Undesirable Effects (UDEs) characteristic of a given SRL level and to establish their root causes. The methods include identifying symptoms of immaturity (for example, low reproducibility, a weak data culture, and administrative overload), constructing causal chains, and isolating primary constraints. The result is a causal architecture of the current SRL level.

SRL Conflict Cloud (SRL-Conflict Cloud)

On the basis of the B-D-D'-C-A structure (Goldratt, 1990), we identify the fundamental institutional conflicts that block transitions between SRL levels. Examples of such conflicts include reporting speed versus research depth, institutional control versus scientific freedom, and process digitalization versus staff competence. The resulting output is interpreted as the SRL Conflict Architecture, reflecting the hidden contradictions of the scientific ecosystem.

SRL Future Reality Tree (FRT-SRL)

FRT makes it possible to construct a model of the target state of scientific maturity (SRL-8, SRL-9, or SRL-10). Our method includes formulating Desirable Effects (DEs), testing their coherence, and identifying possible negative side effects together with the steps needed to neutralize them. The result is interpreted as the SRL Ideal State Architecture, which defines the benchmark configuration of the scientific system.

SRL Prerequisite Tree (PRT-SRL)

PRT formalizes the necessary conditions for moving from the current SRL level to a higher level-for example, from SRL-3 to SRL-4 or from SRL-6 to SRL-8. More broadly, the method makes it possible to structure barriers, identify mandatory preconditions, and develop a map of institutional and cognitive requirements. The outcome is the SRL maturity prerequisite map.

SRL Transition Tree (TRT-SRL)

TRT describes the sequence of steps that must be implemented for a scientific system to move in practice from its current readiness level to the target level. The method includes the specification of actions, logical checks of sufficiency, analysis of risks and alternative routes, and the construction of operational micro steps. The result is the SRL Transformation Pathways-a logically validated roadmap for development.

To ensure the robustness of the integrative model, a three-level validation procedure was employed.

1) Conceptual validation.

Verification of the theoretical compatibility of SRL and TOC through literature analysis and logical consistency.

2) Case-based validation.

The model is applied to several real Kazakhstani cases to test the adequacy of the reconstructed causal structures.

3) Logical validation (SRL-LVP).

Use of a causality-checking protocol: absence of hidden assumptions, rigor of transitions, internal consistency of the trees, and sufficiency of the transformation conditions.

Thus, our TOC-SRL methodology represents a multilevel architecture that diagnoses constraints on scientific maturity, identifies structural conflicts, formulates a target model of maturity, defines the necessary conditions for development, and constructs a validated roadmap of transitions. This approach transforms SRL from a static taxonomy into a dynamic theory of development and TOC into an instrument for analyzing one of the most complex classes of systems: research ecosystems and scientific institutions.

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RESULTS

Within the proposed TOC-SRL integrative methodology, a systemic analysis of scientific maturity was conducted using five types of TOC logical trees. Each instrument was adapted to the SRL structure and applied sequentially, making it possible to reconstruct the causal architecture of the current state, identify fundamental institutional conflicts, formulate a model of desired future maturity, and describe the necessary conditions and transition steps between levels.

To demonstrate the analytical application of the proposed framework, Figure 2 reconstructs the current reality tree of scientific readiness constraints in the Kazakhstan case. The Figure connects observed undesirable effects with intermediate causal mechanisms and underlying structural constraints, showing how fragmented symptoms converge into a limited number of deep drivers that reproduce low or uneven scientific readiness.

The current reality tree of scientific readiness constraints is presented in Figure 2. The scheme shows how observed undesirable effects are reduced through intermediate causal mechanisms to a more limited number of root constraints. We classify the following as undesirable effects: low methodological coherence, fragmented research capacity, weak science-policy alignment, the absence of cumulative integration across reforms, and poor translation of activity into mature scientific performance. The Figure thus demonstrates that low or fragmented scientific readiness is not a set of isolated deficiencies but the result of a structurally reproduced causal configuration.

The descriptive complexity is translated into a causal structure (Figure 2). Rather than treating the weaknesses of the scientific system as separate problems, the current reality tree shows convergence into a limited number of deep constraints-specifically, the absence of a coherent logic of scientific development, the misalignment between institutional control and epistemic growth, and the weakness of mechanisms for cumulative capability formation.

Accordingly, Figure 2 illustrates the central thesis of this article: scientific readiness is not merely a position on a scale but a condition produced by the interaction of structural causes.

The key analytical findings are presented below.

SRL Current Reality Tree (CRT-SRL): The Causal Structure of Constraints on Scientific Maturity

CRT analysis revealed a set of Undesirable Effects (UDEs) reflecting the characteristic manifestations of insufficient scientific maturity. The most persistent effects include low reproducibility of research, a weak data culture, fragmentation of research processes, the dominance of reporting metrics over scientific priorities, excessive administrative burden, and limited access to adequately trained personnel.

The reconstructed causal links showed that these UDEs do not arise autonomously but are derived from several root constraints, including the following:

- *Cognitive immaturity of research practices, expressed in the absence of methodological schools and insufficient epistemic training.*
- Institutional inertia caused by the stability of managerial procedures and the lack of incentives for change.
- Insufficient integration of scientific, educational, and digital infrastructure, which limits the accumulation of knowledge and its translation into durable capability.
- Systemic distortions of motivation arising from the dominance of quantitative indicators (publications, reporting) over qualitative criteria of scientific robustness.

Thus, the resulting CRT-SRL forms a foundational causal matrix of constraints explaining why research organizations become fixed at low or intermediate SRL levels.

SRL Conflict Cloud: Institutional Conflicts within the Scientific Ecosystem

In the next stage, an SRL Conflict Cloud was constructed, allowing us to identify the key contradictions that structurally impede transitions between levels of scientific maturity. The analysis revealed that the core of most conflicts consists of misaligned institutional logics, including the following:

- The need for depth in scientific work versus the demand for high-speed reporting.
- The need for researcher autonomy versus administrative control and regulatory constraints.
- The expansion of digitalization versus insufficient digital and analytical competence.
- An orientation toward innovation versus the predominance of conservative educational and scientific practices.

These conflicts form a mutually blocking structure that leads to SRL stagnation and the maintenance of low-maturity "local equilibria." The reconstructed SRL Conflict Architecture shows that SRL constraints are not individual but systemically conflictual in nature.

SRL Future Reality Tree (FRT-SRL): A Model of the Target State of Scientific Maturity

The future reality tree made it possible to formulate the concept of SRL-10 as the ideal state of a scientific ecosystem characterized by the following:

- A strong culture of evidence and reproducibility.
- Mature research practices and methodological schools.
- Transparent and integrated digital infrastructure.
- A developed system for training researchers.
- A high degree of interdisciplinary cooperation.
- Stable mechanisms for regulating scientific quality.
- International connectedness and competitiveness.

Overall, the FRT-SRL shows that attaining SRL-10 is possible only through the resolution of the identified conflicts and the coordination of institutional elements. On this basis, we formulate the SRL ideal state architecture as a structural map of the desired scientific system.

SRL Prerequisite Tree (PRT-SRL): A Map of the Necessary Preconditions for Advancing Maturity

The PRT-SRL made it possible to describe the set of conditions required for key transitions-in particular, SRL-3 to SRL-4, SRL-4 to SRL-6, and SRL-6 to SRL-8. Among the most critical conditions are as follows:

- The introduction of mandatory validation and replication practices.
- Improving researchers' analytical literacy.
- Institutional support for research schools.

- The integration of scientific and digital infrastructure.
- The reform of incentive systems.
- Regulatory mechanisms for supporting research quality.

The resulting SRL maturity prerequisite map provides a structured model that organizes the requirements associated with each stage of growth.

SRL Transition Tree (TRT-SRL): Pathways for the Transformation of the Scientific System

The final stage consisted of developing the TRT-SRL, which describes logically validated trajectories for moving scientific organizations from their current level of maturity to a target one. The model includes a sequence of micro- and macrosteps designed to support movement toward SRL-6 or SRL-8, including the following:

- The development of analytical culture and methodological competence.
- The introduction of digital platforms for research management.
- The reform of scientific reporting processes.
- The development of mechanisms for assessing quality and reproducibility.
- The creation of institutional structures for scientific coordination.
- The integration of educational programs with scientific tasks.
- The formation of sustainable systems of scientific leadership.

Thus, the SRL transformation pathways convert the level-based SRL model into an operational system of scientific transformation by describing not only the desired goals but also the concrete routes by which they may be achieved.

Validation of the TOC-SRL Integrative Model

The validation of the proposed TOC-SRL model is multilayered and combines conceptual, expert-documentary, and case-based verification using Kazakhstani examples. Our aim is not only to demonstrate the internal logical consistency of the constructed trees but also to compare the conclusions of the model with the actual characteristics of the national scientific and educational system.

Conceptual and Documentary Validation

From the standpoint of conceptual consistency, the integration of SRL and TOC rests on two stable empirical observations.

First, international reviews confirm that Kazakhstan's science and innovation system possesses the basic elements of modern infrastructure (research organizations, grant mechanisms, and innovation support programs) but faces persistent constraints related to fragmentation, weak coordination, and insufficient effectiveness of knowledge-transfer mechanisms (OECD, 2017; Stavbunik, 2019).

Second, the volume of resources invested in science remains markedly out of line with the declared ambition of transitioning to a knowledge economy: in Kazakhstan, gross domestic expenditure on R and D amounted to approximately 0.14% of GDP in 2023-well below OECD averages and the levels observed in a number of countries with similar diversification ambitions (World Bank, 2025).

Thus, even at the level of official statistics and international reviews, one can observe the classic pattern of "limited scientific readiness" (low SRL) despite the presence of formal institutions and strategies.

We argue that this corresponds closely to the assumptions embedded in CRT-SRL: the presence of multiple undesirable effects (low research sustainability, weak data culture, institutional inertia) in the absence of an explicitly articulated causal structure explaining their interrelations.

Case 1: Kazakhstan's National Science System as an Object of CRT-SRL and the SRL Conflict Cloud

As a first empirical case, the TOC-SRL model was compared with the characteristics of Kazakhstan's national science system.

International and national sources document several persistent features:

1. Chronically low levels of R and D investment (approximately 0.12-0.14% of GDP in recent years) are accompanied by regional inequality and dependence on a limited set of state programs.
2. Substantial growth in publication activity, including in Scopus and Web of Science journals, is often accompanied by the prioritization of quantitative indicators and financial incentives for publication, which has already led to a notable number of retractions and criticism of "metric-chasing" practices in both the medical literature and the broader scientific literature (Teixeira, 2025).
3. Structural problems in innovation policy described in OECD reviews and specialized studies include a gap between science and business, weak commercialization mechanisms, institutional fragmentation, and the effects of the "Dutch disease" on resource allocation (Saiymova *et al.*, 2018).

When these empirical facts are compared with CRT-SRL and the SRL Conflict Cloud, a high degree of correspondence becomes apparent.

The UDEs identified in the current reality tree (the dominance of quantitative publication metrics, low reproducibility, a weak validation culture, and institutional inertia) directly correlate with the "publication boom" documented in the literature against a backdrop of limited structural change and episodes of mass article retraction (Zhanzhigitov, 2024).

The structure of SRL conflicts reconstructed in the Conflict Cloud reproduces real dilemmas of national policy: the pursuit of rapid indicator growth (university rankings, article counts, international index participation) versus the need for long-term development of methodological and institutional maturity. This is explicitly noted in innovation policy reviews and analytical materials on the national science system.

Thus, the Kazakhstani case demonstrates that the causal structure reconstructed in CRT-SRL and the SRL Conflict Cloud is not an abstract model: it describes real, documentarily confirmed contradictions and constraints of the scientific system.

Case 2: Digital Transformation of Education and Science as a Test of FRT-SRL and PRT-SRL

The second empirical case concerns the digitalization of education and science, one of the key directions of Kazakhstan's public policy. At the level of normative documents and programmatic initiatives, a transition toward digital infrastructure in higher education and the scientific sphere is explicitly declared (the State Program "Digital Kazakhstan," along with the digitalization of science and higher education within the mandate of the профиль ministry) (https://www.gov.kz/).

Moreover, studies devoted to the digital transformation of higher education identify a number of persistent problems:

- A gap between technological possibilities and the readiness of teachers and students.
- Uneven infrastructural provision.
- Difficulties in ensuring the quality of digital content and integrating digital tools into actual research and teaching practices.
- A limited connection between digital initiatives and the development of research competence and scientific maturity.

A comparison of these findings with those of the FRT-SRL and PRT-SRL reveals the following:

1. The target-state model (FRT-SRL), in which digital infrastructure appears not as an autonomous project but as an element of SRL-10 (support for reproducibility, access to data, integration of educational and scientific processes), corresponds to the goals declared in national digitalization programs and policy documents (UNESE, 2019).
2. The map of necessary conditions (PRT-SRL)-the development of digital competences, the establishment of data-management systems, and the integration of digital platforms with research practices-directly corresponds to the problems described in empirical studies of higher education digitalization: insufficient methodological and pedagogical training and the detachment of digital initiatives from actual educational and scientific activity.
3. Thus, in this case, the Kazakhstani experience of digital transformation confirms that FRT-SRL and PRT-SRL adequately capture both the target vision and the set of prerequisites without which digitalization remains formal and does not lead to genuine SRL growth.

Thus, in this case, Kazakhstan's digital-transformation trajectory confirms that FRT-SRL and PRT-SRL adequately capture both the target vision and the set of prerequisites without which digitalization remains formal and does not lead to genuine SRL growth.

Logical and Structural Validation (SRL-LVP)

Finally, internal logical validation (the SRL logical validity protocol) was designed to verify the following:

- Each Undesirable Effect (UDE) in CRT-SRL is explained not by an arbitrary set of factors but by a minimal set of causes that are consistently reproduced across documents and studies.
- The conflicts identified in the SRL Conflict Cloud are not reducible to trivial oppositions but instead express real institutional dilemmas (for example, "speed-quality" and "quantitative indicators-methodological depth").
- The transition from CRT-SRL to FRT-SRL and then to PRT-SRL and TRT-SRL contains no logical gaps: each desirable state rests on clearly formulated conditions and steps rather than on declarative assertions.

Our comparison of the trees with external sources (international reviews, national statistics, and studies on digitalization and innovation policy) reveals that the structure of causes, conflicts, conditions, and transitions proposed in the TOC-SRL model is consistent with the empirical evidence and, in a number of cases, makes it possible to systematize and interpret that evidence more deeply than the sources themselves do.

Thus, the validation conducted on two Kazakhstani cases-the national science system and the digital transformation of education and science-demonstrates that the TOC-SRL integrative model possesses not only internal logical integrity but also substantial explanatory value with respect to the actually observed constraints, conflicts, and developmental pathways of scientific maturity.

DISCUSSION

The results presented here allow the TOC-SRL integrative model to be understood not as a local methodological device but as a conceptual step toward a new metatheory of scientific maturity. In what follows, we show how the proposed approach relates to existing lines of science-of-science research, managerial models, and maturity frameworks and how it changes the familiar optics through which the Kazakhstani-and, more broadly, post-Soviet-scientific system is analyzed.

First, the integration of the logical trees of the Theory of Constraints with the level-based SRL model offers a fundamentally different interpretation of scientific "readiness." In classical maturity models (TRL, CMMI, HIMSS digital-health models, and others), readiness is interpreted primarily as the accumulation of certain characteristics-technologies, processes, procedures, and competences. That logic is close to inventory-taking: a system ascends the ladder of maturity as it gradually "adds" the missing modules. In the proposed approach, by contrast, SRL is understood not as a static set of attributes but as the dynamic result of a struggle with constraints. The level of scientific maturity is thus interpreted not as the sum of resources but as the state of the system after the action of its key constraints, conflicts, and compensatory mechanisms. In this sense, TOC-SRL returns science to the field of systems thinking in Goldratt's spirit: any complex organization is shaped by one or several critical constraints, and durable improvement is possible only through purposeful work on them.

Second, the TOC-SRL model is conceptually consonant with contemporary developments in the science of science, which seek to describe science as a complex, multilayered networked system with nonlinear effects and a strong sensitivity to the architecture of incentives. The work of S. Fortunato and colleagues has shown that scientific production, career trajectories, and the dynamics of discovery follow stable regularities that can be described using network models, big-data analysis, and complexity theory.

However, most research in the science of science focuses on already observable patterns-citation distributions, collaboration clusters, and cumulative advantage effects-and only indirectly addresses the question of how scientific systems may be consciously governed toward greater maturity and resilience. The TOC-SRL integration proposed here complements that body of work. It does not compete with metrics or network models; rather, it provides a causal map of institutional and cognitive constraints that explains why certain patterns arise in the first place and why they persist even under conditions of formal reform.

Third, it is important to emphasize that the TOC-SRL directly responds to challenges highlighted in critiques of contemporary scientific production, beginning with Ioannidis's (2014) work on

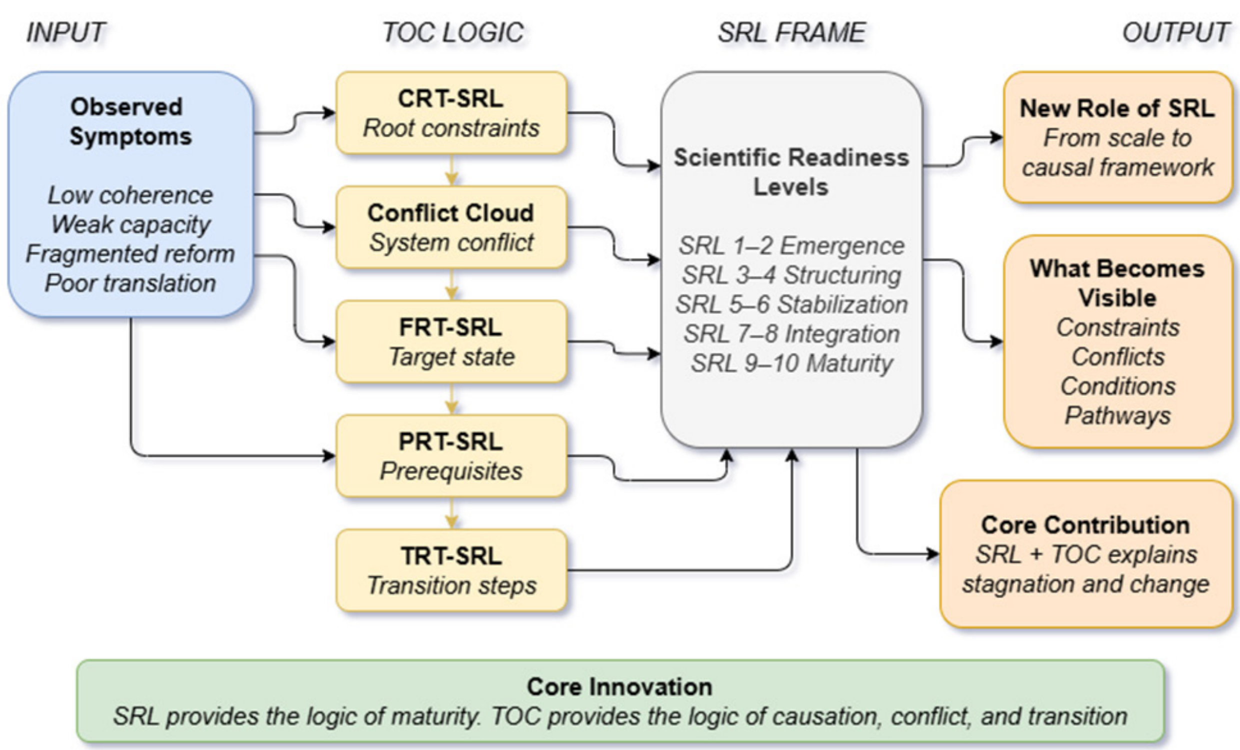

Figure 1: Conceptual architecture of the SRL-TOC integration.

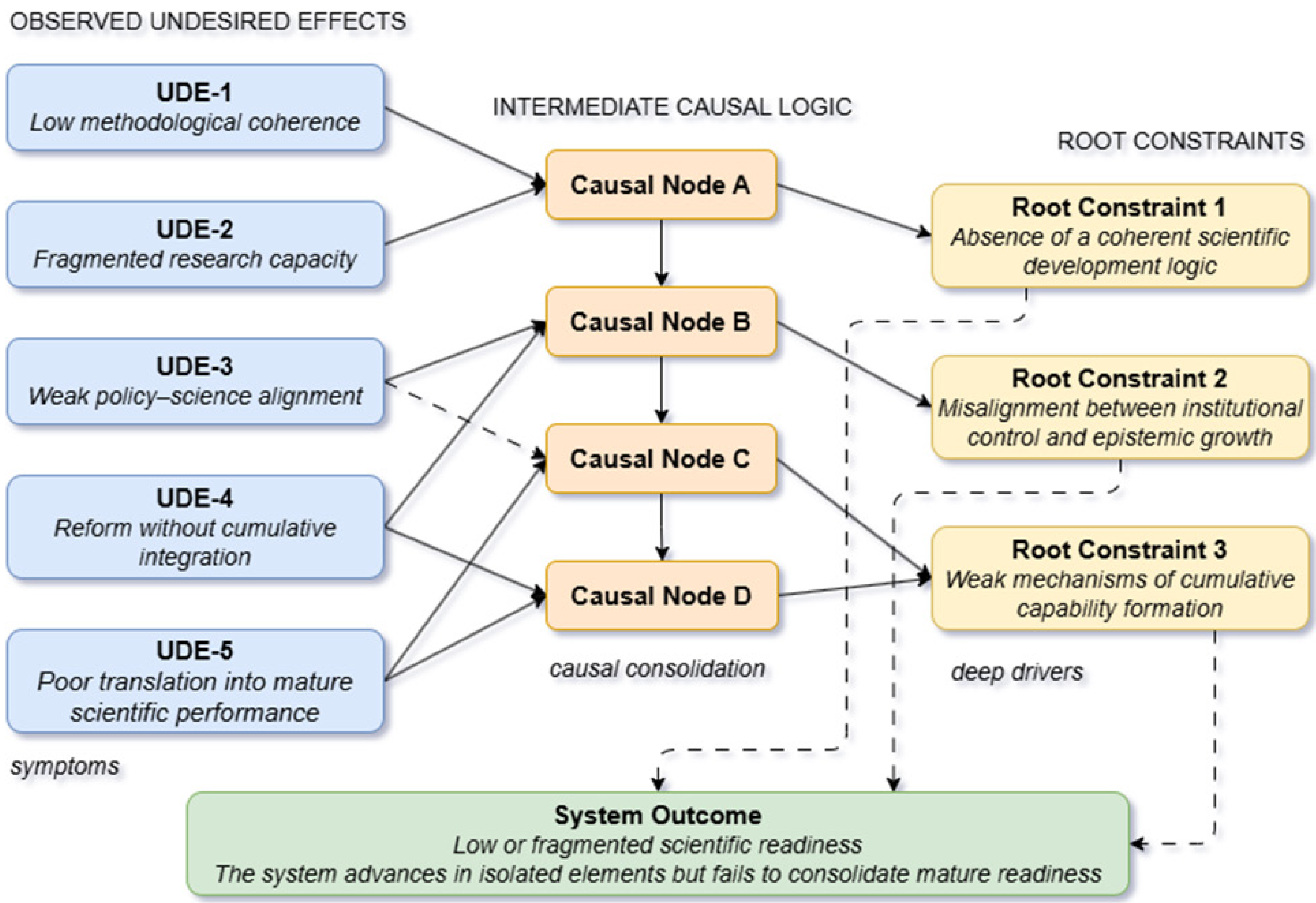

Figure 2: Current Reality Tree of Scientific Readiness Constraints.

the falsity and hyperexpansion of part of the published record. Ioannidis shows that the central problem is not simply a lack of resources but also a distorted structure of incentives: publication pressure, selective reporting, low reproducibility, and weak mechanisms of methodological control.

In this context, the SRL constraints identified in CRT-SRL (the dominance of quantitative metrics, a weak data culture, and institutional inertia) are not specifically "Kazakhstani" phenomena; rather, they belong to the broader global crisis of trust in scientific results. However, the integration with the TOC makes it possible to convert these problems from abstract complaints into a structured tree of causes and conflicts on the basis of which transformation pathways can be designed.

The Kazakhstani cases used for the model's validation perform a dual function in this respect

On the one hand, they serve as a stringent test of the model: if the TOC-SRL is capable of explaining the dynamics of a system undergoing partial modernization, with low R and D investment, institutional fragmentation, and a mixture of post-Soviet bureaucratic logic and global agendas, then it should be all the more applicable to more stable and better-resourced systems.

On the other hand, these cases show that Kazakhstan's national science policy fits into the broader pattern of catch-up development described in OECD innovation-policy reviews: the formal creation of institutions, strategies, and programs without the full removal of systemic constraints leads to a "showcase" growth of metrics, while deeper structural problems remain intact.

Importantly, this is also the point at which the TOC-SRL moves beyond classical political economy or managerial diagnoses. If OECD reviews and similar studies document "what does not work"-weak coordination, imbalances between science and innovation, and insufficient business participation-the integrative model offers a language of the system's internal logic: which conflicts exactly (reporting speed versus research depth, digitalization versus competence, control versus autonomy) reproduce SRL constraints and how they are interconnected. TOC-SRL therefore offers not only a set of recommendations but also a cognitive framework for designing reforms in which each intervention must be considered in terms of its effect on root constraints and conflicts rather than on surface indicators alone.

From a theoretical standpoint, the model proposed here also extends the theory of constraints itself. TOC has traditionally been applied to production systems, project management, logistics, and, to a certain extent, education and healthcare.

Transferring its logical trees into the space of science and science policy requires intensified reflection. Science is not a system with a single unambiguous objective function: the cognitive, symbolic, institutional, and economic dimensions are intertwined within it. Nonetheless, the application of TOC trees to SRL shows that even complex "open" systems can be causally reconfigured if the multilayered nature of constraints-from epistemic and methodological to managerial and cultural-is taken seriously. In this sense, the TOC-SRL may be regarded as a step toward a "metatheory of constraints" for complex social and cognitive systems.

The practical implications likewise extend far beyond the Kazakhstani context. In effect, the proposed model provides a universal protocol for working with scientific systems:

1) Reconstruct the current reality tree.
2) Analyze conflicts.
3) The future reality tree is formulated as follows.
4) Identify the necessary conditions.
5) Describe step-by-step transition pathways.

Applied to universities, this means the possibility of constructing SRL profiles at the level of individual faculties or laboratories, where constraints will have their own local specificity (for example, a deficit of scientific supervision schools, weak practices of collective peer review, or overload from teaching duties). Applied to national agencies, it means the possibility of designing grant schemes and performance indicators not on the basis of abstract "international best practices" but on the basis of which bottlenecks and conflicts they actually eliminate-or, conversely, intensify.

Moreover, we must acknowledge the limits of the proposed approach.

First, any reconstruction of causal structures in social reality inevitably relies on interpretation: CRT-SRL and the related trees are, in a certain sense, "theoretical maps," not direct empirical objects. This requires constant feedback from practitioners and experts, as well as repeated recalibration of the models as the institutional environment changes.

Second, the TOC-SRL has not yet been integrated with formal quantitative models in the science of science-network, bibliometric, or econometric. A promising direction for future work lies in building hybrid models in which causal trees of constraints and conflicts are calibrated using real data on citations, collaboration structures, grant dynamics, and related indicators.

Finally, an important direction for future research is to test the TOC-SRL across other types of scientific ecosystems: major research universities with advanced autonomy, international collaborations, open-science networks, and different disciplinary configurations (natural sciences, humanities, and applied research). This will make it possible to distinguish the universal from the context-specific elements of SRL constraints and conflicts and to assess the extent to which the architecture developed here applies to highly competitive and highly resourced systems.

Overall, the TOC-SRL model proposed here demonstrates that the problem of scientific maturity can be removed from the realm of declarations and intuitive diagnoses into the domain of rigorous systems analysis. By combining the level-based structure of SRL with the causal-logical apparatus of the theory of constraints, it creates a new language for describing science-a language of constraints, conflicts, conditions, and transitions that is equally relevant to national policy, university governance, and the internal strategies of scientific communities.

CONCLUSION

The TOC-SRL integrative model presented in this article was conceived as a response to two principal lacunae in the contemporary discourse on science.

The first is that most existing level-based models of scientific maturity-including scientific readiness levels-remain primarily descriptive instruments that register the state of a system but do not disclose the mechanisms of its evolution.

Second, theories oriented toward causal analysis and the governance of complex systems, such as the Theory of Constraints (TOC), have traditionally been applied only rarely to the domain of science, which is more often perceived as an autonomous cultural-epistemic sphere than as an object of deliberate systemic management.

The integration of SRL and TOC allowed us to bridge this divide. By introducing the concept of the SRL Constraint System, we showed that scientific maturity can be understood not simply as the sum of resources, competences, and institutions but as the resultant state of a system after the action of its key constraints. An SRL level reflects the degree to which science has succeeded in overcoming its own cognitive, institutional, infrastructural, and cultural bottlenecks. This interpretation substantially enhances the explanatory force of any level-based model: levels cease to be static rungs on an abstract ladder and become "cross-sections" of a dynamic struggle with constraints.

The unfolding of TOC logical trees within the coordinates of SRL demonstrated that the causal structure of scientific immaturity is amenable to systematic reconstruction. The Current Reality tree (CRT-SRL) made it possible to identify stable chains of undesirable effects-from the dominance of formalized quantitative indicators to the weakening of data culture and reproducibility-and to connect them to root constraints: a distorted incentive structure, institutional inertia, fragmented infrastructure, and a deficit of methodological schools. The SRL Conflict Cloud revealed that these constraints are not autonomous but are formed within a field of competing institutional logics-between reporting speed and research depth, digitalization and real competence, and control and autonomy. In this way, the SRL conflict architecture model portrays the scientific system as a space of structural conflict rather than simply a collection of "weak spots."

No less significant was the construction of the Future Reality Tree (FRT-SRL) and the prerequisite tree (PRT-SRL), through which the target configuration of scientific maturity (conventionally SRL-10) and the set of preconditions required for movement to higher levels were articulated. FRT-SRL made it possible to conceptualize the ideal state not as a utopian projection but as a logically connected set of desirable effects: a high culture of evidence, stable research schools, advanced digital infrastructure, the integration of science and education, and international competitiveness. PRT-SRL, in turn, structured the conditions without which this state remains declarative: mechanisms of validation and replication, reform of the incentive system, institutional support for research schools, the development of analytical and digital literacy, and calibrated regimes of data governance. Finally, The Transition Tree (TRT-SRL) gave the entire construction an operational character by describing the sequences of steps through which an organization, a system, or a national scientific sector can actually move from its current SRL level to a higher one rather than merely declare such an intention.

The Kazakhstani cases examined in the validation section provided an important test of the TOC-SRL model. Kazakhstan's national science system, which combines a formally developed institutional framework (grant programs, universities, centers, and strategies) with chronically low levels of R and D investment, fragmentation, and the dominance of quantitative metrics, showed a high degree of correspondence with the CRT-SRL and SRL Conflict Cloud reconstructed in the article. Similarly, the case of the digital transformation of education and science demonstrated that FRT-SRL and PRT-SRL adequately describe both the target horizons (an integrated digital ecosystem supporting research activity) and the set of systemic barriers-from competence deficits to the gaps between infrastructure and practice. In this way, the TOC-SRL model demonstrated not only logical coherence but also empirical consistency with the actual dynamics of reform in the context of catch-up modernization.

The theoretical significance of this study lies in the fact that SRL is developed here into a fully dynamic theory of scientific maturity rather than remaining merely a classificatory scale. This brings the discussion of science policy closer to the level characteristic of contemporary work in the science of science, where science is understood as a complex adaptive system with nonlinear evolution and sensitivity to the architecture of incentives, network structures, and institutional rules. However, unlike predominantly descriptive and metric-oriented approaches, TOC-SRL offers a toolkit for systemic intervention: it makes "engineering" of the scientific system at the level of causal structures rather than merely at the level of indicators possible.

The practical significance of the model is no less substantial. For national agencies and ministries, the TOC-SRL can serve as a basis for designing reform programs, making it possible to assess in advance which measures genuinely remove the root SRL constraints and which merely intensifies the appearance of change. For universities and research centers, the model can become the foundation of an internal analytical framework-one for SRL profiling of faculties and laboratories, identifying local conflicts, and constructing roadmaps for increasing scientific maturity. For particular research communities, the TOC-SRL provides a language for describing their own problems and trajectories of development that moves beyond familiar complaints about "funding" or "bureaucracy" and recasts the discussion in terms of structural constraints and conflicts.

Naturally, the proposed approach is not without limitations. It relies on interpretation and requires continuing dialog with empirical data, expert knowledge, and local context. It is still only partially integrated with quantitative models in the science of science and requires further formal development, including mathematical specification, calibration against data, and the modeling of alternative reform scenarios.

Even at this stage, however, it is evident that the TOC-SRL functions as a powerful epistemic amplifier, allowing us to discern, within the familiar discussion of "quality of science," "reforms," and "innovation," structural causal patterns that previously remained implicit.

In this sense, the study may be regarded not only as a proposal for a new methodology but also as an invitation to shift the perspective from describing symptoms to mapping constraints, from static levels to dynamic trajectories, and from sets of measures to sequences of logically grounded transformational steps.

If science is indeed becoming one of the key resources and arenas of competition in the twenty-first century, then the governance of its maturity cannot remain a domain of intuition and fragmented decisions. The TOC-SRL integrative model demonstrates that a scientific system can-and perhaps must-be treated with the same rigor as a complex technical, organizational, or economic system for which constraints, goals, conflicts, necessary conditions, and transition routes are explicitly formulated.

In this sense, the approach proposed here may be seen as one step toward a more mature, reflective, and responsible science of science itself.

ABBREVIATIONS

SRL: Scientific Readiness Levels; **TOC:** Theory of Constraints; **CRT:** Current Reality Tree; **FRT:** Future Reality Tree; **PRT:** Prerequisite Tree; **TRT:** Transition Tree; **TRL:** Technology Readiness Levels; **CMMI:** Capability Maturity Model Integration; **HIMSS:** Healthcare Information and Management Systems Society; **UDEs:** Undesirable Effects; **CRT-SRL:** Current Reality Tree for Scientific Readiness Levels; **FRT-SRL:** Future Reality Tree for Scientific Readiness Levels; **PRT-SRL:** Prerequisite Tree for Scientific Readiness Levels; **TRT-SRL:** Transition Tree for Scientific Readiness Levels; **SRL-LVP:** Scientific Readiness Level Logical Validity Protocol; **OECD:** Organisation for Economic Co-operation and Development; **UNESCO:** United Nations Educational, Scientific and Cultural Organization; **R&D:** Research and Development; **GDP:** Gross Domestic Product; **DEs:** Desirable Effects; **Scopus**: Elsevier Abstract and Citation Database; **WoS:** Web of Science; **SRL-10:** Scientific Readiness Level 10; **SRL-8:** Scientific Readiness Level 8; **SRL-6**: Scientific Readiness Level 6; **SRL-4:** Scientific Readiness Level 4; **SRL-3:** Scientific Readiness Level 3.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTION OF THE ARTICLE

This study contributes to the literature on scientific maturity, research governance, and the analysis of research systems by moving from predominantly descriptive readiness models toward a more causal and transformation-oriented analytical framework. It demonstrates that scientific readiness levels can be understood not only as a scale indicating the position of a scientific system but also as an instrument for identifying structural constraints, systemic conflicts, prerequisites of maturity, and pathways of transition toward a more coherent state. In this sense, the article broadens the conventional understanding of scientific readiness and reworks it into a logic of diagnosis and change.

The main conceptual contribution of the article lies in the integration of scientific readiness levels with the theory of constraints. This integration makes it possible to connect levels of readiness with the causal architecture of a scientific system and thereby reduce the gap between assessing a system's condition and explaining the causes of stagnation. On this basis, the study develops a set of interconnected analytical components: a current reality tree of scientific readiness, a conflict architecture, a maturity prerequisite map, and a transformation pathway. In doing so, the article offers a more structured model for interpreting scientific readiness as a dynamic and reproducible condition of a research system.

The methodological contribution of the article lies in demonstrating how TOC logic can be used to analyze scientific systems and the policy dynamics of scientific development. Unlike purely indicator-based or linear maturity approaches, the proposed framework links observed undesirable effects with deeper constraints and transition mechanisms. This makes the model useful not only for classification but also for the analytical reconstruction of the causes that inhibit the accumulation of research capacity and institutional maturity.

The practical contribution of the study is related to its applicability to the analysis of national research systems, university policy, scientific development strategies, and instruments of research governance. Using the case of Kazakhstan, the article shows that problems of scientific readiness can be interpreted not as isolated deficiencies but as the outcome of structurally interrelated constraints. In this way, the study provides a framework that can support more precise diagnosis, better prioritization of reforms, and the design of sequential steps in institutional development.

ADDED VALUE OF THE ARTICLE

The added value of the article lies in the fact that it offers not only a new terminological construct but also a more integrated way of reading the scientific system. Rather than merely recording separate indicators, deficiencies, or maturity levels, the article shows how symptoms, constraints, conflicts, conditions of maturity, and trajectories of change can be connected within a single analytical logic. This increases the explanatory coherence of the study and makes the category of scientific readiness more substantive and more practically actionable.

An additional value of the study lies in its interdisciplinary character. This article combines perspectives from research evaluation, science policy, systems analysis, and constraint-based reasoning, thereby expanding the analytical toolkit available for the study of scientific development. Such a synthesis is especially useful in contexts where standard maturity frameworks are too static and traditional policy descriptions remain insufficiently causal.

Finally, the article has added value as a platform for future research. The proposed framework can be adapted for the comparative analysis of countries, universities, research organizations, and innovation ecosystems, and it can be further operationalized into diagnostic protocols, assessment matrices, and more formalized analytical instruments. In this respect, the study not only interprets the current constraints of scientific systems but also presents a path toward a new line of research in which scientific readiness is treated as a dynamic and transformation-oriented category.

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