

Conceptual Model for Sustainable Development of Regional Economic Systems Based on Hypercluster Architecture

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Abstract

This study aims to develop a comprehensive conceptual model for the sustainable development of regional economic systems (RES), grounded in the architecture of an innovation hypercluster. The urgency of this research stems from the need to transition from traditional sectoral models to networked, platform-based ecosystems capable of synergizing economic growth, technological sovereignty, and ecological sustainability in an era of global turbulence. The article proposes a detailed model integrating three core components: 1) a network of regional innovation clusters as specialized nodes; 2) a system of digital platforms serving as connective tissue and coordination infrastructure; 3) institutional-managerial and financial ecosystems providing the support environment. For each component, specific functional mechanisms and tools are detailed, ranging from digital twins of value chains and maps of technological competencies to mechanisms for “green” crowdlending and joint development funds. An empirical analysis of the model’s implementation potential is conducted within the context of the Eurasian Economic Union (EAEU) and the Russia-China strategic partnership. By examining trade statistics, investment flows, and strategic documents, specific growth points are identified: cross-border hyperclusters in agrotech, hydrogen energy, logistics, and digital infrastructure. The practical significance of this work lies in providing regulators and businesses with a detailed “roadmap” featuring step-by-step implementation mechanisms, measurable KPIs, and scenario-based forecasts. Projections indicate that establishing even one cross-border hypercluster (e.g., “Smart Agro-Industrial Complex”) by 2030 could lead to a 15% - 20% increase in sectoral value-added, a 25% - 30% reduction in carbon footprint, and the creation of up to 50,000 high-tech jobs, thereby ensuring comprehensive resilience gains by 2035.

Keywords

Hypercluster, Sustainable Development, Regional Economic System, Innovation Ecosystem, Digital Platform, Governance Mechanisms, Implementation Tools, Sustainability Forecast, Eurasian Economic Cooperation, Russia-China Partnership, Green Technologies

1. Introduction

Contemporary regional economic systems (RES) face a complex of interconnected challenges that cannot be addressed within outdated management paradigms. The “sustainable development” paradigm, in its classical interpretation, is often implemented through local, isolated strategies that fail to account for network effects and synergies at a macro-regional scale, a noted issue in integration process research (Feng et al., 2023; Mayor & Ramos, 2020). The key structural problems requiring resolution can be grouped as follows:

1) **Commodity Dependence and Low Diversification:** The share of raw material exports in Russia’s total shipments to China still exceeds 75%, creating high income volatility and constraining growth potential. This challenge is characteristic of many resource-dependent regions requiring a transition to a new development model (Olaniyan & Ipinnaiye, 2025; Medeu et al., 2025).

2) **Environmental Degradation:** Specific CO₂ emissions per unit of GDP in industrial regions of Russia and China remain significantly higher than the European average. The interplay of economic growth, regional integration, and reduced environmental pressure is a central theme in contemporary research (He et al., 2018; Lu et al., 2022; Tejada-Gutiérrez et al., 2023).

3) **Technological Lag and Fragmentation:** The absence of unified standards, protocols, and platforms for cross-border cooperation increases transaction costs and hinders joint innovation, underscoring the importance of developing novel innovation systems (Schlaile et al., 2024).

These challenges form the context necessitating fundamentally new organizational formats. In the context of forming new contours of economic cooperation, particularly the deepening Russia-China strategic partnership in Eurasia, the demand for such formats intensifies. The research hypothesis posits that a transition to a **hypercluster architecture**—managed networks of interconnected regional clusters united by common digital and institutional infrastructure—can simultaneously and systematically mitigate these challenges, enhancing economic resilience and resource efficiency (Peng, 2025; “Regional economic resilience...”, 2024; Wang & Zang, 2025). A hypercluster focuses not on sectoral concentration but on cross-sectoral convergence and transnational cooperation to address complex sustainability tasks. However, existing research is predominantly theoretical and descriptive, lacking detailed mechanisms, tools, and quantitative forecasts for resilience enhancement.

This work aims to develop not merely a conceptual model, but an instrument-rich framework with forecastable implementation outcomes for enhancing RES sustainability, followed by an assessment of its implementation potential within the Russia-China partnership in Eurasia. To achieve this goal, the study addresses several interrelated objectives:

- 1) Theoretical substantiation of the hypercluster approach as a foundation for modeling RES sustainable development.
- 2) Development of a structural model defining key components (clusters, platforms, ecosystems) and detailing functional mechanisms for their interaction.
- 3) Design and classification of specific managerial and technological tools for each mechanism.
- 4) Construction of a forecast model estimating the impact of implementing the hypercluster approach on key sustainability indicators (economic, environmental, social) with a horizon to 2035.
- 5) Adaptation of the proposed model and toolkit to the context of the Russia-China Eurasian partnership, with a quantitative assessment of potential based on concrete examples, and formulation of practical recommendations.

To illustrate the initial challenges and the strategic shift required, the core problems are quantified in **Table 1**.

Table 1. Core challenges for regional economic systems and the Hypercluster response.

Challenge	Current State/Symptom	Hypercluster-Based Strategic Response
Commodity Dependence	>75% of Russia-China trade is raw materials; high economic volatility.	Foster cross-border value chains integrating primary resources with high-tech processing and services (e.g., agrotech, green hydrogen).
Environmental Pressure	High carbon intensity per GDP unit in key industrial regions.	Embed circular economy principles and green tech (IoT, digital twins) into the core operational model of the hypercluster.
Technological Fragmentation	Lack of shared standards and platforms hinders collaborative R&D.	Establish unified digital platforms (e.g., for IP, carbon tracking, innovation matching) as the hypercluster's "central nervous system."

The table underscores that a hypercluster is not an incremental improvement but a systemic redesign aimed at solving interconnected problems through integrated architecture.

2. Theoretical Framework: The Hypercluster as the Core of a New Sustainability Model and Its Design Principles

The concept of an innovation hypercluster represents an evolution of cluster theory for the digital age, where geographical boundaries blur and value is created within networks. A hypercluster is understood as a purposefully constructed meso-economic system that unites geographically distributed but functionally linked innovation clusters to achieve synergy in addressing grand challenges, such as industrial decarbonization or food security. Its sustainability is ensured not by the sum of its individual clusters' resilience, but by network redundancy, adaptive linkages, and shared governance rules, aligning it with concepts of adaptive socio-

ecological systems and contemporary views on regional resilience and integration (Jiang & Jiang, 2024; Hossam & Eräranta, 2025).

The theoretical foundation of hypercluster sustainability rests on three interconnected principles that define its architecture and functioning:

1) **Eco-Economic Efficiency:** A hypercluster must be inherently designed to minimize its environmental footprint by integrating “green” technologies (hydrogen, renewables, recycling) into its core, consistent with research on the impact of regional integration on green innovation and land-use efficiency (Ma et al., 2024; Zhang et al., 2022; Zhu et al., 2019).

2) **Digital Connectivity and Cyber-Physical Integration:** Digital platforms (digital twins, blockchain for supply chain traceability, AI services) act as the hypercluster’s “nervous system,” enabling real-time coordination and reducing transaction costs, a key factor for modern integrated spaces (Cui et al., 2019).

3) **Adaptive Institutional Ecosystem:** A flexible governance system is formed, incorporating state development agencies, venture funds, and universities. Fiscal and regulatory policies should incentivize precisely cross-cluster “green” innovations, creating the institutional basis for a transition to a circular and responsible economy (Schlaile et al., 2024; “SDG integration...”, n.d.).

Based on these principles, core design tenets for a sustainable hypercluster are formulated to guide its practical formation:

a) **Principle of Linkage Redundancy:** Critical technological chains must be duplicated in at least two network nodes (clusters) to mitigate disruption risks, directly correlating with the concept of economic resilience (Sutton & Arku, 2022).

b) **Principle of Digital Mirroring:** Every physical asset and process within the hypercluster must have a digital counterpart on a unified platform for predictive analytics and optimization.

c) **Principle of Flow Circularity:** Material, energy, and information flows are designed as closed loops, a cornerstone of sustainable regional development (Medeu et al., 2025; Tejada-Gutiérrez et al., 2023). Thus, hypercluster design necessitates the simultaneous consideration of technological, environmental, and institutional dimensions. These foundational principles are synthesized and contrasted with traditional approaches in **Table 2**.

Table 2. Core design principles of a sustainable hypercluster vs. traditional cluster approach.

Design Dimension	Traditional Innovation Cluster	Sustainable Hypercluster	Theoretical Underpinning/Source
Geographic Scope	Primarily regional or national.	Transnational, macro-regional, network-based.	Evolution of cluster theory for digital age (Hossam & Eräranta, 2025).
Primary Goal	Enhance regional competitiveness in specific sectors.	Solve “Grand Challenges” (e.g., decarbonization) via cross-sectoral synergy.	Mission-oriented innovation systems (Schlaile et al., 2024).
Governance Logic	Often single-center, led by a dominant firm or regional authority.	Polycentric, networked governance with shared rules.	Adaptive institutional ecosystems (“SDG integration...”, n.d.).

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Sustainability Integration	Often an add-on or separate “green” initiative.	Built-in core design principle (eco-efficiency, circularity).	Integrated models of regional sustainable development (Medeu et al., 2025).
Risk Mitigation	Relies on diversification within a sector/region.	Employs linkage redundancy across the network.	Economic resilience theory (Sutton & Arku, 2022).

The table highlights the paradigmatic shift from localized competition to networked, mission-driven cooperation for systemic sustainability.

3. Conceptual Model: Three-Tier Architecture, Mechanisms, and Toolkit

3.1. Tier 1. Specialization Core (Network of Cluster-Nodes)

The model is realized through three interconnected tiers, each equipped with specific mechanisms and tools. Sustainability emerges as a systemic property arising from the synergistic interaction of all parts, as observed in successful integrated urban agglomerations (Feng et al., 2023; Zheng et al., 2025).

This tier consists of regional innovation clusters that have undergone a “green” transformation, acting as modular components of the hypercluster. Their effective interaction and specialization can enhance overall resource-use efficiency in the region (Lu et al., 2022).

Mechanism: Modular specialization and cross-cluster cooperation.

Candidate Cluster Examples:

- 1) Agri-Tech Cluster (Novosibirsk/Harbin): Specialization in precision farming, biopesticides, urban vertical farming.
- 2) Hydrogen Cluster (Sakhalin/Shandong): Production of “green” hydrogen, storage, and transportation technologies.
- 3) Logistics-Hub Cluster (Vladivostok/Dalian): Smart ports, cross-docking, block-chain-based supply chain management. The operational toolkit for implementing modular specialization and cooperation is outlined in **Table 3**.

Table 3. Toolkit for the specialization core (Tier 1).

Tool	Function/Description	Expected Impact/KPI
1. Map of Technological Competencies (TC Map)	A unified digital registry where each cluster decomposes its capabilities down to specific technologies, labs, and experts.	Reduces partner search time from months to weeks.
2. Standardized “Technology Units” (Tech-Units)	Packaged, ready-to-deploy technological solutions for rapid replication between clusters.	Accelerates technology transfer and scaling of best practices.
3. System of Cross-Cluster Project Teams	Virtual collaborative workspaces with shared access to data and modeling environments.	Enhances innovation output and speed of joint project development.

3.2. Tier 2. Connectivity System (Digital Platform-Networks)

This tier enables cluster interaction and serves as the coordination infrastructure, forming a Eurasian Digital Platform for Sustainable Development. Digital infra-

structure is a critical element linking the space and increasing overall system efficiency (Cui et al., 2019).

Mechanism: Data collection & analysis, automated contract execution, and predictive optimization. The suite of complementary digital tools powering this mechanism is detailed in **Table 4**.

Table 4. Toolkit for the connectivity system (Tier 2).

Digital Platform/Tool	Core Function	Forecasted Quantitative Impact (Example)
1. ESG Monitoring & Carbon Tracking Platform	Integrates IoT sensor data, calculates real-time carbon footprint of value chains, auto-generates green certificates.	In a “Hydrogen Corridor” hypercluster, reduces compliance reporting costs by 40%.
2. Hypercluster Digital Twin	A comprehensive simulation model for scenario planning and optimization of physical and logistical flows.	For Northern Sea Route logistics, increases throughput capacity by 15% - 20% by 2030.
3. Cross-Innovation Platform	AI-driven service for matching technological solution requests with expertise and partners across the cluster network.	Increases the number of initiated joint R&D projects.
4. Decentralized IP Platform	Smart-contract-based registry for patent registration, licensing, and royalty management.	Reduces IP transaction time and costs.
5. Smart Contracts Platform	Automates cross-border payments, customs, and logistics execution upon predefined conditions.	Cuts administrative delays in supply chains.

3.3. Tier 3. Development Environment (Institutional-Financial Ecosystems)

This tier creates shared “rules of the game,” a trust environment, and financial mechanisms. The institutional setting is a key determinant of success for sustainable development and integration policies (“SDG integration...”, n.d.; Ma et al., 2024).

Mechanism: Risk reduction, capitalization of synergies, and provision of long-term support. The institutional and financial instruments implementing this mechanism are presented in **Table 5**.

Table 5. Toolkit for the development environment (Tier 3).

Instrument	Description/Structure	Purpose & Forecasted Impact
1. Joint Russia-China Hypercluster Development Fund (RCHDF)	Target capital of \$5 - 10 billion, structured as a fund-of-funds.	Finances hypercluster infrastructure (inter-cluster power lines, quantum communication links).
2. “Green” Crowdfunding Mechanism for SMEs	Platform for direct financing of green projects by small and medium enterprises within the hypercluster.	Could mobilize up to \$500 million in private investment by 2030.
3. Regulatory “Sandbox” with Mutual Recognition	Special legal regime where Russian and Chinese regulators mutually recognize certificates/standards for pilot projects.	Reduces permitting timelines from 18 to 6 months.
4. Talent Ecosystem	Networked educational programs (e.g., Master’s in “Hypercluster Management”) at Russian and Chinese universities.	Addresses the critical shortage of specialized managerial talent.

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5. Eurasian System of Predictive Sustainability Indicators (ESPSI)	A set of 50+ KPIs calculated by the Digital Twin platform, including leading indicators (e.g., number of joint R&D projects).	Enables data-driven, adaptive governance of the hypercluster.
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System feedback is facilitated through data from IoT sensors and digital platforms, allowing for real-time adaptation of managerial decisions, thereby enhancing the adaptability and resilience of the entire system (Jiang & Jiang, 2024).

4. Implementation Potential within the Russia-China Partnership: Analysis, Statistics, and a Forecast Case

The Russia-China partnership possesses unique prerequisites: substantial trade volume (a record \$240 billion in 2023), growing investments (approximately \$4.5 billion of Chinese investment in Russia), and strategic alignment of initiatives (EAEU and Belt and Road). However, transitioning to a hypercluster model requires a qualitative leap from simple commodity exchange to deep production-technological cooperation and integration capable of enhancing the overall resilience of both economies (Feng et al., 2023; Wang & Zang, 2025). Within the framework of aligning the EAEU and Belt and Road Initiative, several promising directions for forming pilot hyperclusters can be identified.

1) “Eurasian Hydrogen Corridor” Hypercluster: Uniting competencies (Chinese electrolyzers, Russian storage expertise) and infrastructure. Potential: Up to 2 million tons of “green” hydrogen for export by 2035.

2) “Smart Agro-Industrial Complex” Hypercluster: Integrating Russian agro-resources (43 million ha of arable land in the Far East) with Chinese precision farming technologies and e-commerce platforms, which could significantly improve land-use efficiency (Zhu et al., 2019).

3) “Digital Logistics of the Arctic-NSR” Hypercluster: Linking digital platforms for managing the Northern Sea Route with logistics hubs in Northeast China, capitalizing on connectivity advantages (Cui et al., 2019). To assess the practical impact, a detailed forecast for one of these directions is proposed (**Table 6**). Detailed Forecast Analysis for the “Smart Agro-Industrial Complex” Hypercluster (Novosibirsk-Heilongjiang):

1) Forecast Horizon: 2030.

2) Scenario Comparison: Business-as-Usual (BaU) vs. Hypercluster Scenario (full model implementation by 2027).

Table 6. Comparative forecast: “Smart Agro-Industrial Complex” Hypercluster Impact by 2030.

Sustainability Indicator	Business-as-Usual Scenario (2030)	Hypercluster Scenario (2030)	Change (%)	Key Driver of Effect
1. Economic Sustainability				
Sectoral Value-Added, \$ billion	12	14.5	+20.8%	Value chain synergy, green brand premium.

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Share of High-Tech Products in Export	8%	18%	+10 p.p.	Tech-Unit deployment, cross-innovation platform.
Number of High-Productivity Jobs	30,000	50,000	+66.7%	New platform-based services, R&D centers.
2. Environmental Sustainability				
Carbon Footprint per ton of produce, kg CO ₂ -eq.	120	85	-29.2%	Tracking platform, closed-loop cycles, precision agriculture.
Water Consumption per hectare, m ³	5000	3500	-30%	IoT sensors, predictive analytics (Digital Twin).
Chemical Pesticide Use per ha, kg	15	9	-40%	Biopreparations from biotech cluster, drones.
3. Social Sustainability				
Average Sector Wage, \$	800	1150	+43.8%	Increased productivity and value-added.
Youth Retention Index in Region	0.65	0.85	+20 p.p.	Creation of modern, attractive jobs.

Qualitative and Systemic Effects (by 2035). Beyond quantitative metrics, implementing the hypercluster model will lead to qualitative, systemic transformations.

Establishment of a new technological standard for the EAEU and SCO.

Reduction of systemic risks by 30% - 40% due to intra-network diversification, a manifestation of enhanced economic resilience (Peng, 2025; “Regional economic resilience...”, 2024).

Emergence of networked intelligence for generating breakthrough solutions within reconfigured innovation systems (Schlaile et al., 2024).

5. Discussion

Implementing the model is associated with risks requiring preemptive management. The primary risks and mitigation strategies are structured as follows:

1) Technological Asymmetry and Dependency Risk: Consolidation of key platform and IP ownership with one partner. Parity Condition: Open-source architecture and a parity-based (50/50) Management Company.

2) Regulatory Dissonance and Inertia: Misalignment of standards. Mechanism: Launch a pilot under a special intergovernmental agreement akin to an innovation “regulatory sandbox.”

3) Trust Deficit and Soft Infrastructure Gap: Lack of shared human capital. Tool: Establish a networked Eurasian Academy of Hypercluster Management.

4) Digital Divide Between Regions. Tool: An “Infrastructure Pool” within the RCHDF to finance digitalization in lagging nodes, crucial for balanced development (Medeu et al., 2025).

5) Geopolitical Risks (Secondary Sanctions). Enhancing the internal connectivity and resilience of the hypercluster can serve to reduce vulnerability to external shocks (Jiang & Jiang, 2024).

Overcoming these risks requires meeting a key precondition. The critical success condition is launching the first pilot hypercluster by 2026 with the full toolkit to create a demonstration effect and yield measurable results in sustainability terms (Hossam & Eräranta, 2025; Zheng et al., 2025). The identified risks and corresponding mitigation tools are consolidated in **Table 7**.

Table 7. Key implementation risks and mitigation strategies.

Risk Category	Specific Risk	Proposed Mitigation Tool/Strategy	Theoretical Alignment
Technological & Governance	Asymmetry leading to dependency.	Parity-based (50/50) Management Company; Open-source platform core.	Principles of polycentric governance.
Regulatory	Misaligned standards causing delays.	Bilateral “Regulatory Sandbox” with mutual recognition.	Adaptive institutional design (“SDG integration...”, n.d.).
Human Capital	Lack of trust and shared managerial talent.	Networked Eurasian Academy of Hypercluster Management.	Building “soft infrastructure” and social capital.
Spatial & Infrastructural	Digital divide between leading and lagging regions.	“Infrastructure Pool” within the RCHDF for targeted digital upgrades.	Balanced regional development (Medeu et al., 2025).
External Geopolitical	Vulnerability to secondary sanctions.	Enhancing internal network resilience and redundancy.	Economic resilience theory (Jiang & Jiang, 2024).

6. Conclusion

The developed conceptual model translates the idea of a hypercluster into a practical design framework, offering a three-tier architecture with detailed mechanisms and tools that incorporate contemporary scientific perspectives on regional integration, resilience, and green development (Ma et al., 2024; Zhang et al., 2022). The quantitative forecast confirms significant potential for comprehensive sustainability enhancement: economic (20% value-added growth), environmental (30% emission reduction), and social (44% wage growth).

To initiate the practical launch of this process, the following set of priority recommendations for government bodies and development institutions is proposed:

- 1) Initiate negotiations to establish a legal “sandbox” for a pilot hypercluster within the framework of the Russia-China Investment Cooperation Commission.
- 2) Form a consortium of technology companies, development banks, and universities from both countries to develop the core Digital Platform for Sustainable Development.
- 3) Incorporate the target indicators from the forecast table (Section 4) into cooperation programs between Russian regions and Chinese provinces, integrating sustainability approaches into governance (“SDG integration...”, n.d.).
- 4) Establish a Management Company for the pilot hypercluster on a parity basis, with a clear mandate and access to the RCHDF tools and regulatory “sandbox.”

Further research should focus on detailed economic-mathematical modeling of network effects using agent-based models and on comparative analysis of international megaprojects to adapt best practices to the Eurasian context. Implement-

ing this model can create a working example of a new sustainable development paradigm based on technological sovereignty, environmental responsibility, and mutually beneficial cooperation, addressing the challenges outlined in contemporary scientific literature (Tejada-Gutiérrez et al., 2023; Olaniyan & Ipinnaiye, 2025).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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