




Bayesian Modeling for Regional Sustainable Development

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Abstract: In this paper, a Bayesian network framework has been applied to analyse the probabilistic dynamic of sustainable development at the regional level. The model integrates economic, social, environmental, and governance indicators to capture the uncertainty and independence of factors that conventional deterministic approaches often overlook. Principal nodes, such as economic diversification, innovation capacity, governance quality, energy efficiency, CO₂ emissions, social welfare, and a composite sustainable development index form the core structure of the network. Conditional probability tables have been constructed using a hybrid approach that combines statistical data, likelihood-based estimation. Scenario analysis demonstrates that governance quality and innovation capacity exert the strongest influence on sustainability outcomes, while environmental efficiency and emissions reduction provide complementary but less decisive effects. Combined interventions in governance reform, green technology, and innovation yield the highest probability of sustainable development. The findings highlight the risk of a «technological trap» for Russian regions with weak institutions and limited innovation, extending the debate on resource dependency. From a policy perspective, Bayesian networks provide monitoring tools that enable evidence-based decision-making, continuous updating of probability distributions, and better alignment of regional strategies with national goals of sustainability and technological sovereignty.


1 INTRODUCTION


Sustainable development at the regional level is influenced by multiple interdependent factors, including economic performance, social welfare, technological capacity, environmental quality, and governance effectiveness. Basic statistical approaches often fail to capture the inherent uncertainty and the nonlinear, context-dependent interaction among these factors; by contrast, Bayesian modeling supplies a coherent probabilistic framework that integrates prior knowledge, empiric data to estimate the likelihood of achieving sustainable development objectives under alternative conditions.

Bayesian networks (BNs) and their dynamic extensions (DBNs) have become established tools for environmental decision support and regional planning because they allow explicit representation of causal structure, propagation of uncertainty and systematic exploration of «what-if» scenarios that policy makers can use to priorities interventions (Aguilera et al., 2011; Fenton & Neil, 2012).

Recent methodological reviews and applied studies further document the rising use of BNs and DBNs across environmental management, infrastructure planning and socio-ecological risk assessment, demonstrating both conceptual perfection and practical relevance for regional sustainability problems (Chang J., Bai, Y. & Xue, J., 2023).

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2 MATERIALS AND METHODS

In this paper a Bayesian network was constructed to represent key causal relations that determine regional sustainable development outcomes. The network comprises seven principal nodes: Economic Diversification (ED), Innovation Capacity (IC), Governance Quality (GQ), Energy Efficiency (EE), CO₂ Emissions (CO₂), Social Welfare (SW) and a composite Sustainable Development Index (SDI). That aggregates economic, environmental and social subcomponents according to an explicit weighting scheme (Xiangyu Rui).

Structural links were defined based on theoretical arguments on drivers of regional resilience and technological adoption (Meadows et al., 2004; North, 1990) and informed by the policy and conceptual literature in technology sovereignty and governance-driven innovation policy (Edler et al., 2023).

Conditional probability tables (CPTs) for each node were produced using a hybrid procedure combining (i) regional statistical summaries (2015-2023) for observables such as a GRP growth, energy intensity and patent counts (ii) maximum-likelihood learning where sufficient historical record exists, and (iii) structured expert elicitation to parameterize ratio with limited empirical coverage (good practice methods after Chen & Pollino, 2012).

Model specification and calibration were implemented in GeNIe/SMILE (Marek J. Druzdzel) and crosschecked using alternative CPT parametrizations to ensure robustness. Sensitivity to prior assumptions was assessed by variance-reduction analysis and value-of-information computations following standard BN validation protocols (Frame et al., 2023). Dynamic aspects (time lags, path dependence) are acknowledged as important and are recommended for future work using DBNs; recent reviews show DBNs are particularly useful when the temporal evolution of indicators and policy impacts must be represented explicitly (Frame et al., 2023).

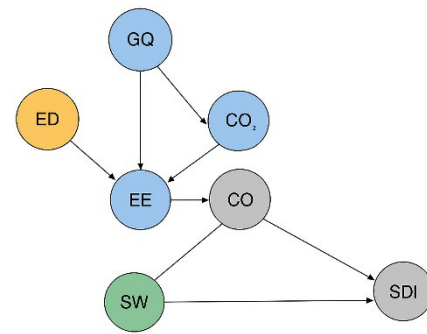


Figure 1: Network diagram with colors for nodes and dependency arrows.

The Bayesian Network visualizes the probabilistic dependencies among key determinants of sustainable development. Colored nodes represent the main factors all converging on the target node SDI. Arrows indicate the direction of conditional influence, reflecting causal ratios inferred from empirical data. Strong governance and innovation capacity enhance energy efficiency and reduce emissions gains. Together, these interactions determine the probability distribution of SDI outcomes across different policy scenarios.

3 RESULTS

The baseline parametrization of the Bayesian network yields a probability of 0.42 for High SDI, 0.44 for Medium SDI, and 0.14 for Low SDI, reflecting the average conditions of Russian regions with moderate governance, innovation capacity, and environmental efficiency. Scenario experiments indicate strong sensitivity of sustainable development outcomes to changes in governance quality, energy efficiency, and emissions reductions

Table 1: Scenario results for the Sustainable Development Index (SDI).

Scenario	P(SDI = High)	P(SDI = Medium)	P(SDI = Low)
Baseline (all Medium)	0.42	0.44	0.14
GQ → Strong	0.61	0.31	0.08
EE → High & C O ₂ → Low	0.69	0.26	0.05
Combined intervention	0.84	0.12	0.04

Source: Complicated by the authors

Table 1 summarizes the probability distribution of SDI across four main scenarios. Strengthening governance quality alone raises the probability of High SDI to 0.61, while green technology investments in energy efficiency and CO₂ reduction increase the probability to 0.69. A combined intervention yields the most pronounced effect, with High SDI reaching 0.84.

To illustrate how conditional probability tables (CPTs) determine outcomes, Table 2 provides example entries. When all parent indicators perform strongly, the probability of High SDI is 0.85, compared to only 0.05 when all indicators remain weak.

Table 2: Illustrative CPT entries for SDI under representative parent-state configurations.

Parent configuration (ED/ IC/GQ/EE/ CO ₂ /SW)	P(SDI = High)	P(SDI = Medium)	P(SDI = Low)
High/High/Strong/High/Low/High	0.85	0.12	0.03
Medium/ Medium/ Medium/ Medium/ Medium/ Medium	0.40	0.45	0.15
EE → High & CO ₂ → Low	0.05	0.20	0.75

Data sources: Federal State Statistics Service, (2023); OECD (2023); WIPO (2023); IEA (2023)

Finally, sensitivity analysis identifies governance quality and innovation capacity as the dominant drivers of outcome variance (together ≈ 50%), followed by environmental efficiency and emissions (25%), with social welfare and economic diversification having moderate but indirect influence.

Table 3: Sensitivity of SDI outcomes to parent indicators.

Rank	Node	Variance contribution (%)
1	Governance Quality (GQ)	28
2	Innovation Capacity (IC)	22
3	Energy Efficiency (EE)	14
4	CO ₂ Emissions (CO ₂)	11
5	Social Welfare (SW)	15
6	Economic Diversification (ED)	10

Data sources: Federal State Statistics Service, (2023); World Bank WGI (2022); Hickel, J (2019)

4 DISCUSSION

The results highlight three main findings. First, governance quality exerts a disproportionately strong effect on sustainability outcomes. Even without major environmental investments, stronger institutions increase the likelihood of achieving high SDI by almost 20 percentage points. This supports the hypothesis that institutional reform is the most cost-effective and leverage-rich agency for Russian regions, consistent with the literature emphasizing governance as a cornerstone of sustainable development (North, 1990; Edler et al., 2023).

Second, green technology investments in Europe and there is more and more of the future in Russia provide significant but slightly smaller marginal gains compared to institutional improvements. When energy efficiency is raised and emissions are reduced, the probability of high SDI increases by 27 percentage points relative to the baseline. These findings are in line with other studies showing that ecological interventions yield substantial returns, but their effectiveness depends on complementary governance and innovation frameworks (Prokop, et al., 2023; Khan, et al., 2020).

Third, the combined scenario demonstrates strong synergy. Governance reform and green investments together raise the probability of high SDI to 0.84, which is more than the additive effect of separate interventions. This underscores the necessity of integrated multi-sectoral policy packages that align institutional capacity with environmental and innovation-oriented measures.

When compared to Christensen (2023), who models a Bayesian game of resource exploitation in hinterland regions, our results extend the analysis from the «staples trap» to what may be called a «technological trap». Whereas Christensen shows that weak institutions combined with resource dependence reinforce unsustainable equilibria, our findings indicate that Russian regions risk technological dependency when innovation capacity and governance are weak. Bayesian updating reveals that subjective probabilities of success are heavily conditioned by perceptions of institutional strength, which suggests that regions with low governance quality systematically underestimate their potential for sustainable transformation.

This perspective adds a novel dimension to the resource-based development debate and a probabilistic dilemma of technological sovereignty versus dependency for regions. From a policy standpoint, the Bayesian networks demonstrate how scenario analysis can be used as a monitoring tool to

evaluate the effectiveness of national projects such as Science and Universities or Digital Economy in raising the probability of sustainable outcomes at the regional level.

4.1 Policy implications

The Bayesian network analysis provides several actionable policy implications for Russian regions. First, institutional reform should be prioritised as a foundational driver of sustainable development. Stronger governance frameworks including transparent regulatory systems, participatory decision-making and anti-corruption measures substantially increase the probability of achieving high SDI. This suggests that institutional investments may yield higher returns on sustainability outcomes than purely economic incentives.

Second, environmental measures such as improvements in energy efficiency and reduction of CO₂ emissions should be pursued in tandem with governance reforms. The analysis shows that green investments alone raise the likelihood of sustainability but achieve maximum effectiveness only when institutional quality is sufficiently high. Policymakers should therefore integrate environmental goals into regional development strategies rather than treat them as separate agendas.

Third, innovation capacity emerges as a strategic lever. Strengthening regional research and development systems, supporting patent activity, and encouraging university-industry partnerships are crucial to avoiding the «technological trap». Without innovation-driven diversification, regions risk reinforcing resource dependency and vulnerability to external shocks.

Finally, the combined scenario emphasizes the need for integrated policy packages. Governance reforms, green investments, and innovation promotion should be designed as mutually reinforcing components rather than isolated interventions. Bayesian modeling further suggests that monitoring should be adaptive. As new data becomes available, probability estimates can be updated, allowing regional authorities to recalibrate strategies in real time. This approach aligns with the transition from deterministic planning to probabilistic, evidence-based policymaking, which is increasingly recognized as essential for sustainable development in complex environments.

5 CONCLUSIONS

In this study, we have applied a Bayesian network framework to evaluate the probabilistic dynamic of sustainable development in Russian regions by integrating economic, social, environmental, and governance indicators. The model captures the inherent uncertainty and interdependence that basic deterministic approaches often overlook. The results demonstrate that governance quality and innovation capacity are the most critical levers for raising the likelihood of high sustainable development outcomes, while energy efficiency and emissions reduction provide substantial but complementary effects.

From a policy perspective, the findings emphasize that governance reform alone can significantly increase the probability of sustainable development, while green technology investments reach their maximum potential only when combined with strong institutions.

Moreover, the analysis identifies a specific risk for Russian regions, such as the «technological trap», when insufficient innovation and weak governance reinforce dependency on imported technologies. This extends the existing literature on resource dependency by introducing a Bayesian interpretation of technological sovereignty, where subjective probabilities of success and failure strongly influence regional strategic choices.

The Bayesian networks approach is also a flexible monitoring tool that enables continuous updating of probability distributions as new empirical data emerges. Thus, it provides regional authorities with an adaptive instrument for evaluating the effectiveness of national projects. In this way, the framework supports evidence-based policymaking and strengthens the capacity to anticipate risks, prioritize interventions, and align regional trajectories with long-term national goals of sustainable development and technological sovereignty.

In conclusion, the contribution of this study lies in demonstrating how probabilistic modelling can bridge the gap between theoretical debates on sustainability and practical challenges of regional governance by quantifying the uncertainty surrounding institutional, technological, and environmental factors. Bayesian networks offer a novel pathway to design integrated strategies that enhance both sustainability and resilience of Russian regions in challenging conditions.

REFERENCES

- Aguilera, P., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. *Environmental Modelling & Software*, 26(12), 1376–1388.
- Chang, J., Bai, Y., Xue, J., Gong, L., Zeng, F., Sun, H., Hu, Y., Huang, H., Ma, Y., 2023. Dynamic Bayesian networks with application in environmental modeling and management: A review. *Environmental Modelling & Software*, 170, 105835.
- Chen, S. H., Pollino, C. A., 2012. Good practice in Bayesian network modelling. *Environmental Modelling & Software*, 37, 134–145.
- Christensen, L. D., 2022. A Bayesian game of resource exploitation in hinterland regions: modelling scenarios for sustainable development. *Environment Development and Sustainability*, 25(1), 277–296.
- Elder, J., Blind, K., Kroll, H., Schubert, T., 2023. Technology sovereignty as an emerging frame for innovation policy. Defining rationales, ends and means. *Research Policy*, 52(6), 104765.
- Elder, J., Cunningham, P., Gök, A., Shapira, P., 2023. Handbook of innovation policy impact. *Edward Elgar Publishing, ISBN: 978 1 78471 184 9*
- Federal State Statistics Service, 2023. *Russian Federal State Statistics Service: Regional database 2015 – 2023*. Moscow: Federal State Statistics Service. Retrieved from <https://rosstat.gov.ru/>
- Federal State Statistics Service, 2023. *Russian Federal State Statistics Service: Data on SDG indicators*. Moscow: Federal State Statistics Service. Retrieved from <https://rosstat.gov.ru/>
- Fenton, N., Neil, M., 2012. Risk Assessment and Decision Analysis with Bayesian Networks. In *CRC Press eBooks*.
- Frame, M. E., Acker-Mills, B., Maresca, A., Patterson, R. E., Curtis, E., Buccello-Stout, R., Nelson, J., 2023. Evaluation of a decision support system using Bayesian network modeling in an applied Multi-INT surveillance environment. *Military Psychology*, 1–13.
- Hickel, J., 2019. The sustainable development index: Measuring the ecological efficiency of human development in the anthropocene. *Ecological Economics*, 167, 106331.
- International Energy Agency (IEA). (2023). *IEA data and statistics*. Paris: IEA. Retrieved from <https://www.iea.org/data-and-statistics>
- Khan, H., Khan, S., Zuojun, F., 2020. Institutional Quality and Financial Development: Evidence from Developing and Emerging Economies. *Global Business Review*, 23(4), 971–983.
- North, D. C., 1990. *Institutions, institutional change and economic performance*.
- OECD, 2023. *OECD. Stat database*. Paris: Organization for Economic Co-operation and Development. Retrieved from <https://data-explorer.oecd.org/>
- Prokop, V., Gerstlberger, W., Zapletal, D., Gyamfi, S., 2023. Do we need human capital heterogeneity for energy efficiency and innovativeness? Insights from European catching-up territories. *Energy Policy*, 177, 113565.
- Rui, X., Cao, X., Xie, Q., Yue, Z., Zhao, Q., Meng, D., 2021. Learning an explicit weighting scheme for adapting complex HSI noise. *2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 29, 6735–6744.
- World Intellectual Property Organization (WIPO). (2023). *WIPO statistics database*. Geneva: WIPO. Retrieved from <https://www.wipo.int/web/ip-statistics>
- World Bank, 2022. *World Governance Indicators (WGI) database*. Washington, DC: World Bank. Retrieved from <https://www.worldbank.org/en/publication/worldwide-governance-indicators>