

Territorial Typologies of Innovation-to-Sustainability Transformation: Evidence for EU Member States

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Extended Abstract

Aim

This paper aims to bring light into the process of transforming the strategic innovation capacity into sustainable development outcomes in the case of the European Union (EU) Member States, with the aim of identifying territorial typologies relevant for the design of EU Cohesion Policy post-2027. In a context marked by geopolitical uncertainty, green and digital transitions, and increasing pressure on public budgets, understanding the efficiency of this transformation process becomes crucial for shaping more targeted and performance-oriented policy interventions.

Methodology

Using Eurostat data, two composite dimensions are constructed, namely an input dimension measuring the strategic innovation capacity of the member states, and an output dimension related to sustainable development outcomes. Considering that the extracted data are either benefit-type or cost-type variables, a normalization or an inverse normalization step was performed prior to using the indicators for the analysis. For the normalization, the following formula has been used (Han et al. 2012):

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)}$$

The number of clusters has been determined as suggested in the scientific literature by considering the values obtained for the Silhouette score (Rousseeuw 1987), Davies-Bouldin index (Davies and Bouldin 1979), Calinski-Harabasz score (Calinski and Harabasz 1974), and dendrogram (Murtagh 1985; Wilkinson and Friendly 2009). As a result, three clusters have been used.

Grey systems theory, through the grey clustering method, offers a distinct tool for complex and uncertain situations, characterized by limited data. Over years, it has been proven that grey systems theory has proved its applicability in a wide range of domains, which have made it the primarily option for the researchers in the field when dealing with incomplete data. In

particular, the grey clustering analysis has been used in research papers from various research directions, such as, but not limited to (Dumitrescu et al. 2025): economics (e.g. Wiecek-Janka et al. (2020), Li et al. (2014), Delcea et al. (2025), Tilica et al. (2024)), risk and security (e.g. Wu et al. (2019), Qi et al. (2021), Chen et al. (2023), Hu et al. (2020), Liu et al. (2015), Kumar (2021), Hossain et al. (2022)), project and sustainability evaluation (e.g. Chen et al. (2024), Tan et al. (2020), Huo et al. (2023), Wang et al. (2022), Zhang et al. (2022)), environment evaluation (e.g. Liu (2021) , Yu et al. (2019), Delgado et al. (2020), Delgado et al. (2021)), industry and materials (e.g. Tan et al. (2024), Guo et al. (2021), Li et al. (2020), Tian (2016), Yue et al. (2018), Zhao et al. (2024)).

Three classical forms of the grey clustering functions have been used as suggested in the dedicated scientific literature (Crisan et al. 2025; Ioanas et al. 2026; Liu et al. 2016, 2012; Marin et al. 2025; Panait, et al. 2026; Delcea et al. 2021; Xie et al. 2019), which are briefly depicted in Table 1. Based on the data, the turning points of these functions have been established for each indicators considered in the analysis.

Table 1. Forms of grey clustering functions

Type	Graphical representation	Equation
1		$f_j^k(x) = \begin{cases} 0, & x \notin [x_j^k(1), x_j^k(4)] \\ \frac{x - x_j^k(1)}{x_j^k(2) - x_j^k(1)}, & x \in [x_j^k(1), x_j^k(2)] \\ 1, & x \in [x_j^k(2), x_j^k(3)] \\ \frac{x_j^k(4) - x}{x_j^k(4) - x_j^k(3)}, & x \in [x_j^k(3), x_j^k(4)] \end{cases}$
2		$f_j^k(x) = \begin{cases} 0, & x \notin [0, x_j^k(4)] \\ 1, & x \in [0, x_j^k(3)] \\ \frac{x_j^k(4) - x}{x_j^k(4) - x_j^k(3)}, & x \in [x_j^k(3), x_j^k(4)] \end{cases}$
3		$f_j^k(x) = \begin{cases} 0, & x < x_j^k(1) \\ \frac{x - x_j^k(1)}{x_j^k(2) - x_j^k(1)}, & x \in [x_j^k(1), x_j^k(2)] \\ 1, & x \geq x_j^k(2) \end{cases}$

To capture the complexity of the innovation-to-sustainability nexus, multiple weighting scenarios are developed, ranging from full emphasis on innovation capacity to full emphasis on sustainable outcomes. Additionally, a four-year dynamic perspective is incorporated using a grey clustering approach, allowing the observation of countries’ movements across clusters. Overall, the scenarios presented in Figure 1 have been considered.

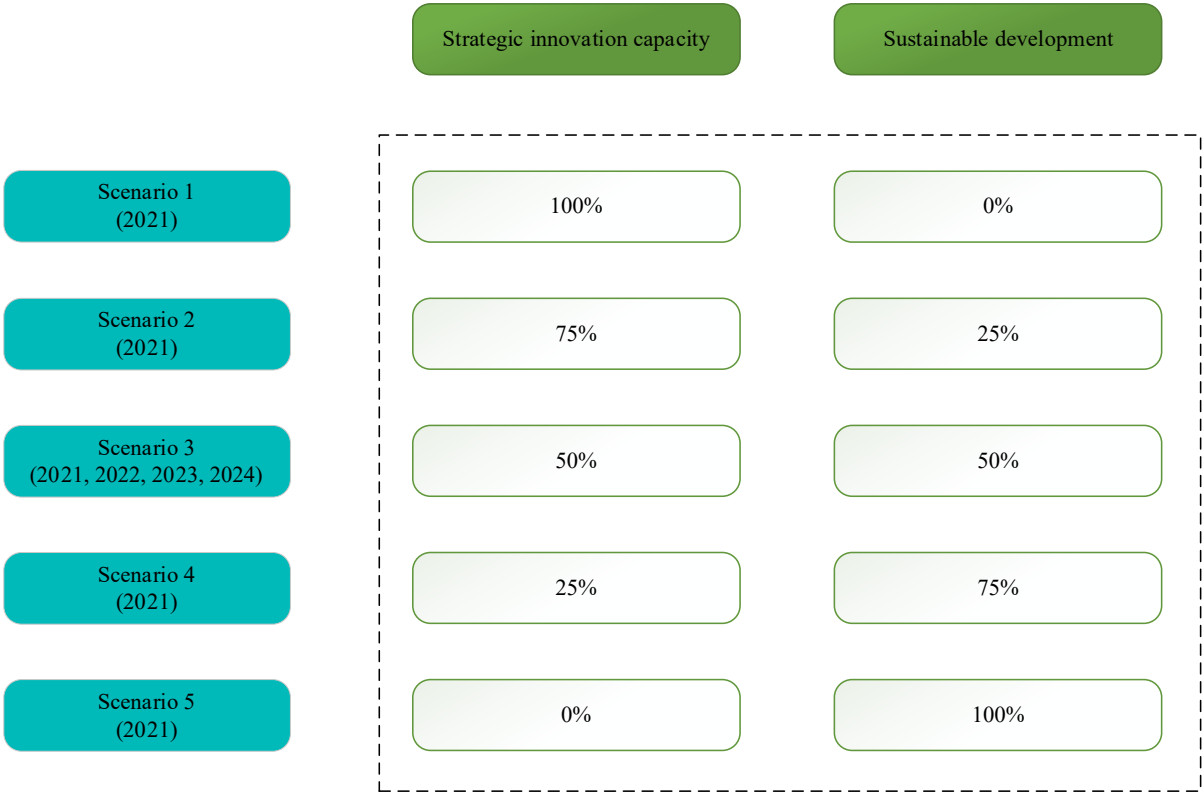


Figure 1. The scenarios considered in the analysis

Additionally, robustness is ensured through 100,000 simulations with slightly varying coefficients, enabling an assessment of cluster stability.

Results

The results reveal distinct territorial typologies. “Systematic leaders” demonstrate a consistent ability to translate innovation inputs into sustainable outcomes. Other groups include countries with strong innovation capacity but limited sustainability performance, as well as states achieving relatively good outcomes despite weaker innovation inputs. These asymmetric patterns suggest that innovation capacity alone does not automatically guarantee sustainable transformation.

The findings provide evidence for a more nuanced, place-based approach to EU Cohesion Policy post-2027. Rather than uniform support mechanisms, differentiated strategies are needed to address structural inefficiencies in the innovation-to-sustainability conversion process and to foster upward convergence across Member States.

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References

- Calinski, T., and J. Harabasz. 1974. 'A Dendrite Method for Cluster Analysis'. *Communications in Statistics - Theory and Methods* 3 (1): 1–27. <https://doi.org/10.1080/03610927408827101>.
- Chen Qihua, Long Danbing, Yang Cheng, and Xu Hu. 2023. 'Knowledge Graph Improved Dynamic Risk Analysis Method for Behavior-Based Safety Management on a Construction Site'. *Journal of Management in Engineering* 39 (4): 04023023. <https://doi.org/10.1061/JMENEA.MEENG-5306>.
- Chen, Yongxia, Wenna Li, and Xiaomeng Wang. 2024. 'An Investigation into the Risk Assessment of Building-Integrated Photovoltaic Residential Project Development Utilizing the DEMATEL-ANP Methodology: A Chinese Case Study'. *Buildings* 14 (3). <https://doi.org/10.3390/buildings14030623>.
- Crisan, Alina Georgiana, Madalina Ecaterina Popescu, Adrian Domenteanu, Mihnea Panait, and Camelia Delcea. 2025. 'Grey Relational Analysis Model: Application in Evaluating Digitalisation Impact on Economic Prosperity'. Paper presented at GSUA 2025.
- Davies, David L., and Donald W. Bouldin. 1979. 'A Cluster Separation Measure'. *IEEE Transactions on Pattern Analysis and Machine Intelligence* PAMI-1 (2): 224–27. <https://doi.org/10.1109/TPAMI.1979.4766909>.
- Delcea, Camelia, Liviu-Adrian Cotfas, R. John Milne, Naiming Xie, and Rafał Mierzwiak. 2021. 'Grey Clustering of the Variations in the Back-to-Front Airplane Boarding Method Considering COVID-19 Flying Restrictions'. *Grey Systems: Theory and Application* 12 (1): 25–59. <https://doi.org/10.1108/GS-11-2020-0142>.
- Delcea, Camelia, Constantin Marius Profiroiu, Alina Georgiana Profiroiu, Bianca Raluca Cibu, Ionuț Nica, and Liviu-Adrian Cotfas. 2025. 'Complex Decision Making in Counties Socio-Economic and Security Contexts through Grey Clustering'. *The Journal of Grey System* 37 (2): 115.
- Delgado, Alexi, Anabel Fernandez, Brigitte Chirinos, Gabriel Barboza, and Enrique Huamani Uriarte. 2021. 'Impact of the Mining Activity on the Water Quality in Peru Applying the Fuzzy Logic with the Grey Clustering Method'. *International Journal of Advanced*

- Delgado, Alexi, Jharison Vidal, Jhon Castro, Jhonel Felix, and Jorge Saenz. 2020. 'Assessment of Surface Water Quality on the Upper Watershed of Huallaga River, in Peru, Using Grey Systems and Shannon Entropy'. *International Journal of Advanced Computer Science and Applications* 11 (December).
<https://doi.org/10.14569/IJACSA.2020.0111156>.
- Dumitrescu, Gabriel, Andra Sandu, Mihnea Panait, and Camelia Delcea. 2025. 'Grey Clustering Methods and Applications: A Bibliometric-Enhanced Review'. *Mathematics* 13 (24): 4040. <https://doi.org/10.3390/math13244040>.
- Guo, Ziyu, Yueming Lu, Huiping Tian, Jinxin Zuo, and Hui Lu. 2021. 'A Security Evaluation Model for Multi-Source Heterogeneous Systems Based on IOT and Edge Computing'. *Cluster Computing* 26 (September). <https://doi.org/10.1007/s10586-021-03410-4>.
- Han, Jiawei, Micheline Kamber, and Jian Pei. 2012. 'Data Preprocessing'. In *Data Mining*. Elsevier. <https://doi.org/10.1016/B978-0-12-381479-1.00003-4>.
- Hossain, Md, Vikas Thakur, and Yiğit Kazançoğlu. 2022. 'Developing a Resilient Healthcare Supply Chain to Prevent Disruption in the Wake of Emergency Health Crisis'. *International Journal of Emerging Markets* 18 (May). <https://doi.org/10.1108/IJOEM-10-2021-1628>.
- Hu, Lin, Xingqian Bao, Hequan Wu, and Wu Wenguang. 2020. 'A Study on Correlation of Traffic Accident Tendency with Driver Characters Using In-Depth Traffic Accident Data'. *Journal of Advanced Transportation* 2020 (June): 1–7.
<https://doi.org/10.1155/2020/9084245>.
- Huo, Xiaosen, Hao Xue, and Liudan Jiao. 2023. 'Risk Management of Retrofit Project in Old Residential Areas under Green Development'. *Energy and Buildings* 279 (January): 112708. <https://doi.org/10.1016/j.enbuild.2022.112708>.
- Ioanas, Ioana, Adrian Domenteanu, Mihnea Panait, and Liviu-Adrian Cotfas. 2026. 'AI-Driven Insights for Understanding Employee Retention Dynamics in Complex Organizational Ecosystems'. Paper presented at 54th EBES Conference.
- Kumar, Aalok. 2021. 'Transition Management Theory-Based Policy Framework for Analyzing Environmentally Responsible Freight Transport Practices'. *Journal of Cleaner Production* 294 (April): 126209. <https://doi.org/10.1016/j.jclepro.2021.126209>.
- Li, Lin, Kai Zhang, and Tao Li. 2020. 'A Performance Analysis Model for the Training and Education of Information Security Talents'. *International Journal of Emerging Technologies in Learning (iJET)* 15 (March): 140.
<https://doi.org/10.3991/ijet.v15i05.13329>.

- Li, Tianbo, Ershi Qi, and Yimin Huang. 2014. 'Grey Clustering Evaluation Based on Triangular Whitenization Weight Function of Enterprise's Management Innovation Performance'. *Grey Systems: Theory and Application* 4 (3): 436–46. <https://doi.org/10.1108/GS-05-2014-0017>.
- Liu, Sifeng, Jeffrey Forrest, and Yingjie Yang. 2012. 'A Brief Introduction to Grey Systems Theory'. *Grey Systems: Theory and Application* 2 (2): 89–104. <https://doi.org/10.1108/20439371211260081>.
- Liu, Sifeng, Yingjie Yang, Naiming Xie, and Jeffrey Forrest. 2016. 'New Progress of Grey System Theory in the New Millennium'. *Grey Systems: Theory and Application*, ahead of print, February 1. <https://doi.org/10.1108/GS-09-2015-0054>.
- Liu, Sifeng, Shaoguang Zhang, Lirong Jian, Wenfeng Yuan, and Yingjie Yang. 2015. 'Performance Evaluation of Large Commercial Aircraft Vendors'. *Journal of Grey System* 27 (January): 1–11.
- Liu, Zhongping. 2021. 'Water Quality Evaluation and Guarantee Treatment of Outdoor Landscape Water'. *Desalination and Water Treatment* 242 (December): 195–202. <https://doi.org/10.5004/dwt.2021.27572>.
- Marin, Erika, Bianca Cibu, Ana-Maria Marcu, Mihnea Panait, and Gabriel Dumitrescu. 2025. 'Complex Socio-Economic Perceptions in Romania and Moldova: Business Environment Implications'. Paper presented at 9th CERS - Central European Conference in Regional Science - "Sustainability-driven territorial development. Challenges for CEECs". November 27.
- Murtagh, F. 1985. *Multidimensional Clustering Algorithms*. Physica.
- Panait, Mihnea, Adriana Cosac, Gabriel Dumitrescu, and Liviu-Adrian Cotfas. 2026. 'Modeling IT Workforce Skills via Grey Clustering and Agent-Based Simulation'. Paper presented at 54th EBES Conference,.
- Qi, Weiwei, Lianjie Ruan, Yue Zhi, and Bin Shen. 2021. 'Risk Area Identification Model of Bus Bay Stops Based on Distribution of Conflicts'. *Discrete Dynamics in Nature and Society* 2021 (1): 9663966. <https://doi.org/10.1155/2021/9663966>.
- Rousseeuw, Peter J. 1987. 'Silhouettes: A Graphical Aid to the Interpretation and Validation of Cluster Analysis'. *Journal of Computational and Applied Mathematics* 20 (November): 53–65. [https://doi.org/10.1016/0377-0427\(87\)90125-7](https://doi.org/10.1016/0377-0427(87)90125-7).
- Tan, Qingkun, Tang Wei, Wu Peng, Zhang Yu, and Chenrui Wu. 2020. 'Comprehensive Evaluation Model of Wind Farm Site Selection Based on Ideal Matter Element and Grey Clustering'. *Journal of Cleaner Production* 272 (November): 122658. <https://doi.org/10.1016/j.jclepro.2020.122658>.

- Tan, Xianlong, Shuhua Mao, Xiping Xiao, and Yingjie Yang. 2024. 'Explainable Rumor Detection Based on Grey Clustering: Fusion of Manual Features and Deep Learning Features'. *Information Sciences* 679 (September): 121055. <https://doi.org/10.1016/j.ins.2024.121055>.
- Tian, Qingji. 2016. 'Network Information Security Research Based on the Grey Matter Element Analysis Method'. *International Journal of Security and Its Applications* 10 (October): 107–18. <https://doi.org/10.14257/ijisia.2016.10.10.11>.
- Țilică, Elena Valentina, Victor Dragotă, Camelia Delcea, and Răzvan Ioan Tătaru. 2024. 'Portfolio Management under Capital Market Frictions: A Grey Clustering Approach'. *Financial Innovation* 10 (1): 110. <https://doi.org/10.1186/s40854-024-00634-2>.
- Wang, Ailing, Yixin Yang, Shaonan Sun, Yiming Zuo, Zhihui Wang, and Haili Sun. 2022. 'Developing an Evaluation Model to Measure the Intelligence Level of Smart Industrial Parks'. *Buildings* 12 (10). <https://doi.org/10.3390/buildings12101533>.
- Weiyang Yu, Songjia Zhang, Huitao Shen, Shaodong Yu, and Teng Chen. 2019. 'Air Quality Evaluation of Bo Hai Coastal Region Based on Entropy Weight Method'. *Journal of Coastal Research* 94 (sp1): 83–86. <https://doi.org/10.2112/SI94-015.1>.
- Więcek-Janka, Ewa, Joanna Majchrzak, Magdalena Wyrwicka, and Gerhard Wilhelm Weber. 2020. 'Application of Grey Clusters in the Development of a Synthetic Model of the Goals of Polish Family Enterprises' Successors'. *Grey Systems: Theory and Application* 11 (1): 63–79. <https://doi.org/10.1108/GS-12-2019-0062>.
- Wilkinson, Leland, and Michael Friendly. 2009. 'The History of the Cluster Heat Map'. *The American Statistician* 63 (2): 179–84. <https://doi.org/10.1198/tas.2009.0033>.
- Wu, Xia, Wenlong Jia, and Zhuoran Li. 2019. 'Synthetic Evaluation of Natural Gas Pipeline Operation Schemes Based on the Multi-Level Grey Cluster Decision Method'. *Arabian Journal for Science and Engineering* 44 (6): 6045–56. <https://doi.org/10.1007/s13369-018-3553-z>.
- Xie, Naiming, Bentao Su, and Nanlei Chen. 2019. 'Construction Mechanism of Whitenization Weight Function and Its Application in Grey Clustering Evaluation'. *Journal of Systems Engineering and Electronics* 30 (1): 121. <https://doi.org/10.21629/JSEE.2019.01.12>.
- Yue, Chen, Lu Tianliang, Cai Manchun, and Li Jingying. 2018. 'Evaluation of the Attack Effect Based on Improved Grey Clustering Model'. *Int. J. Digit. Crime For.* (USA) 10 (1): 92–100. <https://doi.org/10.4018/IJDCF.2018010108>.
- Zhang, Jingqi, Hui Zhao, and Ziliang Guo. 2022. 'Fuzzy Gray Clustering Evaluation of Green Building Operation Effect: A Case Study of Shenzhen Bay One, China'. *Kybernetes* 52 (12): 5977–6000. <https://doi.org/10.1108/K-04-2022-0623>.

Zhao, Guosheng, Runjie Chen, and Jian Wang. 2024. 'A Cooperative Detection Scheme for Malicious Nodes Based on D-S Trust Evidence Reasoning in Mobile Crowdsensing Networks'. *Comput. Electr. Eng.* (USA) 118 (PB).
<https://doi.org/10.1016/j.compeleceng.2024.109456>.