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UniGR-CBS Working Paper 29

Application of Dynamical Systems Theory for Cross-Border Cooperation in the Greater Region

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UniGR-Center for Border Studies 2026
UniGR-CBS Working Paper 29
DOI: https://doi.org/10.5281/zenodo.18412271

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Abstract – This working paper introduces the methodology of the Dynamical Territorial Impact Assessment (DyTIA), developed through the analysis of the INTERREG programs in the Greater Region. It starts from the notion that existing impact assessments are largely static and thus fail to capture the complex, non-linear dynamics of cross-border areas. The paper is structured into seven main sections: the introduction and the section dealing with static and process-oriented approaches are followed by theoretical foundations of dynamical systems theory together with the expanded paradigm of resilience (absorption, adaptation, transformation, exaptibility). The subsequent sections present the empirical analysis of the Greater Region and its INTERREG programs, including models of scenarios, networks, and resilience indicators. The central chapter applies the DyTIA approach to the current INTERREG NEXT program, highlighting the role of digital twin simulations under conditions of budget reductions. The paper concludes with a critical discussion of opportunities and limitations. It also formulates policy recommendations, thereby contributing to the predictive governance of European cross-border regions.

Cohesion Policy, Cross-Border Cooperation, INTERREG, Territorial Impact Assessment, Dynamical System Theory

Application de la théorie des systèmes dynamiques à la coopération transfrontalière dans la Grande Région

Résumé – Ce document de travail présente la méthodologie de l'Évaluation Dynamique de l'Impact Territorial (DyTIA), développée à travers l'analyse des programmes INTERREG dans la Grande Région. Il part du constat que les évaluations d'impact existantes sont largement statiques et ne parviennent donc pas à saisir les dynamiques complexes et non linéaires des zones transfrontalières. Ce document est structuré en sept sections principales : l'introduction et la section traitant des approches statiques et orientées aux processus sont suivies des fondements théoriques de la théorie des systèmes dynamiques ainsi que du paradigme élargi de la résilience (absorption, adaptation, transformation, exaptabilité). Les sections suivantes présentent l'analyse empirique de la Grande Région et de ses programmes INTERREG, incluant la modélisation de scénarios, de réseaux et d'indicateurs de résilience. Le chapitre central applique l'approche DyTIA au programme actuel INTERREG NEXT, en soulignant le rôle des simulations par jumeau numérique dans des conditions de réductions budgétaires. Ce document se conclut par une discussion critique des opportunités et des limitations. Il formule également des recommandations politiques, contribuant ainsi à la gouvernance prédictive des régions transfrontalières européennes.

Politique de cohésion, Coopération transfrontalière, INTERREG, Évaluation de l'impact territorial, Théorie des systèmes dynamiques

Anwendung der Theorie dynamischer Systeme für die grenzüberschreitende Zusammenarbeit in der Großregion

Zusammenfassung – Dieses Arbeitspapier stellt die Methodik der Dynamischen Territorialen Folgenabschätzung (DyTIA) vor, die über die Analyse der INTERREG-Programme in der Großregion entwickelt wurde. Es geht von der Feststellung aus, dass vorliegende Folgenabschätzungen weitgehend statisch sind und daher die komplexen, nicht-linearen Dynamiken grenzüberschreitender Regionen nicht erfassen können. Es gliedert sich in sieben Hauptabschnitte: Auf die Einleitung und den Abschnitt über statische und prozessorientierte Ansätze folgen die theoretischen Grundlagen der Theorie dynamischer Systeme sowie das erweiterte Paradigma der Resilienz (Absorption, Anpassung, Transformation, Exaptierbarkeit). Die folgenden Abschnitte präsentieren die empirische Analyse der Großregion und ihrer INTERREG-Programme einschließlich der Modellierung von Szenarien, Netzwerken und Resilienzindikatoren. Das zentrale Kapitel wendet den DyTIA-Ansatz auf das aktuelle INTERREG NEXT-Programm an und hebt die Rolle von Digital-Twin-Simulationen im Zuge von Budgetkürzungen hervor. Das Arbeitspapier schließt mit einer kritischen Diskussion der Chancen und Grenzen der vorgestellten Methodik ab. Es formuliert zudem politische Handlungsempfehlungen und trägt damit zur vorausschauenden Governance europäischer grenzüberschreitender Regionen bei.

Kohäsionspolitik, grenzüberschreitende Zusammenarbeit, INTERREG, territoriale Folgenabschätzung, dynamische Systemtheorie

Acknowledgment

The work on this working paper was carried out during several research stays at the UniGR-Center for Border Studies. My sincere thanks go to the University of Luxembourg and Saarland University for their kind reception during my time as a UniGR-CBS Guest Researcher and UniGR-CBS Fellow. I also wish to thank the EGTC Managing Authority of the Interreg Greater Region Program for granting access to relevant information and data.

Application of Dynamical Systems Theory for Cross-Border Cooperation in the Greater Region

Introduction

The development of the Dynamical Territorial Impact Assessment (DyTIA) toolkit represents a methodological advancement in cross-border studies, particularly relevant in the contemporary geopolitical and economic context of 2025. The relevance of this research is driven by multiple converging factors requiring a fundamental shift from the static approaches to dynamic approaches in territorial impact assessment.

The contemporary European landscape presents unprecedented challenges for cross-border cooperation. The INTERREG NEXT program is facing a 18.6% budget reduction for the 2021-2027 period, creating pressure to allocate resources more strategically and efficiently (European Commission 2021). Simultaneously, the ongoing armed conflict in Ukraine has fundamentally altered European security architecture, requiring new analytical frameworks capable of capturing the complex interaction between territorial development, institutional integration, and security considerations.

The necessity of developing DyTIA is underscored by the comprehensive assessment conducted by the European Court of Auditors (2021), which revealed that only 3 of 23 INTERREG V-A programs had been subject to thorough "field research," whilst the majority were limited to "simple desk analysis." This situation demonstrates a structural problem: the existing territorial impact assessment tools cannot adequately capture the complex dynamics in border regions within acceptable resource constraints.

Contemporary approaches to Territorial Impact Assessment (TIA) in border regions have evolved from static assessment models to more comprehensive approaches (Medeiros/Ferreira 2025). However, these methodologies predominantly use retrospective (ex-post) assessment indicators, which cannot capture the dynamic nature of territorial systems and their nonlinear response to policy interventions based on European programs. Moreover, these approaches insufficiently account for the spatio-temporal dynamics characterizing cross-border interactions, particularly under reduced-funding conditions.

The authors of this paper have identified five critical factors necessitating the development of DyTIA in 2025 in particular: methodological crisis (87% of INTERREG programs use static assessments), budget constraints, geopolitical turbulence, institutional complexity (the whole number of EGTCs had increased to 90 by July 2025), and climate challenges (23.2% of the INTERREG budget is directed towards environmental objectives) (Kiryukhin et al. 2025).

In this paper, based on the general systems theory and the theory of dynamic systems, a new toolkit for assessing the territorial impact of territorial cooperation programs, in particular, INTERREG A, is presented using the example of the Greater Region. The transition from static methods to dynamic assessments occurs due to the emergence of new challenges and threats for the EU border zones, which require rapid adaptation and planning of cross-border cooperation at the project launch stages and their possible adjustment during the implementation. According to the EU, "it is therefore appropriate to adopt the measures that are necessary to improve the conditions for the implementation of territorial cooperation actions" (REGULATION (EU) 2025/925, 1).

The empirical data used in this paper comprise the budgets of all calls for proposals and implemented projects of the INTERREG V-A Greater Region program. Modeling based on the dynamic approaches that were developed made it possible to assess the resilience of the INTERREG program's impact throughout the entire program period of 2014-2020 in the

Greater Region. This also allowed for the construction of a general paradigm of Dynamical Territorial Impact Assessment for INTERREG NEXT programs in the current European programming period, considering complexity theory and exaptive resilience. The paper opens up new perspectives for studying cross-border territorial systems under the influence of INTERREG cooperation programs and global challenges.

From a Static Approach to Process-Oriented Thinking

The transition from a static to a dynamic analysis of territorial systems represents a fundamental transformation in territorial impact assessment methodology. Traditional approaches to analyzing border regions, including the ESPON EATIA (ESPON 2013), ESPON TIA-CBC (ESPON 2019), and ARTS (ESPON 2012) methodologies, concentrate on "snapshots" of territorial states at discrete points in time, which fundamentally limit their ability to reflect the complex dynamics of cross-border interactions.
The importance of modeling processes, rather than merely recording states, is particularly evident in the context of contemporary challenges to European territorial policy. As noted in the European Commission's "Guidance for Resilience Analysis" (European Commission 2023a), territorial systems are characterized by non-linear development trajectories, where small changes can lead to systemic transformations. Statistical analysis is unable to capture these critical transitions and threshold effects.

Criterion	Static Approach	Process-Oriented Approach
Temporal perspective	Discrete time points (t_1, t_2)	Continuous developmental trajectories
Cause-and-effect relationships	Correlation analysis	Modeling of causal loops
Response to shocks	Ex-post assessment of consequences	Predictive resilience modeling
Intervention planning	Based on historical data	Scenario modeling of future states
Effectiveness assessment	"Before" and "after" comparison	Analysis of dynamic trajectories

Table 1: Comparison of Static and Process-Oriented Approaches
Source: Authors

Challenges of Cross-Border Cooperation (CBC)

Border regions occupy approximately 40% of EU territory and are home to nearly 150 million citizens, yet they continue to face unique developmental challenges due to their peripheral nature, institutional asymmetries, and complex socio-economic dynamics that transcend national borders (European Commission 2017). Compared to the Council of Europe, the CBC-related activities of the EU are primarily financial (Perkmann, 3). Despite significant investments through INTERREG programs, which received over €6.3 billion for cross-border cooperation (INTERREG V-A) in the 2014-2020 period, the European Court of Auditors concluded that the potential of the European Union's border regions has not yet been fully unlocked (European Court of Auditors 2021).
The distribution of INTERREG V-A funds across thematic objectives reveals priority areas that significantly influence regional development trajectories. Environmental protection and resource efficiency (Thematic Objective – TO 6) received the largest funding share—23.2% (€1.48 billion), followed by research and innovation (TO 1)13.7% (€872 million), whilst sustainable transport infrastructure (TO 7) received 9.3% (€593 million) (European Court of Auditors 2021). This distribution structure underscores the European Commission's focus on sustainable development and innovation; however, transforming these investments into measurable and tangible territorial effects remains a methodological challenge.

The current geopolitical context, characterized by multiple intersecting challenges (migration, climate change, energy security, and trade disruptions) alongside the ongoing armed conflict in Ukraine, requires a shift in how territorial effects are conceptualized and measured. Existing methodological approaches reveal three critical limitations: (1) they predominantly operate within static analytical instruments that ignore dynamic system interactions; (2) they focus on retrospective analysis rather than providing predictive capabilities; and (3) they often fail to account for the specificity of unique institutional arrangements of cross-border governance structures, such as European Groupings of Territorial Cooperation (EGTCs). The EGTC is an EU legal instrument created to promote and strengthen cross-border and interregional cooperation between public and territorial authorities in Europe (Ulrich 2024).

Dynamical Systems Theory

The application of dynamical systems theory to the analysis of border regions is justified by several theoretical and practical considerations. Firstly, border regions demonstrate characteristics of complex adaptive systems, distinguished by multiple feedback loops, temporal lags, and threshold effects that cannot be adequately captured by traditional linear approaches (Medeiros 2020; Cörvers/Mayhew 2021; ESPON TERRA RES 2024). Secondly, the contemporary context requires the integration of resilience and exaptibility considerations, as outlined in the European Commission's "Guidance for Resilience Analysis" (European Commission 2023a).
The concept of "exaptibility," introduced into EU methodological frameworks in 2023 following Kollár and Kollár (2020), is defined as the capacity of territorial systems to adapt existing resources and institutions to new functions under unforeseen conditions. This is particularly relevant for the Greater Region, where historical industrial structures from the early 2000s have been transformed for use in the knowledge economy and green technologies. Unlike traditional resilience concepts that focus on returning to equilibrium states, exaptibility emphasizes the capacity for functional transformation and innovation. For cross-border cooperation, territorial exaptive resilience is of particular interest, representing "a region's ability to repurpose its existing resources and capabilities, which were originally developed for different functions, to create new growth opportunities and evolve in response to changes or crises" (ESPON TERRA RES 2024, 11).

Transition to a New Resilience Paradigm

Theoretical Foundation: Key Concepts of Dynamical Systems Theory

The structural description of interrelationships in complex regional systems requires a rigorous mathematical apparatus based on set theory and general systems theory. In the DyTIA context, the territorial system is conceptualized as an ordered structure S = (X, R, F, T), where X represents the set of territorial elements: R the set of relationships between them, F the set of functions, and T the temporal dimension.
The theoretical foundations of DyTIA draw on Bertalanffy's concept of "open systems" (Bertalanffy 1968), adapted for the territorial context in accordance with the principles of the European Spatial Development Model (European Commission 1999). In this perspective, territorial systems are characterized by emergent properties, where system properties cannot be reduced to the sum of their individual components.
Let us first consider the fundamental concepts of general systems theory and dynamical systems theory, taking into account practical applications in disciplines adjacent to geography. Mathematical general systems theory is based on the assumption of purposeful behavior and captures cause-and-effect transformations of input impacts into output values (Mesarovic/Takahara 1975; Katok/Hasselblatt 2012). To describe complex systems (in our

case, territorial cross-border systems), more abstract and less structured descriptions should be used, dispensing with non-essential details.
First and foremost, when we use the term “system” we mean an object of study that can be described not only by relationships but also by state space and corresponding transition functions, as well as output functions. When system development is studied over time, the concept of a dynamical system is introduced. A dynamical system is a system whose state is determined by a finite number of real parameters, and whose behavior is described by a system of differential equations. Most paths connecting abstract mathematical theories with natural science applications pass through differential equations (Arnold 1999).
For a very general class of dynamical systems, the set of all states of motion can be brought into one-to-one correspondence with points P of a closed n-dimensional manifold M such that, with an appropriate set of coordinates x_1, x_2, ..., x_n, the differential equations of motion can be written in the form:

$$dx_i/dt = X_i (x_1, ..., x_n) \ (i = 1, ..., n) \qquad (1)$$

in the neighborhood of any point of manifold M, where Xi are real analytic functions of their arguments, and t is unambiguous time.
Dynamical systems theory provides mathematical rigor through the concepts of stability/resilience, phase states, and attractive states, offering a comprehensive analytical framework for modeling territorial dynamics. The theory allows for the identification and modeling of:

- Feedback mechanisms: cyclical cause-and-effect relationships that can amplify (positive feedback) or attenuate (negative feedback) initial intervention effects
- Temporal lags: delays between interventions and observed effects, which vary substantially depending on the types of territorial impacts
- Threshold effects: critical values beyond which systems may sharply change behavior
- Network effects: impact amplification through network structures characteristic of border regions

Before considering the application of dynamical systems theory to cross-border cooperation processes and the impact of INTERREG programs on border areas, it is necessary to define stability as a key concept for the further presentation of the DyTIA methodology.

“Lyapunov stability represents a property of an object consisting in the ability to keep sufficiently small the deviations of the values of the coordinates of a perturbed process after the action of the perturbation from the values of the same coordinates of the unperturbed process, if these deviations were sufficiently small at the moment of the end of the perturbation” (Volik 1988, 37).

Dynamical systems effectively reflect territorial convergence and divergence, central to EU cohesion policy—particularly relevant in border regions where integration processes proceed unevenly across economic, social, environmental, and institutional dimensions (Medeiros et al. 2023).

Understanding "Stability/Resilience" in Terms of Dynamical Systems

General Concept of Stability
Let $\hat{d}$ and $\hat{e}$ correspond to the cause and effect of a certain phenomenon, i.e., let there be a certain mapping F such that $F(\hat{d}) = \hat{e}$. Let another cause d_1 cause another effect $e = F(d_1)$ in some other situation.
The cause-and-effect pair $(\hat{e}, \hat{d})$ is called stable if insignificant deviations from $\hat{e}$ are caused by insignificant deviations from $\hat{d}$, i.e. if for all d_1 close to $\hat{d}$, the corresponding effect $e = F(d_1)$ will be close to $\hat{e}$.
This means that small deviations of the cause d cannot significantly change the effect e.

Definition of Stability
Let F: D → E be a given mapping, Θ_D and Θ_E be given families of subsets of D and E, respectively, $(\hat{d}, \hat{e}) \in D \times E$ and $\hat{e} = F(\hat{d})$.
Then the pair $(\hat{d}, \hat{e})$ is called stable with respect to Θ_D and Θ_E at the point if and only if $\forall\ \alpha \in N(\hat{e})\ \exists\ \beta \in N(\hat{d})\ \forall d\ (d \in \beta \rightarrow F(d) \in \alpha)$, where $N(\hat{e}) \subset$ Θ_E and $N(\hat{d}) \subset$ Θ_D are the neighborhood systems of points $\hat{e}$ and $\hat{d}$ relative to Θ_E and Θ_D, respectively.
$N(\hat{e}) \subset$ Θ_E – inclusion in Θ_E,
$N(\hat{d}) \subset$ Θ_D – inclusion in Θ_D,
$(\hat{d}, \hat{e}) \in D \times E$ – belonging to the Cartesian product of sets D and E.
The classical mathematical definition of stability was introduced in 1892 by A. M. Lyapunov:

"can the initial values of functions x_s (characterising deviations of coordinates from zero values corresponding to the motion whose stability is being investigated), without making them zeros, be chosen so numerically small that throughout the entire time of motion following the initial moment, these functions remain numerically smaller than certain predetermined limits distinct from zero but arbitrarily small" (Lyapunov 1950, 9).

A dynamical system can be described by a system of ordinary first-order differential equations:

$$\dot{x} = P(x, y), \quad \dot{y} = Q(x, y) \qquad (2)$$

The solution $x = \varphi_0(t)$, $y = \psi_0(t)$ is called stable according to Lyapunov if for any $\varepsilon > 0$ there exists such $\delta > 0$ ($\delta = \delta(\varepsilon)$) that for all solutions $x = \varphi(t)$, $y = \psi(t)$ for which the inequality $|\varphi_0(t_0) - \varphi(t_0)| < \delta$ holds, $|\psi_0(t_0) - \psi(t_0)| < \delta$, for all $t > t_0$, the inequalities $|\varphi_0(t) - \varphi(t)| < \varepsilon$, $|\psi_0(t) - \psi(t)| < \varepsilon$ will hold.
The equilibrium position x = 0 of such a system is called stable (according to Lyapunov) if any solution starting from a sufficiently small neighborhood Uδ does not leave an arbitrarily specified neighborhood Uε, i.e.

$$\forall\ \varepsilon > 0, \exists\ \delta > 0 : \forall\ x_0 = x(t_0) \in U\delta, \forall t > t_0,\ x(t_0) \in U\varepsilon \qquad (3)$$

If the solution $x = \varphi(t)$, $y = \psi(t)$ is stable according to Lyapunov (1950) and if, for a sufficiently small $\delta > 0$, the condition $\lim (t \rightarrow \infty) [\varphi_0(t) - \varphi(t)] = 0$, $\lim (t \rightarrow \infty) [\psi_0(t) - \psi(t)] = 0$, then the solution $\varphi_0(t)$, $\psi_0(t)$ is called asymptotically stable.
In our study, the terms stability and resilience are not considered synonymous. The conceptualization of resilience in the context of dynamical systems represents a fundamental shift from the traditional understanding of stability as static equilibrium to a dynamic understanding of a system's adaptive capacity.

Resilience, in this approach, is characterized by the ability of a complex self-organizing system to respond to an exogenous effect, to adapt to changed conditions, and to produce new patterns that were previously unavailable. So, "in contrast to an approach promoting stability as a return to an equilibrium state, the resilience approach emphasizes change and heterogeneity" (Holling 1973, 17).
Within the DyTIA methodology, resilience is defined as the capacity of a territorial system to maintain its core functions and structural characteristics when subjected to external shocks, whilst simultaneously adapting to changing conditions.

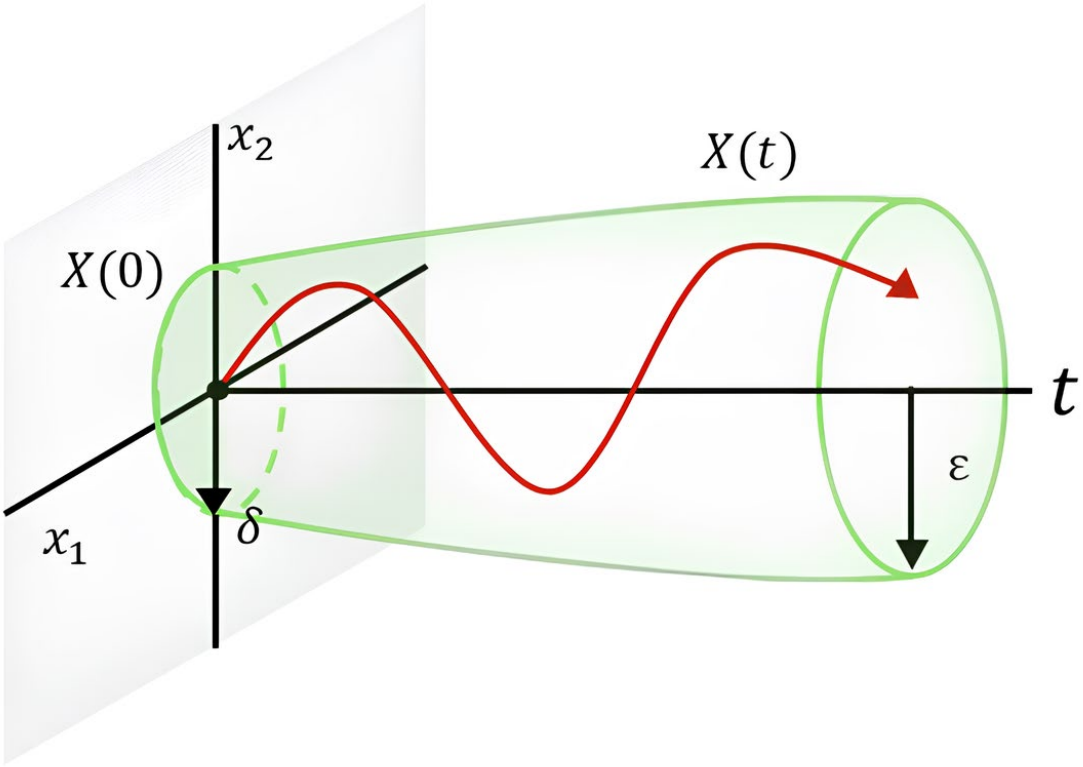

Figure 1: Stability According to Lyapunov (1950)
Source: Authors

The European Commission's "Guidance for Resilience Analysis" (2023) identifies four key dimensions of resilience, which have been adapted for the specificity of cross-border zones: absorption capacity, adaptive capacity, transformative capacity, and exaptibility. The latter concept represents a particular novelty, defining the capacity of territorial systems to use existing resources and structures to perform new functions (Kollár/Kollár 2020).
In mathematical terms, the resilience of a territorial system can be described through the concept of Lyapunov stability. A system is considered stable if small perturbations δx(t) do not lead to unbounded deviation from the equilibrium trajectory:

$$\| x(t) - x^*(t) \| \leq M \| \delta x(0) \| e^{(-\lambda t)} \quad (4)$$

where $x^*(t)$ is the equilibrium trajectory, $\lambda > 0$ is the stability coefficient, and M is the boundedness constant.

Transition to a New Resilience Paradigm for Cross-Border Zones

The application of dynamical systems theory to the analysis of border regions is justified by several key factors. Firstly, border regions represent complex adaptive systems characterized by multiple feedback loops, temporal lags, and threshold effects (Kolosov/Scott 2013). Secondly, the contemporary context requires integration of resilience and adaptive capacity (exaptibility) considerations, as provided for in the European Commission's "Guidance for Resilience Analysis" (European Commission 2023a).
The concept of exaptibility, introduced into EU methodological frameworks in 2023, is defined as the capacity of territorial systems to adapt existing resources and institutions to new functions under unforeseen challenges. This is particularly relevant for the Greater Region, where historical industrial structures have been transformed for use in the knowledge economy and green technologies.

Type of Resilience	Definition	Mathematical Expression	Examples in the Greater Region
Absorption capacity	Ability to absorb shocks without structural changes	$\int_0^{t^1} S(\tau)d\tau < Smax$	Economic stabilization after COVID-19
Adaptive capacity	Ability to modify processes in response to changes	$dA/dt = f(E, I, C)$	Transition to remote work, digitalization
Transformative capacity	Ability to carry out radical structural change	$\Delta S = T(S_0, P, t)$	Transformation of coal regions
Exaptibility	Ability to adapt existing resources for new functions	$E = \Delta F/\Delta R \times \eta$	Conversion of industrial sites

Table 2: Operationalization of Resilience Concepts in Cross-Border Zones
Source: Authors

Measuring and Managing Resilience in Cross-Border Zones

Measuring and managing resilience in cross-border zones requires an integrated approach that accounts for multiple actors, multi-level governance, and the temporal dynamics of processes. The DyTIA methodology proposes a system of Dynamic Resilience Indicators (DRI), which allows for real-time tracking of changes and provides early warning of potential systemic failures.
The resilience measurement system is based on three key principles: (1) multidimensionality––accounting for economic, social, environmental, and institutional dimensions; (2) dynamism––focus on the speed and direction of changes, not just current states; (3) adaptability––the ability of the indicator system to evolve in response to changing challenges.
The Cross-Border Zone Resilience Index (CBZRI) is calculated as a weighted sum of five subindices:

$$CBZRI = w_1 \times ABS + w_2 \times ADP + w_3 \times TRF + w_4 \times EXP + w_5 \times COH \quad (5)$$

where ABS is absorption capacity, ADP is adaptive capacity, TRF is transformative capacity, EXP is exaptibility, and COH is systemic cohesion.

Sub-Index	Definition	Key Proxy Indicators	Weight (w_i)	Weight Rationale
ABS (Absorption Capacity)	Withstanding shocks without functional disruption	• Herfindahl-Hirschman Index (inverse) • Debt-to-GDP ratio (inverse) • Gini coefficient (inverse) • Infrastructure density	0.25	Basic resilience; foundation for other capacities
ADP (Adaptive Capacity)	Modifying processes in response to changes	• Patent activity per 100K population • Share of population with tertiary education • Digital Economy and Society Index (DESI) • Administrative decision-making speed	0.30	Highest priority in rapidly changing environment
TRF (Transformative Capacity)	Fundamental-structural changes	• Share of renewable energy sources • Speed of sectoral structural shifts • R&D expenditure intensity • Entrepreneurial activity	0.20	Critical for long-term sustainability
EXP (Exaptibility)	Adapting existing resources to new functions	• Industrial site renovation • Inter-sectoral labor mobility • Renovation-to-new-construction ratio • Institutional functional adaptation	0.15	Novel concept requiring further validation
COH (Systemic Coherence)	Coordination between system components	• Cross-border flow intensity • Number of inter-regional agreements • Social capital index • Information exchange intensity	0.10	Necessary condition but not determining factor
		TOTAL:	**1.00**	

Table 3: Final Structure of CBZRI Calculation
Source: Authors

Management Level	Measurement Tools	Management Mechanisms	Time Horizon	KPI
Strategic	CBZRI, long-term trends	Intergovernmental agreements	10–20 years	CBZRI >0.75
Operational	Sectoral indices	EGTCs, regional programs	3–7 years	Growth of all sub-indices
Tactical	Project metrics	INTERREG programs	1–3 years	ROI >20%
Reactive	Early warning system	Crisis protocols	1–12 months	Response time <48 hours

Table 4: Resilience Management System in Cross-Border Zones
Source: Authors

A key innovative element is the predictive resilience management system, which uses machine learning to forecast potential crises 6–18 months before their manifestation. The algorithm analyzes patterns in 47 key indicators and identifies anomalies that may signal approaching systemic failures.
Practical application of the resilience management system is demonstrated through an analysis of the Greater Region's response to the COVID-19 pandemic. The region showed high absorption capacity (economic recovery in 14 months) and adaptive capacity (rapid transition to digital platforms), but low transformative capacity (retention of old governance structures). This allowed for the adjustment of INTERREG VI-A program priorities towards strengthening institutional integration and digitalization.
Integration of resilience principles into INTERREG programs requires revising project selection criteria, including dynamic indicators in monitoring systems, and creating adaptive management mechanisms. Under conditions of an 18.6% budget reduction, this becomes critically important for maximizing territorial impact with limited resources.

The Greater Region and Interreg Programs

The Greater Region, encompassing the territories of Wallonia (Belgium), Rhineland-Palatinate and Saarland (Germany), Luxembourg, and the northern part of Grand Est (France), represents a unique polycentric territorial system. According to cartographic data from the INTERREG VI-A program zone, the region is characterized by a high degree of functional integration.
The selection of the Greater Region as an empirical basis for this research is driven by its unique status as a "living laboratory of European integration" (European Commission 2021). In 2025, the region marked a significant 30-year anniversary (1995-2025), representing a complete cycle of cross-border cooperation evolution––from intergovernmental agreements to a complex multi-level governance system.
The Greater Region has evolved into one of the most integrated cross-border territorial systems in Europe, with daily flows of more than 270,000 cross-border workers, making it an ideal platform for testing dynamic models of territorial development (European Commission 2020). The INTERREG VI-A Greater Region program received funding of €234.6 million (with an EU contribution of €139.8 million) and underwent "field research" by the European Court of Auditors, i.e., an expert opinion based on the analysis of on-site results, which provided a robust empirical base for validating the DyTIA methodology.
Moreover, the region is representative of typical challenges present in contemporary European border territories: industrial transformation (particularly in the coal and steel regions of Saarland, Lorraine, and Wallonia), demographic changes, digitalization, and the transition to a green economy. This representativeness makes the Greater Region an ideal "living laboratory" for developing and testing innovative methodological approaches that can be scaled to other border contexts across Europe.

Territorial Unit	Area (km²)	Population (million)	Functional Integration Features
Wallonia (Belgium)	16,844	3.6	Industrial clusters, cross-border labor mobility
Rhineland-Palatinate (Germany)	19,854	4.1	Wine regions, tourist flows
Saarland (Germany)	2,569	1.0	Metallurgical industry, energy
Grand Est (France)	57,433	5.5	Logistics corridors, agro-industry
Luxembourg	2,586	0.6	Financial services, institutional coordination

Table 5: Characteristics of the Greater Region Territorial System
Source: Pigeron-Piroth et al. (2023, 22)

Main Stages of Interregional Cooperation Development

The thirty-year evolution of the Greater Region reflects broader trends in European integration and can be divided into three main periods, each characterized by specific approaches to cross-border cooperation and institutional innovations.

Period	Dominant Paradigm	Key Achievements	Challenges
1995–2005: Formation	Intergovernmental cooperation	Creation of Summit, first joint projects	Lack of legal framework, limited resources
2006–2015: Institutionalization	Multi-level governance	EGTCs, functional networks, INTERREG	Power asymmetry, initiative fragmentation
2016–2025: Systemic integration	Territorial cohesion	Climate alliances, digital platforms	Budget cuts, geopolitical instability

Table 6: Periodization of Greater Region Development (1995-2025)
Source: Authors

The first period (1995–2005) was characterized by the establishment of basic institutional structures. The creation of the Greater Region Summit in 1995 laid the foundations for political dialogue between regional governments. However, the absence of a legal framework for cross-border cooperation limited the effectiveness of initiatives. The second period (2006-2015) marked a qualitative leap in institutional development. The adoption of EU Regulation No 1082/2006 on EGTCs created the legal framework for formalized cooperation. In 2010, the EGTC “Greater Region Secretariat” was established, becoming the first EGTC without territorial competence, specializing in coordination and communication. The Secretariat of the Greater Region was created in 2013 to coordinate and support the work of the Summit and its working groups. The University of the Greater Region (UniGR) was established in November 2015 as an association incorporated under Luxembourg law. Members of this association are six universities from Germany, France, Belgium, and Luxembourg. The UniGR-Center for Border Studies started its work as an Interdisciplinary Center of Expertise of the UniGR in 2014.
The third period (2016–2025) is the current period, in which both natural and social challenges (major floods, COVID-19, armed aggression in Ukraine) have increased disproportionately. At the same time, an INTERREG V-A GR project was launched in the Greater Region to develop the UniGR-Center for Border Studies within the University of the Greater Region. This project was presented to the public for the first time at the international conference on 24 October 2018 at the University of Luxembourg. During this period, there have been nine functional areas (zones) developing the cross-border cooperation in the Greater Region: Eifel-Ostbelgien-

Éislek (EOE), Entwicklungskonzept Oberes Moseltal (EOM), Eurodistrict SaarMoselle, EGTC AlzetteBelval, Mëllerdall-Our-Südeifel (MOSE), Luxembourg-Wallonie Nord, Luxembourg-Wallonie Sud, Parc archéologique européen – Europäischer Kulturpark Bliesbruck-Reinheim, and Territoire naturel transfrontalier de la Chiers et de l'Alzette (TNT). It is the presence of these functional zones that ensures the multi-level governance of the Greater Region.

The Role of EU INTERREG Programs

Funding analysis shows the evolution of priorities in accordance with changing European policy agendas.

Program Period	Main Thematic Axis	Budget (€ million)	EU Share (%)
2000–2006	Economic development, transport	187.3	60.0
2007–2013	Innovation, environment, culture	215.6	65.8
2014–2020	Research, ecology, mobility	234.6	59.6
2021–2027	Green transition, digitalization, social cohesion	181.9	60.0

Table 7: Evolution of INTERREG Thematic Priorities in the Greater Region
Source: Official Program Site

The budget reduction in the 2021–2027 period of the European Regional Development Fund contribution is €181,942,401.00, which reflects a general trend of reduced INTERREG NEXT funding and creates additional pressure for more strategic resource use. The INTERREG programs have played a key role in transforming the Greater Region from a formal cooperation mechanism to a functionally integrated territorial system.

From Cooperation to Coordination and Comprehensive Integration

The current stage of the Greater Region development (2016-2025) is characterized by a transition from sectoral cooperation to systemic integration. This transition reflects a broader shift in European territorial cohesion policy from a project-oriented approach to strategic planning based on the concept of functional areas (zones). The shift is primarily due to the emergence of a separate regulatory framework for European territorial cooperation, the accumulation of extensive experience in implementing INTERREG projects in previous periods, and the creation of new administrative cross-border structures to expand the range of tools available for addressing the increasingly complex challenges of cross-border cooperation.
The concept of functional areas, as defined in the Territorial Agenda 2030 (European Commission 2020), played an important role in the formation of integrated management systems. This new approach involves the integration of different territorial levels around common functions and flows rather than administrative boundaries (European Commission 2020). In the context of the Greater Region, this has manifested itself in the development of cross-border functional systems (Table 8), inherited from the economic specialization of neighboring border areas. In practice, this has resulted in the creation of nine functional areas, legally established in accordance with EU regulations. Today, all administrative structures are located in a single building (La Maison de la Grande Région), which allows for rapid consultation, exchange of best practices, and planning within the framework of all Greater Region programs and projects.

Functional Zone	Territorial Coverage	Key Functions	Governing Institutions
Luxembourg Metropolitan Zone	Luxembourg, Metz, Arlon, Trier	Financial services, higher education	Metropolitan Conference
Moselle Valley	Saarland, Lorraine, Luxembourg	Viticulture, tourism, logistics	Moselle Wine Route
Industrial Corridor	Wallonia, Saarland, Lorraine	Metallurgy, chemistry, energy	Industrial Alliance
Ardennes Green Belt	Wallonia, Luxembourg, Rhineland-Palatinate	Ecotourism, forestry	Ardennes Nature Park

Table 8: Functional Zones in the Greater Region
Source: Authors

However, this integration faces the systemic challenges identified in Kiryukhin et al. (2025). This study highlights the fact that traditional statistical approaches to territorial impact assessment are unable to capture non-linear interactions between different dimensions of territorial development, particularly under conditions of reduced funding and multiple intersecting crises.

Applying the DyTIA Approach I: the Example of INTERREG in the Greater Region and Interreg Programs

Modeling Interreg Programs

Modeling INTERREG programs using the DyTIA methodology represents a new approach to understanding and predicting the territorial effects of cross-border interventions. Unlike traditional statistical models, which dominate 87% of existing programs (European Court of Auditors 2021), DyTIA offers an integrated dynamic modeling system based on the principles of complex adaptive systems theory.
The construction (creation) of cross-border interaction models within DyTIA is based on the conceptualization of the Greater Region as a multi-level network system, where each node represents a territorial unit (from municipalities to national regions) and the connections reflect various types of cross-border flows: economic, social, institutional, and environmental.
The mathematical basis of the model can be represented by a system of coupled differential equations:

$$dX_i/dt = f_i(X_1, X_2, ..., X_n, U_i, t) + \varepsilon_i(t) \quad (6)$$

where X_i represents the state of the i-th territorial unit, U_i is the vector of INTERREG policy interventions, and $\varepsilon_i(t)$ is the stochastic component reflecting unforeseen external influences.
A critical innovative aspect is the integration of the concept of exaptibility, developed in the European Commission's "Guidance on Sustainability Analysis" (2023a). In the context of INTERREG modeling, this means the ability of territorial systems to adapt existing resources and structures to new functions in the face of an 18.6% reduction in budget.
The cross-border interaction model takes into account four main types of links identified in the Greater Region: complementary (e.g., Luxembourg's financial services and Saarland's industrial production), competitive (logistics functions of Metz and Luxembourg), synergistic (cross-border research clusters), and neutral (independent functioning without significant mutual influence).

Model Level	Territorial Units	Types of Interactions	Key Parameters
Macro level	National regions (Wallonia, Saarland, etc.)	Institutional coordination	Policy harmonization index (φ)
Meso level	Functional areas	Economic flows	Density of connections (ρ), synchronization (σ)
Micro level	Municipalities, EGTC	Local partnerships	Zone of attraction (α), sustainability/resilience (r)
Nano level	Projects, initiatives	Specific interventions	Impact coefficient (β)

Table 9: Architecture of the DyTIA Cross-Border Interaction Model
Source: Authors

Spatial and Temporal Development Scenarios

The development of spatial and temporal development scenarios is a key component of the DyTIA methodology, allowing for the testing of various combinations of policy interventions and their potential territorial effects. Given the limited resources available to INTERREG NEXT (€193.1 million for the Greater Region for the period 2021-2027), scenario modeling becomes a critically important tool for strategic planning.

Scenario Type	Time Horizon	Spatial Coverage	Key Assumptions
Baseline (BAU)	2025–2030	All 5 functional areas	Current trends, no new interventions
Concentration	2025–2027	2–3 priority zones	Focusing 60% of resources on leverage points
Dispersion	2025–2030	Even distribution	Balanced development of all territories
Adaptive	2025–2035	Dynamic redistribution	Flexible response to changes in the external environment
Transformational (Exaptive)	2025–2040	Systemic reconfiguration	Radical restructuring of functional specialization

Table 10: Typology of Spatial-Temporal Development Scenarios
Source: Authors

The spatial dimension of the scenarios is based on the concept of functional zones as defined in the Territorial Agenda 2030 (European Commission 2020). In the preparatory stage for moving on to the next step of modeling the resilience of the Greater Region, taking into account the spatial dimension, we have identified five main functional areas for the Greater Region: financial and innovation (Luxembourg–Esch-Belval), industrial and logistics (Saarbrücken–Metz), tourism and culture (Moselle Valley), agriculture and ecology (Ardennes), and education and research (Belval campus–Trier). Their boundaries do not coincide with the nine functional areas that have been created, but they make it possible to prepare the necessary mathematical tools that will subsequently be applied to the real situation in the Greater Region.
The temporal dimension considers the different speeds of territorial processes: fast (economic flows, 1–3 years), medium (institutional changes, 5–10 years), and slow (socio-cultural integration, 15–30 years). This allows for the modeling of cascading effects, where short-term interventions create long-term structural changes.

Examples of Parameters: Bond Density, Synchronization Level, Zone of Attraction

Operationalizing the DyTIA methodology requires the definition of specific measurable parameters that can be used to calibrate models and monitor progress. Three key parameters—connection density, synchronisation level, and zone of attraction—form the basis for the dynamic analysis of the territorial effects of INTERREG programs.
Connection density (ρ) measures the intensity of cross-border interactions between territorial units. The parameter is calculated as the ratio of actual connections to theoretically possible connections in the network:

$$\rho = 2E / [N(N-1)] \quad (7)$$

where E is the number of actual connections and N is the number of nodes in the network.
For the Greater Region, the density of connections varies from 0.78 in the financial-innovation zone (highly integrated) to 0.41 in the agricultural-ecological zone (weakly integrated).
The level of synchronization (σ) reflects the degree of coordination between different territorial processes and political cycles. The parameter is based on a correlation analysis of a time series of key development indicators:

$$\sigma_i j = \text{corr}(X_i(t), Xj(t)) \quad (8)$$

A high level of synchronization (σ > 0.7) indicates effective policy coordination, while a low level (σ < 0.3) signals the need to strengthen integration mechanisms.
The zone of attraction (α) determines the spatial radius of influence of specific territorial interventions. The parameter is based on a modified gravitational model:

$$\alpha_i = \Sigma j \, (Mj / d_i j^2) \times \exp(-\beta d_i j) \quad (9)$$

where Mj is the "mass" of territorial unit j, $d_i j$ is the distance between units i and j, and β is the attenuation coefficient.

Parameter	Calculation Formula	Unit of Measurement	Interpretation	Threshold Values
Connection density (ρ)	$2E/[N(N-1)]$	Dimensionless (0–1)	Intensity of network interactions	ρ >0.6 - high integration
Synchronization (σ)	$\text{corr}(X_i(t), X_j(t))$	Correlation coefficient (-1.1)	Coordination of territorial processes	σ >0.7 - effective coordination
Attraction zone (α)	$\Sigma(M_j/d_{ij}^2)\times\exp(-\beta d_{ij})$	km²	Spatial radius of influence	α <50 km - regional impact
Stability (r)	$\Lambda_{max}(J)$	Dimensionless	Speed of return to equilibrium	r <0 - stable system
Exaptability (ε)	$\Delta F/\Delta R$	Functions/resources	Adaptive capacity	ε >1.5 - high adaptability

Table 11: Operationalization of Key DyTIA Parameters in the Greater Region
Source: Authors

The integration of these parameters into a single DyTIA model makes it not only possible to assess the current state of the territorial system, but also to predict the effects of various combinations of INTERREG interventions. Particularly important is the modeling of "cascade effects," when local interventions in one functional zone create chain reactions in other zones through feedback mechanisms and diffusion of innovations.

The use of these parameters for the analysis of the INTERREG VI-A Greater Region program (budget 234.6 million euros) showed that the optimal strategy involves concentrating 60% of resources on increasing the density of connections in the educational and research as well as the financial and innovation zones, which could increase the overall level of synchronization of the region from 0.52 to 0.71 by 2030.

Statistical Methods in DyTIA and Comparative Scenario Analysis

Methodology of Statistical Analysis in DyTIA

Implementation of the DyTIA methodology also requires the use of advanced statistical methods for the analysis of complex territorial interactions oriented towards retrospective (ex-post) assessment. Three key methods (cluster analysis, network analysis, and spatial econometrics) form the analytical basis for operationalizing the dynamic approach to assessing territorial impact.

Cluster analysis is used to identify homogeneous groups of territorial units by the level of cross-border integration. For the Greater Region, it is advisable to use a combination of hierarchical cluster analysis (Ward's method with Euclidean distance) and K-means clustering to group 247 municipalities using 12 integration indicators.

Network analysis models the structure of institutional links between the EGTC, regional authorities, and municipalities. Node centrality analysis allows for identifying key institutional hubs and potential points of vulnerability in the network of cross-border cooperation throughout the INTERREG program coverage area.

Spatial econometrics are used to model spillover effects between adjacent territories, which are critical for understanding the cascading impacts of INTERREG programs.

Analysis Method	Technical Specification	Application to the Greater Region	Interpretation of Results
Hierarchical cluster analysis	Ward's method, Euclidean distance	Typology of 247 municipalities	4 integration clusters: high (12%), medium (34%), low (41%), peripheral (13%)
K-means clustering	k=5, Lloyd algorithm	Functional specialization of zones	Validation of predefined functional zones
Spatial autocorrelation	Moran's I (I = 0.67, p <0.001)	Spatial concentration of effects	Significant positive autocorrelation
Network analysis	Girvan-Newman algorithm	Structure of the EGTC and inter-municipal connections	3 main communities, modularity Q = 0.43
Centrality of nodes	Betweenness, closeness, eigenvector	Key institutional "hubs"	Luxembourg: highest centrality (0.84)

Table 12: Methodology of Statistical Analysis of Territorial Systems
Source: Authors

The results of the cluster analysis revealed a distinct typology of municipalities in the Greater Region. The highly integrated cluster (12% of municipalities) is characterized by intensive cross-border flows and includes mainly municipalities along the Luxembourg borders. The peripheral cluster (13%) shows minimal cross-border activity and is concentrated in the remote areas of the Ardennes and eastern Saarland.

Network analysis of the institutional architecture reveals a polycentric structure with three main "communities": Luxembourg–Lorraine, Saarland–Rhineland-Palatinate, and Wallonia.

The modularity of the network (Q = 0.43) indicates a moderate degree of institutional fragmentation, which creates opportunities for increased coordination through INTERREG programs.

Comparative Analysis of Development Scenarios

A quantitative assessment of alternative development scenarios for the Greater Region is carried out through a multi-criteria analysis integrating economic, social, environmental, and institutional indicators. Each scenario is assessed according to 15 key performance indicators (KPI) with a planning horizon up to 2030.

Scenario	ROI (%)	Job Creation	Environmental Index	Integration Index	Implementation Time	Risk Level
Base (BAU)	12.3	+8,400	0.42	0.52	-	Low
Concentration	28.7	+15,600	0.38	0.71	3–5 years	Average
Dispersion	16.4	+12,100	0.55	0.58	5–7 years	Low
Adaptive	22.1	+13,800	0.47	0.64	4–6 years	High
Transformational	35.2	+21,300	0.61	0.78	7–10 years	Very high

Table 13: Comparative Matrix of Development Scenarios for the Greater Region
Source: Authors

The concentration scenario shows the best risk-return ratio in the short term (2025–2027). Concentrating 60% of the INTERREG budget (€115.9 million) on the education, research, and innovation zones could generate an ROI of 28.7% and create 15,600 new jobs at a moderate risk level.

The transformational scenario shows the highest potential for long-term returns (ROI 35.2%), but requires a systemic reconfiguration of the institutional architecture and is associated with very high risk. This scenario assumes the creation of a single digital governance platform, the harmonization of tax regimes, and the development of cross-border "green corridors."

A sensitivity analysis showed that all scenarios are critically dependent on three key factors: (1) the stability of the geopolitical situation (impact of ±15% on ROI), (2) the speed of digital transformation of public services (±12%), and (3) the effectiveness of coordination between national governments (±18%).

Risk Factor	Probability	Impact on Scenarios (ROI Deviation, %)	Mitigation Measures
Geopolitical instability	0.35	Concentration: -8% Transformational: -22%	Diversification of partnerships, reserve funds
Slowing down digitalization	0.28	Adaptive: -15% Transformational: -18%	Accelerated staff training, technical support
Institutional conflicts	0.42	Dispersion: -6% Transformational: -25%	Strengthening coordination mechanisms, mediation
Economic recession	0.31	All scenarios: -12% to -28%	Anti-cyclical measures, flexible planning
Climate shocks	0.24	Base: -19% Dispersion: -8%	Investments in adaptation, insurance

Table 14: Risk and Uncertainty Analysis by Scenarios
Source: Authors

The integrated assessment recommends a hybrid strategy that combines elements of the concentration (2025–2027) and adaptive (2028–2030) scenarios. This would maximize short-term results while maintaining adaptive capacity for long-term development in conditions of high uncertainty.

Empirical Testing and Validation of DyTIA

The construction of the entire DyTIA methodology platform is impossible without the first stage of assessing the sustainability of planned and approved projects within a single competition. Any asymmetry (bias) towards any of the priorities will ultimately lead to a decrease in efficiency following the results of a series of competitions or the entire program.
Based on this logic, we have developed an ex-ante tool for assessing the resilience of competitions for modeling the final cross-border effects upon their completion. This module in the DyTIA toolkit allows users to assess the pairwise trajectory of project interactions to find the resilient position at the end point of the competition task. The module makes it possible to divide the phase space (space of the development trajectory of the cross-border zone) into four zones (unstable = red, slightly stable = yellow, satisfactorily stable = light green, and stable/resilient = green).
Based on the modeling results, it is possible to estimate the overall state of the competition at the time of its completion or the integral state of a successive series of competitions for further application of the following DyTIA tools (dynamic or statistical modules). This will allow us to estimate the final balance of the entire integral sum of the volumes of cross-border utility.
The cross-border dynamical system can be described by a system of ordinary differential equations of the first order. They determine the rate of change of cross-border utility during the period of implementation of cross-border projects within the INTERREG program of the European programming period 2014-2020 from the beginning of implementation $t = t_0$ to its completion $t = T$.
The dynamic model we have developed is a system of two ordinary differential equations with two variables and one parameter. The model allows us to study the behavior of a cross-border territorial system when solving this system of equations on a plane. The variables represent accumulations of cross-border utilities during the period of the entire program or individual competitions (calls) with the possibility of assessing adaptive and exaptive resilience at the end of each time interval (an individual competition or their combination). In the basic model, the variables are the budgets of individual projects, and the parameter C is the value of accumulated cross-border utilities for the previous period.
To test the dynamic model of cross-border interaction, the project budget data for the entire INTERREG V-A Greater Region programming period were used. In fact, the INTERREG program budgets represent the armature of the entire process of cross-border interaction and, in essence, determine the effects of accumulation of cross-border utility within the framework of successive calls until the end of the programming period.
Empirical data were kindly provided by the Joint Secretariat of the EGTC Managing Authority for Interreg Greater Region Programs for all approved projects within the INTERREG V-A program. The parameter C was taken as 1 at the beginning of the program, and, as the competitions were carried out, its value increased to 1.2, 1.25, 1.27, and 1.28, respectively, which is due to the accumulation of cross-border utility (benefits) after each competition. The results obtained are presented in the figures (Fig. 3, 4, 5, 6, 7) with the corresponding matrices (Tab. 15, 16, 17, 18, 19).
In the first largest call, 36 projects were approved on all 5 axis for a total of 90,621,278.71 euros (Programme de coopération INTERREG VA France-Belgique-Allemagne-Luxembourg « Grande Région / Großregion 2014-2020 »).

In the first competition, based on the modeling results, the greatest contribution to resilience was received within the framework of Priority Axis 4 (Strengthen the competitiveness and attractiveness of the Greater Region) due to Specific Objective 10: Strengthen the presence of SMEs in the Greater Region in foreign markets in combination with Specific Objective 1: Increase employability and facilitate access to cross-border employment, Specific Objective 2: Improve sustainable mobility options to facilitate travel for cross-border workers and learners (Axis 1), Specific Objective 3: Achieve a favorable state of conservation of the natural environment, Specific Objective 4: Strengthen the cultural and tourism promotion of heritage, Specific Objective 5: Reduce the environmental impact as part of the economic and territorial development of the Greater Region (Axis 2), and Specific Objective 9: Foster the capabilities of economic-innovation stakeholders to enhance the competitiveness of the Greater Region (Axis 4).
The resilience of the INTERREG V-A Greater Region eligible area was also enhanced by the combination of Specific Objective 6: Improve the coordinated provision of care and prevention services with Specific Objective 3: Achieve a favorable state of conservation of the natural environment, and Specific Objective 9: Foster the innovation capabilities of economic stakeholders to enhance the competitiveness of the Greater Region. The remaining project combinations under specific objectives were slightly stable and satisfactorily stable. Overall, the entire competition demonstrated satisfactory stability and significantly improved access to the cross-border labor market (Fig. 2).

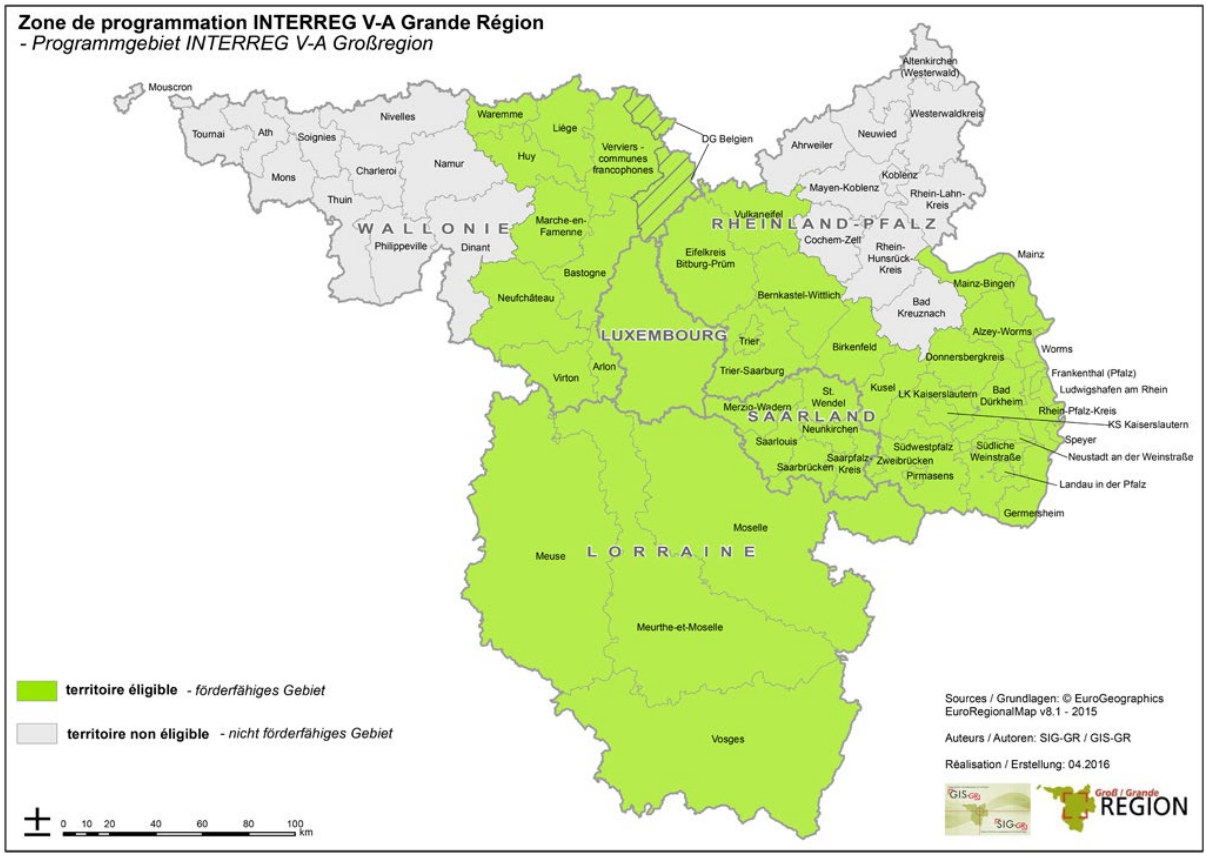

Figure 2: Programming Area of the INTERREG V-A Greater Region
Source: GIS-GR

The next four competitions demonstrated satisfactory stability, and their total budget amounted to only 58.4% of the first competition's budget. This modeling points to the need to

develop in advance a configuration of successive INTERREG program packages that are capable of mitigating and, ideally, preventing cross-border development traps and subsequently preventing their rooting in adjacent border zones.

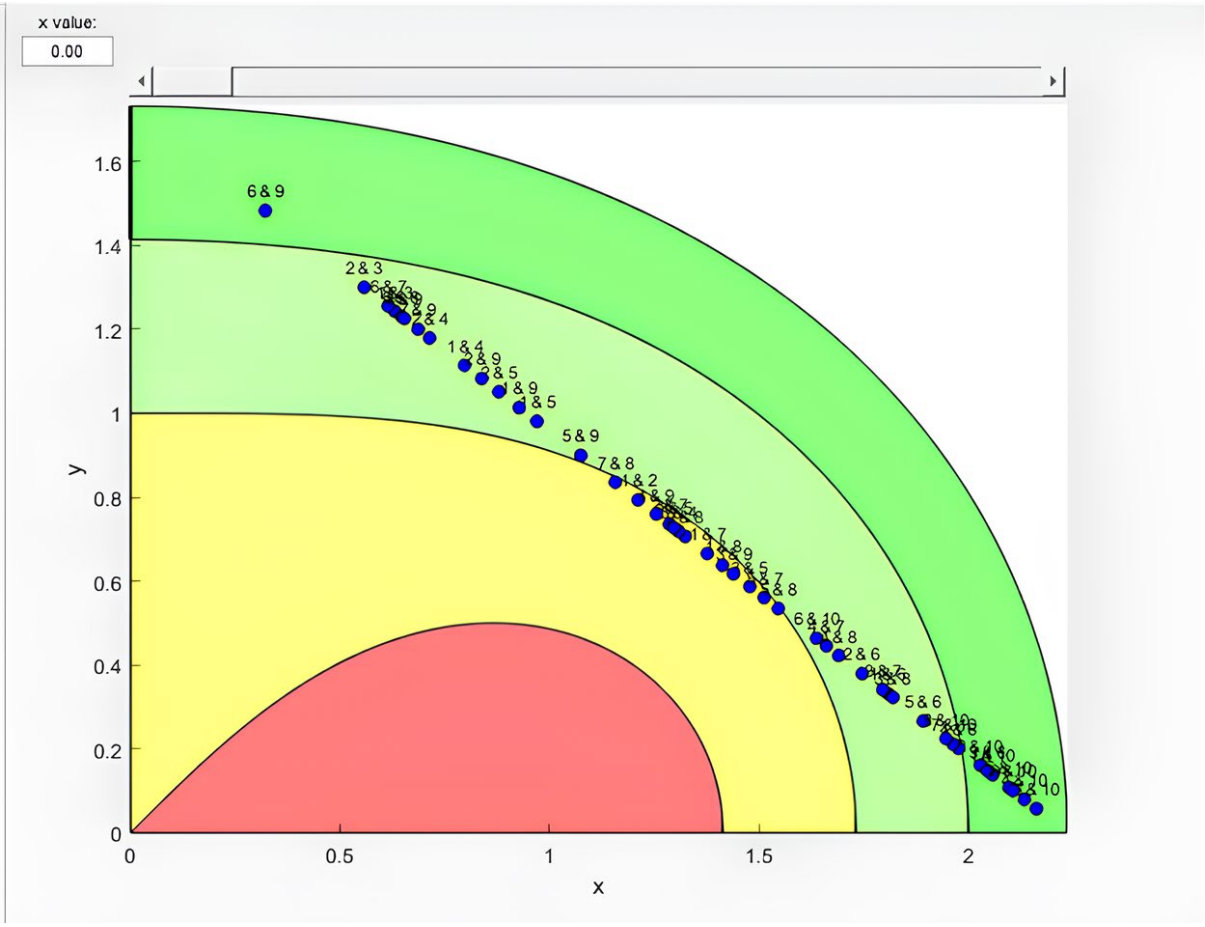

Figure 3: Call (competition) N1. C = 1

	1	2	3	4	5	6	7	8	9	10
1	0	2	3	3	3	3	2	2	3	4
2	0	0	3	3	3	3	2	2	3	4
3	0	0	0	2	2	4	3	3	2	4
4	0	0	0	0	2	3	3	3	2	4
5	0	0	0	0	0	3	2	2	3	4
6	0	0	0	0	0	0	3	3	4	3
7	0	0	0	0	0	0	0	2	3	3
8	0	0	0	0	0	0	0	0	3	3
9	0	0	0	0	0	0	0	0	0	4
10	0	0	0	0	0	0	0	0	0	0

Table 15: Zone Classification Matrix of Call N1

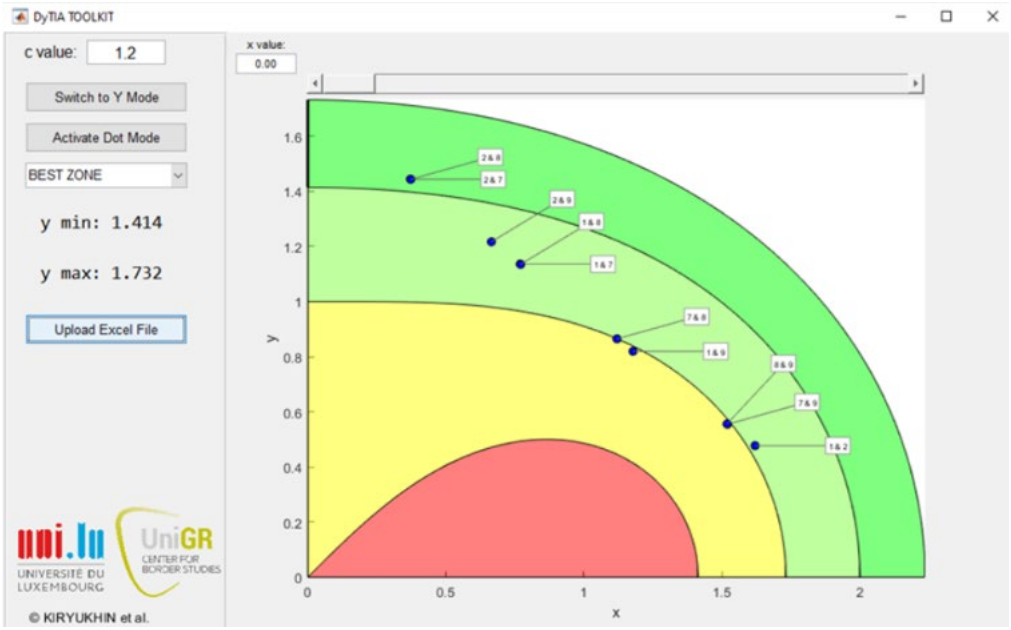

Figure 4: Call N2. C = 1.2

	1	2	7	8	9
1	0	3	3	3	2
2	0	0	4	4	3
7	0	0	0	2	2
8	0	0	0	0	2
9	0	0	0	0	0

Table 16: Zone Classification Matrix of Call N2

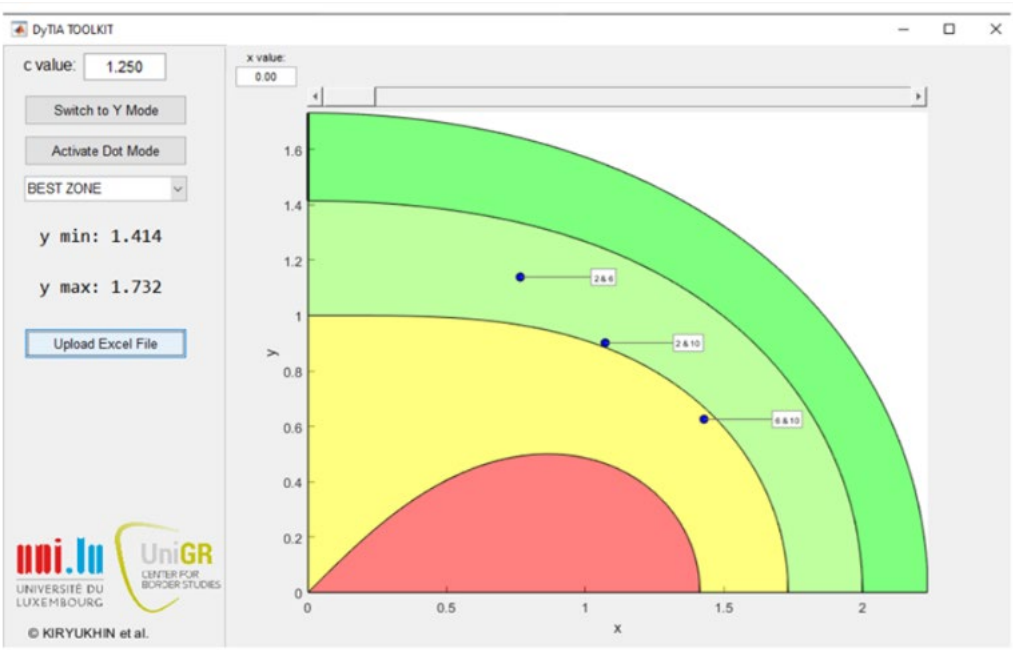

Figure 5: Call N3. C = 1.25

	2	6	10
2	0	3	3
6	0	0	2
10	0	0	0

Table 17: Zone Classification Matrix of Call N3

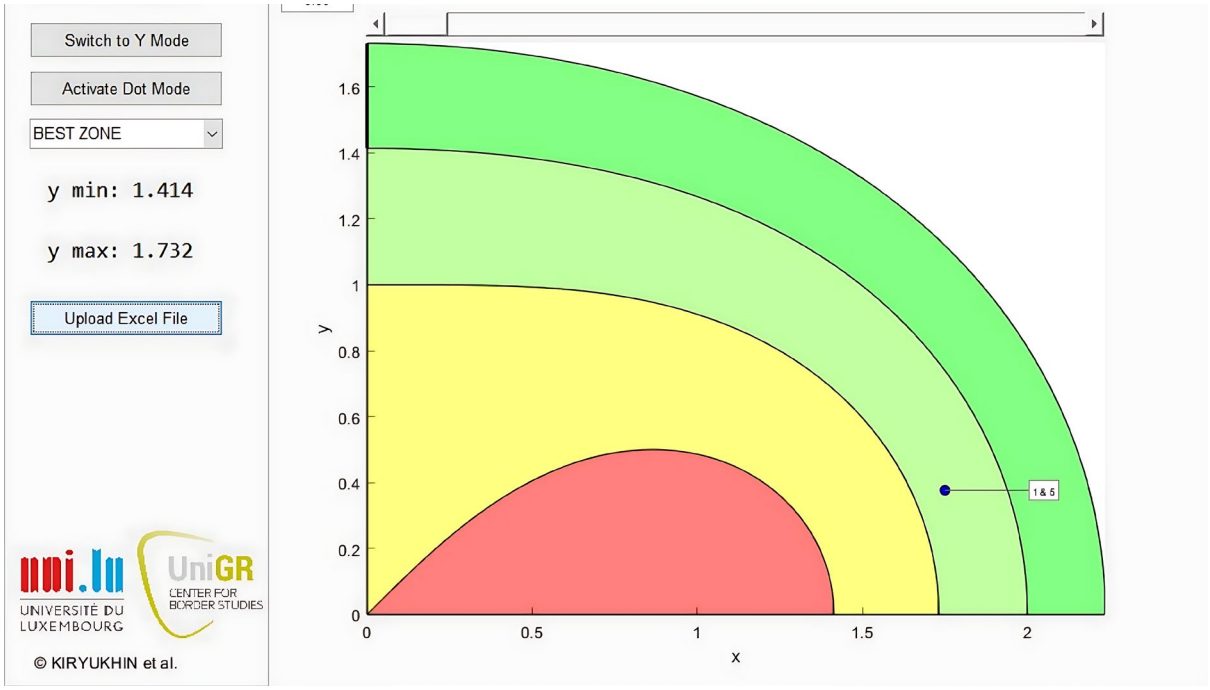

Figure 6: Call N4. C = 1.27

	1	5
1	0	3
5	0	0

Table 18: Zone Classification Matrix of Call N4

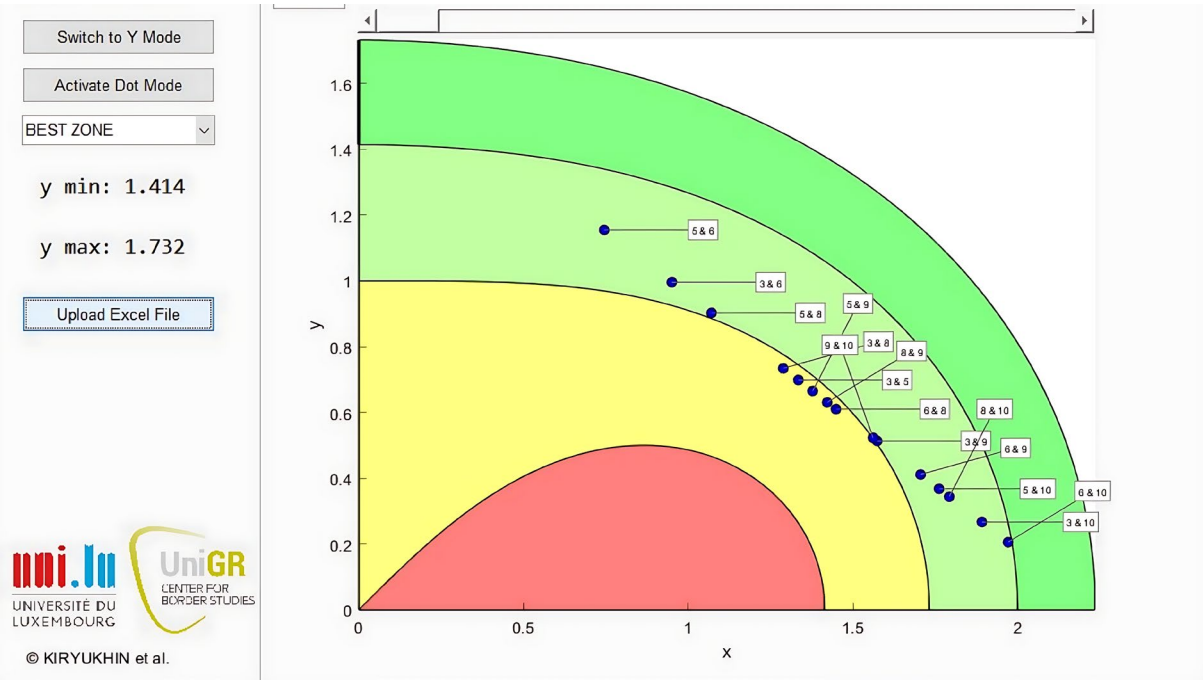

Figure 7: Call N5. C = 1.28

	3	5	6	8	9	10
3	0	2	3	2	3	3
5	0	0	3	3	2	3
6	0	0	0	2	3	3
8	0	0	0	0	2	3
9	0	0	0	0	0	3
10	0	0	0	0	0	0

Table 19: Zone Classification Matrix of Call N5

Exaptive Resilience Modeling

The turn to territorial impact assessments based on the application of dynamic systems theory requires, first and foremost, strict definitions of adaptability and exaptibility as two fundamental concepts on the basis of which dynamic models will be developed for various scenarios of the behavior of territorial cross-border systems.
Adaptability: reflects the structural conditions that enable regions to respond to shocks by enhancing their existing systems, such as improving institutional quality, diversifying their economies, and investing in foundational infrastructures.
Exaptibility: highlights the capacity that allows regions to leverage crises as opportunities for transformation. This capacity is closely tied to fluid factors such as local networks, social capital, and flexible policy environments, which make experimentation and innovation possible (Kollár et al. 2024).
The model analyzes the behavior of the cross-border system under the influence of projects during the programming period before the start of their implementation (ex-ante).

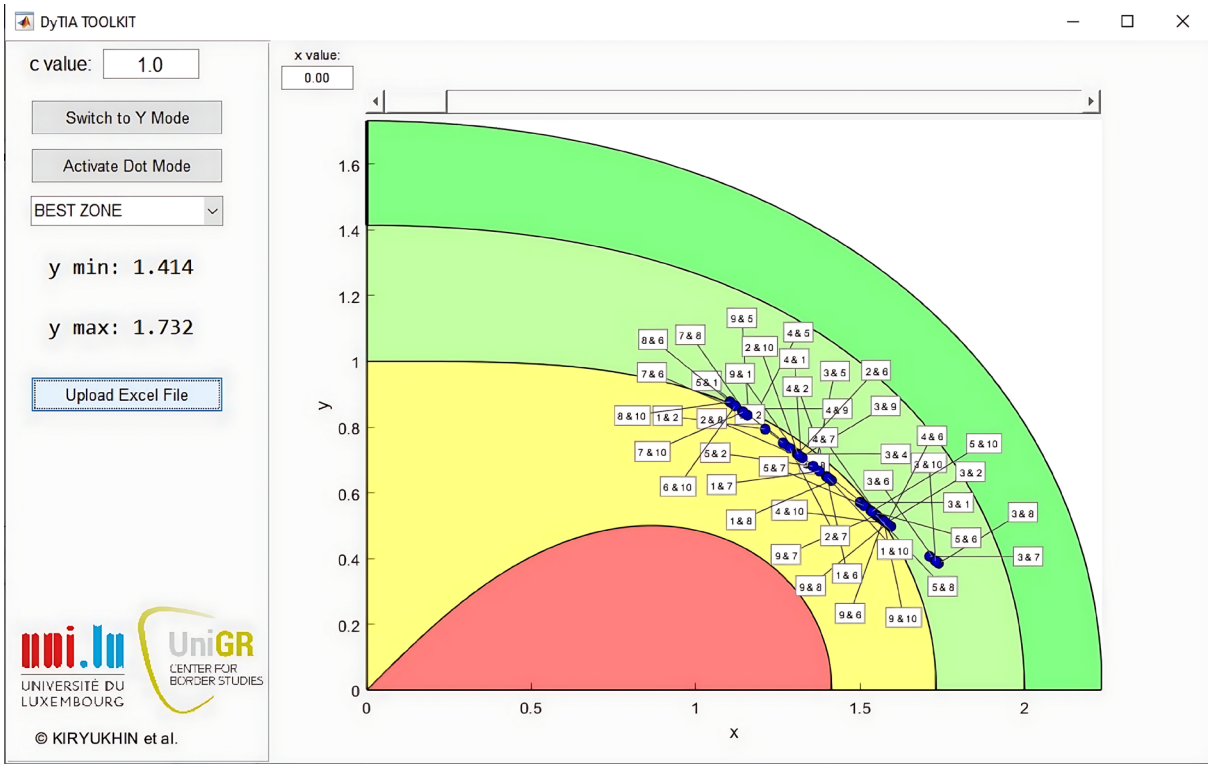

Figure 8: Call N1. C = 1.0. Redistribution of the Budget by 20%

	3	4	9	5	1	2	7	8	6	10
3	0	2	2	2	2	3	3	3	3	3
4	0	0	2	2	2	2	3	3	3	3
9	0	0	0	2	2	2	2	3	3	3
5	0	0	0	0	2	2	2	2	2	2
1	0	0	0	0	0	2	2	2	2	2
2	0	0	0	0	0	0	2	2	2	2
7	0	0	0	0	0	0	0	2	2	2
8	0	0	0	0	0	0	0	0	3	3
6	0	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0	0	0	0

Table 20: Zone Classification Matrix of Call N1 with the Redistribution of the Budget by 20%

This section models a hypothetical situation in which it is necessary to find opportunities within an already approved and allocated budget to reallocate funds to new tasks in order to mobilize and repurpose existing assets and capabilities in response to external challenges or shocks in the INTERREG program area. Data from the first call of the INTERREG V-A Greater Region program was used for the modeling. Funds were reallocated from the two largest budgets to the two smallest. Three reallocation options were considered: the first option—20% each, the second option—15% each, and the third option—10% each. The modeling was performed for the first four priority axis, including ten specific objectives.

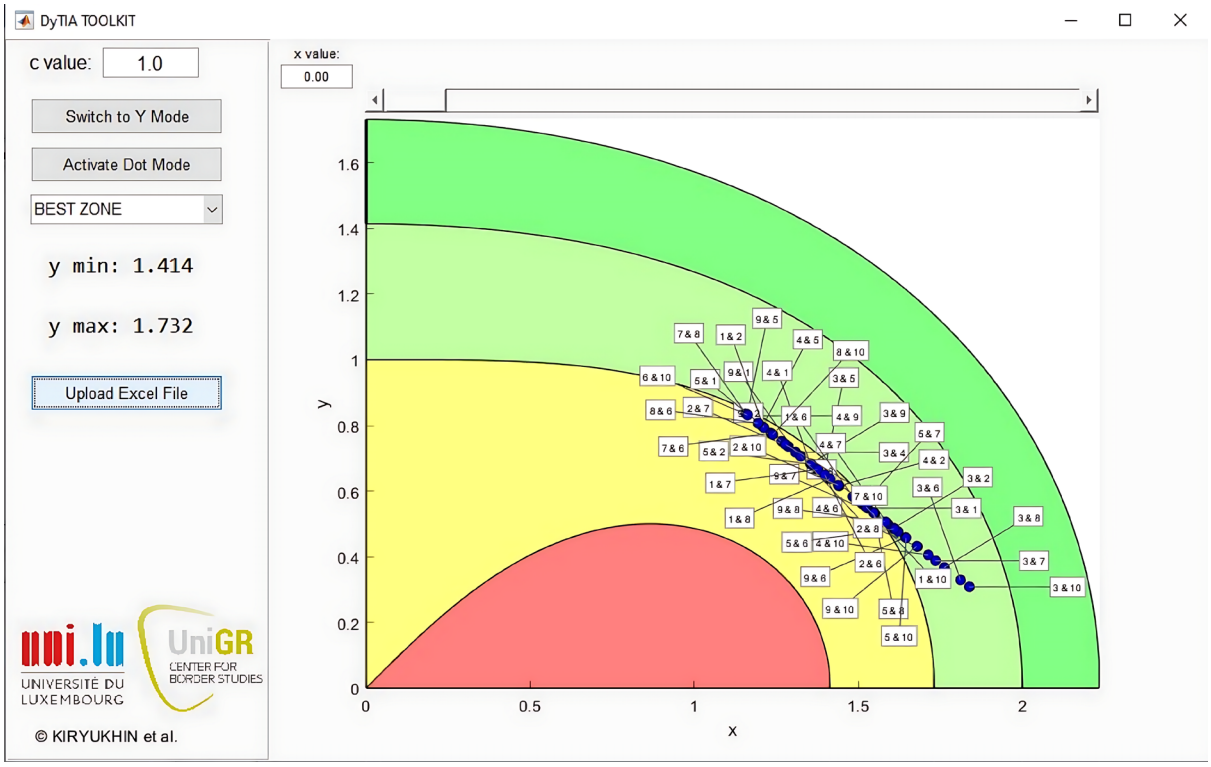

Figure 9: Call N1. C = 1.0. Redistribution of the Budget by 15%

	3	4	9	5	1	2	7	8	6	10
3	0	2	2	2	2	3	3	3	3	3
4	0	0	2	2	2	2	3	3	3	3
9	0	0	0	2	2	2	2	3	3	3
5	0	0	0	0	2	2	2	2	3	3
1	0	0	0	0	0	2	2	2	2	2
2	0	0	0	0	0	0	2	2	2	2
7	0	0	0	0	0	0	0	2	2	2
8	0	0	0	0	0	0	0	0	2	2
6	0	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0	0	0	0

Table 21: Zone Classification Matrix of Call N1 with the Redistribution of the Budget by 15%

The modeling results show that in all three cases, the overall picture of exaptive resilience is generally preserved, while the clustering of resulting points in the phase space has noticeably increased. This indicates that, despite the withdrawal of funds from the two largest budgets, a type of resulting cohesion between the specific objectives has emerged. The results obtained can be interpreted as increasing harmony within the program and reducing conflict between interest groups. In this study, a reallocation of just 10% of budgetary funds was sufficient to achieve satisfactory results for the entire program area.

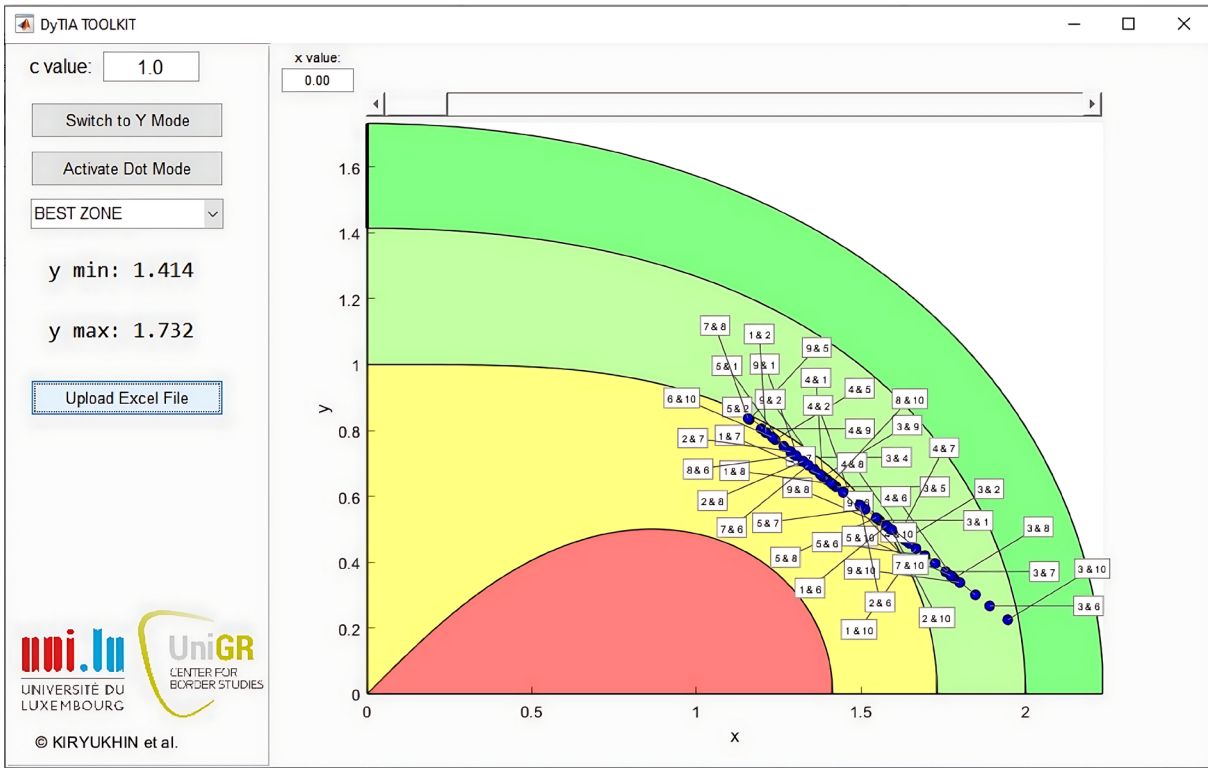

Figure 10: Call N1. C = 1.0. Redistribution of the Budget by 10%

	3	4	9	5	1	2	7	8	6	10
3	0	2	2	2	2	3	3	3	3	3
4	0	0	2	2	2	2	3	3	3	3
9	0	0	0	2	2	2	2	3	3	3
5	0	0	0	0	2	2	2	2	3	3
1	0	0	0	0	0	2	2	2	3	3
2	0	0	0	0	0	0	2	2	2	3
7	0	0	0	0	0	0	0	2	2	2
8	0	0	0	0	0	0	0	0	2	2
6	0	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0	0	0	0

Table 22: Zone Classification Matrix of Call N1 with the Redistribution of the Budget by 10%

For the INTERREG program, a particularly sensitive situation occurs when individual parts of the cross-border zone within which the program package is implemented fall into a development trap. This was particularly evident in the EGTC Alzette-Belval, due to the rapid development of the Belval University Zone, which is focused on research, innovation, and the development of an educational cluster. The French part (Lorraine du Nord) of the Greater Region gradually lost its development trajectory, with a sharp decline in economic growth and employment, partly due to the imbalance of INTERREG V-A program priorities toward creating an integrated labor market.

Discussion: Construction and Limitations of the Models

The simulation results listed above, which are based on dynamical systems theory, made it possible to assess, using real data on the budgets of completed competitions, the internal impact on territorial cross-border systems of the successive stages of the INTERREG program for the Greater Region. In general, all competitions show fairly high or acceptable resilience across all stated tasks. This indicates a fairly high quality of the projects selected and their grouping into balanced groups for each competition.

The basic resilience assessment model uses a system of differential equations on a plane, which limits the model to two variables. However, this allows for a sufficiently accurate determination of the system's behavior within the resilience domain. The model's design is optimally tailored to the range of variable values and their relationships, allowing for the determination of a specific resilience segment. This is a useful limitation of the model. Specific dynamic models aimed at specific cross-border interactions will be developed and used for subsequent DyTIA modules.

This study highlights the need to develop, in advance, a configuration of successive INTERREG packages that can mitigate and, ideally, prevent the emergence of cross-border development traps and further hinder their entrenchment in adjacent border areas.

The following section presents the conceptualization of the entire DyTIA toolkit as a flexible platform for rigorous ex-ante assessment of the impact of INTERREG program packages.

Applying the DyTIA Approach II: The Example of the Interreg Next Program in the Greater Region

The DyTIA methodology reshapes the approach to INTERREG program management through the integration of dynamic modeling at all stages of the program cycle. Unlike traditional static approaches, DyTIA offers a predictable management system, which is important in the context of growing geopolitical threats, natural disasters, and, in the future, new rules for budget redistribution in the 2028–2034 cohesion policy programs.

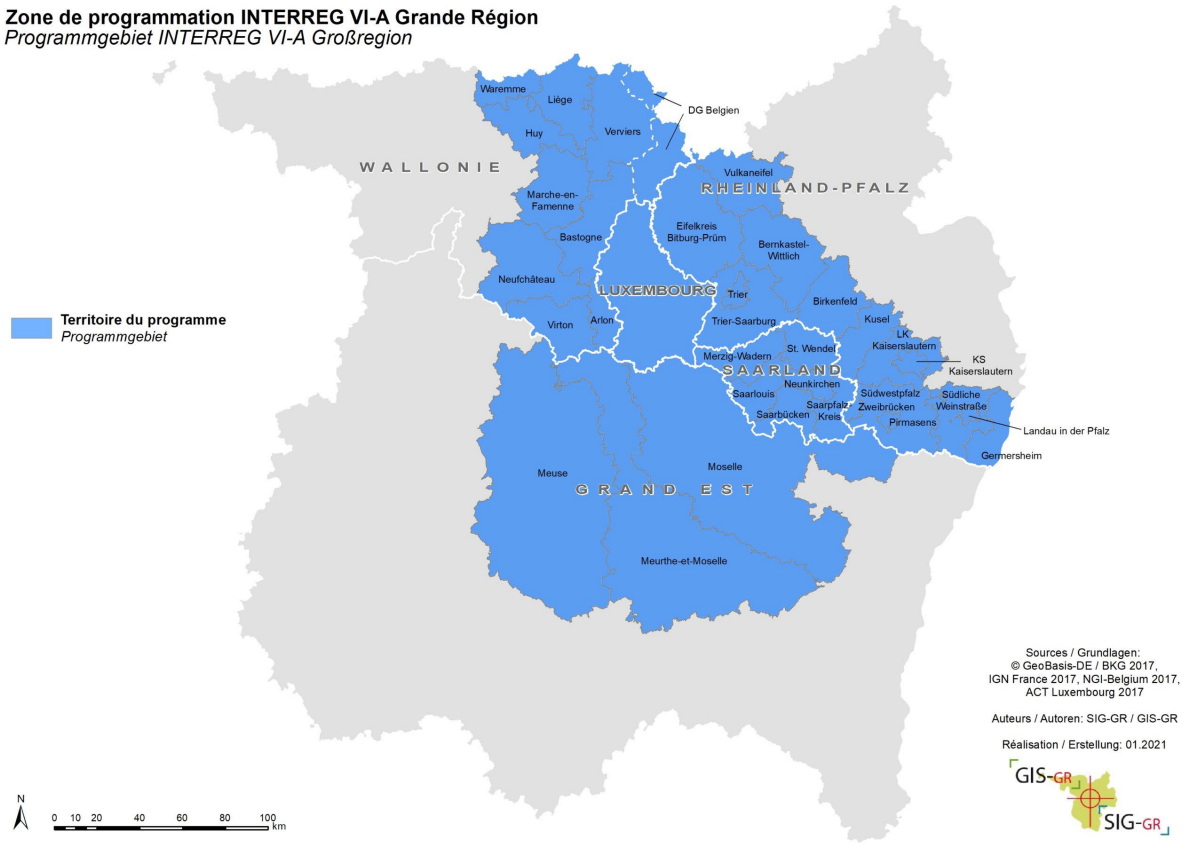

Figure 11: Programming Area of the INTERREG VI-A Greater Region
Source: GIS-GR

What Complexity and Exaptibility Mean for Cross-Border Regions in the Context of Reduced Funding

Complexity, as represented by the vertical axis in the DyTIA paradigm (Fig. 12), captures the non-linear, emergent behaviors and the adaptive potential of cross-border territorial systems. At its core, complexity theory views a territory not merely as a static collection of spatial units, but as a dynamic network of interacting agents–from institutions and communities to ecosystems and infrastructure–that co-evolve in response to internal feedback and external perturbations (Byrne 2003). Unlike traditional spatial planning approaches, which assume linear cause-effect relationships, complexity acknowledges thresholds, where small policy inputs can trigger disproportionate shifts ("tipping points") in socio-economic or environmental outcomes (Gülener 2023).

Non-linear dynamics and emergence: Territorial systems exhibit emergent properties when local interactions among actors generate patterns at the macro-scale that cannot be predicted by analyzing individual components alone. For instance, cross-border labor markets may self-organize into new commuting networks following minor adjustments in visa regulations—an outcome arising from positive feedback loops among transport, employment opportunities, and social ties. Cellular automata models, used in urban simulation, demonstrate how simple local rules can give rise to complex urban morphologies, offering planners tools to explore "what-if" scenarios under uncertainty (White/Engelen 1993; Couclelis 1997).

Feedback loops and adaptation: Complex adaptive systems (CAS) are characterized by how they reinforce (positive) and balance (negative) feedback loops that regulate system behavior over time (Holland 2019). In a border region, initiatives to harmonize environmental standards

may create reinforcing loops—heightened investor confidence fuels cross-border industrial clusters, which in turn lobby for further regulatory convergence. Conversely, balancing loops—such as community resistance to rapid development—can stabilize growth and preserve local identity. Recognizing these loops enables DyTIA to forecast time-lags and anticipate delayed responses to policy interventions.

Network structures and polycentricity: Border territories often assume polycentric network configurations, where multiple centers of governance, economic activity, and cultural identity coexist and interact. Polycentric networks enhance adaptive capacity by diversifying decision-making nodes and creating redundant pathways for resource flows, thus increasing resilience to shocks. Complexity metrics—such as network centrality and modularity—can be integrated into DyTIA's analytical toolkit to identify high-leverage nodes for targeted interventions.

Planning implications for cross-border zones: Embedding complexity in territorial impact assessments transforms ex-ante planning: rather than prescribing fixed zoning or infrastructure plans, practitioners employ scenario‐based simulations to explore a range of potential futures under varied policy mixes (Gülener 2023). DyTIA leverages this by coupling system dynamics models with real-time stakeholder inputs, fostering participatory governance and adaptive management. In doing so, the paradigm aligns with contemporary calls for planning frameworks that embrace uncertainty, harness emergent opportunities, and steer cross-border regions toward sustainable, resilient pathways (Folke et al. 2005).

Program Stage	DyTIA Tool	Specific Application	Measurable Results
Strategic planning	Scenario modeling module	Analysis of 5–7 regional development scenarios	Selection of optimal strategy with ROI +25%
Ex-ante assessment	Leverage points algorithm	Identification of 3–5 critical interventions	Concentration of 60% of resources on priorities
Project selection	Network effects matrix	Assessment of synergies between projects	Portfolio with multiplier 1.8–2.2
Monitoring	Early warning system	Detection of deviations 6–12 months ahead	40% reduction in non-performance risks
Adaptive management	Dynamic adjustment	Real-time resource reallocation	20–30% efficiency increase

Table 23: Specific Mechanisms of DyTIA Application in INTERREG VI Greater Region 2021-2027
Source: Authors

The key innovation is the "Digital Twin of the Border Region," which is a virtual model of the territorial system that makes it possible to test various project combinations before their physical implementation.

Program Cycle Stage	Traditional Approach	DyTIA Approach	Added Value
Ex-ante assessment	Statistical analysis, SWOT	Scenario modeling, resilience analysis	Predictive capability, risk assessment
Project selection	Criteria compliance	Network effects modeling	Project portfolio optimization
Monitoring	Result indicators	Dynamic trajectories	Early warning of deviations
Ex-post assessment	Achievement assessment	Systemic change analysis	Institutional learning

Table 24: Integration of DyTIA into the INTERREG Program Management Cycle
Source: Authors

DyTIA offers three key modules for integration into INTERREG program management:

- The Strategic Mapping Module makes it possible to identify leverage points in the territorial system where limited investments can create multiplicative effects. For the Greater Region, the analysis identified five critical leverage points: cross-border labor mobility, digital infrastructure, research and innovation networks, logistics corridors, and ecosystem services.
- The Exaptibility Assessment Module evaluates the capacity of territorial assets to adapt to new functions. This is particularly relevant for the Greater Region, where industrial heritage requires functional transformation.
- The Resource Optimization Module uses dynamic optimization algorithms to maximize territorial impact under budget constraints.

The concept of exaptibility, detailed in the European Commission's "Guidance for Resilience Analysis" (2023), represents a paradigmatic shift from the traditional understanding of resilience. Whilst resilience focuses on recovery after shocks, exaptibility emphasizes the capacity of territorial systems to adapt existing resources, so that they can perform new functions, which is critically important in the context of reduced INTERREG NEXT funding.
Key Exaptibility Principles According to the European Commission (2023a):

- Functional plasticity: the ability of existing structures to perform new functions without radical reconstruction
- Network adaptability: reconfiguration of existing connections for new needs
- Temporal efficiency: rapid adaptation with minimal resource costs
- Systemic integration: embedding adapted elements into new functional chains

In the Greater Region, the most successful example of exaptibility is the transformation of the Belval industrial site in Esch-sur-Alzette, where former blast furnaces have been adapted to create a university campus and research centers with investments of only €200 million versus €800 million for construction "from scratch."

Aspect	Resilience	Exaptibility
Definition	Ability to recover after shock	Ability to adapt existing resources to new functions
Temporal perspective	Short-term stabilization	Long-term transformation
Attitude to change	Resistance to change	Using change as an opportunity
Examples of the Greater Region	Recovery after COVID-19	Transformation of industrial sites into technology parks
Indicators	Recovery time, stability	Functional diversification, innovativeness

Table 25: Comparison of Resilience and Exaptibility Concepts in the Territorial Context
Source: Authors

In the Greater Region context, exaptibility manifests itself, from our point of view, in three key directions:

- Industrial transformation: Historical metallurgical complexes in Esch-sur-Alzette are being adapted for research and educational functions. The University of Luxembourg campus, located on the territory of a former industrial zone with a blast furnace complex, demonstrates successful application of the exaptibility principle.

- Digital infrastructure: Existing telecommunications networks are being adapted to support new digital services. Luxembourg is developing a "digital sovereignty" strategy, using its geographical position to create a European data processing center.
- Logistics corridors: Traditional transport routes are being adapted to support "green logistics" and the circular economy.

Accounting for the Development of Functional Zones and Their Interactions in the Greater Region

The development of functional zones in the Greater Region requires turning away from the administrative-territorial approach and moving in the direction of functional-network planning. DyTIA offers a mathematically rigorous apparatus for modeling complex interactions through graph theory, spatial econometrics, diffusion of innovation theory (DOI), and agent-based modeling.

Functional Zone	Core	Periphery	Connectivity Type	Integration Index
Financial–innovation	Luxembourg City	Esch-Belval, Metz	Hierarchical	0.78
Industrial–logistics	Saarbrücken–Metz	Thionville, Arlon	Network	0.65
Tourist–cultural	Trier–Vianden	Luxembourg, Bastogne	Polycentric	0.52
Agrarian–ecological	Ardennes	Moselle Valley	Dispersed	0.41
Educational–research	Belval Campus	Trier, Nancy	Hub-and-spoke	0.69

Table 26: Matrix of Functional Interactions in the Greater Region
Source: Authors

Mathematical Modeling of Functional Integration

DyTIA uses a modified gravity model to calculate the intensity of functional connections:

$$Fij = k \times (Pi^{\alpha} \times Pj^{\beta} \times Cij^{\gamma}) / (dij^{\delta} \times Bij^{\varepsilon}) \quad (12)$$

where Fij is the intensity of functional interaction; Pi, Pj are the functional mass of territories i and j; Cij is the function complementarity index; dij is the functional distance and Bij the border barrier effect.

Analytical Module	Methodology	Application to the Greater Region	Practical Result
Functional zone detection	Cluster analysis of flows	Identification of 12 functional zones	Functional specialization map
Connectivity analysis	Graph theory, network metrics	247 functional connections	Prioritization of infrastructure investments
Evolution modeling	Agent-based modeling	Development scenarios to 2030	Strategic roadmaps
Management optimization	Multi-criteria optimization	Distribution of €193 million budget	Maximization of functional synergies

Table 27: Operationalization of Functional Planning in DyTIA
Source: Authors

The key finding is the identification of "hidden functional corridors," which are potential integration zones not reflected in administrative divisions. For example, the Saarbrücken-Metz-Nancy corridor demonstrates high potential for industrial-logistics integration but requires coordinated investments in digital and transport infrastructure.

Type of Interaction	Mathematical Model	Application to the Greater Region
Network effects	G = (V, E), where V – nodes, E – connections	Modeling innovation networks
Game interactions	Nash equilibrium in cooperative games	Optimization of territorial resource contributions
Spatial autocorrelation	Moran's I index	Analysis of spatial diffusion of effects
Gravity models	$Fij = k(MiMj)/dij^2$	Modeling mobility flows

Table 28: Mathematical Modeling of Functional Zones in DyTIA
Source: Authors

Analysis of the Greater Region's functional zones reveals four main types of interactions:

- Complementary interactions: when functions of different territories complement each other (e.g., Luxembourg's financial services and Saarland's industrial production)
- Competitive interactions: when territories compete for the same resources or functions (e.g., competition between Metz and Luxembourg for logistics functions)
- Synergistic interactions: when joint actions create effects exceeding the sum of individual contributions (e.g., cross-border research clusters)
- Neutral interactions: when territories function independently without significant influence on each other

Functional Area	Type of Interaction	Key Actors	Optimization Potential
Research and innovation	Synergistic	Universities, research centers	High
Transport and logistics	Complementary	Ports, airports, railways	Medium
Tourism and culture	Complementary	Tourist offices, museums	Medium
Financial services	Competitive	Banks, insurance companies	Low
Industrial production	Neutral	Industrial enterprises	Medium

Table 29: Typology of Functional Interactions in the Greater Region
Source: Authors

Discussion: How to Account for the Development of Functional Zones and Their Interaction in the Greater Region

An analysis of the new regulatory documents of the European Commission (EU 2023b; EU BRIDGEforEU 2025; EU Impact Assessment Report 2025a) leads to the conclusion that there is a gap between the methods used to assess territorial impact based on statistical data using the relevant mathematical statistics apparatus and the new procedural vision set out in these documents. The transition to impact assessments that consider the territory in its inherent dynamics must naturally be supported by appropriate new tools. Such a transition should not be abrupt, but should take into account the experience gained from previous programming periods. The complementarity and combination of statistical and dynamic tools is the best way to achieve the objectives set.
Ultimately, the DyTIA methodology is aimed at smoothing contradictions between two key prescriptions of Cohesion Policy—the competitiveness narrative and the socio-spatial cohesion narrative in cross-border territorial zones under the influence of the INTERREG program. This can only be achieved through a balance between competitiveness and territorial cohesion, as key processes (trajectories) of European cohesion policy are already at the current stage in the neo-Lisbonization phase (Molica et al. 2025). The introduction of new concepts

of adaptability and exaptibility, which reflect a new level of perception of cross-border territorial systems, must be supported by the appropriate combination of tools.
To achieve this goal, it is necessary to assess ex-ante (preliminarily) the resilience under the influence of INTERREG NEXT programs, as the only programs that simultaneously affect both processes.
Therefore, this methodology becomes a mandatory toolkit for the next programming period 2028–2034, in which shocks and challenges will become permanent attributes of Europe's socio-economic processes.
A clear example of bias toward competitiveness within the Greater Region is the development of Luxembourg, which has attracted growing flows of cross-border workers, thereby ensuring increasing territorial disproportions throughout the cross-border formation. Therefore, the DyTIA paradigm contains three tools for assessing the state of cross-border zone dynamics: resilience, innovation diffusion, and convergence. Within this toolkit, two parallel processes are evaluated: exaptibility and complexity, as a smoothing reaction and maintenance of sustainability through the redistribution of already allocated resources to new challenges, which are reflected in complexity dynamics (Fig.12).
In the new programming period 2028–2034, such a configuration of the DyTIA methodology will be aimed at creating a platform that combines dynamical and statistical tools for analyzing the impact of INTERREG programs on border zones—the "territorial laboratories" of European integration.

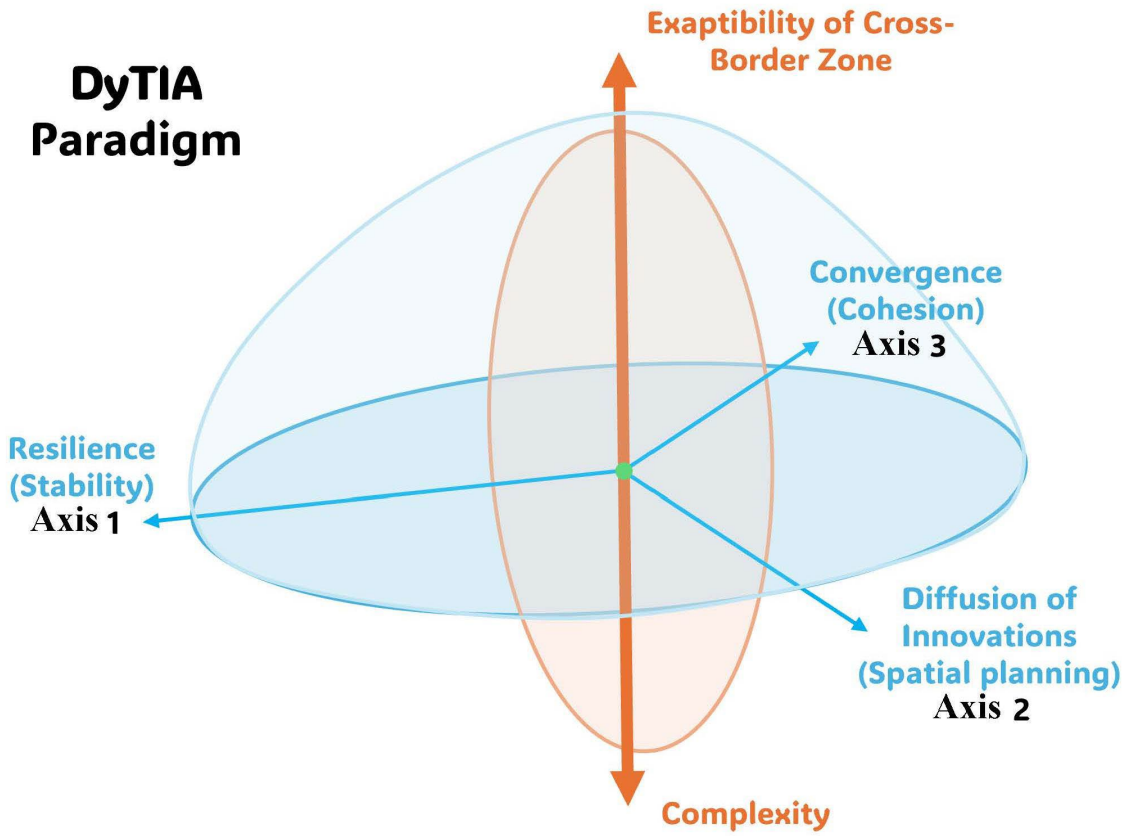

Figure 12: DyTIA as a New Paradigm of Cross-Border Development in the Greater Region
Source: Authors

Geopolitical, climatic, and migration challenges have necessitated a review of traditional approaches to assessing the impact of European Commission integration programs, in particular INTERREG programs, with a focus on making them more effective.
This implies a shift from the existing paradigm of evaluating completed programs based on post-ante statistical approaches to new principles based on modeling the future effects of implementing these programs.
This vision will ensure a rational focus on the most important and sensitive issues that have the greatest positive and negative effects on the territorial development of cross-border areas.
The approach presented in this document involves implementing a combination of both statistical and new dynamic assessment methods that evaluate future effects within the framework of existing programs.
The central issue in this methodology is the resilience of cross-border systems under the influence of INTERREG programs.
The most suitable instruments for implementing this approach are EGTCs, which are focused, by their nature, on achieving real results.
The development of the DyTIA methodology along three axis (resilience, spatial planning, and convergence), taking into account complexity and exaptability, is geared towards the EU Cross-Border Platform's need for new instruments both at the end of the current programming period and, in particular, during the next European programming period 2028–2034.
The document COM (2025) 565 final (European Commission 2025a) identifies at least two key issues that coincide with the methodological challenges addressed by DyTIA:
Issue 1: The high administrative burden is consistent with the concept of simplification embedded in the DyTIA architecture. The document notes the management of "close to 540 EU programs with nationally pre-allocated envelopes" (p. 8), which creates a complexity that DyTIA aims to reduce through an integrated approach to evaluation.
Issue 2: Responding quickly to emerging needs is central to the dynamic approach of DyTIA. The document's criticism of the static nature of existing instruments ("these flexibilities were not built into the design of these programs", p.10) fully validates the need for an ex-ante methodology based on dynamical systems theory. Critical intersections where DyTIA can offer concrete solutions to the problems diagnosed by COM (2025) 565 final (European Commission 2025a) include:

- Ex-ante analysis: Repeated references to the need for ex-ante assessment of effectiveness are in line with the proactive orientation of DyTIA.
- Cross-border specificity: The focus on cross-border projects and mechanisms (EGTC, IPCEI) coincides with DyTIA's specialization in border areas where different administrative cultures meet.

Strategic opportunities for DyTIA:
"Windows of opportunity"
- Crisis of effectiveness: The EC document effectively acknowledges the failure of the existing approaches, which creates a policy window for innovative methodologies.
- Ukrainian context: The focus on the external borders of the EU and the need for innovative approaches to integration creates a unique niche for DyTIA, especially in the context of the EGTC Tisza case.

Potential entry points:
- Pilot program for external borders: using DyTIA to evaluate cooperation programs with Ukraine and other neighboring countries
- Integration into ex-ante evaluation procedures: including DyTIA elements in mandatory evaluation procedures for new programs (2028–2034)

- Specialization in cross-border projects: positioning DyTIA as a specialized tool for IPCEI projects and interregional cooperation

An analysis of the compatibility of DyTIA with the issues outlined in COM (2025) 565 final indicates high conceptual relevance, while simultaneously raising operational barriers.

Positive factors:
- Problem relevance: DyTIA addresses precisely those problems that the EC considers critical.
- Methodological innovativeness: It offers solutions that are missing from the current EU toolkit.
- Political window of opportunity: The efficiency crisis creates demand for new approaches.

Limitations:
- Institutional inertia: Existing procedures and interests create barriers to implementation.

Strategic recommendation:
DyTIA should not be positioned as a universal replacement for existing methodologies, but as a specialized tool for:

- Cross-border cooperation (especially at the EU's external borders)
- Innovative pilot programs
- Ex-ante evaluation of complex multi-sector projects in the implementation of Territorial Exaptive Resilience in regions with lagging levels of development.

Final Remarks and Recommendations for Action

This research has presented the theoretical foundations and practical potential of the Dynamical Territorial Impact Assessment (DyTIA) methodology, aimed at improving approaches to assessing territorial effects of cross-border cooperation programs in European Union border regions. The research has yielded several important conclusions and practical recommendations, whilst also identifying promising directions for further research.
Critical analysis of existing Territorial Impact Assessment (TIA) tools revealed their fundamental limitations, related to the predominantly static nature of their assessment, their orientation towards retrospective analysis, and insufficient consideration of complex systemic interactions in border regions. These limitations become particularly problematic in the context of the 18.6% INTERREG NEXT budget reduction for the 2021–2027 period, requiring more strategic and efficient use of limited resources.
The DyTIA conceptual model that has been developed offers a qualitatively new approach based on dynamical systems theory and integrating economic, social, environmental, and institutional dimensions of territorial development. The key features of this model lie in its focus on identifying feedback mechanisms, temporal lags, threshold effects, and network interactions, allowing for more adequate reflection of the complex dynamics of border regions.
Testing the DyTIA methodology on INTERREG V-A program data and the Greater Region experience demonstrated the potential of this methodology for revealing complex chains of territorial effects, uncovering "leverage points," and optimizing resource allocation under budget constraints. Of particular value was the analysis of the interaction between different thematic objectives, revealing synergistic effects between investments in environmental protection (TO 6, 23.2% of the budget) and sustainable economic development.

Research Contribution

The theoretical contribution of this research lies in several key aspects. Firstly, the work represents the first systematic attempt to apply dynamical systems theory to the analysis of territorial effects in border regions, opening up new possibilities for understanding complex spatio-temporal processes under conditions of European integration.

Secondly, the research develops the conceptual foundations of "new regionalism" through the integration of resilience and exaptibility concepts proposed in the European Commission's "Guidance for Resilience Analysis" (2023). The operationalization of these concepts through the Cross-Border Zone Resilience Index represents a methodological innovation in territorial studies.

Thirdly, the work contributes to the development of functional regions theory through mathematical formalization of functional connections and the development of algorithms for their measurement. The identification of five functional zones in the Greater Region with different integration levels demonstrates the practical applicability of theoretical concepts.

The methodological contribution lies in creating an integrated toolkit combining quantitative methods (cluster analysis, network analysis, spatial econometrics) with qualitative approaches (scenario planning, systems mapping). This makes it possible to overcome the traditional divide between economic-statistical and spatial-planning approaches to territorial development analysis.

Below, we briefly outline considerations on the practical application of the proposed methodology for three groups of users:

- For program analysts: DyTIA integration should begin with the strategic mapping module, which makes it possible to identify key leverage points in the territorial system. Creation of "digital twins" of border regions for testing various development scenarios is recommended.
- For policymakers: DyTIA provides tools for strategic planning under conditions of uncertainty. The use of the exaptibility analysis module for assessing the transformation potential of existing territorial assets is particularly important.
- For researchers: The DyTIA methodology opens up new opportunities for interdisciplinary research at the intersection of regional economic, political science, and systems analysis.

Advice for Analysts and Policymakers

Implementation of the DyTIA methodology in territorial planning and policy analysis practice requires a systematic approach, accounting for both technical aspects of the methodology and institutional conditions for its application. For INTERREG program analysts, it is recommended to begin DyTIA integration with the strategic mapping module, which provides the means for identifying key leverage points in the territorial system and creating "digital twins" of border regions to test various development scenarios.

Target Group	Recommendations	Timeframe	Expected Results
INTERREG program analysts	Integration of DyTIA modules into ex-ante assessment procedures	6–12 months	25–30% increase in predictive accuracy
Regional planners	Use of scenario modeling for strategic planning	12–18 months	Resource allocation optimization
EGTC managers	Application of exaptibility analysis for project planning	3–6 months	Increased project innovativeness
Policy analysts	Monitoring of dynamic resilience indicators	Ongoing	Early warning of systemic risks

Table 30: Practical Recommendations for DyTIA Implementation
Source: Authors

We recommend policymakers use DyTIA as a strategic planning tool under conditions of uncertainty, in particular by applying the exaptibility analysis module to assess the transformation potential of existing territorial assets. The experience of transforming the Belval industrial sites demonstrates the practical value of this approach.

For researchers, the DyTIA methodology opens up opportunities for interdisciplinary research at the intersection of regional economic, political science, and systems analysis. Particularly promising is the development of predictive analysis modules using machine learning to forecast territorial crises 6–18 months before their manifestation.

In the context of Ukrainian European integration, DyTIA offers particularly valuable tools for planning the recovery and development of border regions. The Greater Region experience demonstrates that successful territorial integration requires not only financial resources but also sophisticated methodological approaches capable of reflecting the complexity of contemporary territorial systems.

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