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Design of a Composite Geospatial Model for Assessing Territorial Stability

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Abstract

Assessment of the operational environment for military operations planning increasingly requires, alongside physical terrain evaluation, the systematic integration of socio-economic, institutional, and security-related data into coherent analytical frameworks. Traditional geopolitical and regional analyses often treat these dimensions separately, limiting the capacity to evaluate territorial stability as a multidimensional and spatially differentiated phenomenon. This contribution introduces the Socio-Economic Area Stability (SEAS) model, conceptualized as a geospatial composite index designed to quantify territorial stability through the structured synthesis of heterogeneous spatial indicators. The model builds upon principles of composite indicator construction and geospatial data modelling grounded in ISO 191XX standards, transforming conceptual socio-geographical structures into a spatially explicit analytical framework. Investigation results confirm that the proposed index architecture is internally coherent, theoretically grounded, and structurally compatible with multi-source spatial datasets.

KEY WORDS: *composite index, territorial stability, geospatial modelling, socio-economic analysis, spatial aggregation*

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1. Introduction

The contemporary security environment is characterised by increasing complexity and the blurring of boundaries between military and non-military threats, which raises the demands placed on analytical support for planning processes [1]. Military planning therefore requires the operational environment to be interpreted not merely as physical space, but as a dynamic socio-geographical system in which economic, institutional, and security factors operate simultaneously [2]. Doctrinal approaches to intelligence preparation of the operational environment, such as Joint Intelligence Preparation of the Operational Environment (JIPOE) [3], conceptually assume this broader perspective. In practice, however, they encounter a methodological challenge: the systematic and quantitative integration of heterogeneous data into an analytically coherent picture that can be used for decision-making and planning.

This paper presents the design of the Socio-Economic Area Stability (SEAS) model, i.e., a geospatial composite index intended to support military planning processes at the operational to strategic levels by quantifying territorial stability. The model responds to fragmented assessment of individual dimensions of the operational environment by integrating socio-economic, institutional, and security indicators into a single, multidimensional, and spatially differentiated analytical framework [4]. SEAS is constructed on the principles of composite indicators (selection and justification of indicators, normalisation, weighting, and aggregation logic) and decomposes territorial stability into three complementary components: the *Economic Strength Index (ESI)*, the *Institutional Integrity Index (III)*, and the *Security Instability Index (SII)*, which are subsequently integrated into a single index via a weighted synthesis.

This contribution is conceived as a methodological-conceptual intermediate step between conceptual modelling of socio-geographical data and the planned geoinformatics operationalisation in a GIS environment. Its aim is not to present a final implementation workflow or cartographic outputs, but to formalise the architecture of the model and to define the conditions for its future implementation and testing across different territorial concepts.

Although SEAS is primarily targeted at supporting operational planning, its architecture is designed to be scalable to strategic assessments of the security environment as well, particularly for the spatial identification of regions with structural instability and elevated crisis potential. The structure of the paper subsequently presents the methodological and theoretical framework, specifies the SEAS model architecture and its components, discusses limitations of the proposed design (including sensitivity to the weighting structure and the definition of aggregation unit), and outlines directions for further research.

2. Methodology and theoretical framework

This subsection delineates the methodological and theoretical framework for the SEAS model design and clarifies the relationship between the data and computational layers of the solution. The proposed conceptual model of socio-geographical data serves here as a data architecture intended for implementation in a geodatabase environment (i.e., it defines domain classes, attributes, and relational logic) [5], while SEAS builds on this data substrate as a geoprocessing analytical model that specifies, over future data stored within this structure, the computation of partial components and the resulting composite stability index. In this paper, a geoprocessing analytical model is understood as a reproducible workflow consisting of spatial analytical operations performed on geodata, regardless of the software platform used for implementation [6].

The methodological approach applied in this work is based on a combination of abstraction, systems analysis, formalisation, and structured modelling, enabling the creation of a formally specified and reproducible construction of a composite geospatial index. These methods are complemented by a methodological synthesis whose purpose is to connect the principles of composite indicators with the logic of geospatial modelling so that the resulting specification is ready for subsequent operationalisation in GIS.

For the construction of both partial and final indices, min-max normalisation and subsequent weighted synthesis are considered. For the institutional component, a multiplicative aggregation is theoretically specified, aiming to reduce compensatory effects among partial indicators and to emphasise their mutual interdependence. At this stage, the choice of weights is understood as expert parameterisation and is deliberately left open for subsequent sensitivity and validation analyses.

The theoretical framework is further complemented by principles of conceptual modelling of geographic information and interoperability of data structures. The proposed data architecture emphasises semantic unambiguity, consistency of classes and attributes, and implementability in GIS [7], so that for each indicator it is possible to unequivocally determine its data origin (class, relevant attributes, and computational operation) and thereby ensure a traceable and semantically consistent selection of variables. Conceptual modelling thus provides a semantic anchor for defining indicators and assigning them to individual index dimensions, supporting consistency between the conceptualisation of the domain, the data structure, and the subsequent computational specification.

3. SEAS architecture: formal definition and integration logic

The SEAS model architecture is based on the principle of multidimensional spatial synthesis, in which heterogeneous data layers with different topology and attribute structures are transformed into a unified index space through aggregation, normalisation, and weighted integration [4]. In this way, the model aligns with the requirements of the doctrinal JIPOE framework, within which it represents a specific tool for quantifying and visualising the Security Environment Assessment dimension in connection with PMESII-ASCOPE methodological frameworks [3].

The conceptual architecture of SEAS builds on a conceptual model of socio-geographical data that structures real-world objects of the environment into three thematic packages: *EconomyStructures*, *PoliticalStructures*, and *MilitaryStructures*. These packages form the data substrate for the three partial components of the model: the *Economic Strength Index (ESI),* the *Institutional Integrity Index (III),* and the *Security Instability Index (SII).* The integration of these components into the final index is defined by an explicit integration scheme of a composite index based on weighted synthesis. The formal definition of the final index is expressed as a weighted linear combination of the partial components:

$$SEAS_i = \alpha \cdot ESI_i + \beta \cdot III_i + \gamma \cdot (1 - SII_i), \qquad (1)$$

where *i* denotes the assessed spatial unit of analysis for which the indicators are aggregated. At the current stage of the model, the unit is considered in general terms, and its specific delineation is subject to subsequent operationalisation. The coefficients α, β, γ represent the weights of the individual components, subject to the condition $\alpha + \beta + \gamma = 1$. The weighted linear combination method is regarded in geoinformation sciences as a standard approach for multi-criteria analysis [8].

4. Construction of SEAS component models (ESI, III, SII)

The *Economic Strength Index (ESI)* is a spatial composite indicator that integrates the structural characteristics of economic activity within the assessed spatial unit *i*. It is defined as a weighted combination of partial indicators expressing the intensity, diversity, and significance of economic structures, optionally complemented by a proxy indicator of real activity. Input variables are derived from the thematic package *EconomyStructures* of the proposed conceptual model, specifically from classes and attributes representing economic entities, their sectoral classification, and significance characteristics that can be aggregated to the level of the assessed unit. In general, ESI_i can be expressed as a weighted combination of partial indicators:

$$ESI_i = \lambda_1 \cdot D_i + \lambda_2 \cdot DIV_i + \lambda_3 \cdot SV_i + \lambda_4 \cdot NTL_i, \quad (2)$$

where $\lambda_k \geq 0$ and $\Sigma\lambda_k = 1$.

The individual partial indicators entering the *ESI* construction are characterised as follows:

1. *Intensity of economic activity* D_i expresses the spatial concentration of economic entities in unit *i*. In its basic form, it is defined as the density of economic facilities relative to the size of the unit. To increase informational value, D_i can be generalised to a weighted density, for example, by size, type, or importance, thereby distinguishing ordinary economic infrastructure from elements with a higher systemic role.
2. *Diversity of economic structure* DIV_i captures whether and how economic activity is distributed across sectors. Diversification reduces territorial vulnerability to shocks and increases regional adaptability [9][10]. Practically, it can be defined as the complement of a concentration measure based on sectoral shares within unit *i*. For quantifying diversity, the Herfindahl-Hirschman Index (HHI), commonly applied in regional economics and the geography of production systems [11], is proposed. DIV_i is higher when economic entities are not concentrated in a single sector but are distributed across sectors. Where relevant entity attributes are available, sectoral shares can be modified by a weighting function that accounts for differences in the strategic importance of individual structures within the assessed unit.
3. *Strategic significance* SV_i represents an aggregated measure of the significance of economic structures with respect to their strategic contribution (e.g., criticality for logistics, industry, or key services). Formally, SV_i may be expressed as a weighted average of strategic scores assigned to entities in unit *i*.
4. Proxy indicator NTL_i uses satellite night-time lights data to spatially approximate economic activity and energy use [12]. For spatial unit *i*, it can be defined as the mean (or sum) radiance within the unit, optionally area-normalised. In the model, NTL_i is understood as a complementary indicator capturing real economic activity.

The *Institutional Integrity Index (III)* expresses the degree of integrity of the institutional arrangement within the assessed spatial unit *i*. It is based on two complementary dimensions: institutional presence and the quality of institutional capacities, and the coherence of control and affiliation. These dimensions are designed to distinguish situations where a relatively extensive institutional network exists without coherent power execution from situations where control is coherent, but institutions are weak or sparsely represented. Indicators of the *III* component build on the thematic package *PoliticalStructures* of the proposed conceptual model, from which variables are derived describing institutional elements, their quality or integrity, and control or affiliation ties necessary for constructing the dimensions IF_i and CAC_i. Both dimensions constitute independent yet mutually contingent components of institutional stability. Strong institutional presence without unified governance, as well as a loyal but weakened administrative system, cannot on their own ensure the stability of the operational environment. The proposed multiplicative aggregation ensures that a low value in either component markedly reduces the overall index outcome. This yields non-compensatory behaviour, which is appropriate for indicators whose components are not substitutable and whose effects are synergistic [13]. In general terms, the multiplicative aggregation of the partial dimensions into *III* can be expressed as:

$$III_i = (IF_i)^{\alpha} \cdot (CAC_i)^{\beta} \quad (3)$$

The individual indicators entering the construction of *III* are as follows:

1. *Institutional Footprint* IF_i expresses the extent, spatial distribution, and functional quality of institutional elements. The indicator captures not only the number of institutional nodes but also their relative importance and integrity; it is therefore conceptualised as an area-normalised aggregation of institutional elements with the possibility of weighting by type, function, or performance quality. Area-normalised aggregation is defined as expressing the aggregated value of a phenomenon within the assessed spatial unit (a vector zone or a raster region) as an areal density, i.e., as the count or weighted sum of relevant elements referenced to the area of that unit. Higher values of *IF* correspond to higher institutional capacity and the ability to secure basic administrative, control, and service functions in the territory. Such a territory is associated with stronger preconditions for stable civil-military engagement, the sustained conduct of operations, and the provision of a support base for logistical and enabling activities [3].
2. *Control & Affiliation Coherence* CAC_i captures the degree of unity of the institutional structure in terms of power execution and affiliation to a dominant authority [14]. The indicator expresses the extent to which institutional elements in spatial unit *i* are consistently controlled by a single actor, or conversely, the degree to which the institutional environment is fragmented among multiple competing authorities. High values of *CAC* correspond to high coherence and low institutional fragmentation, whereas low values indicate fragmented power execution or the existence of parallel structures [3].

The *Security Instability Index (SII)* expresses the degree of security instability within the assessed spatial unit *i* and captures both structural and dynamic aspects of the security environment. The *SII* component is designed to distinguish spaces with a long-term elevated security burden resulting from the presence of armed actors and strategically significant security elements from spaces where instability is driven primarily by the current dynamics of security events. Indicators of the *SII* component build on the thematic package *MilitaryStructures* of the proposed conceptual model, from which variables are derived describing security-relevant presence and the spatio-temporal record of events with security impact.

SII is based on two complementary dimensions: the structural presence of armed and security elements MPD_i and the intensity of security events MEI_i. The integration of both dimensions into the resulting index SII_i is implemented through weighted linear aggregation of both indicators and is formalised as:

$$SII_i = \alpha \cdot MPD_i + \beta \cdot MEI_i, \tag{4}$$

where α and β represent weighting coefficients.

This approach is consistent with the principle of combining static and dynamic indicators, which underpins a range of internationally recognised analytical frameworks for assessing the security environment (e.g., OECD, UNDP, World Bank). By integrating both components, a balanced representation of the security situation is achieved, reflecting both the spatial disposition of forces and their observed activity over time. This conceptualisation is aligned with "spatial conflict modelling" methodologies employed in conflict geography [15]. The resulting value SII_i represents the degree of security burden of the environment. In the SEAS integration scheme, this component is considered with reversed polarity (1) in order to preserve a unified interpretation of the resulting composite stability index.

The partial indicators of *SII* are proposed as follows:

1. *Military Presence Density* MPD_i expresses the spatial structuring of unit i by security-significant elements. MPD_i captures not only their number but also their relative importance; it is therefore conceptualised as an area-normalised aggregation of security structures with the possibility of weighting by type, capacity, or strategic importance of individual elements. Higher values of *MPD* correspond to a higher degree of long-term militarisation or security control of the space.
2. *Military Event Intensity* MEI_i captures the intensity of security events in the assessed unit *i* over a defined time period. It is conceptualised as an area-normalised aggregation of events with security impact, weighted by severity or type. Higher values of *MEI* correspond to higher dynamics of security incidents and increased volatility of the security environment.

5. Discussion

The proposed SEAS model constitutes a methodological contribution primarily in its systematic treatment of socio-geographical data as a formally defined and geospatially analysable component of operational environment assessment. Unlike traditional approaches in which socio-economic and institutional characteristics of a region often appear only as qualitative context, SEAS provides a structured analytical framework enabling their quantification, spatial synthesis, and subsequent interpretation in relation to the security dimension. This strengthens the consistency of analytical outputs and their usability in operational-level planning processes, where spatially explicit justification of identified risks and unstable areas is required.

At the same time, the model architecture is designed to be transferable to strategic-level security environment assessments. In this context, the resulting composite index is not understood as a one-off diagnostic tool but as a potential framework for longer-term monitoring of regions' structural vulnerabilities and tracking their development over time. Integrating economic, institutional, and security dimensions makes it possible to identify not only currently burdened spaces but also areas where adverse structural factors accumulate and which may exhibit increased crisis potential over a longer time horizon.

From a methodological perspective, a key interpretative aspect is the choice of weights in the model's integration scheme. Weights are not treated as a purely technical parameter but as an expression of analytical preferences corresponding to a specific operational or strategic tasking. At the current stage, weights are specified by expert judgement, drawing on methodological guidance for composite indicator construction and on published weighting approaches employed in analogous indices developed for different analytical or policy purposes [4][16][17][18][19]. The current weight values primarily serve to operationalise the model's integration logic in this version of the specification. This, however, should not be viewed as a weakness of the architecture; rather, it enables transparent delineation of parametric uncertainty and shifts the focus of interpretation from absolute index values to the robustness of spatial stability patterns under changing weights. A suitable approach is a scenario-based framework in which weights are configured for typical analytical tasks and their impact is assessed in terms of the stability of the resulting spatial arrangement.

Another methodologically significant factor affecting interpretation is the choice of the aggregation unit to which individual indicators are synthesised. At this stage, the spatial unit is treated in general terms and its specific delineation is deferred to the subsequent operationalisation phase. This solution corresponds to the paper's focus on specifying the model architecture while allowing flexible adaptation of SEAS to different analytical contexts—from administrative units through functional regions to purpose-defined analytical zones.

Interpretation of the resulting composite index is further conditioned by the quality, completeness, and heterogeneity of input data. The model integrates layers differing in thematic granularity, topology, and reliability, while data availability may vary substantially not only across territories but also across model dimensions. In practice, low or high index values may therefore reflect not only the real state of the assessed phenomenon but partly also the quality of data evidence. For this reason, results must be interpreted in the context of the availability of input data, and this fact should be transparently accounted for in analytical conclusions.

Subsequent research will therefore focus primarily on strengthening the methodological grounding of weight parameterisation through expert elicitation tied to specific analytical tasks, on practical geoinformatics operationalisation of the model over a populated geodatabase architecture, and on validation applications in the form of case studies. Extending the model with a spatio-temporal dimension will subsequently enable tracking stability dynamics over time and contribute to early identification of destabilisation trends in crisis-exposed regions. Such a research continuity makes it possible to gradually strengthen both the validity and the practical usability of the model while maintaining transparent delineation of its assumptions and limitations.

6. Conclusions

This paper presented the design of the SEAS composite geospatial model intended to quantify territorial stability through the synthesis of socio-economic, institutional, and security indicators. The core contribution is the formal specification of the model architecture, integration logic, and partial components, which enable heterogeneous data layers to be transformed into a unified index space while preserving semantic consistency and interpretative transparency. The proposed solution is conceived as a methodological–conceptual intermediate step between conceptual modelling of socio-geographical data and their practical geoinformatics operationalisation.

Emphasis is placed on the reproducibility of the design and on clearly delineating the relationships between the data architecture, indicator construction, and the resulting geospatial synthesis, rather than on presenting a closed implementation workflow or final cartographic outputs.

The proposed architecture creates preconditions for further model development, particularly by refining weight parameterisation in relation to specific analytical scenarios, practically verifying the feasibility of populating the geodatabase structure, and conducting validation applications through case studies. This approach will make it possible to assess the robustness and interpretative stability of the model across different analytical contexts and to progressively verify its practical usefulness in operational and strategic-level security environment assessments.

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