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# Multilayer Models of Spatial Conflicts: Couplings Between Infrastructure and Socio-Spatial Dynamics*

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## Abstract

This paper presents a conceptual multilayer model designed for the analysis and simulation of spatial conflicts, incorporating the interdependencies between infrastructural layers and socio -spatial dynamics. The model employs a cellular automata (CA) approach, enabling the exploration of local interactions within complex spatial systems. Each layer represents a distinct aspect of the system: society, technical infrastructure, and the spatial- environmental context. The paper discusses the mechanisms of information exchange between layers, conflict escalation processes, and example scenarios derived from dependency network analysis. Conceptual results indicate that the multilayer approach provides a more realistic representation of crisis dynamics and supports the development of more effective strategies for spatial planning and response management.

**Keywords:** cellular automata, spatial conflicts, multilayer modeling, infrastructure, social dynamics, internal security

## Introduction

Spatial conflicts are emergent phenomena arising from the overlapping of social, economic, and infrastructural processes [Chen & Feng, 2022]. Modern cities - complex socio-technical systems - are increasingly becoming arenas of tension caused by infrastructure overload, social inequality, and inefficient spatial planning. Urban development studies using spatial simulations based on cellular automata confirm that even minor changes in infrastructural configurations can trigger abrupt socio-spatial transformations [Lu, Laffan, & Pettit, 2024].

With progressing urbanization, there is a growing need for models that not only analyze existing phenomena but also forecast their dynamics and identify potential critical points [Arfiansyah, Hawken, Zlatanova, & Han, 2024]. Single-layer models, focused solely on social or environmental structures, often fail to capture the interdependencies among infrastructure, space, and human behavior.

The aim of this paper is to propose and discuss a conceptual multilayer model based on cellular automata that enables the analysis of couplings between infrastructural and socio-spatial layers. This model may serve as a foundation for further simulation research and decision support in areas such as internal security, crisis management, and urban planning.

## Theoretical Background and Literature Review

The application of spatial models in social and security research has a long tradition. As early as the 1970s, statistical models were used to analyze territorial conflicts; however, their ability to capture local interactions was limited [Tong & Feng, 2020; Chakraborty, Sikder, Omrani, & Teller, 2022].

A breakthrough came with the development of cellular automata (CA), which allow the simulation of spatial processes driven by simple local rules. In urban and social geography, the work of Batty [2005] and Torrens [2010] demonstrated that CA models are effective tools for analyzing emergent phenomena in urban environments [Falah, Karimi, & Harandi, 2020].

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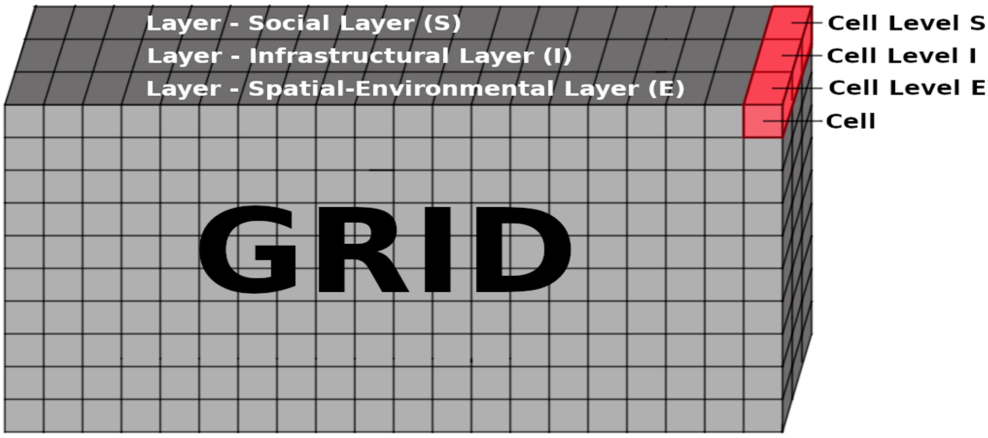
Parallel to CA, agent-based models (ABM) were developed to simulate the behavior of individuals and social groups [Epstein, 2006]. Their integration with CA led to hybrid models combining behavioral realism with the topological structure of space [Ligęza & Stachura, 2015; 2021; Pinto, Antunes, & Roca, 2021].

In the literature on internal security and urban resilience, there is an increasing emphasis on systemic analyses encompassing both critical infrastructure and social interdependencies [Yigitcanlar, 2018; Kaluza & Thiemann, 2010; Li, Zhou, & Chen, 2020]. The multilayer approach allows the modeling of interactions between various components of the urban system, interpreting conflicts as outcomes of dynamic equilibrium between infrastructure, resources, and population.

## Concept of the Multilayer Model

### *System Structure*

The proposed model consists of three interacting layers: social, infrastructural, and environmental. Studies have shown that this structure allows for a more accurate representation of complex spatial interdependencies [Xu, Zhou, & Li, 2022].




**Picture 1. Graphic presentation for grid use in Multilayer Model (LCCA)**

The **social layer** reflects interactions and tensions among social groups, while the **infrastructural layer** represents resource accessibility and the resilience of technical systems [Chen et al., 2020]. **Environmental factors** influence spatial propagation and can modulate the dynamics of conflict escalation [Saulawa, Ibrahim, & Bello, 2024].

1. **Social Layer (S)** - describes collective behaviors and group states as functions of tension, cooperation, or conflict.
2. **Infrastructural Layer (I)** - represents the condition and capacity of transport, energy, and communication systems.
3. **Spatial-Environmental Layer (E)** - captures physical and administrative constraints that limit or facilitate spatial flows.

Each cell (x,y) in the model has a state vector within each layer: $S(x,y,t) \in \{calm, tense, conflict\}$, $I(x,y,t) \in [0,1]$, $E(x,y,t) \in \mathbb{R}^n$.

### *Interlayer Couplings*

Relations between layers are bidirectional and dynamic:

- **S → I:** Escalation of social conflict causes infrastructure degradation, such as road blockages or energy supply interruptions, potentially damaging critical assets.

- **I → S:** Reduced infrastructure accessibility increases social tension in neighboring cells.
- **E → S, I:** Environmental and spatial conditions can either amplify or dampen conflict propagation.

The system dynamics are described by a recursive equation:

$S_{t+1}(x,y) = f(S_t(x,y), I_t(x,y), E_t(x,y), N(S_t))$,

where $N(S_t)$ defines Moore or von Neumann neighborhoods, and *f* represents local interaction rules.

## Methodology and Simulation Assumptions

The model is formulated conceptually, assuming future implementation in a simulation environment integrated with GIS data [Musikhin & Karpik, 2023]. The use of cellular automata in studies of spatial conflict dynamics captures localized mechanisms of interaction, including the accumulation of tension [Chen & Feng, 2022].

Such spatial simulations enable the assessment of intervention outcomes and the identification of potential critical points [Liu et al., 2021]. The spatial domain is represented as a two-dimensional grid, where each cell corresponds to a spatial unit (e.g., an urban block).

For each cell, a set of state-transition rules is defined, considering:

- the influence of neighboring cells (e.g., tension propagation),
- the local state of infrastructure,
- spatial constraints limiting diffusion (e.g., rivers, administrative boundaries).

In the conceptual analysis, it is assumed that the system initially contains a small number of conflict cells concentrated in densely populated areas.

## Conceptual Results and Scenario Analysis

Conceptual simulations indicate that in systems with dense infrastructural connectivity (e.g., large cities), degradation of a single infrastructural node can lead to rapid propagation of social tensions [Pinto et al., 2021]. In more fragmented spatial structures, this propagation is slower, suggesting that spatial heterogeneity may act as a buffer [Lu et al., 2024].

Critical points were also identified where minor changes in one layer (e.g., a temporary transport disruption) trigger abrupt escalation in the social layer [Li et al., 2020]. This phenomenon can be interpreted analogously to phase transitions in physical systems [Helbing & Johansson, 2011].

The analysis shows that intervention effectiveness - whether technical or organizational - depends on spatial deployment and response time. Infrastructure repair in key network nodes results in a rapid decline in social tensions, while peripheral interventions have limited impact.

## Discussion

The proposed model extends classical concepts of spatial conflict by introducing feedback loops among distinct system layers. This framework allows for the analysis of complex escalation and de-escalation mechanisms that are difficult to capture in one-dimensional models.

Integration with real-world datasets (e.g., GIS, mobility data, energy consumption) offers potential for practical application as a decision-support tool in crisis management. In particular, it can assist in assessing urban resilience and prioritizing infrastructural interventions.

Future research will involve the model's computational implementation with a machine learning component, allowing for automatic parameter calibration based on empirical data.

## Conclusions

Multilayer cellular automata models constitute a valuable tool for analyzing spatial conflicts. By integrating social, infrastructural, and environmental aspects, they provide deeper insight into the mechanisms shaping crisis dynamics and enable the prediction of intervention outcomes.

The model presented in this paper serves as a conceptual basis for further exploration of complex urban systems, especially in the context of strategic planning and internal security.

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