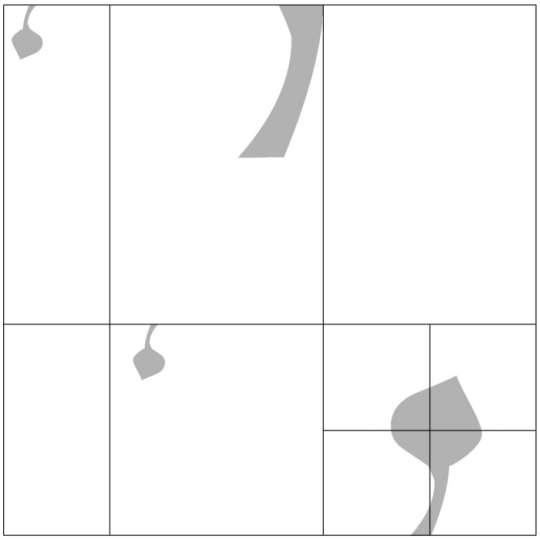
Extended abstract

System Dynamics and Agent-Based Modeling applied to the study of depopulation: a systematic literature review



Luis Llases, Juanjo Mediavilla

Universidad de Valladolid, Spain

DOI: 10.4422/ager.2026.06

ager

Revista de Estudios sobre Despoblación y Desarrollo Rural
Journal of Depopulation and Rural Development Studies

Highlights:

1. Depopulation is a systemic and self-reinforcing process.
2. System Dynamics and Agent-Based Modelling are well-suited for its study.
3. Many reviewed models omit the fundamental feedback loops of depopulation.
4. The "relational" dimension (social capital, community ties, sense of belonging) is underrepresented in the models.
5. It is necessary to develop feedback-based models that integrate all relevant dimensions in greater detail.

Abstract: Depopulation is a global challenge with implications for the economy, public services and social cohesion. Therefore, it cannot be understood solely as a population deficit, but rather as a systemic and self-reinforcing process: the loss of inhabitants generates economic and essential service shortages, leading to further emigration. This systematic review analyses the academic literature that applies System Dynamics and Agent-Based Models to the study of depopulation, as both approaches allow these characteristic feedback loops to be represented explicitly. Thirty-one publications were classified according to categories such as geographical context, methodology, dimensions represented, drivers of population change, policies evaluated and main conclusions. The results show that only a minority of studies reflect these loops endogenously. This implies the need to advance in this line of research, increasing the level of detail of the interactions. Furthermore, the relational dimension is currently underrepresented, and its inclusion is an important way to improve the ability of models to simulate how community cohesion, social ties, and sense of belonging affect migration and residence decisions, thus providing better tools for the design of mitigation and management policies.

Keywords: Feedback loops, vicious circles, endogenous modelling, relational dimension, shrinking cities.

Luis Llases. https://orcid.org/0009-0000-9529-5152
E-mail: luis.llases@uva.es
Juanjo Mediavilla. https://orcid.org/0000-0001-5638-4347
E-mail: juanjose.mediavilla@uva.es

Extended Abstract

1. Introduction and justification

Depopulation must be conceptualised as a systemic and endogenously self-reinforcing process, not as a mere deficit in population stock: the loss of inhabitants contracts economic activity and the provision of essential services —healthcare, education, transport, infrastructure—, which in turn activates new emigration incentives and discourages fertility and immigration, deepening the spiral of demographic decline. This negative feedback loop constitutes the dynamic core of the phenomenon and determines its long-term territorial trajectory. The scholarly literature on local development further underscores that a territory's resilience depends on interrelated endogenous capitals —economic, human, social, institutional, cultural and natural—, among which social capital acts as the key articulating mechanism capable of modulating the impact of exogenous pressures on community sustainability.

Conventional methodological approaches —econometric models, cohort-component projections, GIS analysis, machine learning— have proven useful for identifying statistical correlations between demographic and socioeconomic variables. However, they share a structural limitation: their static or linear configuration prevents the explicit dynamic representation of the circular causality that characterises depopulation. A regression model can identify the correlation between service deficits and emigration, but cannot simulate how progressive service erosion —driven by the very population contraction the model seeks to explain— amplifies future decline. To overcome this constraint, System Dynamics (SD) and Agent-Based Models (ABM) emerge as privileged methodological frameworks, as both paradigms are designed to represent feedback loops natively: SD through aggregate stock-and-flow structures with circular causalities, and ABM through a bottom-up logic in which macro-level patterns emerge from the interactions of heterogeneous individual agents.

2. Objectives, methodology and sources, areas of study

The central objective of this work is to systematise the body of research applying SD and ABM to the study of depopulation, identifying its fundamental characteristics, thematic trends and methodological shortcomings. It seeks to provide a critical foundation for future research and improve the utility of models for public policy design.

A systematic literature review was conducted in Scopus and Web of Science, combining descriptors related to demographic decline (*depopulation*, *population decline*, *demographic shrinkage*, *demographic collapse*, *exodus*) with methodological terms (*system dynamics*, *agent-based*, *multi-agent*). After removing 73 duplicates, screening by title and abstract, and applying inclusion criteria —requiring an implemented computational model whose central phenomenon was depopulation—, 33 publications were selected for full-text retrieval. Two were subsequently excluded for insufficient thematic alignment, and three were added via snowball sampling, yielding a final corpus of 31 publications. Analysis was structured around seven analytical categories: (1) geographical context; (2) methodology —pure SD, pure ABM or hybrid—; (3) subject matter and relationship to depopulation; (4) dimensions represented; (5) population drivers and their endogenous or exogenous character; (6) policies evaluated; and (7) main conclusions.

3. Results

Our review of the literature shows sustained growth over the past two decades at a rate exceeding that of global scientific output, reflecting both the rising academic concern for depopulation and the growing accessibility of SD and ABM software within the social sciences. Methodologically, 56% of studies employ SD and 46% ABM, with five hybrid models combining these approaches with tools such as Land Use and Transport Interaction (LUTI) (models or environmental water-quality models.

Geographically, research concentrates in Japan (23%), Germany (13%) and China (13%), followed by Spain and the United States (6% each). Municipal-scale studies predominate (55%), consistent with the local manifestation of decline effects, while the distribution across urban (42%), rural (29%) and mixed (29%) contexts confirms that depopulation transcends the rural sphere. Regarding dimensions represented, demography (90%), economy (81%) and territory (77%) are the most common, followed by infrastructure and services (65%), environment (48%) and housing (32%). The relational

dimension —social capital, community networks, sense of belonging— appears in only 19% of the models, making it the most systematically absent category despite its recognised theoretical relevance.

Critically, only a minority of studies endogenously model the core feedback loop linking population loss to economic contraction and service reduction. The majority treat aggregate population dynamics as an exogenous input or define them through predefined scenarios. A cohesive subgroup of shrinking cities studies —prominent in Japan and Germany— partially addresses this by endogenizing intraurban residential location, while keeping overall demographic dynamics exogenous.

4. Discussion

The geographical concentration of the reviewed corpus in a limited set of countries —with the notable absence of southern and eastern European economies experiencing marked demographic contraction, such as Italy, Greece, Bulgaria or the Baltic states— constrains the transferability of findings and points to an underexplored research frontier.

The most critical methodological shortcoming is the limited endogenous modelling of the central depopulation feedback loop. Despite SD and ABM being paradigms conceived to capture circular causalities, a substantial proportion of reviewed models externalises population dynamics, thereby underutilising their core analytical capacity. Treating demographic decline as a system input rather than as an emergent outcome prevents these models from simulating how socioeconomic variables, environmental conditions and public service provision interact with and reinforce demographic decisions over time. The underrepresentation of the relational dimension compounds this limitation: the difficulty of quantifying social capital, the absence of standardised calibration data, the complexity of formalising dynamic processes such as trust generation or community bond erosion, and disciplinary inertia all converge to perpetuate a systematic bias towards the materially measurable. Models omitting this dimension risk overestimating the effects of included variables and implicitly assuming constancy in factors that are, in reality, endogenous to the system.

The conclusions of the most endogenized models reveal two transversal findings of high analytical interest: the existence of critical thresholds or tipping points beyond which decline becomes self-reinforcing and irreversible, and the presence of hysteresis,

whereby the system —once its resistance capacity is exceeded— is unlikely to return to its prior equilibrium. Both findings underscore the importance of policy timing: intervention effectiveness decreases non-linearly as demographic deterioration advances, reinforcing the case for early, integrated and synergistic policy action.

5. Conclusions

This systematic review confirms the structural suitability of SD and ABM for addressing the inherent complexity of depopulation as a systemically self-reinforcing process. The multidimensional classification of 31 models has enabled the mapping of the state of the art and, most importantly, the detection of the shortcomings charting the course for future research. The key finding is that only a minority of studies endogenously models the central feedback loop, implying a systematic underutilisation of the analytical strengths of these paradigms. Furthermore, the relational dimension remains absent from most quantitative simulation models despite its well-established theoretical centrality. Incorporating it requires not merely adding new variables, but developing mechanisms capable of representing how social relations are generated, sustained or eroded, and how they shape individual and collective migration and residence decisions.

6. Next steps

Four priority lines of future research emerge from the review. First, advancing models that more fully endogenise the demographic-economic-services feedback loop, increasing the level of detail in inter-subsystem interactions. Second, operationally incorporating the relational dimension —through empirically calibrated proxy indicators of social capital or ABM behavioural rules integrating territorial attachment and community ties— to enable simulation of policies targeting social fabric strengthening beyond purely economic or infrastructural interventions. Third, expanding geographical coverage towards underrepresented contexts, particularly in southern and eastern Europe, to test the transferability of existing models and enrich the understanding of the phenomenon with new territorial case studies. Finally, developing comparative studies that analyse depopulation dynamics across different countries or regions, a barely explored line of work with considerable potential for generating generalisable knowledge about the universal mechanisms and local specificities of demographic decline.