TYPE Original Research
PUBLISHED 26 September 2022
DOI 10.3389/fbuil.2022.908698

OPEN ACCESS

EDITED BY
Peter John Marcotullio,
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REVIEWED BY
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Northeastern University, China
Ernan Rustiadi,
Bogor Agricultural University, Indonesia

*CORRESPONDENCE
Grace Abou Jaoude,
g.abou-jaoude@tu-braunschweig.de

SPECIALTY SECTION
This article was submitted to Urban Science,
a section of the journal
Frontiers in Built Environment

RECEIVED 30 March 2022
ACCEPTED 08 August 2022
PUBLISHED 26 September 2022

CITATION
Jaoude GA, Mumm O, Karch A and Carlow VM (2022), Understanding land take in small and medium-sized cities through scenarios of shrinkage and growth using autoregressive models.
Front. Built Environ. 8:908698.
doi: 10.3389/fbuil.2022.908698

Understanding land take in small and medium-sized cities through scenarios of shrinkage and growth using autoregressive models

Grace Abou Jaoude[1]*, Olaf Mumm[1], André Karch[2] and Vanessa Miriam Carlow[1]

[1]ISU—Institute for Sustainable Urbanism, Technische Universität Braunschweig, Braunschweig, Germany, [2]Institute for Epidemiology and Social Medicine, Westfälische Wilhelms-Universität Münster, Münster, Germany

Rapid transitions induced by migration flows and socio-economic developments brought about massive changes in urbanization processes and resulted in increasingly uncertain futures. The implications and complexities of the ensuing urbanization patterns are difficult to predict and project into the future. While most studies are focused on large cities and major urban centers, urbanization processes in small and medium-sized cities have garnered little scholarly and political attention. To understand future urbanization patterns, we used the TOPOI method, a novel approach for classifying territorial settlements, and spatial autoregressive models to examine contrasting futures of population growth and shrinkage in one small and one medium-sized city in Lower Saxony, Germany. Results revealed that despite planning frameworks, high population density and functional mix, respectively, were insufficient mechanisms to reduce land take. Contrary to current assumptions on the functional mix of small and medium-sized towns, our findings showed that more than half of the settlements across the study area accommodated three or more functions. Since the share of residential buildings and functional mix strongly influenced land take, further research is needed to understand their implications on sustainable urban planning. Shrinking towns in Lower Saxony continue to present multidimensional challenges and emphasize the need for transforming local planning cultures and institutional frameworks to sustainably manage and repurpose these potentially vacant areas.

KEYWORDS

urbanization patterns, demographic change, spatial regression models, Germany, TOPOI method

1 Introduction

In an age of planetary urbanization, understandings of the urban are continuously challenged (Lefebvre, 2003; Merrifield, 2013; Brenner and Schmid, 2014). Once bound to historical city centers, urbanization expanded beyond dense cores transforming landscapes into a mosaic of uneven spatial developments (Lefebvre, 2003; Soja, 2011; Brenner, 2013). To understand these expanding territorial settlements, demographic factors were conventionally used to delineate administrative boundaries and classify spatial formations following the urban-rural binary (Davis, 1955; Brenner, 2013; BBSR, 2018). Undermining the heterogeneity of territorial transformations, this long-standing dichotomy exhibited many shortcomings (Champion and Hugo, 2004; Wood, 2009). With time, this conventional distinction was superseded by various concepts such as Zwischenstadt (Sieverts, 1997) Netzstadt (Oswald et al., 1998), Metacity (McGrath and Pickett, 2011), Stadtlandschaft (Hofmeister and Kühne, 2016), Territories-in-between (Wandl et al., 2014), among others that explored new spatial formations and patterns of urbanization. Overall, new territorial transformations and emergent patterns of population and employment begged a shift from the focus on traditional dense centers to engage with dynamics across territories and regions.

Settlements dispersed across a region are characterized by socio-economic and metabolic linkages where flows of labor, capital, energy, information and commodities generate interactions and territorial complexity. These processes are not restricted to specific administrative boundaries, rather extend over territories characterized by a diversity of spatial practices, land uses and functions. Favored by their strategic location, small and medium-sized cities within these regions exhibit robust socio-economic interdependencies and act as centers for the provision of services and goods to surrounding areas (Tacoli, 1998; Satterthwaite and Tacoli, 2003). Despite their critical role in spatial development and dynamics, a limited number of studies has quantitatively assessed the significance of small and medium-sized cities in spatial planning and policy (Demazière, 2017; Atkinson, 2019; Porsche et al., 2019a,b; Wagner and Growe, 2021). Indeed, multidimensional and structural phenomena in small and medium-sized cities have garnered little scholarly and political attention since these areas are less emblematic with minor political impact and an insufficient capability to problematize and promote debate and policy response (Nelle et al., 2017). In addition, the potential role of small and medium-sized towns has largely been neglected across national and regional levels of governance (Servillo et al., 2017). In Europe, various research projects that focused on small and medium-sized towns have been carried out under the European Spatial Planning Observation Network (ESPON) cooperation established by the European Union (EU). An example is the ESPON TOWN project that analyzed the functional relations between small and medium-sized towns, proposed a method for identifying settlement types and considered the ways in which policy implications influence them. Despite the project's efforts, a systematic definition of small and medium-sized towns remains ambiguous in literature (Porsche et al., 2019a,b; Servillo et al., 2014; Wagner and Growe, 2021). Notwithstanding the plethora of methodologies, most studies classify small and medium-sized towns according to their population density and spatial distribution (Russo et al., 2017; Gareis and Milbert, 2020). Apart from the difficulties in defining small and medium-sized towns, policies that support their bottom-up activities and facilitate multi-scalar dynamics are lacking across the European and regional levels. Additionally, most towns are "restricted by [their] location, economic and demographic structure and lack of local capacity to react proactively and creatively to problems" (Atkinson, 2019, 7). Thus, scholars argued that research approaches should focus on the specificities of small and medium-sized towns while understanding their role as embedded settlements within a region (Servillo et al., 2017; Atkinson, 2019). In Germany, research and public discourse on small and medium-sized towns increased in the last five years; however, most work focused on case studies rather than systematic structural research (Porsche and Milbert, 2018; Beetz et al., 2019).

Concurrent growth and shrinkage and their spatial outcomes are central to urban discourse. In this regard, understanding and measuring levels of urbanization in small and medium-sized cities is an imperative to effectively manage future developments. Therefore, we apply spatial autoregressive models to analyze and simulate patterns of urbanization across one small and one medium-sized city, respectively, in Lower Saxony, Germany. The federal state of Lower Saxony makes a strong case study since 71% of the population resides in small towns and cities, suburban as well as rural areas, compared to 20% of the population living in large cities, and 9% in medium-sized towns (LSN, 2019). Using the TOPOI method (Carlow et al., 2022), the study aims to understand the implications of different scenarios of population change on the levels of the built area. The study also seeks to inform policy and decision makers to develop effective and sustainable mechanisms. It, therefore, contributes to the debate on urbanization by focusing on small and medium-sized cities, which are widely underrepresented in urban studies literature.

The paper is organized as follows. Section 2 provides an overview of concurrent processes of growth and shrinkage in Germany. The TOPOI method, case studies, relevant data sets and autoregressive models are later introduced in Section 3 followed by the results and simulations for the built area in Section 4. The paper concludes with a discussion on potential solutions and the need for further research in Section 5.

2 Understanding concurrent processes of expansion and shrinkage

Urbanization, which entails the conversion of open landscapes into built areas, is a critical phenomenon across regions (Hersperger et al., 2020). While the population grew only by one third, European cities expanded by approximately 78% since the mid-20th century (Nilsson et al., 2014). Overall, expansion, demographic change and shrinkage are prevalent trends in Europe (Haase and Tötzer, 2012). In Germany, land conversion rates were among the highest of all EU member states reaching up to 12 m^2 per second between 2000 and 2010 (Kroll and Haase, 2010; Kretschmer et al., 2015). Industrial and commercial sites as well as residential expansion were the main drivers behind the increasing land take which accumulated to an average of 56 ha per day between 2015 and 2018 (UBA, 2020). Setting normative objectives, Germany has pledged to reduce the built-up area and transport infrastructure expansion to 30 ha per day by 2030 (Die Bundesregierung, 2021). While land use reduction is a priority on the agenda of several federal states, land take and urbanization patterns vary across different areas in Germany.

Successive out-migration to the peripheries prompted growth beyond inner-city centers to surrounding areas where new patterns of consumption, ownership and commuting prevailed (Andersen et al., 2011; Hesse and Siedentop, 2018). Influenced by residential preferences, tax incentives and employment concentration, suburbanization was characterized by discontinuous residential areas, with no uniform pattern. Expanding settlements accommodated services, logistics, production and retail functions, as well as economic activities and large-scale infrastructure (Borsdorf and Zembri, 2004; Burdack and Hesse, 2007). Parallel to the ongoing decentralization phenomenon, the re-development of inner-city areas, particularly former brownfields and industrial grounds, has gradually prompted the return of high-income earners to cities (Haase and Rink, 2015). Based on theoretical and empirical analysis, Frank (2018) averred the formation of 'middle-class family enclaves' in inner city areas—an ongoing trend in various regions across Germany. Analysis by Sander (2014) resulted in similar observations and revealed that adults between the age of 30–49 years old remain in urban areas and centers. His findings oppose prevalent stereotypes around middle-aged adults moving to suburban areas. As recently as 2000, re-urbanization tendencies have been identified in various East German cities that witnessed a population increase in their inner-city neighborhoods, particularly those with universities such as Leipzig and Dresden (Sander, 2014). Spatio-temporal analysis of Leipzig by Kabisch et al. (2019) revealed that re-urbanization not only affected inner-city areas but extended throughout the city to peripheral areas and along regional railway lines beyond city borders.

Concurrent to inner-city growth and expansion, several German areas are confronted with the challenges of population shrinkage (Bartholomae et al., 2017). While shrinkage is considered a global planning and political issue, its manifestations, consequences and strategies are specific to the local context. In Germany, the term shrinkage first appeared in policy debates in the 1970s, but it was not until the early 2000s that the topic was explicitly discussed in policy and academia (Oswalt, 2005; Nelle et al., 2017). Debates on shrinkage in Germany gained momentum after reunification particularly when growth-oriented models, that disregarded initial factual warnings, proved unsuccessful. These discussions culminated in large-scale research projects, such as the Shrinking Cities (Oswalt, 2005); redevelopment programs such as *Stadtumbau Ost* and *Stadtumbau West*; and the International Building Exhibition Emscher Park. Several social and economic drivers such as slow economic growth, population decline, erosion of industries, out-migration, suburbanization and disinvestment have brought about uneven patterns of shrinkage (Luescher and Shetty, 2013; Döringer et al., 2020). Globalization has also significantly contributed to this multidimensional phenomenon by consolidating resources and capital in cities that attracted people and skills (Martinez-Fernandez, 2012). Sustained population loss has resulted in low-density housing, vacant buildings and demolition of built-up areas (Haase, 2008). While migration has halted shrinkage in several large German cities, sustained population loss due to ageing is becoming critical, particularly in small and medium-sized towns (Nelle et al., 2017).

Demographic change across different areas in Germany has been widely analyzed where various studies focused on the spatial implications of land take (Nuissl and Rink, 2005; Kroll and Haase, 2010; Heider, 2019). Lauf et al. (2012; 2016) investigated the effects of concurrent demographic trends, and socio-spatial processes such as growth, shrinkage, reurbanization, aging and residential preference shifts on land consumption in urban and peri-urban areas in Leipzig and the metropolitan region of Berlin, respectively. Deriving from the Weighted Urban Proliferation method implemented in Switzerland, Behnisch et al. (2018) quantitatively measured and assessed urban sprawl at the municipal scale in Germany for the year 2010. Their findings revealed an urgent need to address urbanization as a critical environmental challenge. Other studies have quantitatively analyzed population loss and emphasized the role of deindustrialization, out-migration and decreasing fertility rates in several East German cities (Heider, 2019; Konietzka and Martynovych, 2022). Results revealed increasing household numbers and intensified land consumption despite the sustained population decline (Couch et al., 2005; Lauf et al., 2012; Haase et al., 2013). This paradox is largely attributed to the decrease in the average household size and the increase in the number of single households as well as to aging, where a tendency of the elderly to live in single households was observed (Lauf et al., 2016). Despite the plethora of studies, land take and its spatial implications remain important topics to date as the land occupied by settlements and transport infrastructure in Germany expanded by around 28% from 40,305 to 51,692 km^2 between 1992 and 2020 (UBA, 2022). While different land use models have been developed by various scholars, a handful of studies have employed econometric based land use models that consider spatial autocorrelation and heterogeneity (Keller and Vance, 2017; Hagenaeur and Helbich, 2018). Disregarding these spatial effects in modelling processes results in misleading and biased inferences. We, therefore, aim to understand the spatial implications and land take in one small and one medium-sized city in Lower Saxony, Germany, using spatial autoregressive models. In addition, we seek to explore different scenarios of shrinkage and growth to understand future changes in urbanization patterns.

3 Materials and methods

3.1 Use of TOPOI: A method for analyzing settlement units across regions

Recent territorial transformations challenge conventional settlement classifications and understandings of urbanization. These changes necessitate new approaches to analyze spatial processes and interlinkages across territories (Brenner and Schmid, 2014). Various attempts to map and categorize territorial units were largely applied at the regional and pan-European levels. However, these approaches, such as the CORINE method (European Commission, 1994) and the Organisation for Economic Co-operation and Development (OECD) typology (Brezzi et al., 2011), failed to account for the specificities of different areas. The failure of these approaches is largely attributed to 1) using narrow spatial definitions (urban, peri-urban and rural), 2) classifying certain areas while ignoring others and 3) delineating boundaries according to the existing administrative jurisdictions, at the NUTS3 level, which does not take into consideration spatial adjacency or the specificities and differences between sites (Zasada et al., 2013).

While various scholars have called for typologies that reflect complex relationships across territories (Wandl et al., 2014), national census agencies continue to differentiate between settlement types using existing administrative boundaries which are either overbounding (covering large swathes of land) or failing to account for the total built area (Davoudi, 2020). Additionally, a range of indicators, mostly economically driven or based on population studies, is typically used, which fails to reflect the realities and dynamics of the built environment (Satterthwaite, 2010). In Germany, the settlement's structural characteristics are based on population levels and mainly include into city (county free); urban county; rural county with densification tendency; and sparsely populated rural county (BBSR, 2018). However, much of the emerging territorial settlements do not fit established categories but rather have distinct spatial characteristics and functionalities (Sieverts, 1997). Indeed, Carlow et al. (2022) showed that territories categorized as "city" or "urban county" often contain settlement units with rural characteristics in terms of public transport accessibility, functional mix or density. In response, the authors proposed the TOPOI method, a novel approach for mapping and classifying territorial settlements and spatial formations based on the building as the smallest unit. The method maps, characterizes and classifies areas using four major steps: 1) defining boundaries of settlement units based on the aggregation of building footprints; 2) assessing functional properties of settlement units, 3) analyzing spatial linkages between units; and 4) synthesizing and classifying settlement units into different TOPOI types (Carlow et al., 2022).

Based on 11 indicators, including functional mix, accessibility to public transport, population density and urban form, the clustering algorithm 'affinity propagation' was used to classify the settlement units into 13 different settlement types (TOPOI) (Carlow et al., 2022). The 13 ensuing TOPOI types are listed in Figure 1 and include: 'Node city', 'Node town', 'Periurban town', 'Exo-satellite town', 'Periurban village', 'Small periurban village', 'Exo village', 'Small exo village', 'Disseminated village', 'Agri village', 'Disseminated hamlet', 'Disseminated living agri hamlet' and 'Exo industrial zone' (Carlow et al., 2022). Overall, the TOPOI approach transgresses the long-established dichotomy by offering a more granular and differentiated view on settlement types and exposes processes of uneven and variegated spatial developments. As an alternative approach, it supports policy development to improve decision-making and governance across regions (Carlow et al., 2022).

3.2 Study areas

The study areas, Braunschweig and Salzgitter, are part of the larger Braunschweig region located south-east of Lower Saxony, Germany (Figure 1). As a significant economic cluster, the area is characterized by a concentration of manufacturing firms and ancillary specialized services that benefit from the pool of high-skilled workers and research institutions. The automotive industry is key to the region's industrial sector and contributes to the area's identity. The region is also characterized by research-intensive industries and seeks to attract highly specialized workers to maintain its competitiveness (Brandt et al., 2009; Eurostat, 2020).

According to the TOPOI method, the cities of Braunschweig and Salzgitter consist each of different TOPOI types (Carlow et al., 2022). Therefore, we restrict the study areas to specific settlements units as identified by the method (Figure 1).

3.2.1 Braunschweig

Braunschweig is considered a medium-sized city and has historically been the powerful and influential trading center of the region. After a period of decline, population growth in Braunschweig regained momentum in 2000 parallel to a period of intraregional (re)concentration that was taking place in Germany. Rising migration in the past years have contributed

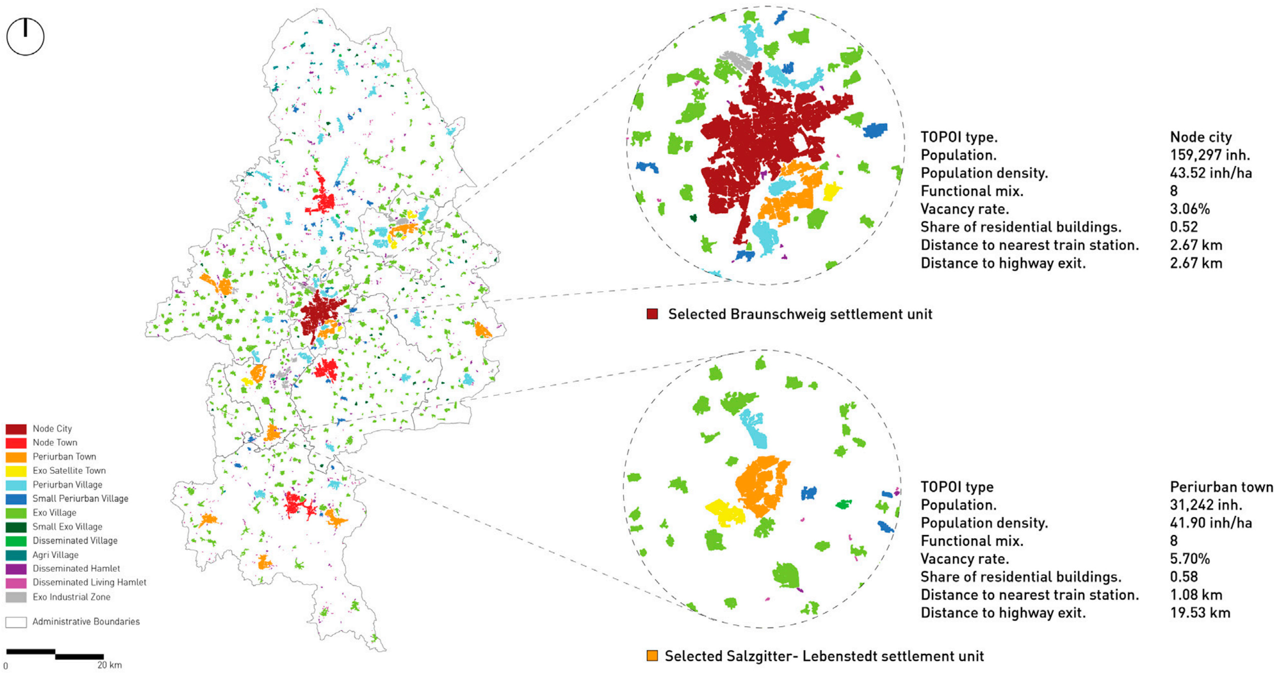

FIGURE 1
TOPOI method applied to the Larger Braunschweig area.

to an increase in the population to 248,575 inhabitants in 2019 from 245,816 in 2000 (LSN, 2020a). The universities and research institutions in Braunschweig are a source of innovation and influx of skills and young people. In this regard, Braunschweig ranked highest in research and development intensity in 2020 compared to other areas in Europe (Eurostat, 2020).

As per the TOPOI method, the largest area of the Braunschweig settlement is classified as a node city (Figure 1). With a population of 159,297 inhabitants, this settlement unit has the highest population in the study area, a diversity of functions along with a high connectivity. Compared to other settlement units or TOPOI, the Braunschweig settlement comprised a high population density, namely 43.52 inhabitants per hectare (inh/ha) (Carlow et al., 2022).

3.2.2 Salzgitter: Lebenstedt district

Once a flourishing and dynamic mining city, Salzgitter has been witnessing a sustained population decline. Given its large iron ore deposits, the city was selected as a site for industries and factories and was established in 1942 in accordance with the Salzgitter Law during the National Socialist period (Hulskes, 2017). The city, an agglomeration of 31 small towns and villages including Lebenstedt, Salzgitter-Bad and Hallendorf, is 25 km away from Braunschweig. Similar to other industrial towns in capitalist economies, Salzgitter's growth and decline was historically dependent upon the global mining industry. Seeking new economic paths beyond mining, Salzgitter sought to diversify its economy through the introduction of the automotive and service industries. However, the growth of the service sector in the region has not sufficiently compensated for unemployment in mining and thus the population of Salzgitter decreased from 120,126 inhabitants in 1973 to 104,138 in 2020 (LSN, 2020a).

Among the conglomeration of towns, Lebenstedt, the most populous district, is considered the administrative center of Salzgitter. According to the TOPOI approach, the Lebenstedt settlement unit is classified as a periurban town. With a population of 31,242 inhabitants, the area is well connected to nearby towns and has an adequate mix of functions. The population density of Lebenstedt is 41.90 inh/ha, just slightly lower than that of Braunschweig.

3.3 Data and variables

The primary unit of analysis in this study is the settlement unit, alternatively referred to as TOPOS (n = 1,245) (Carlow et al., 2022). The dependent variable is the amount of built area, which encompasses all buildings within a unit for the year 2011, expressed in square meters (m^2). Given the high variability of the data, the amount of built area was log-transformed. The selection

TABLE 1 Characteristics of the TOPOI under study (n = 1,245).

Theme	Variables		Description	Source	Mean	SD	Min	Max
	Amount of built area		ALKIS (LGLNa;b)	Total area of buildings within a settlement unit	9.4	1.9	4.6	15.8
Demography	Population density		Number of inhabitants per hectare	Destatis (2015a)	8.5	8.8	0	83.3
Spatial configuration	Building types	Single family houses	Total area of single family houses in ha. They refer to detached structures with 1–2 dwellings	Destatis (2018)	2.55	6.20	0	110.92
		Terraced houses	Total area of terraced houses in ha. They refer to semi-detached or terraced structures with 1–2 dwellings	Destatis (2018)	0.85	4.45	0	104.25
		Multi-family houses	Total area of mutli-family or row houses in ha. These are connected structures with common sidewalls. They typically consist of 3–12 dwellings	Destatis (2018)	0.55	5.40	0	170.83
		Apartment blocks	Total area of apartment buildings in ha. They refer to high-rise structures with 13 or more dwellings	Destatis (2018)	0.02	0.33	0	11.40
	Share of residential buildings		ALKIS (LGLNa;b)	Ratio of the total area of residential buildings to the total built area	0.4	0.4	0	1
	Vacancy rate		Percentage of vacant dwellings within a settlement unit	Destatis (2018)	1.8	5.2	0	100
Mix of functions	Functional mix		The number of different functions in a settlement unit ranging from 0 to 8	(LGLN, 2016a; b)	4.1	2.5	0	8
Infrastructure as spatial linkages	Distance to nearest train station		Shortest distance from the center of the settlement unit to the nearest regional train station based on the street network (in km)	DB (2013; 2016) and Connect (2019)	20.4	11.1	0.5	50.2
	Distance to nearest highway exit		Shortest distance from the center of the settlement unit to the nearest highway exit based on the street network (in km)	DB (2013; 2016) and Connect (2019)	7.1	4.6	0.003	24.9

of explanatory variables was contingent upon the availability of data and a literature review (Kretschmer et al., 2015; Colsaet et al., 2018). Based on several studies that analyzed the characteristics of emergent and expanding territorial settlements, the set of independent variables in this study corresponded to three main themes: 1) spatial configuration; 2) infrastructure and 3) mix of functions (Wandl et al., 2014). A fourth category, population density, was included as a necessary requirement that highly relates to patterns of urbanization. The geospatial data used in this study was provided by the Federal Agency for Cartography and Geodesy (BKG), the Federal Statistical Office (Destatis), and the State Office for Geoinformation and Land Surveying Lower Saxony (LGLN) (Destatis, 2015a; 2018; LGLN, 2016a; 2016b). The data was compiled based on national standards (c.f. ALKIS/ATKIS; Destatis, 2015b). Census 2011, which is the most recent database for Germany with its spatial resolution (1ha), was obtained from Destatis and used in this study. All variables were calculated following the methods described in Carlow et al. (2022; 2020) and Mühlbach et al. (2021). An overview of all the variables and their data sources is provided in Table 1.

3.3.1 Population density

Demographic data continue to serve as a basis to analyze patterns of urbanization (Champion and Hugo, 2004). Shown in several studies to correlate with land take (Salvati and Carlucci, 2016), population density has been calculated for each TOPOS following the method described in Carlow et al. (2022), where the sum of the total population per 1 ha cell within one settlement unit was divided by the area of the settlement unit. Demographic data was obtained from Destatis (2015a) census 2011.

3.3.2 Spatial configurations

With increasing urbanization processes, new urban forms and spatial configurations emerge. To capture the spatial complexity and urbanization patterns across the study area, four representative building types were distinguished as a proxy for urban morphology (Mühlbach et al., 2021). These include 1) single family houses; 2) multi-family houses; 3) terraced houses and 4) apartment blocks.

Studies that addressed population decline emphasized housing vacancy as a major implication of shrinkage (Kabisch, 2005; Haase et al., 2013). Perceptions of vacancy further accelerate rates of residential vacancy and eventually result in neighborhood deterioration (Lauf et al., 2016). Thus, residential vacancy, which is the percentage of empty dwellings within a TOPOS, and the share of residential buildings were also included in this study. Data on vacancy and building types was obtained from Destatis (2015a, 2018).

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3.3.3 Mix of functions

Settlement units across regions not only consist of monofunctional residential premises but are also characterized by a diversity of uses such as retail, logistics, industries, public utilities and production facilities. Functional mix which refers in this study to the diversity of land uses within each TOPOS, has been calculated on a scale of 0–8, based on land use data obtained from the Authoritative Real Estate Cadastre Information System (ALKIS) (LGLN, 2016a; 2016b). The data consists of eight different classes, namely 1) residential areas; 2) retail and services; 3) public facilities; 4) industrial and commercial areas; 5) agricultural facilities; 6) supply facilities; 7) disposal facilities; 8) parks, sports ground and recreation (Carlow et al., 2022). A score of zero refers to settlements that comprised buildings with no functional use at the time of the study; one indicates monofunctional units while a score of eight corresponds to the highest mix of functions.

3.3.4 Infrastructure as spatial linkages

Apart from enabling flows and strengthening linkages, infrastructure affects the spatial structure and organization of territorial units across regions. While infrastructure can physically divide areas or separate functions at the local scale, it can connect and integrate settlements into a network to improve economic activities and cohesion at the regional scale (Wandl et al., 2014; OECD, 2020). In this regard, two measures of accessibility were considered. Distance to the nearest regional train station was included as a proxy for the settlement's accessibility and as a variable that reduces land take and land conversion processes in the context of a region (Kretschmer et al., 2015). Given the causal relationship between proximity to motorways and urban growth (Müller et al., 2010), distance to the nearest highway exit was also included. Data on rail infrastructure was obtained from Deutsche Bahn (DB, 2013; 2016) and Connect (2019). Overall, the data was compiled, merged and analyzed using ArcGIS10.6 (ESRI, 2018).

3.4 Spatial autoregressive models

We initially used an ordinary least squares regression approach (OLS) that regresses the built area and the variables previously described. A multicollinearity test showed that the variance inflation factor (VIF) values ranged between 1.09 and 4.00 but exceeded 10 for apartment buildings, terraced and multi-family housing. Low-density developments, including single family and terraced houses, refer to detached or semi-detached structures, with one or two dwellings. Due to the similarity between single family and terraced houses, we initially combined the variables. However, multicollinearity was still detected and terraced housing was ultimately eliminated. To test for spatial dependence, Moran's I statistic was applied and revealed a positive spatial autocorrelation 0.034 (p-value < 0.020) for the OLS model. In the case of spatial dependence, spatial regression models are typically used given their capacity to account for spatial effects (Anselin, 1988; LeSage and Pace, 2009). Therefore, we applied two spatial regression models, namely a spatial lag model (SLM) and a spatial error model (SEM). The SLM model assumes that dependencies exist directly among the levels of the dependent variable (Golgher and Voss, 2016). The SEM model assumes that the autoregressive process occurs in the error term (Fischer and Wang, 2011). The Lagrange multiplier (LM) test was also used to test for spatial dependence in the models. The SLM model is expressed as:

$$y = X\beta + \rho Wy + \varepsilon$$

where y is the n[MediumSpace]×[MediumSpace]1 vector of the built area (log-transformed) for each study unit, X is the n ×[MediumSpace] p matrix of explanatory variables; β represents the regression slope coefficients in a p[MediumSpace]× [MediumSpace]1 vector; Wy denotes the spatially lagged dependent variable for weights matrix W; ρ is the spatial autocorrelation coefficient; and ε is the vector of error terms.

The SEM model is expressed as:

$$y = X\beta + \lambda W\mu + \varepsilon$$

where λ refers to the average spatial correlation among the errors (conditional on W); W is the weight matrix and μ is the spatial error term. We used an inverse-distance spatial-weighting matrix of power one. The spatial weights matrix was row standardized. We conducted k nearest neighbors analysis (k – 5). A 5 × 5 nearest neighbors matrix was found to be the most robust weighting scheme that best reflected the distribution of settlements in the study area. The research methods are further explained in Figure 2.

4 Results

4.1 Data analyses

We analyzed a total of 1,245 TOPOI with a wide range of characteristics (Table 1). Statistical analyses were performed using R 4.1.1. Table 2 presents the results of the analysis for all models. In both the SLM and the SEM models, we found a positive effect of population density where an increase of one inhabitant per hectare corresponded to an increase of 0.05 in the built up area per TOPOI. The share of residential buildings, which was found to be statistically significant, was negatively associated with the built area in both models (SLM = –[MediumSpace]0.8767 and SEM = –[MediumSpace]0.8047). While a negative but significant association was found between the distance to the nearest highway exit and the built area in the OLS model (–0.0658), the variable was not statistically significant across the SLM and SEM models (Table 2). All building types' relation to the built area was statistically significant across the models, except for multi-family housing.

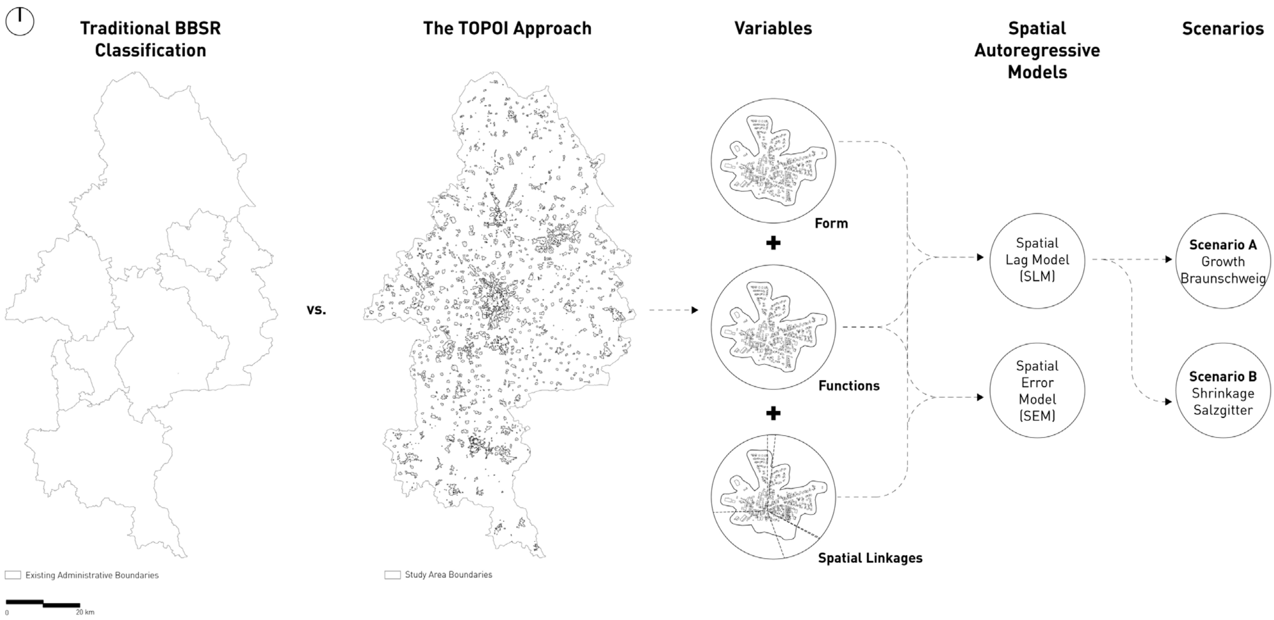

FIGURE 2
Flowchart explaining the research methods used in the study.

TABLE 2 Ordinary least squares and spatial model results (n = 1,245).

	OLS	SLM	SEM
rho	—	0.0514	—
		(0.0263)	
Population density	0.4600***	0.0520***	0.0526***
	(0.0450)	(0.0051)	(0.0050)
Functional mix–One function	0.5540	0.5524	0.6449
	(0.3641)	(0.3611)	(0.3534)
Functional mix–Two functions	0.8998*	0.8947*	0.9962**
	(0.3660)	(0.3630)	(0.3560)
Functional mix–Three functions	1.4551***	1.4464***	1.5507***
	(0.3699)	(0.3669)	(0.3585)
Functional mix–Four functions	2.2656***	2.2618***	2.3408***
	(0.3742)	(0.3711)	(0.3641)
Functional mix–Five functions	2.5985***	2.5941***	2.7225***
	(0.3740)	(0.3709)	(0.3638)
Functional mix–Six functions	3.1050***	3.0949***	3.2052***
	(0.3730)	(0.3700)	(0.3624)
Functional mix–Seven functions	3.5297***	3.5238***	3.6082***
	(0.3717)	(0.3687)	(0.3619)
Functional mix–Eight functions	3.6567***	3.6579***	3.7404***
	(0.3810)	(0.3778)	(0.3706)
Distance to nearest train station	−0.0234	−0.0033	−0.0041
	(0.0254)	(0.0055)	(0.0071)
Distance to nearest highway exit	−0.0658*	−0.0043	−0.0052

(Continued on following page)

TABLE 2 (*Continued*) Ordinary least squares and spatial model results (n = 1,245).

	OLS	SLM	SEM
	(0.0258)	(0.0024)	(0.0031)
Vacancy	0.0476	0.0091	0.0045
	(0.0259)	(0.0049)	(0.0048)
Building Type—Apartment blocks	−0.1927**	−0.5719**	−0.5368**
	(0.0623)	(0.1833)	(0.1794)
Building Type—Multi-family houses	0.1167	0.0211	0.0180
	(0.0713)	(0.0131)	(0.0128)
Building Types– Single family houses	0.3904***	0.0638***	0.0659***
	(0.0409)	(0.0065)	(0.0064)
Share of residential buildings	−0.3230***	−0.8767***	−0.8047***
	(0.0347)	(0.0941)	(0.0931)
R^2			
	0.7957	0.7963	0.8063
AIC	—		
		3,168.3092	3,122.9155
Log	—		
		−1,565.1546	−1,542.4577

More specifically, apartment buildings were found to be significant and negatively related with the built area. In contrast, single-family housing was positively associated and highly significant confirming the notion that single and detached dwellings typically require more land. While the distance to the nearest train station was not significant in our study, functional mix was positively associated, where a higher number of functions corresponded to an increase in the built area. Generally, functional mix coefficients across settlements with three or more functions were found to be highly significant in our study across all models. However, monofunctional settlements were not statistically significant. Overall, the coefficients were higher in the SEM than the SLM model across all ranges (Table 2). We still found evidence of spatial auto-regression after accounting for all explanatory variables used in the SLM model (rho = 0.0514). The Akaike's information criterion (AIC) values of the SEM model (3,122.9155) did not vary considerably from the ones of the SLM model (3,168.3092) indicating that the fit did not improve by allowing for auto-correlation in the error term. Overall, the parameters of the SLM were between −0.0033 and 3.6579 and those of the SEM were between −0.0041 and 3.7404 denoting similar parameter ranges when comparing the two models.

4.2 Scenarios of growth and shrinkage

We used our SLM model to predict how areas might develop under different scenarios for population change. For the growth scenario, we considered the Braunschweig settlement unit as an example. The selected Braunschweig TOPOS is characterized by the highest population density among all settlements in our study (43.52 inh/ha), a high diversity of functions (eight functions), and a proximity to the regional train station (2.67 km). The settlement consists largely of multi-family houses (45.36%) along with a variety of other types: 23.97% single family houses; 27.67% terraced houses and 3.03% apartment buildings. Almost half of the building stock is dedicated for residential uses (share of residential buildings = 0.52) and the vacancy rate is low (3.06%). With the diversity of research and education institutions, the population in Braunschweig is expected to grow by 5% till 2030 (LSN, 2020b). University towns attract large numbers of students and induce positive effects on local employment, population development and the provision of local amenities. While the moderate growth of the city was identified as a potential to be addressed in future plans, the amount of built area required to accommodate this population change remains unclear. Increasing the population density by 5%, our study predicted an increase in the built area by 12%. While the average spillover effects in surrounding neighborhoods seemed negligible (0.12%), these effects mirror potential processes of suburbanization and sprawl.

Similar to the Braunschweig, Lebenstedt settlement unit, has a high population density (41.90 inh/ha) and a mix of functions (eight functions). Given its smaller area, the settlement is more proximate to the regional train station (1.08 km) compared to the Braunschweig settlement. Lebenstedt has an equal share of multi-family and terraced houses; a negligible percentage of apartment buildings (0.77%) and a low percentage of single family houses (14.84%). Almost 60% of the building stock is residential with a higher vacancy rate than that of Braunschweig (5.70%). Due to the ongoing population loss, ageing, and out-migration, Salzgitter has suffered inadequate access to services and amenities with predictions of 30% population decline by the year 2030 (LSN, 2020b). Correspondingly, our model predicted a decrease in the built area by 48.02% (with a population loss of 30% for the settlement unit). The decrease, which corresponds to half of the built area, may indicate a rise in vacant buildings and abandoned plots. However, shrinkage is negligible in surrounding areas reaching up to 0.70%.

5 Discussion and conclusion

This study compared two spatial models and predicted urbanization patterns across one small and one medium-sized town in Lower Saxony, Germany. Our findings aligned with previous studies that emphasized the highly significant and positive influence of population density on land take (Martinuzzi et al., 2007; Behnisch et al., 2016). Contrary to numerous studies that assumed a causal relation between proximity to central train stations and urban growth or land conversion (Padeiro, 2014), our study found no significant effect of distance on the amount of built-up area. However, our OLS model revealed a significant influence between the proximity to the nearest highway exit and the built area. These findings are in accordance with Müller et al. (2010) who demonstrated that the further a settlement is to the highway exit, the lower is the land take. The negative relation between apartment blocks and the built area (SLM = –[MediumSpace]0.5719 and SEM = –[MediumSpace]0.5368), which was found to be significant, confirms established notions that high-density developments conserve land (Towers, 2002; Glaeser, 2011). A corollary of these building types is a high population density per unit area (Hu et al., 2021). In contrast, single-family dwellings, which were highly significant in our study, positively influenced land take. Our findings aligned with previous studies reported by Ewing (2008) and Peiser (1989) that asserted an increase in land take due to low density developments. Moreover, a high share of residential buildings decreased the built area by 0.8767 in the SLM and 0.8047 in the SEM. In Germany, residential buildings have a share of 87.5% of the total building stock (DENA, 2019). Since the share of residential buildings and the building types significantly influenced the land take in our study, a thorough understanding of the urban fabric and its dynamics is recommended, particularly at the local scale. In this regard, further research is needed for small and medium-sized towns experiencing positive population developments, re-urbanization trends or processes of urban restructuring and shrinkage that stimulate or diminish housing demand, respectively, and impact urban form. In effect, these demographic changes and their ensuing spatial developments can have implications on future planning and policy in small and medium-sized towns.

While 26.02% of the settlement units in our study can be characterized as monofunctional areas, 69.80% of the settlement units accommodated three or more functions. Our results are similar to findings from Wandl and Hausleitner (2021), who concluded following the analysis of dispersed areas, or territories in between, across four European countries, that these areas are mixed—contrary to prevalent assumptions that presume monofunctionality. In accordance with previous studies that correlated functional mix and sprawl (Abdullahi et al., 2015; Lan et al., 2021), our study showed that functional mix significantly influenced the amount of built area, where the higher the diversity of functions, the higher the coefficient of the variables. Compared to monofunctional TOPOI, functionally diverse TOPOI (up to 8 different uses) increased the built area by 3.6579 for the SLM and 3.7404 for the SEM. Given functional mix's strong influence on the amount of built area, further research is needed to understand its implications on sustainable urban development. This is particularly relevant for small and medium-sized towns since their role, functions and socio-economic development have largely been neglected in literature with misleading assumptions that these areas are predominately monofunctional. Indeed, prevalent assumptions restricted the role of small and medium-sized towns to merely supporting major urban centers or hosting "productive, extractive, circulatory and informational infrastructure" with expansive requirements for land that would otherwise be expensive in large cities (Brenner and Katsikis, 2020, 27; Gareis and Milbert, 2020). Therefore, a thorough understanding of small and medium-sized towns' functional mix is necessary. Such an understanding supports the design of local development strategies and policy approaches by providing insights into small and medium-sized towns' potential role and contribution to the development of the region.

As Salzgitter continues to suffer from population decline, our study revealed a dramatic decrease in the built area (approximately 48%) in the selected TOPOS signaling a rise in vacant spaces, abandoned plots and demolished buildings. The population decline can also induce changes in the population structure, such as population aging, and erode the town's economic base (You et al., 2021). With further population influx, land take is expected to persist in the Braunschweig TOPOS (approximately 12%) with potential impacts on surrounding areas. Hence, stringent planning regulations are required to limit expansion further out and provide housing opportunities in inner areas. Further research can also investigate new building types and regulations that improve the quality of life while allowing for higher densities. Given these concurrent changes, flexible planning frameworks and multi-level governance systems that support bottom-up and multi-scalar initiatives are required to promote adequate spatial strategies and alleviate the repercussions of land take in small and medium-sized towns. While this study has not addressed the effectiveness of postindustrial transformation processes and policies for shrinking towns, the predicted decline in the amount of built area in Lebenstedt may be indicative of the need to alter local planning cultures to sustainably manage and repurpose potentially vacant areas. In this regard, smart shrinkage frameworks and form-based codes can be implemented to capitalize on the industrial and cultural history of the town. In addition, proactive policy schemes that diversify and foster innovative activities as well as a research and development (R&D) infrastructure, are key for deindustrializing areas (Bartholomae et al., 2017). Other approaches to address shrinkage in the small towns can focus on place-oriented transdisciplinary solutions to explore potentials and respond to challenges. Above all, planning strategies for small and medium-sized towns become more effective once a better understanding of the specificities of these towns is achieved.

While many traditional methods delineated settlements with reference to population thresholds and a limited number of measures, the TOPOI method classified settlements based on a fine-grained analysis of the built environment. Through equally weighted indicators that depicted accessibility, function and form, the novel method contributed towards a thorough understanding of dispersed settlements and challenged inherited urban-rural binaries. Despite following a territorialist approach, the TOPOI method considered the limitations of other approaches and offered an overview of the variety of settlement types. Contrary to conventional federal classifications (c.f. BBSR, 2018), which are based on simplistic generalizations and thus a limited number of classes, the TOPOI method revealed the heterogeneity of the settlements across the region and provided detailed insights into their characteristics. More specifically, variegated settlements with comparatively high population densities, connectivity and functional mix are delineated as Node towns, Periurban Towns or Exo-satellite towns according to the TOPOI method yet categorized as rural areas based on the BBSR method. The TOPOI method can be applied across different regions to understand urbanization patterns and the settlement structure. In this regard, comparative research using the TOPOI method can help capture the specificities of different dispersed territories, their complexities, and diversity of spatial configurations. A comparative approach can also contribute to understandings of small and medium-sized towns across different contexts and form the basis for further research on their political, economic and cultural differences.

This study has a number of limitations. Since socio-economic factors are major drivers underlying urbanization processes, their understanding is key to designing effective strategies (Couch et al., 2005; Lauf et al., 2016). Due to limited data availability for small and medium-sized towns, the study covered a small number of drivers and lacked influential socio-economic variables, such as age groups (Sander, 2014), and income (Kabisch et al., 2019), as well as historic land use data, which largely contributes to and affects socio-spatial processes. Accounting for additional socio-economic, environmental and demographic drivers can yield more accurate estimates of land take. Within this study, the TOPOI method was implemented, where designated settlements were considered as spatial reference units. While this method abandons conventional analysis restricted to administrative boundaries, it poses challenges regarding the aggregation of data to the TOPOI level. More specifically, data on the variables, which was reconstructed at the TOPOI level, was initially derived from various sources that offered different spatial resolutions. The aggregation to spatially defined boundaries can result in biases and errors related to the modifiable areal unit problem (MAUP). The MAUP can affect the consistency of the results and shape the outcomes of the analysis.

Future research can potentially couple spatial autoregressive models with cellular automata and machine learning approaches to better simulate and understand the dynamics of future developments. In addition, future studies could also merge predictive and simulation models, such as SEM and SAR, with scenario planning approaches to inform and substantiate the design of scenarios and planning instruments. Finally, multidimensional and multi-scale analysis that take into consideration the temporal dynamics of small and medium-sized towns could potentially yield better results and a comprehensive understanding of their future land take patterns.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

GJ, OM, and VC contributed to the study conception and design; AK contributed to the analysis and interpretation of results; GJ prepared and wrote the original draft; OM, AK, and VC reviewed and edited the manuscript.

Funding

This work was supported by the Ministry for Science and Culture of Lower Saxony, Volkswagen Foundation (grant number ZN3121).

Acknowledgments

The authors would like to thank Dr. Sebastian Juhl for his insightful comments and substantial support in the analysis of the data. The authors sincerely acknowledge the constructive comments of two reviewers which substantially improved the quality of the article. The authors also acknowledge the financial support of the Open Access Publication Funds of the Technische Universität Braunschweig.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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