INFILLING IN GERMAN CITIES. ANALYSING THE EXTENT AND SPATIAL DISTRIBUTION OF INFILLING AND ITS EFFECTS ON **HOUSING DENSITY BETWEEN 1991 AND 2011**

SEBASTIAN EICHHORN

With 7 figures

Received 30 January 2024 · Accepted 13. May 2024

Summary: Infilling is considered one of the most important planning principles worldwide to reduce urban growth and urban sprawl. This also applies to Germany. However, due to a lack of nationwide small-scale data, there are hardly any empirical findings on how infilling has taken place in German cities. Using a newly developed GIS-based algorithm and small-scale data on residential construction activity (100x100m grid cells) and built-up areas, we analyse how residential development has evolved in 30 German case studies over a study period from 1991 to 2011. Within concentric 1km rings, our analysis differentiates residential construction activity by infilling, building types, land cover and housing density. Using cluster analysis, we further group the case studies into more homogeneous groups. The findings show that infilling has been pursued and implemented by most of the case studies since the 1990s. However, it becomes clear that there are large differences in the extent of infilling and that it does not necessarily lead to an increase in housing density. The findings show - in addition to national regulations and guidelines as well as population development - that it is primarily the structural framework conditions, the specific commitment of the municipalities as well as local and regional challenges that determine the type of residential construction activity.

Keywords: Infilling, residential construction activity, GIS analysis, evaluation, Global Human Settlement Layer (GHSL), census

1 Introduction

Urban growth and urban sprawl are important topics in today's world as the global population continues to urbanise (GERTEN et al. 2019). On the one hand, urban growth refers to the growth of urban areas through the take-up of surrounding natural lands. On the other hand, urban sprawl refers to low-density development of land that results in dispersed cities. This pattern of development is often marked by single-use zoning, limited public transportation options and increased dependence on cars. Both urban growth and urban sprawl can result in negative externalities, such as increased air and water pollution, traffic volume and loss of green space (BEHNISCH et al. 2022).

It is, therefore, not surprising that resource-efficient urban development has long been a central issue in spatial planning and growth management on various levels of action around the world (EWING et al. 2022, SIEDENTOP et al. 2022). The European Commission, for example, has repeatedly emphasised the importance of reducing urban growth in its strategic documents on environmental and sustainability policy issues (see, e.g., EUROPEAN COMMISSION 2006, EUROPEAN COMMISSION 2011). In Germany,

discussion about reducing urban growth and urban sprawl can be traced back to the 1960s (SIEDENTOP 2008). Here, terms such as land consumption and urban sprawl were already used in early political agendas including the Green Charter of Mainau and the first environmental programme of the German Federal Government (DEUTSCHER BUNDESTAG 1971). However, a general turnaround in urban land use change only became apparent in the early 1980s as a response to disproportionate urban growth and a crisis in inner-city development (BMI 1985).

Infilling is considered a key strategy to counteract the negative externalities of dispersed urban growth (EICHHORN et al. 2021). It involves the development of vacant or underutilised land within existing urban areas, making use of existing infrastructure, transportation systems and resources. Potential areas may be gaps between buildings, sites with suboptimal urban land use and restructuring or densification potential, brownfields formerly used for commercial or traffic purposes, former rail facilities or airports and military conversion sites as well as the conversion or reuse of existing buildings (REISS-SCHMIDT 2018). On the one hand, studies have shown that infilling can lead to higher economic growth, better access to public transportation, reduced reliance on private

cars and a reduced need for new greenfield development (MOURATIDIS 2018, HORTAS-RICO & SOLÉ-OLLÉ 2010, EWING & CERVERO 2017). On the other hand, however, studies have also shown that it can result in increased traffic congestion, higher housing costs, downsizing of cold air corridors, more urban heat islands and the displacement of low-income residents (THORNE et al. 2017, CHAKRABORTY et al. 2021). Although BERGHAUSER PONT et al. (2021) show that positive effects predominate, corresponding side effects must be carefully taken into account when planning infill and densification measures.

In Germany, infilling is an important planning principle. Since 2002, as part of Germany's first sustainability strategy, the construction of new housing units should be realised at a ratio of 3:1 in favour of infill over greenfield development (DIE BUNDESREGIERUNG 2021). Since then, there have been a number of legislative changes to strengthen infilling and speed up the mobilisation of potential development sites (e. g. Section 1a BauGB and Section 13a BauGB). Although there is a consensus at federal level that infilling is of key importance for increasing existing housing densities and reducing urban sprawl, there are hardly any analyses on whether residential construction activity has actually been concentrated on the existing settlements and whether this has led to higher housing densities. Due to the databases used (e.g. settlement area, population, official building completion statistics), most studies in the German context - but also in other parts of the world - are limited to their municipal level and to analyses of citywide or regional development trends.

We want to address this research gap by using the Global Human Settlement Layer (GHSL) and the 2011 Building and Housing Census (STATISTISCHES BUNDESAMT 2010, CORBANE et al. 2019). Together, these two datasets offer the opportunity to gain insights into the development of infilling at a level of detail that goes beyond previous studies. In particular, by using the 2011 census, we are able - in comparison to studies using land use data - to analyse infilling on the basis of housing units and building types and examine how infilling developed at submunicipal level in Germany between 1991 and 2011 and how this is related to changes in housing density.

To apply this, we use the context of German higher-order centres. These are bigger cities that offer important services to their local and regional population. Using this group of more homogenous cities as case studies, we develop a method to measure infilling and the change in urban density. Besides the quantitative analysis of residential construction activity, Germany as well as the period under study offer the opportunity to examine qualitatively how cities developed in the context of the German reunification in 1990 under radically changed political and planning conditions and whether different urban strategies emerged between eastern and western German cities. We, therefore, analyse existing studies and planning documents and discuss development trajectories and possible drivers of infilling and densification in our case studies.

In section 2, we introduce the state of research on the measurement of infilling, focusing on the European context. After that, we present our own methodology to analyse the share of infill and greenfield development and the trends in housing density at a sub-municipal level. In Section 4, we present our results. Following a reflective discussion of the findings in section 5, we draw a conclusion and give an outlook on the need for further research in section 6.

2 State of research – Measuring infilling

Analyses of infilling are designed as ex-post evaluations and deal with the classification and quantification of construction activity. They are designed as longitudinal analyses and provide information on the spatio-temporal development patterns of the construction activity of a specific area. Due to the data available, existing, and especially international comparative studies, have primarily used land use data to examine infilling. Here, geospatial analyses are frequently used to examine the development of urban densities as well as to check whether new built-up patches were developed within, adjacent to or apart from existing built-up areas. Results suggest that - although usually occurring together with other growth types, such as edge-expansion and leapfrog development (NOVOTNÝ et al. 2022) infilling is more characteristic of cities in the Global North (CHAKRABORTY et al. 2022b). However, despite an increasing consolidation of urban centres in recent decades (GERTEN et al. 2019), infilling does not necessarily contribute to an increase in existing densities due to high initial densities in these cities (CHAKRABORTY et al. 2022b).

Although studies have come to similar conclusions on the basis of very large samples in some cases, it must be noted that the analysis of infilling using land use data is not the most appropriate way to draw firm conclusions about stock-oriented residential construction activity. On the one hand, land use data

rarely has a sufficiently high resolution to capture structural change processes on a small scale and, on the other hand, it does not contain information on the number of new buildings or housing units. As a result, two new development sites of the same size - if they have similar spatial locations - would be assessed identically, although the number of buildings and housing units may differ significantly. So, results provide a comprehensive overview of local, regional and global spatio-temporal patterns of urban land use change. However, it is not possible to analyse whether this land use change (e.g. infilling) has led to an increase in urban density. To be able to analyse how infill measures actually materialise spatially and how patterns of residential construction activity differ across cities, small-scale building data are essential.

In the European context, there are only a few studies that have investigated settlement development on the basis of small-scale building data: GÖTZE & JEHLING (2022) analysed densification processes in the city regions of Utrecht (NL) and Bern (CH) between 2011 and 2019. Based on the morphological and sociodemographic context, they identify five densification types and come to the conclusion that large-scale densification projects occur more often in Utrecht than Bern due to active land policy. In two Dutch studies, small-scale topographical raster data were used and intersected with high-resolution building and dwelling data (BROITMAN & KOOMEN 2015, CLAASSENS et al. 2020). The authors show that in the 2010s there were significant densification processes in the existing settlements in the Netherlands, although national policies to promote housing were phased out at the same time. BIBBY et al. (2020) were able to link data from the English Land Use Change Statistics with address data provided by the UK's Post Office. They show that a large part of the housing construction volume in the first decade of this century contributed to densification of existing settlements. MUSTAFA et al. (2018) used Belgian cadastral data to generate four classes of built-up areas to analyse the transitions between different densities between 1990 and 2010. Findings highlight the centrality of zoning policies in explaining expansion processes, especially in the case of high-density expansions. In contrast, physical and neighbourhood factors play a larger role in the implementation of dense infill measures.

In Germany, studies measuring infilling remain the exception, due to limited data availability, especially for older and longer time series. Currently, there are only two studies that have used small-scale building data to determine shares of infilling for large study areas (EICHHORN & SIEDENTOP 2022a, EICHHORN & SIEDENTOP 2022b). Another study captured infilling in the context of the city region of Karlsruhe (JEHLING et al. 2018). Although there are considerable differences in the implementation of infill measures between urban and rural regions, results show that infilling has gained in importance in Germany since the 1980s. To date, other German studies, including surveys and GIS analyses, have focused primarily on identifying infill development potential (SCHILLER et al. 2021, BBSR 2022).

3 Data and Methodology

3.1 Input data

To analyse the trends in housing density and the share of infill and greenfield development at a submunicipal level, small-scale input data are required. On the one hand, data are needed to differentiate between inner urban areas and outer undeveloped areas. On the other hand, small-scale data on housing stock and residential construction activity are needed to calculate housing densities and to check whether new housing units were built inside or outside existing settlements. Regarding the built-up areas, we use the GHSL. The GHSL is a freely available, remotely sensed dataset on developed and undeveloped land that covers the entire surface of the earth. The built-up areas are derived from Landsat satellite data with native spatial resolutions of 80 metres (Landsat MSS sensor), 30 metres (Landsat TM sensor) and 15/30 metres (Landsat ETM sensor) (CORBANE et al. 2019). The final dataset is provided free of charge by the European Commission at a spatial resolution of 30 metres for 1975, 1990, 2000 and 2014. As for small-scale housing stock and residential construction activity, data from the Building and Housing Census 2011 meet our requirements. This nationwide dataset is based on the results of the 9 May 2011 Census and is available at the level of 100m grid cells with address-specific geo-coordinates (STATISTISCHES BUNDESAMT 2010). To further analyse on which land uses the residential construction activity has taken place, we use the Europe-wide harmonised CORINE Land Cover dataset (EUROPEAN COMMISSION 2023). It consists of an inventory of land cover in 44 classes, uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and is available for 1990, 2000, 2006, 2012 and 2018.

3.2 Data processing

To analyse the trends in housing density and the share of infill and greenfield development, we use an algorithm developed in ArcGIS. The algorithm processes the input data in ten steps calculating housing densities for 1990, 2000 and 2011 as well as the share of infill and greenfield development for the study periods 1991-2000 and 2001-2011 using 1 km multi-ring buffers starting at the town hall. Since the majority of town halls are located in the centre of European cities, they provide comparable starting points for our analysis. Test calculations with both wider and thinner rings (e.g. 200 m or 2 km) produced less interpretable results. Wider rings masked important small-scale information, for example. Thinner rings have partly led to rings without residential construction activity. In the end, 1 km rings turned out to be a suitable compromise between an appropriate level of detail and the possibility of a meaningful interpretation of the results. The calculation steps are described below and visualised in Figure 1 (for better readability, the text is structured with numbers, which are also included in Fig. 1).

Residential built-up areas: (1) Since the GHSL dataset only distinguishes between built-up and nonbuilt-up areas, the first two steps are used to capture all built-up areas for residential use. As industrial and commercial areas would otherwise also be included in the calculation (although no residential development is allowed), this step is necessary to obtain correct housing densities. To obtain a mask to cut out the residential built-up areas, we extract all 100m grid cells with housing units built before 1990, 2000 and 2011 from the Census dataset by using the information on the year of construction contained in the metadata. According to the feature description, the year of construction means the year in which the building was completed. In the case of completely destroyed and reconstructed buildings, the date of reconstruction is considered the year of construction. Then, all grid cells are grouped into contiguous multipart polygons, aggregated with an aggregation distance of 150m and adjusted with a smoothing tolerance of 250m. Different values were tested. However, the best results were obtained with the given values. (2) To preserve residential built-up areas, the built-up areas of the GHSL in 1990, 2000 and 2014 are intersected with the residential areas in 1990, 2000 and 2011. (3) Moreover, we intersect the residential built-up areas with the 1 km rings to get residential built-up areas per ring.

Housing density: (4) Next, we intersect the housing stock in 1990, 2000 and 2011 with the 1 km rings to get the housing stock per ring. (5) To determine the housing density per ring, we divide the extracted housing stock by the residential built-up areas, giving us 1 km density gradients.

Infill and greenfield development: (6) In addition to housing density, we also identify the residential construction activity by building type (e.g., detached houses and apartment blocks). To do this, we extract all newly built housing units between 1991 and 2000 as well as 2001 and 2011 again using the information on the year of construction contained in the metadata. (7) To separate residential construction activity into infill and greenfield development, a geographic information system (GIS) is used to check whether the centroids of the 100m grid cells, in which new housing units were built, are located within the residential built-up areas or not. In doing so, according to German planning law, building projects in development plan areas (Section 30 BauGB) and within contiguously built-up settlement areas (Section 34 BauGB) are approximately captured. The information on building types not only allows us to capture the housing units realised as infill or greenfield development, but also to analyse whether the housing units were built in detached houses or apartment blocks.

Housing density in the surroundings and previous land use: (8) In a further step, we capture the housing density in the surroundings of the newly built housing units. Therefore, we count the already existing housing units in all neighbouring 100m grid cells (N=8) and in the grid cell under consideration. This allows us to check whether the construction of detached houses and apartment blocks is influenced by the existing housing densities in the surroundings. (9) Furthermore, we use the CORINE land cover dataset (CLC) to analyse for which land uses the new housing units were built. To do this, we utilise the status layer for 1990 and 2000 and intersect them with the residential construction activity. (10) In a final step, we intersect the residential construction activity with the 1 km rings to obtain the residential construction activity per ring. This provides information about the building types, the housing density in the surroundings and the previous land uses.

Since residential construction activity falls under municipal planning sovereignty and cities themselves decide on the type and location of their residential development, we calculate the housing density and residential construction activity exclu-



Fig. 1: Workflow diagram with processing steps

sively within the city boundaries – in contrast to other studies where multi-ring buffers run across city boundaries (BROITMAN & KOOMEN 2020, MOHAJERI et al. 2023). To do this, we cut out the multi-ring buffers using the respective city boundaries. This leads to different radii in the analysis (from 6 to 18 km) – depending on the territory of the city.

3.3 Cluster analysis

Finally, we apply a hierarchical cluster analysis to group our case studies according to their characteristics of residential development and to uncover latent structures and similarities. This facilitates a deeper understanding of the relationships between various residential development parameters (CHAKRABORTY et al. 2022a). Based on the data processed and obtained by our algorithm, we use the following indicators – aggregated at city level – for our cluster analysis.

- New housing units per 1,000 existing housing units
- Share of new housing units realised as infilling
- Share of new housing units built in detached houses
- Share of new housing units built on commercial and industrial sites. Industrial, commercial and transport units are based on the CLCnomenclature including industrial or commercial units, road and rail networks and associated land, port areas and airports.
- Share of new housing units built in the city centre. Depending on the size of the municipality, city centres comprise 1 to 4 km rings.
- Average density in the surroundings of new housing units

We assume that we can use these indicators to capture general development trends in residential construction activity, as they reflect various aspects, such as the intensity and type of new residential construction, spatial distribution patterns and the development of urban density. Technically, the cluster analysis groups the sample in such a way that the variance of indicators within the clusters is minimal and between the clusters maximal. The indicators are z-standardised to keep the weighting of all indicators equal. The clusters are formed using Euclidean distance measurement and the Ward fusion method. It must be noted that the indicators obviously cannot cover all factors relevant to residential development. Therefore, we interpret our results in Section 5 qualitatively, taking into account the social and political context in Germany in the 1990s and 2000s. Consequently, we analyse existing studies and relevant planning documents from our case studies to gain a better understanding of the reasons for the measured characteristics of our indicators.

3.4 Case study selection

The algorithm is applied to case studies in Germany. To do so, the selection process is based on three criteria: First, only bigger cities that offer important services to the local and regional population ("higher-order centres", N=140 in 2019) are considered in the selection process (GREIVING et al. 2022). This criterion produces a more homogeneous sample against the background of the spatial relevance of the potential case studies. However, case studies can still differ greatly in size from one another, as higher-order centres in Germany are determined normatively by the state planning authorities with no standardised definition of size.

Second, the selection process takes into account shrinking, stagnating and growing case studies, as different demographic trends can have significant impacts on residential construction activity (WOLFF & WIECHMANN 2018). Therefore, we determine the average population growth between 1990 and 2010. Based on threshold values of $0.\overline{3}$ and $0.\overline{6}$, three equally sized groups are formed, representing groups for decline, growth and stagnation (see value range in Fig. 2). To focus on the average cases in these groups, the highest 10% are filtered out from both the "decline" and "growth" groups. In the "stagnation" group, the highest and lowest 5% are filtered out. As a result, the "growth" and "decline" groups contain 42 potential case studies, while the "stagnation" group contains 40 potential case studies.

Third, we select ten case studies from each of these groups. We try to achieve a balanced spatial distribution so that any spatial patterns and characteristics across Germany will become visible (e.g. East and West Germany). Compared to a small number of case studies, a sample of 30 case studies allows us to better identify differences or similarities and also increases the reliability of the findings. The final 30 case studies are shown in Figure 2, including information on the city size and the population trend between 1990 and 2010.



Geodata basis: GeoBasis-DE/BKG 2019 Data basis: Federal Statistical Office and the statistical offices of the Länder, Germany, 2018



4 Results

Figure 3 shows the absolute number of new housing units per 1,000 existing housing units by 1 km ring and study period. First and foremost, the significantly higher residential construction activity between 1991 and 2000 is striking. This finding applies to all case studies. Regarding population growth as well as East and West Germany, there is marginally higher residential construction activity in the growing case studies (comparison of the average values) and significantly higher residential construction activity in the East German case studies. Regarding the distribution of new housing units by 1 km rings, a heterogeneous picture emerges. The majority of case studies show an increase in the amount of new housing units – in relation to the housing stock – as the distance from the city



Fig. 3: Residential construction activity 1991-2000 and 2001-2011 by ring and study period

centre increases (e. g. Chemnitz, Erfurt, Nuremberg and Freiburg im Breisgau). This is particularly true for the period 1991-2000. In comparison, residential construction activity between 2001 and 2011 is more or less evenly distributed across the 1 km rings (except for example in Magdeburg, Nuremberg and Würzburg). The particularly high construction peaks in some rings of the case studies are noteworthy, both in the 1990s and in the 2000s. Here, the cities of Hof, Leipzig, Würzburg and Münster should be highlighted.

In the majority of case studies, the share of infilling in total residential construction activity decreases gradually with increasing distance from the city centre (Fig. 4). Nevertheless, there are also case studies where infilling remains at a similar level throughout the entire area of the city (e.g. Dortmund, Düsseldorf and Munich). Increasing shares of infilling at greater distances can only be observed in individual case studies (Trier and Bayreuth). Stronger fluctuations, like a change from low to high shares or vice versa, are due to the low absolute residential construction activity in individual rings and can be observed, in particular, in the outer rings on the city boundaries. Overall, no systematic differences in the shares of infilling can be identified between our study periods. In both periods, there are individual rings in which the share of infilling is sometimes higher or sometimes lower than in the respective other study period.

Figure 5 shows the absolute change in housing density by 1 km ring and study period. Between 1991 and 2000, a moderate increase in housing density can be observed in the majority of case studies, while hardly any case study shows a significant density increase between 2001 and 2011. In numbers, the average change in housing density between 1991 and 2000 is +2.2 housing units per hectare (hu/ha) and between 2001 and 2011 it is +0.3 hu/ha. With +3.6 and +1.9 hu/ha compared with +1.7 and +0.4hu/ha, eastern German case studies show a stronger increase in housing density in both the 1990s and 2000s. Here, the cities of Potsdam (+5.7 hu/ha), Chemnitz (+4.8 hu/ha) and Leipzig (+4.6 hu/ha) stand out. Spatially, an increase can be observed mainly near the city centres. There are exceptions especially in the eastern German case studies, where densities also increase away from the city centre.

An evaluation by building types and 1 km rings shows that with greater distance from the city centre, the share of detached houses in total residential construction activity gradually increases (Fig. 6).



Fig. 4: Share of infilling by ring and study period

However, a comparison between cities shows varying slopes. With the exception of the cities of Düsseldorf, Cologne and Munich, all cities reach shares of detached houses in total residential construction activity of up to 50% to over 75% even at a short distance from the city centre. In the period 2001-2011, this increase is even more pronounced. In almost all case studies, the share of detached houses is higher than between 1991 and 2000. The analysis by housing density in the surroundings (housing weighted mean) shows - in relation to the total residential construction activity - average values of 22.1 and 24.3 housing units per hectare for the study periods 1991-2000 and 2001-2011 respectively. Differentiated by building type, the average housing densities per hectare for the study periods are 10.5 and 12.3 for detached houses and 25.6 and 30.8 for apartment blocks.

Figure 7 shows the locality, spread and skewness per indicator and cluster as well as the mean value per indicator over the entire sample. The figure allows an assessment of whether the cluster is above or below average compared to the entire sample. Both the elbow criterion and the silhouette coefficient for determining the optimal number of clusters resulted in four clusters (KODINARIYA & MAKWANA 2013).

Figure 7A shows that cluster 1 ("Residential development with no special specifics", n=14) consists of cities with below-average construction activity per 1,000 existing housing units and a below-average share of new housing units on commercial and industrial sites. Compared to the entire sample, the other indicators show rather average values. Cluster 2 ("Infilling with high density", n=9) comprises cities with a below-average share of newly built housing units in detached houses. The high share of infilling and the above-average housing density in the surroundings are striking. Cluster 3 ("High building volume with simultaneous infilling and greenfield development", n=4) is characterised by cities with above-average housing construction activity per 1,000 existing housing units, higher residential construction activity in the city centres and higher shares of new housing units in detached houses. Similar to the cities in cluster 2, cluster 3 shows higher residential construction activity on commercial and industrial sites. Infilling is low compared to the average. Cluster 4 ("Greenfield development with low density", n=3) is characterised by below-average values for infilling, the share of new housing units on commercial and industrial sites and in the city centres as well as housing density in the surroundings. In this cluster, the high share of newly built housing units in detached houses is remarkable.



Fig. 5: Change in housing density 1991-2000 and 2001-2011 by ring and study period



Fig. 6: Share of detached houses in total residential construction activity 1991-2000 and 2001-2011 by ring and study period



Geodata basis: GeoBasis-DE/BKG 2019 Data basis: Federal Statistical Office and the statistical offices of the Länder, Germany, 2018 Fig. 7: Boxplots by indicators and cluster

A heterogeneous spatial picture emerges when we map the clusters (Figure 7B). Cluster 1 represents the largest cluster and includes medium to small and more rural cities in the sample - with the exception of the cities of Dortmund and Hannover with more than 500,000 inhabitants. The cities in cluster 1 are not geographically concentrated and are spread across the entire federal territory. Cluster 2 includes very large and central cities in West and East Germany. Nevertheless, this cluster also includes the smaller cities of Freiburg im Breisgau, Nuremberg and Würzburg. The cities assigned to cluster 3 are smaller and more rural. The cities in cluster 4 are also small cities. The cities in cluster 3 and 4 are found in both West and East Germany. As Figure 7B shows, all clusters include growing, stagnating or shrinking cities. As a result, no uniform development dynamics can be identified by cluster.

5 Discussion

The findings show that the case studies were able to realise a significant share of their residential construction activity as infilling between 1991 and 2011. On average, they achieved a ratio of 3.5:1 in favour of infill over greenfield development (534,384:152,759 housing units). From the perspective of the existing 3:1 German sustainability goal, this can be seen as a positive finding, as infilling clearly outweighed greenfield development. Here, nine cities deserve special mention, as they were able to significantly exceed this target (mean of 6.8:1). At the top end are the cities of Stuttgart (10:1), Nuremberg (8.3:1) and Cologne (7.9:1). All three cities have been pursuing infilling since the 1990s based on the systematic identification, evaluation and mobilisation of infill development potential (Stuttgart Infill Development Model, *Stuttgarter Innenentwicklungsmodel*, and Cologne Vacant Building Site Programme, *Kölner Baulückenprogramm*) and the re-use of inner-city brownfield sites. So, it can be assumed that long-lasting political and planning efforts seem to have a clearly positive effect on the share of infilling.

Overall, findings by BROITMAN & KOOMEN (2015) and BIBBY et al. (2020) can be confirmed for Germany for the case studies and periods studied. However, findings also show that quite a significant part of new housing units continued to be realised on the periphery of existing settlements. The cities of Hof (0.7:1), Lüneburg (1.1:1) and Potsdam (1.2:1), for example, fell well short of the target ratio.

While EICHHORN & SIEDENTOP (2022b) found a regional urban-rural infill divide for Germany at the level of municipalities, analysis at the sub-municipal level shows that such a divide already exists within the cities and that, with increasing distance from the centres, infilling decreases from almost 100% to under 25% in some cases. Consequently, even in the case studies representative of the more densely populated and larger cities in Germany, greenfield development plays a considerable role.

The divide is basically accompanied by an increase in the number of detached houses built. While the majority of residential construction activity near the city centres is dominated by apartment blocks, detached houses reach a share of more than 75% of total residential construction activity in the outer rings of multiple case studies. Detached houses are, consequently, the dominant building form when it comes to the designation and development of new building areas on greenfield sites, in contrast to the densified building in the centres. The analysis of building types by housing density in the surroundings confirms this finding. Apartment blocks are mainly built where the housing densities are already high (28.2 hu/ha). Conversely, detached houses are built where the surrounding densities are low (11.4 hu/ha).

This is a possible explanation as to why new residential development has hardly or only slightly led to an increase in housing density. It can be assumed that new residential development has largely followed the existing housing density and has thereby only marginally contributed to higher densities. Exceptions are the eastern German cities in our study, where higher housing density increases were actually achieved in the existing settlements. It is reasonable to assume that this is due to the greater emphasis on urban renewal and the revitalisation of innercity areas in East Germany, especially in the 1990s. Excluding the eastern German cities as special cases, we conclude – in addition to CHAKRABORTY et al. (2022) – that infilling does not necessarily introduce higher densities into contexts of lower density. The construction of housing units on (former) industrial and/or commercial sites is rather rare and can only be observed on a larger scale in individual cases. The examples of the district of Fulda-Galerie (formerly Sickels Army Airfield), Freiburg-Rieselfeld (formerly Rieselfeld for sewage treatment) and Messestadt Riem in Munich (formerly Munich-Riem Airport) show that such major developments are often linked to preceding political and/or spatial specifics or path dependencies that cannot be transferred universally.

Furthermore, the findings show that residential construction activity in the 1990s was at a significantly higher level than in the 2000s (Figure 3). On the one hand, the reunification of East and West Germany led to massive investments in reconstruction and infrastructure modernisation in the former eastern German cities (ALTROCK 2022). Under the impression of housing market shortages and generally dilapidated housing stock, construction activity was massively boosted in the mid-1990s (e.g. through tax breaks, financial aid and cheap loans) (DEUTSCHE BUNDESBANK 2002). On the other hand, many people from the former East moved to the West in search of better economic opportunities and a higher standard of living, which also put pressure on the housing markets and urban infrastructure of the western German cities (OSTERHAGE 2018, DEUTSCHE BUNDESBANK 2002). Therefore, the state felt compelled to support new residential construction in the West as well (e.g. depreciation options for rental housing and social housing construction). While, in 1990, more housing units were built in owner-occupied detached houses than in apartment blocks, in 1994/95 apartment blocks outnumbered owner-occupied detached houses by 50% (DEUTSCHE BUNDESBANK 2002). Subsequently, the relatively long period of economic weakness at the beginning of the 2000s and the financial market crisis in 2008 had a dampening effect on residential construction activity in the 2000s (AKAN & SOLLE 2022, STORM & NAASTEPAD 2015). In addition, state subsidies were significantly reduced (e.g. the owner-occupied housing subsidy, Eigenheimzulage), which further dampened demand for residential construction activity (Dorffmeister 2017).

Looking at the residential development trends operationalised in our cluster analysis, the cities of cluster 1 are characterised by quite average values compared to the sample. In comparison, the cities in cluster 2 pursued a particularly heavily stock-oriented and dense housing construction. As cluster 2 comprises the largest cities in our sample, high initial densities and high land prices, but also human resources and know-how, might be strong drivers for infilling and dense housing construction. Residential construction activity concentrated on (former) industrial and commercial sites is mainly found in the cities of clusters 2 and 3. However, the variance in values suggests that this indicator only plays a subordinate role in cluster formation. Since the mean value is only slightly higher than the average of the sample, it must be assumed that the conversion of large areas is limited to cities where structural factors provide the appropriate framework conditions for follow-up activities. The residential construction activity of cities in cluster 4 is mainly driven by the construction of detached houses on greenfield sites. As cities in this cluster are located in the more rural regions, this kind of construction activity is likely to be stimulated by demand for detached houses.

The fact that all clusters were affected by growth, stagnation and decline suggests that the type of residential construction activity is not directly linked to population growth. Moreover, the cluster analysis shows no systematic differences between the eastern and western German cities with regard to the housing indicators considered. Three of the four clusters occur in both West and East Germany. Based on our research design, the type of housing construction activity is, therefore, more likely to be determined by other factors. According to EICHHORN et al. (2024), this may include patterns of action by residents, developers and investors as well as city administrations, acting under different - individually rational - interests and constraints. These factors, consequently, lead to specific forms of residential development.

The methodological approach of our study, while robust, does encounter limitations that warrant consideration. Firstly, our reliance on the GHSL for settlement delineation introduces inherent uncertainties, particularly concerning the identification of infilling and greenfield development (EICHHORN 2023). Due to potential errors within this dataset, our ability to accurately differentiate between these types of development may be compromised. Secondly, the resolution of the CORINE dataset, though widely used, is coarse, leading to uncertainties regarding the redevelopment of brownfields (EUROPEAN COMMISSION 2023). This limitation may affect the precision of our analysis, especially when examining nuanced aspects of urban regeneration and land-use change. Thirdly, our study exclusively employs quantitative indicators to analyse residential construction activity. While these metrics provide valuable insights, they inherently lack the depth and context that qualitative methods, such as interviews, could offer. Despite analysing planning documents, their explanatory power is limited compared to the insights that could be gleaned from direct engagement with stakeholders through interviews. Finally, it should be noted that our cluster analysis only takes into account a limited number of indicators that describe residential construction activity. While focusing on these indicators in this study, considering other socio-demographic and socio-economic indicators would lead to different but possibly differentiated findings.

6 Conclusion

Measurement and evaluation are essential aspects of understanding the relevance of infilling in planning and political processes. Without proper measurement and evaluation, it is difficult to assess the effectiveness of infill policies and programmes and determine whether they are achieving their intended outcomes. This study shows that freely available remote sensing data and small-scale census data can be used to measure infilling at the sub-municipal level and for a long period of time. Although this method is subject to some uncertainties (EICHHORN & SIEDENTOP 2022a), the results are plausible and (supra-)regionally comparable. The findings show that infilling has been pursued and implemented by most of the case studies since the 1990s. However, it becomes clear that there are large differences in the extent of infilling and that it does not necessarily lead to an increase in housing density. Based on the results of EICHHORN & SIEDENTOP (2022b), it can be assumed that a study with smaller and more rural case studies would have led to significantly different results. Infilling has continued to gain importance in Germany since 2011 and has been further strengthened through legislative changes. It will be interesting to see whether such political efforts have been able to expand infilling or whether German cities have now reached an upper limit. Another interesting question is whether reurbanisation trends and increasingly tight housing markets in the German metropolitan regions have driven greenfield development and dampened infilling since the 2010s. In addition to solely measuring infilling and changes in housing density, there is a need to develop reliable and valid metrics that can accurately capture the impact on various aspects of urban life, such as housing affordability, transport use and environmental sustainability. With the increasing availability of big and open data and new technologies, there is an opportunity to use innovative data sources to supplement traditional data sources and provide a more comprehensive understanding of the impacts of infilling. Moreover, the evaluation should be conducted over the long term to assess the sustainability and adaptability to the changing needs and preferences of cities. This requires the development of longitudinal studies that can systematically track changes in the impacts of infilling over time. In the German context, the 2022 Census offers the possibility to extend the current analysis for another 10 years. Comparative studies that compare the impacts of different types of infilling can help to identify best practices and inform policy decisions. These studies should be conducted across different contexts to ensure that the findings are generalisable and relevant to different cities.

References

- AKAN T, SOLLE T (2022) Do macroeconomic and financial governance matter? Evidence from Germany, 1950–2019. Journal of Economic Interaction and Coordination 17: 993–1045. https://doi.org/10.1007/s11403-022-00356-7
- ALTROCK U (2022) New (sub)urbanism? How German cities try to create "urban" neighborhoods in their outskirts as a contribution to solving their recent housing crises. Urban Governance 2: 130–143. https://doi.org/10.1016/j. ugj.2022.04.001
- BBSR (Federal Office for Building and Regional Planning) (2022) Bauland- und Innenentwicklungspotenziale in deutschen Städten und Gemeinden. Bonn. https:// www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/ bbsr-online/2022/bbsr-online-11-2022-dl.pdf
- BEHNISCH M, KRÜGER T, JAEGER JAG (2022) Rapid rise in urban sprawl: Global hotspots and trends since 1990. PLOS Sustainability and Transformation 1: e0000034. https://doi.org/10.1371/journal.pstr.0000034
- BERGHAUSER PONT M, HAUPT P, BERG P, ALSTÄDE V, HEYMAN A (2021) Systematic review and comparison of densification effects and planning motivations. *Buildings and Cities* 2: 378. https://doi.org/10.5334/bc.125
- BIBBY P, HENNEBERRY J, HALLEUX J-M (2020) Under the radar? 'Soft' residential densification in England, 2001–2011. Environment and Planning B: Urban Analytics and City Science 47: 102–118. https://doi. org/10.1177/2399808318772842

- BMI (Federal Ministry of the Interior) (1985) Bodenschutzkonzeption der Bundesregierung. Bundestags-Drucksache. Bonn.
- BROITMAN D, KOOMEN E (2015) Residential density change: Densification and urban expansion. *Computers, Environment and Urban Systems* 54: 32–46. https://doi. org/10.1016/j.compenvurbsys.2015.05.006
- BROITMAN D, KOOMEN E (2020) The attraction of urban cores: Densification in Dutch city centres. Urban Studies 57: 1920–1939. https://doi. org/10.1177/0042098019864019
- CHAKRABORTY S, DADASHPOOR H, NOVOTNÝ J, MAITY I, FOLLMANN A, PATEL PP, ROY U, PRAMANIK S (2022a) In pursuit of sustainability – Spatio-temporal pathways of urban growth patterns in the world's largest megacities. *Cities* 131: 103919. https://doi.org/10.1016/j.cities.2022.103919
- CHAKRABORTY S, MAITY I, DADASHPOOR H, NOVOTNý J, BA-NERJI S (2022b) Building in or out? Examining urban expansion patterns and land use efficiency across the global sample of 466 cities with million+ inhabitants. *Habitat International* 120: 102503. https://doi.org/10.1016/j. habitatint.2021.102503
- CHAKRABORTY S, PRAMANIK S, FOLLMANN A, GIRI B, MONDAL B, PATEL PP, MAITY I, DAS J, PUNIA M, SAHANA M (2021) Dominant urban form and its relation to nighttime land surface temperature in the rapidly urbanizing National Capital Region of India. Urban Climate 40: 101002. https://doi.org/10.1016/j.uclim.2021.101002
- CLAASSENS J, KOOMEN E, ROUWENDAL J (2020) Urban density and spatial planning: The unforeseen impacts of Dutch devolution. *PLOS ONE* 15: e0240738. https:// doi.org/10.1371/journal.pone.0240738
- CORBANE C, PESARESI M, KEMPER T, POLITIS P, FLORCZYK AJ, SYRRIS V, MELCHIORRI M, SABO F, SOILLE P (2019) Automated global delineation of human settlements from 40 years of Landsat satellite data archives. *Big Earth Data* 3: 140–169. https://doi.org/10.1080/20964471.2019.1 625528
- DEUTSCHE BUNDESBANK (2002) The housing market during the nineties. Monthly Report. Frankfurt am Main. https://www.bundesbank.de/resource/blob/706144/ baca6452f6d0a086da0c10afd29232d0/mL/2002-01-housing-market-data.pdf
- DEUTSCHER BUNDESTAG (1971) Umweltprogramm der Bundesregierung. Bundestags-Drucksache. Bonn. https:// dserver.bundestag.de/btd/06/027/0602710.pdf
- DIE BUNDESREGIERUNG (2021) Deutsche Nachhaltigkeitsstrategie - Weiterentwicklung 2021. Berlin.
- DORFFMEISTER L (2017) Construction of 1+2 family homes in Germany: Is the golden age over? CESifo Forum 18: 37–42. https://ideas.repec.org/a/ces/ifofor/v18y-2017i04p37-42.html.

- EICHHORN S (2023) Infilling in Germany. Estimating the extent of infilling in German municipalities between 1979 and 2011. *Landscape and Urban Planning* 240: 104895. https://doi.org/10.1016/j.landurbplan.2023.104895
- EICHHORN S, EHRHARDT D, MÜNTER A, BEHNISCH M, JE-HLING M (2024) Understanding land take by low-density residential areas. an institutionalist perspective on local planning authorities, developers and households. *Land Use Policy*. https://doi.org/10.1016/j.landusepol.2024.107198
- EICHHORN S, RUSCHE K, WEITH T (2021) Integrative governance processes towards sustainable spatial development – solving conflicts between urban infill development and climate change adaptation. *Journal of Environmental Planning and Management* 64: 2233–2256. https://doi.org /10.1080/09640568.2020.1866509
- EICHHORN S, SIEDENTOP S (2022a) Innen vor Außen? Eine Schätzung der Innenentwicklung in nordrhein-westfälischen Gemeinden, 1979 bis 2011. Raumforschung und Raumordnung. https://doi.org/10.14512/rur.178
- EICHHORN S, SIEDENTOP S (2022b) Innenentwicklung in Deutschland - ein Klassifizierungsansatz. MEINEL G, KRÜGER T, BEHNISCH M, EHRHARDT D (eds) Flächennutzungsmonitoring XIV. Beiträge zu Flächenmanagement, Daten, Methoden und Analysen: 139–148. Berlin.
- EUROPEAN COMMISSION (EC) (2023) CORINE Land Cover. https://land.copernicus.eu/pan-european/corine-landcover.
- EUROPEAN COMMISSION (EC) (2011) Roadmap to a resource efficient Europe. COM(2011) 571. Brussels. https://www.eea.europa.eu/policy-documents/com-2011-571-roadmap-to
- EUROPEAN COMMISSION (EC) (2006) Soil Thematic Strategy. COM(2006) 231. Brussels. https://www.eea. europa.eu/policy-documents/soil-thematic-strategycom-2006-231
- EWING R, CERVERO R (2017) "Does compact development make people drive less?" The answer is yes. Journal of the American Planning Association 83: 19–25. https://doi.org/ 10.1080/01944363.2016.1245112
- EWING R, LYONS T, SIDDIQ F, SABOURI S, KIANI F, HAMIDI S, CHOI D, AMELI H (2022) Growth management effectiveness: A literature review. *Journal of Planning Literature* 37: 433–451. https://doi.org/10.1080/01944363.2016.1245112
- GERTEN C, FINA S, RUSCHE K (2019) The sprawling planet: Simplifying the measurement of global urbanization trends. *Frontiers in Environmental Science* 7: 140. https:// doi.org/10.3389/fenvs.2019.00140
- GÖTZE V, JEHLING M (2022) Comparing types and patterns: A context-oriented approach to densification in Switzerland and the Netherlands. *Environment and Planning B: Urban Analytics and City Science*: 239980832211421. https:// doi.org/10.1177/23998083221142198

- GREIVING S, FLEX F, TERFRÜCHTE T (2022) Vergleichende Untersuchung der Zentrale-Orte-Konzepte in den Ländern und Empfehlungen zu ihrer Weiterentwicklung. *Raumforschung und Raumordnung* 73: 285–297. https:// doi.org/10.1007/s13147-015-0357-4
- HORTAS-RICO M, SOLÉ-OLLÉ A (2010) Does urban sprawl increase the costs of providing local public services? Evidence from Spanish municipalities. Urban Studies 47: 1513–1540. https://doi. org/10.1177/0042098009353620
- JEHLING M, HECHT R, HEROLD H (2018) Assessing urban containment policies within a suburban context—An approach to enable a regional perspective. Land Use Policy 77: 846–858. https://doi.org/10.1016/j.landusepol.2016.10.031
- KODINARIYA T, MAKWANA PR (2013) Review on determining number of cluster in K-Means clustering. *International Journal of Advance Research in*
- Computer Science and Management Studies 1: 90–95. https:// ijarcsms.com/docs/paper/volume1/issue6/V1I6-0015.pdf
- MOHAJERI N, WALCH A, SMITH A, GUDMUNDSSON A, Assouline D, Russel T, HALL J (2023) A machine learning methodology to quantify the potential of urban densification in the Oxford-Cambridge Arc, United Kingdom. *Sustainable Cities and Society:* 104451. https://doi. org/10.1016/j.scs.2023.104451
- MOURATIDIS K (2018) Is compact city livable? The impact of compact versus sprawled neighbourhoods on neighbourhood satisfaction. *Urban Studies* 55: 2408–2430. https://doi.org/10.1177/0042098017729109
- MUSTAFA A, VAN ROMPAEY A, COOLS M, SAADI I, TELLER J (2018) Addressing the determinants of built-up expansion and densification processes at the regional scale. *Urban Studies* 55: 3279–3298. https://doi. org/10.1177/0042098017749176
- NOVOTNÝ J, CHAKRABORTY S, MATTY I (2022) Urban expansion of the 43 worlds' largest megacities: A search for unified macro-patterns. *Habitat International* 129: 102676. https://doi.org/10.1016/j.habitatint.2022.102676
- OSTERHAGE F (2018) The end of reurbanisation? Phases of concentration and deconcentration in migratory movements in North Rhine-Westphalia. *Comparative Population Studies* 43: 131-15. https://doi.org/10.12765/CPoS-2018-10
- REISS-SCHMIDT S (2018) Innenentwicklung. ARL Akademie f
 ür Raumforschung und Landesplanung (ed) Handwörterbuch der Stadt- und Raumentwicklung: 995–1000. Hannover
- SCHILLER G, BLUM A, HECHT R, OERTEL H, FERBER U, MEI-NEL G (2021) Urban infill development potential in Germany: Comparing survey and GIS data. *Buildings and Cities* 2: 36–54. https://doi.org/10.5334/bc.69

- SIEDENTOP S (2008) Siedlungspolitischer Kontext des 30-Hektar-Ziels. KÖCK W, BIZER K, HANSJÜRGENS B, EINIG K, SIEDENTOP S (eds) Handelbare Flächenausweisungsrechte: 21– 35. https://doi.org/10.5771/9783845211442-21
- SIEDENTOP S, SCHMIDT S, DUNLOP A (2022) Managing urban growth – an overview of the literature. *Raumforschung und Raumordnung* 80: 659–677. https://doi.org/10.14512/ rur.1653
- STATISTISCHES BUNDESAMT (Destatis) (2010) 2011 Census. https://www.zensus2011.de/EN/Home/home_node. html.
- STORM S, NAASTEPAD C (2015) Crisis and recovery in the German economy: The real lessons. *Structural Change and Economic Dynamics* 32: 11–24. https://doi.org/10.1016/j. strueco.2015.01.001
- THORNE JH, SANTOS MJ, BJORKMAN J, SOONG O, IKEGAMI M, SEO C, HANNAH L (2017) Does infill outperform climate-adaptive growth policies in meeting sustainable urbanization goals? A scenario-based study in California, USA. Landscape and Urban Planning 157: 483–492. https://doi.org/10.1016/j.landurbplan.2016.08.013
- WOLFF M, WIECHMANN T (2018) Urban growth and decline: Europe's shrinking cities in a comparative perspective 1990–2010. European Urban and Regional Studies 25: 122– 139. https://doi.org/10.1177/0969776417694680

Author

Sebastian Eichhorn ORCID: 0000-0003-3825-0614 sebastian.eichhorn@ils-forschung.de ILS – Research Institute for Regional and Urban Development Department of Mobilities and Space Brüderweg 22-24 44135 Dortmund Germany