Urban infill development potential in Germany: comparing survey and GIS data

**ABSTRACT**

Limiting land take is an important sustainability target. To this end, infill development is a primary strategy. To implement this strategy, policy-makers need a reliable knowledge base on infill development potential (IDP), such as brownfields, vacant lots and underused lots. This study presents the results of the first comprehensive national survey of IDP in Germany. Almost 12% of German municipalities were contacted by questionnaire. In contrast to previous studies, this study also takes into account smaller towns and small-scale vacant lots, which would otherwise lead to a considerable underestimation. Additionally, a feasibility study shows how IDPs can be identified using a geospatial approach. Here, a procedure is presented that allows the identification of IDPs and the differentiation between vacant and underused lots by analysing urban morphology using nationwide and commonly available geospatial base data. The results provide a good basis for an initial inventory. However, to obtain more accurate results, additional specific data would be required, the accessibility of which is currently limited. With the development of an improved spatial data infrastructure combined with Open Data initiatives, geographical information system (GIS)-based procedures for the automated detection and monitoring of IDPs could become more important in future.

**POLICY RELEVANCE**

If the objectives of land policy, especially the avoidance of urban sprawl, are to be achieved, then the more efficient use of already developed land is essential. At the strategic level of policy development, knowledge of land suitable for infill development is as necessary as knowledge of the land take. Currently, regular standardised questionnaire...
surveying is the effective method for analysing infill development potential (IDP) and its
development on a large scale. Geospatial approaches can help to identify potentials,
especially on vacant and underused lots. Thus, they have a considerable potential to serve
as heuristic tools for local practitioners seeking to begin reflecting on infill development
options. Policy-makers and planners should recognise this potential and develop it further
in cooperation with the scientific community. However, decision-makers are not spared
from weighing the appropriate density in the respective context—and this has not become
easier under the impact of the current COVID-19 pandemic.

1. INTRODUCTION AND AIM OF THE STUDY

In the absence of policy interventions, urban settlements will cover 4–5% of global land area
by 2050 (Kemp-Benedict et al. 2002; Electris et al. 2009), by which point almost 70% of the
world’s population will live in cities (United Nations 2012). ‘As urban areas expand [...] they impact
the environment at multiple spatial and temporal scales’ (UNEP 2014: 50; see also Decoville
& Schneider 2015; Seto et al. 2010; Foley et al. 2005). At the same time, urban expansion is
frequently concomitant with decreasing city densities (UNEP 2014), leading to what is criticised
as urban sprawl: unused or underused spaces emerge, indicating development inefficiencies
(EEA 2006). Infill development is an important approach to reducing land take and countering
ongoing density losses to lead to more efficient land use (e.g. in terms of housing per unit of land
area or utilisation of urban infrastructure) (McConnell & Wiley 2010; Schiller 2007; Schiller et al.
2009). The importance of infill development has been recognised by national and supranational
settlement development strategies when defining growth limits for future land take (e.g. the ‘no
net land take’ goal for 2050 set by the European Commission 2011). Thus, to reduce the sealing
of agricultural land and open space as much as possible, building on land that has already been
used for settlement and construction purposes should be prioritised, and additional land take
should be ‘compensated for elsewhere’ (Science Communication Unit 2016: 6). Germany has set
an ambitious goal for itself to reduce land take from 66 ha/day in 2015 to <30 ha/day by 2030
(Bundesregierung 2016).

For effective policy-making towards these targets, information on the extent and spatial distribution
of likely infill sites, infill development potential (IDP), must be made available. However, there are
considerable gaps in knowledge. For instance, only nine European Union (EU) member states have
data on brownfield areas, and data on small-scale IDP of vacant lots, different from large-scale
IDP on brownfields, are not available in national surveys, with the exception of the analysis of
Germany (Schiller et al. 2013) presented in this paper (Van Long et al. 2014). The lack of up-to-date
national data also applies to the United States. Here, too, attempts are being made to improve
this condition by means of national surveys on urban vacancy in large American cities (Newman
et al. 2016).

In Germany, numerous initiatives at the regional and municipal levels have in the past investigated
IDP (e.g. Elgendy et al. 2011a, 2011b; Iwer 2011; FrankfurtRheinMain 2012). However, these
studies differ in terms of their methodological approaches, regional coverage and the spatial
categories they consider (i.e. vacant lots, brownfields, abandoned buildings and underused
or inappropriately used plots). As a result, the comparability of existing databases on IDP is
limited and not suitable for nationwide quantification of IDP. Existing nationwide surveys (BBR
2004, 2007) have considered only brownfields and included only cities with >5000 inhabitants.
Automated detection of IDP may help overcome the limitations of questionnaire surveys and
generate objective information at a reasonable cost. However, few studies have focused on the
development of geographic information system (GIS)- or remote sensing-based approaches
(e.g. Banzhaf & Netzband 2004; Bacon 2007; Moser et al. 2015; Moudon 2001). Moreover, an
automated procedure for large-scale analysis that builds on geospatial data with nationwide
coverage has not been developed and tested.
This paper presents the conceptual basis and the results of an online questionnaire survey conducted in 2012 and used to generate more comprehensive and reliable nationwide data on IDP in German cities, towns and villages. In addition, an automated GIS approach for monitoring IDP based on the currently available geodata is presented and discussed.

The paper is structured as follows. It begins by providing definitions of the basic terms used in this study. The methods and results of the online survey are then presented. This is followed by the development and testing of an approach for the automated detection of IDP. In the discussion section, the results of the survey and the pilot application of a GIS analysis are discussed, with a focus on key findings regarding the requirements of a nationwide knowledge base on IDP. The conclusions reflect upon the role of surveying and automated GIS analysis for the generation of quantitative data on IDP to support sustainable settlement policies.

2. TERMS AND DEFINITIONS

To generate reliable data, the meaning of ‘infill’ must be clearly defined, the basic definition of ‘potential’ must be determined, and the types of infill development sites that are to be considered must be designated.

For the online survey, the definition of an ‘infill’ site followed the legal planning criteria established in German building legislation (the German building code, BauGB). Thereby particular reference was made to the regulations on the eligibility of construction projects and urban developments on development plan sites (§ 30 BauGB) and within established settlement areas that show a close functional relationship (§ 34 BauGB). The particular wording used for the questionnaire was determined based on Korda (2005) and Lütke-Daldrup (1989):

• **Infill sites**: Public and private land plots in established settlement areas (urban developments, buildings, urban traffic infrastructure and urban green space) that already enjoy a close functional relationship and on development plan sites. Development sites completing existing urban structures at the edge of settlements (so-called *Arrondierungsflächen*) are not regarded as offering IDP. The same applies to development plan areas for which the corresponding building right has not yet been established.

The focus of the analysis is on the theoretical potential of infill development sites. The objects of interest are all sites within established settlement areas that offer space for infill development, regardless of market availability and concrete intentions of use (according to Preuß 2007; MWKEL 2011). These sites do not have to be considered likely sites for construction and may also be suitable for development as green space for leisure and recreation.

In terms of quantification, the IDP can be measured in square meters (m$^2$) or hectares (ha), which can be later related to data on population (e.g. m$^2$ IDP/inhabitant) or total settlement area in use (e.g. percentage of settlement area).

Various definitions of infill development land-use types can be found in the literature (e.g. CABERNET 2006; Preuß & Verbücheln 2013; Newman et al. 2018). To design and implement a nationwide analysis of IDP, it is essential to differentiate sites according to simple, clearly defined classes. Brownfields, vacant lots or underused lots in principle meet these criteria, while also encompassing the most important land-use classes suitable for infill development. However, since no commonly accepted and consistently used definitions are available, the understanding should be made as explicit as possible. To this end, the three classes of IDP were defined as follows:

• **Brownfields** are abandoned or temporarily used built-up sites, e.g. industrial wasteland, conversion wasteland (for which an entirely new function is foreseen), infrastructural and transportation brownfields, commercial brownfields, residential brownfields, abandoned buildings, abandoned agricultural estates, and cultural and social brownfields (following Ferber 1997; Ferber et al. 2004; BBR 2004; Dransfeld et al. 2002).
Vacant lots are non-built-up sites (individual lots and several contiguous lots without buildings) that offer potential for development. These sites lie within established or newly developed settlement areas (following Ferber et al. 2004; MWKEL 2011; Schiller et al. 2009).

Underused lots are plots of land that are already built up but offer space for further development. Some examples are second-row development and courtyard development, as well as complementary buildings in residential, mixed-use and commercial areas (following Gutmann et al. 2004: 149–159; Elgendy et al. 2011a, 2011b).

3. ONLINE SURVEY

3.1 METHODOLOGY OF THE ONLINE SURVEY

Following earlier nationwide surveys on urban construction land that were conducted by the German Federal Office for Building and Regional Planning (BBR) (2004, 2007), data on IDP were gathered using a standardised online questionnaire. However, in contrast to the earlier surveys, the aim was also to capture data on vacant lots and for smaller towns and municipalities with <5000 inhabitants that were expected to have considerable IDP available (e.g. Scholl 2003).

In addition to the core objective of quantifying IDP, i.e. asking for the amount of IDP in hectares and its distribution across brownfields and vacant sites, the questionnaire covered different thematic issues. In order to derive recommendations for the management and increased utilisation of IDP, more qualitative information was gathered, such as experiences and expectations concerning the (re-)use of IDP, local monitoring of IDP data (i.e. frequency, information gathered, obstacles and requirements), and the political, economic and organisational context of infill development activities. The questionnaire also asked whether monitoring of IDP was planned or taking place and if the provided data on IDP were taken from existing databases or based on estimates by local experts. The information on local monitoring of IDP data was also used as an indicator of data reliability.

With respect to sampling, the survey included cities and municipalities of all sizes, ranging from large cities with at least 100,000 inhabitants to rural communities with <5000 inhabitants. However, to ensure feasibility, it was necessary to limit the surveying effort to a certain extent. Adopting the BBSR (2012) typology of cities and communities and taking into account the varying number of cities and communities in the different classes, different subsample sizes were defined: 100% of large cities (≥100,000 inhabitants), 20% of medium-sized cities (20,000–99,999 inhabitants), 10% of small towns (5000–19,999 inhabitants) and 5% of rural communities (≤5000 inhabitants) were included from all German federal states. This approach corresponds to a disproportional stacked random sample. According to literature on survey sampling, by applying a stacked sample, the overall reliability can be increased while the survey costs are reduced compared with a simple random sample (Häder & Häder 2014: 286; Kromrey 2002).

In all, 1315 (11.7%) of the 11,255 German cities and municipalities (at the time of the survey) were contacted via email and asked to participate in the online survey. A total of 451 usable questionnaires were returned (large cities, 62; medium-sized cities, 114; small towns, 209; rural communities, 66). This participation accounted for an overall response rate of approximately 34% and a realised sample rate of 4% of all German cities and municipalities.

Given a total population of 11,255 cities and municipalities, the sampling error was calculated (according to Rinne 2003) to be a maximum of 4.5% for the overall survey result of 451 returned questionnaires, at a confidence level of 95%. Thus, with respect to the number of returns, the survey can be considered representative of the cities and municipalities in Germany. Additionally, the geographical distribution of the participating cities and municipalities covers all the German federal states, thus reflecting the complete range of different context conditions. However, since the targeted critical minimum number of 30 returns was not reached for all federal states, results were calculated only for Germany as a whole and for a comparison of West and East Germany, which still show considerable development differences.

Furthermore, the quantitative survey was supplemented by qualitative, semi-structured, open-ended, case study interviews. Representatives from the planning authorities of 29 medium-sized
cities and small towns from the survey sample that had agreed to provide additional information were contacted as experts to identify sources of errors (e.g. different understanding of IDP and problems of identification of IDP) and to improve the interpretation of the quantitative results (e.g. with respect to deriving explanatory hypotheses). The cases were selected representing East and West Germany, medium-sized cities and small towns, and municipalities providing estimated IDP data as well as those having IDP databases in place. The case study focus was on medium-sized cities and smaller towns because the survey results indicated the most difficulties and uncertainties for this group of municipalities. Sixteen of the interviews were held face to face during a case study visit (including onsite observations), and 13 were conducted as telephone interviews.

When standardised questionnaires are used, ensuring the highest possible degree of interrater reliability is crucial. With respect to quantifying IDP, however, interrater reliability is difficult to control because each ‘rater’ (respondent) ‘rates’ a different subject (quantity of local IDP). Reliable IDP survey data can therefore only be expected for land categories that are likely to be consistently understood and identified by the responding local actors without referring to particular local spatial planning considerations or culture. This condition is true for both brownfield sites and vacant lots, but not for underused lots, since the qualification of ‘underused’ is based on a subjective judgement that is typically influenced by local planning practices, culture and context. Therefore, in order to minimise the likelihood of definitional disparities, the questionnaire concentrated on the most tangible categories of brownfield sites and vacant lots according to the definitions given above. Additionally, as already mentioned, the interviewees were asked whether the reported data on IDP were based on estimates or taken from existing databases. Finally, the consistency of the generated data was controlled using several methods. Implausible data were identified (e.g. extreme outliers of IDP > 50% of overall settlement area), validated (e.g. referring to qualitative comments and explanations in the questionnaire or using aerial photography data of the respective municipality), corrected where the respondents agreed to give contact information, or eliminated if confirmation or correction was not possible. With respect to the categorisation of IDP data provided by the respondents as estimates compared with data taken from existing databases, a tendency of estimated data being clearly lower than data from databases was observed, in particular for municipalities between 1000 and 20,000 inhabitants. Therefore, it was decided to perform two calculations, leading to low and high estimates of IDP (see also the discussion section below). In terms of generalisation, the different subsample sizes and return rates were taken into account by applying city-type-specific weightings derived from a projection of population and settlement area data based on the realised sample.

3.2 RESULTS OF THE ONLINE SURVEY

More than 90% of the municipalities that participated in the survey were able to provide quantitative information on IDP according to the defined classes. After evaluating the collected data as described above, we could calculate a value for the IDP of brownfield sites and vacant lots in Germany of approximately 15 m²/inhabitant as a low estimate. This corresponds to a total area of approximately 120,000 ha. More than one-quarter of this capacity was found in municipalities with <5000 residents, which were not included in earlier surveys.

With corrective factors applied to the assumed incorrect (low) values reported based on local estimates, the calculated overall value for the IDP rose to approximately 20 m²/inhabitant or a total of 165,000 ha as a high estimate. Thus, it was possible to determine an approximate plausible value range for IDP between 15 and 20 m², which is also in line with earlier regional surveys that produced similar results. For a detailed comparison, see Schiller et al. (2013).

Although 30 years have passed since the reunification of East and West Germany, urban development policy-making, among other issues, still has to address different economic and demographic development trends in both parts of the country. Therefore, it makes sense to look at possible differences also with respect to IDP. As a result, the average overall IDP (low estimate) for East Germany adds to 22 m²/inhabitant, while in West Germany it is 13 m²/inhabitant (Figure 1) (all
values representing low estimates). There is also a clear divergence between rural municipalities and towns or cities. Rural municipalities display the highest specific IDP at >25 m²/inhabitant, but this drops as the size of the municipality increases and finally declines to only 9 m²/inhabitant for large cities. However, it can be assumed that these population-based rural–urban differences can, to a large extent, be attributed to the impact of population density effects. When analysed spatially (IDP/settlement area) rather than by population (IDP/inhabitant), the value for the IDP is broadly similar across all types of municipalities and generally constitutes between 5% and 7% of municipalities’ settlement areas.

The IDP is particularly high in municipalities that are strongly shrinking (i.e. loss of population >–1.5% per annum). Calculated as the share of the settlement area, the value for IDP in these shrinking communities is almost three times that in strongly growing (population gains >1.5% per annum) municipalities (7.3% compared with 2.6%). However, population growth is not necessarily associated with low IDP. The calculated potential is somewhat similar in municipalities showing moderate growth or shrinkage; in fact, the IDP in moderately growing municipalities is higher than that of stagnating or moderately shrinking municipalities (5.7% compared with 4.7%) (for a more detailed discussion, see below on population dynamics).

Vacant lots constitute the predominant form of IDP at 56%, whereas brownfields constitute 44% of IDP (Figure 2). In West Germany, vacant lots are dominant (the approximate ratio of vacant lots to brownfields is 60:40), whereas the situation is the reverse in East Germany (40:60). There are also considerable differences among the various types of municipalities. Brownfields clearly predominate in large cities (10:90), but the ratio approaches the average for West Germany in medium-sized and smaller towns and in rural municipalities. Brownfields are slightly dominant in cities (40:60).

Regarding the analysis of the classes of population development described above (strongly shrinking, moderately shrinking, stable, moderately growing and strongly growing municipalities), the results do not suggest a systematic interconnection between population trends and the ratio between these two categories of IDP (brownfields and vacant lots).

Another issue surveyed was the activities of local communities in monitoring IDP data. One unexpected result of the survey was the low level of systematic data capture on IDP undertaken by the municipalities (Figure 3).
Only about one-third (35%) of the responding municipalities had a structured data-collection system for IDP in place, with clear disparities between East and West Germany (20% versus 40%). Figure 3 shows that a relationship between municipality size (in five classes) and IDP data collection can be assumed. The values for the implementation of data collection rise from 25% of rural communities to 100% of large cities. This result is in agreement with the finding that >70% of municipalities indicate that their reported knowledge of local IDP is at least partly based on estimates (e.g. data collection for brownfields is established, whereas the values for vacant lots are estimated). For a discussion of this issue and other uncertainties in quantifying IDP, see also the respective section below. However, the assumption—and experience from earlier, more limited surveys—that questionnaire surveys of IDP have to address certain limitations has led to the second track of research: a feasibility study of automated detection of IDP, which is presented in the following section.

**Figure 3:** Reported activities to capture infill development potential (IDP) data by type of municipality and by region. Source: Authors.
4. FEASIBILITY STUDY OF GIS-BASED AUTOMATED DETECTION OF IDP

In order to potentially overcome limitations of monitoring IDP via a questionnaire survey and to reduce data-collection efforts in the future, a feasibility study was added to the survey conducted in this study. A GIS approach for the automated recognition of IDP based on commonly available geospatial base data was developed. The focus was on using available geospatial data from the National Mapping and Cadastral Agencies with full nationwide coverage and regular updates (e.g. digital landscape models and cadastral information systems).

4.1 PREVIOUS APPROACHES TOWARDS THE AUTOMATED DETECTION OF IDP

Only a few scientific papers deal with the automatic recognition of IDP by means of spatial analysis and remote sensing. Early experiments for the automatic identification of brownfields were based on remote sensing approaches. Banzhaf & Netzband (2004) presented an object-based image classification approach to detect brownfield sites in the US city of Baltimore, Maryland, using high-resolution panchromatic and multispectral imagery from the IKONOS Earth observation satellite. Further attempts aimed at the detection of brownfields using remote sensing imagery were made by Nelson (2005), Atturo et al. (2006), Tarantino & Caprioli (2006), Bacon (2007), Ferrara (2008), Volpe et al. (2008) and Vasques (2009). For instance, Bacon (2007) applied an object-oriented classification approach to high spatial resolution aerial imagery of the city of Syracuse, New York, to identify potential brownfield sites during the inventory stage of the redevelopment process. The results show overall accuracies of 93% and 97%. The high overall accuracy is mainly due to the large number of correctly classified non-brownfields. Class-specific accuracy measures show a high rate of commission error (high number of false positives) for brownfields (i.e. non-brownfield sites that have been wrongly classified as brownfield sites). However, according to Bacon (2007), these errors are preferable to high omission error rates that would exclude many sites for possible redevelopment. Thus, the existing techniques only generate information on potential brownfield sites, and manual field verifications are essential in a post-processing step to eliminate false positives. Additionally, a project that aimed to develop ‘Urban Land Recycling Information Services for Sustainable Cities’ (Moser et al. 2015; Manzke et al. 2016) came to the conclusion that the detection of brownfield sites using available satellite images and the Urban Atlas alone was nearly impossible (Manzke et al. 2016).

The automated or semi-automated identification of vacant and underused lots has only been attempted at the municipal or regional level to date (Moudon 2001; Alles 2007; Mouwerik & Mann 2007; MWKEL 2011; Iwer 2011; FrankfurtRheinMain 2012; Prener et al. 2018). Cadastral agencies provide the appropriate database for a GIS-based analysis at lot level by spatially intersecting lot boundaries with building footprint information and/or other thematic information. The derived information on identified vacant and underused lots can be used to create an inventory of IDP in the context of a land-use management system. However, the state of the art shows that this type of automatically derived information only represents preliminary data, which must be validated with in situ information and local expert knowledge. In addition, the required cadastral data are not always available. Therefore, the aim of the feasibility study was to develop and test an automated procedure for large-scale analyses using geospatial data with nationwide coverage.

4.2 METHODOLOGY OF THE FEASIBILITY STUDY

Automated data processing requires input data that are machine readable and machine interpretable. One precondition for the development of an automated procedure to estimate IDP for a whole nation is the availability of a homogeneous and consistently structured data set with full coverage. Regular updating of the data must be ensured for monitoring over time.

Official geospatial data sets that meet these requirements are the German Digital Landscape Model ‘ATKIS Basis-DLM’ of the Authoritative Topographic Cartographic Information System (ATKIS) (Federal Agency for Cartography and Geodesy 2016) in combination with the Official House Coordinates (HK-DE) and Building Polygons (HU-DE) generated from the German digital cadastral
information system (AdV 2014). These geospatial data sets were used to set up an automated procedure for the recognition of sites suitable for infill development. The detection procedure consists of three basic steps implemented within a GIS (Figure 4).

Figure 4: Workflow of the automated analysis of infill development potential (IDP). Source: Authors.
The first step is to define the input data, i.e. areas of particular types of land use on which infill development can take place (Figure 4a), as well as the building polygons and house coordinates (Figure 4b). In a pre-processing step, all built-up areas (city blocks) with relevant land use (residential, mixed, industrial/commercial, special functional character) and the transport infrastructure network that lie within existing settlement boundaries (ATKIS feature type Ortslage) are extracted from the ATKIS Basis-DLM. The building polygons and house coordinates were taken from the HU-DE and HK-DE data set and pre-processed according to Hartmann et al. (2016).

In the second step, excluded areas not suited for infill development are identified (Figure 4f). This step was performed by spatially overlaying built-up areas with building polygons (Figure 4c), their clearance areas (Figure 4d) as well as the areas for transport infrastructure (i.e. streets and railroads) (Figure 4e). All buildings <20 m² were excluded in this analysis, as we assumed that these are not permanent buildings that hinder infill development. The clearance areas are those areas that are to be kept free of buildings. These areas were computed by formalising the distance rules from German building regulations (‘Musterbauordnung’, MBO). The MBO states that the depth of the clearance area should be at least 0.4 times the building height, with a minimum depth of at least 3 m. In commercial and industrial areas, a depth of 0.2 times the building height or at least 3 m is sufficient. As the building polygons do not have any height information, they were initially classified according to single- and multi-family houses using the underlying land use and a simple threshold of 150 m². All single-family houses were given a mean height of 4.2 m and multi-family houses a height of 10.5 m. A standard depth of 3 m was used for all industrial and commercial buildings. For the generation of the areas for infrastructure, all linear transport infrastructure features of ATKIS were buffered using the feature attributes (e.g. road width or number of lanes). Here we used the procedure from Krüger et al. (2013).

In the third step, potential infill development sites were extracted by erasing the excluded areas from built-up areas (Figure 4g). All sites for which sizes and shapes prevent sensible infill development were omitted by applying morphological filtering (Gonzalez & Woods 2002). Here we applied a morphological opening operation (an erosion followed by a dilation) using a circular structuring element with a diameter of 16 m (defined minimal dimension of a development). The remaining areas (the blue areas in Figure 4g) were then further differentiated based on the connection to the road network. Areas with a small distance to the road network (≤20 m) were classified as vacant lots (the red areas in Figure 4h); the rest were classified as underused lots (the blue areas in Figure 4h).

4.3 PILOT APPLICATION

The developed approach was piloted in 16 small and medium-sized cities for which questionnaire survey data were available and which were visited as case studies for expert interviews and qualitative analysis, as described in the survey methodology section. Thematic maps were derived from an application of the automated procedure that placed the IDP on vacant lots as a thematic layer over the topographical map at a scale of 1:25,000. The identified theoretical IDPs were discussed in detail during the qualitative interviews with experts from the local planning authority. Furthermore, the automatically processed results were compared with those of the survey. The comparison presented and discussed below refers only to vacant lots, since comparative data were available from the questionnaire, which was not true for underused lots.

The discussions with local planning experts provided the information needed to identify and classify sources of error and revealed the practical limitations of the automated analysis.

A manual validation of the results using aerial imagery revealed several sources of errors. Figure 5 shows different categories of errors and their calculated relative shares as percentages. The largest share of errors (39%) is caused by missing lot boundaries. This share is followed by errors that occur due to data abstraction and generalisation in ATKIS, which result in false-positive infill potential sites that are, in reality, public green and leisure spaces within housing blocks (30%), sealed surfaces, such as car parks and town squares (18%), or other small commercial and industrial sites without buildings (9%). Data quality issues, such as up-to-dateness (3%) and mapping errors (e.g. wrong land use) (1%), play a minor role.
For an explorative quantitative validation of the approach, five of the 16 on-site case studies were selected for comparison, for which the qualitative interviews confirmed that the initial data for vacant lots from the questionnaire are correct. This comparison of the results from the automated estimation of the infill potential of vacant lots with the respective questionnaire survey results shows the absolute and total differences in Table 1. The results indicate that the automated procedure tends to result in higher IDP values than the questionnaire survey data. The respective differences for the five test cases range from –6.7% to 342%.

| CASE STUDY | SETTLEMENT AREA (BUILDINGS AND ASSOCIATED OPEN SPACE) (HA) | IDP ON VACANT LOTS (HA) | ABSOLUTE DIFFERENCE (ADP – QS) (HA) | RELATIVE DIFFERENCE (%) |
|------------|----------------------------------------------------------|-------------------------|-------------------------------------|-------------------------|
| 1          | 54                                                      | 3.0                     | -0.2                                | -6.7%                   |
| 2          | 108                                                     | 2.5                     | 0.8                                 | 32.0%                   |
| 3          | 132                                                     | 1.0                     | 2.1                                 | 210.0%                  |
| 4          | 1088                                                    | 14.0                    | 47.9                                | 342.1%                  |
| 5          | 990                                                     | 17.0                    | 35.3                                | 207.7%                  |

Although the results of the pilot application of the automated procedure (especially the cartographic representation) were appreciated by the local experts as a valuable heuristic basis for discussion of local infill development activities, the overestimation due to false-positive detections (in particular caused by missing lot boundary information) (cf. Figure 5) was not acceptable from a practical perspective.

The automatic approach was therefore further developed to show the potential for quality improvement by introducing additional geodata which are not necessarily nationally accessible but contain important information to support the automatic identification process. For this purpose we used data from the Authoritative Real Estate Cadastre Information System (ALKIS®) that contain the lot geometry, on the basis of which better identification of vacant and underused lots is possible. This makes it possible to exclude areas not suitable for development due to an unfavourable lot size, shape or arrangement. ALKIS also provides spatially and thematically higher resolution information on land use. Small public areas such as playgrounds, inner urban green spaces or car parks are modelled explicitly and can be considered as areas not suited for infill development. A further advantage of ALKIS is better modelling of transport infrastructure (streets, roads, etc.) with polygons.

Table 1: Infill development potential (IDP) of vacant lots based on the questionnaire survey and automated detection procedure.
The improvement by using ALKIS in the processing could be demonstrated for a case study in Brandenburg. Equivalent to the approach based on ATKIS, all areas (in this case, lots) that are residential, mixed, or industrial and commercial and that lie within existing settlement boundaries (ATKIS feature type Ortslage) are considered. All other lots belonging to the categories sports, leisure and recreation areas, cemeteries, road and traffic areas, or vegetation and agricultural areas are not taken into account.

The detection of vacant and underused lots was based on the building coverage (BC). For this purpose, the lot areas are intersected with the building polygon and the share of lot area covered by buildings is calculated as a percentage. On the basis of BC and the road connection, the following types could be distinguished using the threshold values according to FrankfurtRheinMain (2012): vacant lots (BC < 3%) and underused lots with a high IDP (BC 3% to <15%), areas with a low IDP (BC 15% to <30%) and areas without an IDP (BC ≥ 30%). Figure 6 shows a section of the result of the automated detection using ALKIS in comparison with the results using ATKIS. Using lot geometry allows better identification of the vacant lots. It can be expected that the use of ALKIS will significantly reduce the overestimation of the automated approach. Other data could also be used to further refine the model, e.g. topographical data using a digital terrain model with resolution of ≥10 m or hazard maps containing information on flood-prone areas. The use of these data would enable significant model improvement if these data were available nationwide. Spatial data infrastructure and Open Data initiatives of the responsible authorities could make this possible in the future.

5. DISCUSSION

5.1 UNCERTAINTIES

For the first time, a comprehensive and detailed quantification of IDP at the national level is provided using the results of a representative online survey. However, some uncertainties remain. A serious uncertainty occurred because the surveyed data from 70% of the respondents were at least partially based on estimates. To this end, additional qualitative information (comments, explanations) collected in the questionnaire, and the comparison of data provided based on existing databases with data provided based on estimates, indicated an underestimation of IDP rather than an overestimation. Respondents referred to factors such as site availability (‘we only consider sites which we are in a position to develop’), notions of what constitutes infill potential
(‘low density housing in villages does not constitute vacant lots’), and individual perceptions (‘what one has in view’). Assuming that the data provided by responding municipalities, which made use of existing data, could be considered more reliable, we could calculate corrective estimates for the assumed incorrect (lower) values based on the estimated data. In short, corrective factors were calculated and applied for different city size classes, assuming that municipalities providing estimated data should in reality have a similar share of IDP as expressed by the data provided by municipalities with IDP databases in place. As a result, the calculated overall data for IDP rose to approximately 20 m²/inhabitant, or a total of 165,000 ha. This calculation suggested that the initial value of 120,000 ha, or 15 m²/inhabitant, was the lowest estimate of the existing potential. This assumption seems even more plausible considering that further IDP are explicitly not considered in the survey, particularly underused lots for which reliable data are difficult if not impossible to capture using a standardised questionnaire survey. According to existing studies (e.g. Müller-Herbers & Kauerts 2010; Nebel et al. 2012), such ‘fuzzy’ potential may even exceed the dimension of existing development potential on brownfields and vacant lots.

5.2 POPULATION DYNAMICS AND IDP

Another factor worth discussing is the link between population dynamics and IDP. As mentioned above, an interconnection of both is only indicated in cases of extreme forms of growth and shrinkage. The survey results show that moderately growing municipalities and moderately shrinking municipalities tend to have similar IDP. This effect can be attributed to the impact of several diverse local conditions. For example, in a context of economic growth, limited development potential in established urban areas can force companies to relocate from urban sites to those outside settlement boundaries. The abandoned urban plots may only partially, and often with a certain time lag, undergo redevelopment for housing or some other function, leading to IDP as a result of structural change and despite economic and population growth.

5.3 MONITORING

The results of the present survey provided a cross-sectional snapshot of a specific point in time. To consider developments corresponding to land-use monitoring, and particularly to achieve sustainability targets, there is also a need to develop an IDP monitoring procedure. As mentioned above, monitoring IDP via a questionnaire survey requires considerable effort, such as generating a mailing list to approach competent municipal representatives, pretesting the questionnaire, sending reminders and quality controlling the returned data. Geospatial base data from national mapping and cadastral agencies can support the monitoring process because the data can be analysed by automated procedures and, in principle, are appropriate to support objective, comparable and reproducible information.

To date, however, remote sensing-based approaches have limitations in the automated estimation of nationwide IDP because the large-scale provision of geospatial data is costly. Both topographical data from ATKIS and building polygon data meet the data requirements for automated monitoring as data are available nationwide in a common data structure and regular updating is ensured by the mapping authorities. However, currently, the application of an automated approach based on these data leads to higher values for IDP than can be empirically verified on-site. These results are not yet suited to making valid estimations of the absolute value of IDP. To recognise IDP more reliably, additional information is required. The use of ALKIS, which contains data on individual lots, results in more precise modelling and identification of vacant and underused lots. The value for IDP was six times lower when using ALKIS, and thus the number of wrongly identified IDP sites (false positives) was reduced accordingly. The main practical issue of using ALKIS data is limited accessibility due to the federal organisational structure of surveying in Germany. The data need to be acquired from each of the 16 German states separately, which currently creates additional licensing costs for nationwide applications. However, even if some federal states already make authoritative data openly available, a key challenge remains unsolved: at present, distinguishing between buildings in use and those not in use is not possible. Thus, brownfields, which are usually built up with abandoned buildings, cannot be adequately detected as IDP. This issue requires
further research, especially using big data, such as sensor data or remote sensing imagery, to measure human activity on the sites (e.g. vehicles or night lights). A further improvement of the GIS-based approach could be achieved by using refined settlement boundaries instead of the given ATKIS feature type Ortslage from ATKIS. These boundaries can be extracted, for example, by using the automatic approach from Harig et al. (2016) that takes into account urban morphology (buildings and road network).

Beyond the top-down perspective outlined above, it is worth changing the perspective to a more bottom-up methodological approach. For the consistent and tailor-made orientation of national land policies towards the existing settlement structure, the government needs reliable information on IDP. This information can be gained from the municipalities using the classic survey approach described in this article. Large cities can provide this information fairly easily because they usually have their own monitoring systems. Efficiency potential regarding the survey and evaluation methodology is to be found in particular in the use of standardised definitions of infill development land-use types in both municipal and nationwide surveys. In medium-sized and small towns, such information is often not available. This makes reporting difficult. Further development of the GIS-based approach into a supporting municipal tool for the initial identification of IDPs could (bottom up) help to improve this situation and thus indirectly improve the effectiveness of repeated monitoring using classic surveys. Another option would be to conduct a GIS-based initial inventory of IDPs at the state level using the developed tool and make the results available to municipalities as a web service (Herold et al. 2014). However, beyond such methodological solutions, the issue of insufficient technological, monetary and, in particular, human resources was also mentioned frequently, particularly by the smaller cities and towns. To this end it is still an open question whether federal and state government could, for example, initiate a support programme for the municipalities with respect to an initial inventory of IDP.

5.4 MARKET AVAILABILITY OF IDP

In addition to the issue of IDP surveying and detection, the questionnaire and the case study research also covered the market availability of IDP. In all, the respondents considered 20% of the reported IDP as available for the market in the short term and 50% in the longer term. The remaining 30% of the IDP were classified as not available for the market. The difficulties of bringing IDP in use were described by one case study example. In this particular case study city, all owners of vacant plots were contacted by mail asking them about their plans with respect to bringing their land to the market. As a result, only 10% answered, and of these again only 10% were interested in making their land available for the market. Another case study representative raised the issue of social resistance against the densification of underused land. For the example of a small apartment house in a neighbourhood of detached single-family homes, the importance of transparent and early-stage participative planning processes was underlined.

In this context, the literature also points to the relevance of a cadastral structure, which has a significant influence on the urban form and infill development options. Specific arrangements can hinder urban densification processes. Adapting the existing built environment to social, ecological and economic changes through infill development often conflicts with a resistant cadastral structure (Gallagher et al. 2020). Analysing the past IDPs using an ATKIS-based approach in combination with a cadastre-based analysis of the changes in densities over time offer the opportunity to analyse retrospectively infill developments and relate them to the cadastral structure. It would be interesting to examine whether residential areas with fragmented cadastral structure are more resistant than less fragmented mixed-use areas with respect to the cadastral organisation.

6. CONCLUSIONS

Despite stagnating or only slightly rising population figures in Germany, urban sprawl continues. In 2010, the reference year for the figures on infill development potential (IDP) presented here, the daily increase in the land area used for settlement and transport in Germany was 87 ha
Approximately 40% of these were settlement areas. Given the determined IDP in the order of 120,000–165,000 ha (see ‘Results of the online survey’), the existing IDP on brownfields and vacant lots in an optimistic variant at that time offered purely the mathematical potential to cover urban new land requirements for the next 13 years within the settlement stock and thus pause urban sprawl accordingly. If the assumed ‘fuzzy’ potential for the densification of underused settlement areas was also taken into account, this period could even increase to 25 years. In such a scenario, the achievement of ‘no net land take’ (European Commission 2014: 27) becomes imaginable. In fact, the latest figures show that, until 2018, the use of previously unused or differently used land (e.g. agricultural land) for settlement and transport purposes in Germany has fallen to around 56 ha/day (Umweltbundesamt 2020). Along with this, settlement density in urban areas in Germany has risen by around 3 percentage points since 2010, while density in rural areas has fallen slightly by 1 percentage point (Destatis 2018). This can have a variety of causes: a stronger pursuit of infill development—which can clearly be observed in particular for housing—is only one of several attempts to explain this. Different dynamics of population development as well as a rising relevance of land-saving construction can be further causes for this. The available figures alone do not answer the question raised here. It is clear, however, that infill development can make a significant contribution to containing urban sprawl and that there still seems to be potential, particularly in rural regions, to strengthen this further by increasing settlement density. To what extent this also applies to urban areas requires further specific consideration. Here it is also worth reflecting on the extent to which social innovations, such as shared space concepts, which entail less consumption of living space, can make an additional contribution to this.

In any case, at the strategic level of policy development, knowledge of potential land suitable for infill development is as necessary as knowledge of the land-take intensity if urban sprawl limits are to be taken seriously. The results of the national survey for Germany indicate the importance of taking into account a wide scope of potential. In particular, this requires considering IDP in large as well as small municipalities and both large sites (typically brownfields) and small sites (typically vacant lots). Half the IDPs identified by the online survey are found in municipalities with populations <20,000. Small municipalities of <5000 residents, which were not included in earlier surveys, still provided more than one-quarter of the overall IDP. Regarding the type of IDP, a survey of IDP that only considers brownfields and disregards vacant lots will capture only approximately half the overall potential.

Currently, regular standardised questionnaire surveying appears to be the most effective method for analysing IDP and its development on a large (e.g. nationwide) scale and can also offer regional differentiations. Standardised questionnaire surveying is particularly recommended for the detection of IDP sites that can be easily and consistently identified by local planning experts (typically, brownfields and vacant lots). IDP on underused lots (due to their subjective character, according to subjective local planning considerations and valuations) is difficult to capture using standardised questionnaire surveys but may be considered in any future automated procedure. Based on geospatial base data, it is possible to estimate the IDP of vacant and underused lots automatically. The advantages of automated procedures are objectivity, comparability and reproducibility and their more efficient application over large areas. Thus, the automated analysis of IDP using spatial base data has clear potential to support the identification and long-term monitoring of IDP at different levels of spatial planning. However, currently, the main obstacles to this goal are gaps in the information base and the incomplete spatial coverage of appropriate data (ALKIS for the German case). Steps taken to remove these obstacles will serve to support an urban development policy that focuses on the conservation of land and the exploitation of IDP. The most promising approach so far seems to be a combination of both approaches: the standardised online questionnaire survey (top down) and the provision of supporting geographical information system (GIS)-based tools that can be used at the municipal level for initial inventory of IDP (bottom up) as a basis for further enrichment with local knowledge. In this way, the strengths of both approaches can be combined: addressing generalisation requirements at the national level, and systematically capturing and integrating contextual knowledge at the local level.
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